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How Can EVs Support High RES Penetration in Islands

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Abstract: The electrification of the transportation sector contributes to a cleaner environment in non-interconnected island (NII) systems or standalone islands. Moreover, e-mobility can significantly contribute to achieving very high renewable energy source (RES) penetration levels in islands, allowing a reduction both in the emissions due to the conventional generation and the system's cost. Increased RES penetration, however, can pose technical challenges for an island's system. In order to overcome these challenges, new technologies like grid-forming converters are important. Moreover, the provision of new ancillary services in relation to battery storage systems might be considered, while novel control and protection schemes are needed to ensure secure operation. E-mobility can also contribute to solving technical problems that arise from very high RES penetration by providing frequency containment reserves or reactive power compensation. Since EV charging demand introduces modifications in the system's load curve, e-mobility may affect the power grid for long-term planning and short-term operation, i.e., line loading and voltages. The application of specifically developed smart charging methodologies can mitigate the relevant grid impact, while effective exploitation of EV–RES synergies can achieve higher RES penetration levels. This paper examines how e-mobility can contribute to increasing RES penetration in islands while considering the technical issues caused. In particular, this paper takes into account the distinct characteristics of NIIs towards the identification of solutions that will achieve very high RES penetration while also addressing the relevant technical challenges (voltage control, frequency control, short circuit protection, etc.). The effect of e-mobility in the power grid of NII systems is evaluated, while smart charging methodologies to mitigate the relevant impact and further increase RES penetration are identified.

Keywords: non-interconnected islands; high RES penetration; electric vehicles; smart charging

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1. Introduction

The transportation sector has a considerably high reliance on fossil fuels and is responsible for around 20% of the global CO_2 emissions [1]. Moreover, emissions from the transportation sector have been growing with an annual average rate of around 1.7% from 1990 to 2021 [2]. Europe has set significant goals toward the decarbonization of the transportation sector with the 2019 EU Green deal that aims to achieve a clear path for a 90% reduction in transport-related GHG emissions by 2050 [3]. Moreover, the REPowerEU plan concentrates on adopting legislative packages on greening the transportation sector while encouraging Member States to consider measures like tax reductions and exemptions from vehicle taxation for the purchase and use of electric vehicles [4]. The increased requirements for the decarbonization of transport have led to high interest in electric vehicles (EVs) all around the world with electric car sales reaching 9% of all vehicles sales in the global car market in 2021 (four times their market share in 2019) [5].

The electrification of the transportation sector is a path towards achieving a cleaner environment in islands around the world. For instance, the ARISE project in Maldives explores the potential of new technologies like EV charging stations and Vehicle-to-Grid (V2G) [6]. E-mobility is also promoted in the island of Astypalea in Greece with plans to replace all types of vehicles in the island with electric ones [7,8]. Similar activities towards a significant promotion of E-mobility are noted in islands all around the world, like the Azores [9], the Ghoramara island in India [10], the Aran islands in Ireland [11], the Sanso island in Denmark [12], or the Porto Santo island in Portugal [13].

E-mobility can also contribute to achieving very high RES penetration levels at NII systems or standalone islands. In particular, NIIs are characterized by high generation costs related to the thermal power generation [13–15]. However, when considering the potential for exploitation of EV–RES synergies, e-mobility can lead to a reduction in the system's generation cost while also achieving a cleaner environment [16]. Pilot programs are significantly important towards indicating the appropriate solutions (e.g., hybrid stations) that will allow increased RES penetration in non-interconnected islands [14], while they can also serve as test beds for innovative technologies and management solutions [17].

Increased RES penetration could introduce technical challenges in an island's system operation, e.g., due to reduction of physical inertia and short circuit currents. In order to overcome these challenges, ancillary services by central battery storage system should be provided. Additionally, novel control and protection schemes can be utilized to strengthen system security [18,19]. E-mobility can contribute to the mitigation of these technical challenges, considering that EVs can provide services related to frequency containment reserves or reactive power compensation [16,20–22].

Although e-mobility can increase the RES penetration in an island, the additional EV charging demand will modify the system's load curve. The impact of EV charging in the grid has been studied in the literature [23–27], while several management strategies have been proposed to mitigate this impact. For instance, the application of a management scheme that indicates the availability of charging stations, taking into account grid-related issues, is described in [28]. Strategies to lower the peak demand are studied in [29], while management schemes to avoid voltage issues and mitigate grid overloading are studied in [30]. Moreover, EV charging strategies considering the transformers' overloading are described [31,32].

Studies have also been performed to address some of the issues that are expected when considering the introduction of e-mobility in islands. For instance, [33] proposes solutions to the problems of imbalance between power supply and demand, while [34] suggests demand response programs to lower the operating costs of generation and reserves in an island. Smart charging methodologies that have been considered in island case studies have also been developed aiming to lower the peak demand [35,36], increase RES penetration [13,37], and reduce CO_2 emissions [16] while also examining V2G solutions [13,35–37].

None of the aforementioned studies related to e-mobility in island systems [13,16,33–37] considers all the above aspects. This paper provides an overview of the ways electric vehicles can contribute to increasing the RES penetration in non-interconnected islands. More specifically, the paper:

- Evaluates the effect of EV charging in the power grid of non-interconnected islands. The paper focuses on smart charging methodologies that can mitigate the relevant impact and increase RES penetration.
- Provides an overview of the challenges expected in the case of very high RES penetration in non-interconnected islands. A review of the relevant solutions to these challenges is presented, focusing on the EVs' contributions. The ways EVs can provide services related to frequency containment reserves or reactive power compensation are discussed.

Section 2 presents the distinct characteristics of NIIs related to their operation and power supply while also identifying effective solutions to achieve very high RES penetration. Section 3 indicates the challenges that should be expected in high-level RES penetration while also identifying potential solutions. Section 4 evaluates the effect of e-mobility on the power grid, focusing on smart charging methodologies that can mitigate the relevant impact and further increase RES penetration. Conclusions are drawn in Section 5.

2. Achieving Very High RES Penetration in Non-Interconnected Islands

Non-interconnected islands (NIIs), or standalone islands, have distinct characteristics compared to those of an interconnected system when considering power generation, resulting in high operational costs.

High RES penetration can reduce the high generation costs in such systems while also significantly reducing CO_2 emissions [16]. RES operation, however, especially wind farms, are constrained by the technical minima of thermal units. In particular, a sufficient number of generators should be in operation to meet the reserve requirements in each island, while the cumulative technical minimum production levels cover a significant amount of load. A penetration level limit is therefore usually applied for stability purposes (e.g., 20–35% of the total demand). Different limits are imposed according to the island and the demand levels.

Several studies have been performed on the operation of islands with high RES penetration, both regarding economic and technical aspects. A study focusing on the Astypalea island [14] has examined the optimal combination of RES technologies that provide high internal rates of return (IRR) for the installation of hybrid station investments in order to achieve RES penetration levels beyond 60%. The system topology for Astypalea is depicted in Figure 1. The indicative results considering various sizes for wind farms and PV stations are depicted in Figure 2a. Considering that the capacity factor for wind generators, which is typically 30–35%, is considerably higher than the relevant capacity factor for PVs (15–18%) at similar investment costs per MW, wind appears to be the dominant RES-generation technology (as is evident in Figure 2a) [14].

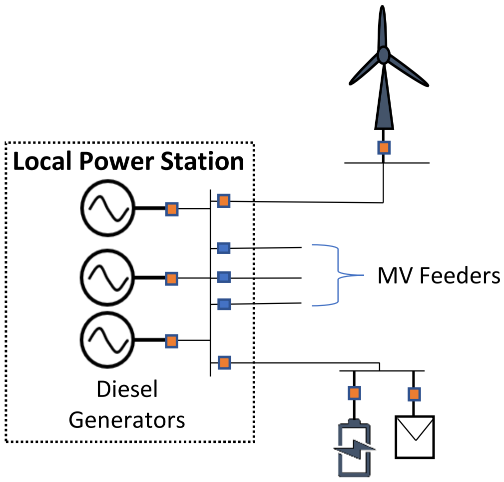
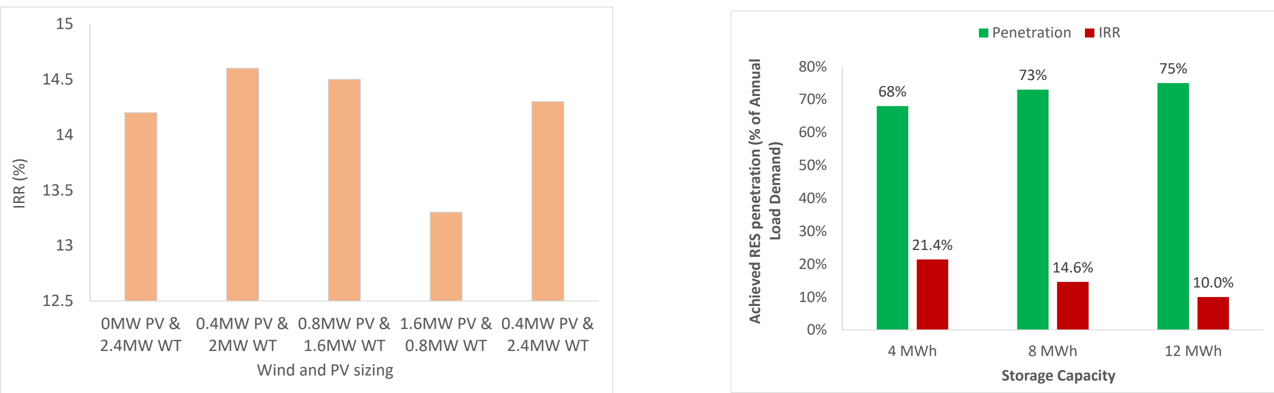


Figure 1. System topology for Astypalea.



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

Figure 2. (**a**) Internal rate of return (IRR) for different RES capacity combinations in Astypalea; (**b**) IRR and achieved RES penetration for different storage capacities [14].

It should be also noted that the sizing of the storage capacity has a major impact on project profitability due to the high cost related to storage components [14]. According to Figure 2b, in case the storage capacity is increased beyond a certain level, slightly higher RES penetration is achieved, while the economic cost of the relevant investment is significantly higher. According to Figure 2b, a hybrid station that comprises a 0.4 MW PV station, a 2 MW wind farm, and a 2 MW/8 MWh battery storage system appears to be a very good option for the system of Astypalea. This selection results in RES penetration levels as high as 73% of the annual demand [14].

3. Challenges and Solutions Related to High RES Penetration Levels

Although e-mobility can assist in increasing the RES penetration in NII systems, technical challenges may arise. In particular, existing protection and control schemes on island systems have been designed according to the characteristics of the installed conventional oil-fired generators. However, the replacement of conventional oil-fired generators with inverter-based generators will introduce critical challenges (e.g., low inertia, low short circuits currents) that need to be addressed. To overcome them, new technologies like grid-forming converters are necessary providing new ancillary services, especially for a central battery storage system. Additionally, novel control and protection schemes should be expected from the smart grids and microgrids domain to ensure secure operation.

In frequency control, RES and battery energy storage technologies, which are inverter-based resources, do not provide physical inertia. Frequency containment reserves (FCR) can be provided and could be requested in an island's grid codes for inverter-based units; however, they are rarely applied in practice. The same holds true for frequency regulation reserves (FRR), which are usually not requested in island grid codes by inverter-based resources. Decarbonization of islands requires the replacement of synchronous generators (conventional units) with inverter-based technologies, which reduces system's inertia and increase the disturbance levels. Thus, critical frequency transients can occur, which can lead to disconnection of generators or loads [18,38]. Fast support of frequency containment reserves by the central battery storage system can mitigate the frequency transient. There is an ongoing trend by system operators to include a fast FCR service in their codes, focusing on battery energy storage (BES) technologies to address the reduced inertia concern [39,40] However, existing requirements for fast provision that have been introduced in interconnected system codes might be insufficient for the case of island systems. Additional services might be required for island systems, i.e., synthetic inertia to address the small amounts of physical inertia in them [39]. In addition, in several island projects, the installation of synchronous condensers with flywheels has been deployed or proposed to increase the physical inertia [18]. Finally, the absence of frequency restoration reserves (FRR) due to the reduced number of conventional generators operating in high RES penetration can be addressed by the provision of automatic FRR by the central battery storage unit.

To meet the annual targets for RES penetration greater than 60%, however, small islands may have to operate with 100% RES penetration at specific hours. Under those conditions, the central BES should form the grid for the RES grid-following inverters. In this respect, the converter of central battery storage units must be "grid-forming", controlling the voltage and frequency at their terminals. There are prominent pilot projects with grid-forming battery units providing black start and ancillary services [41]. To ensure seamless transition between island states, the battery storage unit should be able to operate in grid-forming control even in the presence of conventional units as presented in [42].

The small length of lines in the islands makes their voltage control less challenging compared to that of interconnected systems. Therefore, the most critical task in voltage control is to ensure the power balance in reactive power and the presence of adequate reactive power reserves. Currently, conventional thermal units provide/absorb reactive power by controlling the voltage at their terminals through their automatic voltage regulators. High RES penetration levels can result in less conventional units providing/absorbing reactive power that can lead to their overload. For instance, improper reactive power sharing has led to blackout events in island systems [43]. Inverter-based units can provide reactive power according to commands from the island energy management system and according to the relevant Q(V) characteristics.

The replacement of synchronous generators with inverter-based technologies also introduces a reduction in short-circuit current levels. At the same time, multiple short-circuit current sources are expected to be present on the island. The protection equipment in the island systems comprises digital overcurrent relays in the main feeders and fuses on the lateral lines. The characteristics of this equipment are dictated by the short-circuit current source and the local power station, where the installed synchronous generators can provide multiple times (e.g., 4–5) the nominal current during faults. On the other hand, inverter-based resources are characterized by reduced short-circuit current levels (e.g., 1–1.5 the nominal current) and unconventional behavior (e.g., suppressed negative sequence currents) dictated by the deployed manufacturer control. Thus, in high RES penetration, and specifically in the case where no synchronous generators are operating, the reduction of short-circuit currents increases the fault detection times compared to that in a scenario where diesel generators are connected. There are also additional concerns that arise due to the presence of various short-circuit sources in the island, due to the installation of inverter-based resources or the coordination of protection with FRT. Such issues are described in detail for the island of Astypalea in [44], where mitigation measures are proposed.

4. The Effect of E-Mobility on the Power Grid and Application of Smart Charging Methodologies to Mitigate Impact

Replacing conventional vehicles with electric ones improves the environmental conditions in islands if a reduction in conventional production is also taken into account. In this respect, the impact of the EV charging demand in the long-term planning of an island's network should be considered, evaluating how smart charging can increase the RES penetration levels as well as the economic feasibility of the relevant RES-related investments. Moreover, it is important to evaluate the potential of EVs to contribute to the mitigation of technical challenges in islands (providing frequency containment reserves, etc.). The potential impact of EV charging in the line loading and the voltage values in the islands' system should also be considered, and it is essential to evaluate how smart charging methodologies could mitigate them. E-mobility in island systems allows the exploitation of synergies among EVs and RESs. In particular, smart charging or V2G methodologies can be employed in order to increase both EV and RES hosting capacity in an island network.

4.1. Impact of EV Charging in Long-Term Plannig

EV charging demand is expected to introduce an additional load in the system that can modify the load curve, affecting the expected RES penetration levels and the economic feasibility of the relevant RES-related investments (for instance, those related to the installation and operation of hybrid stations). Additional EV charging demand may negatively affect the cost for the operation of an island's network, particularly when conventional generation is required to cover the additional demand. In this respect, it is important to study the impact of EV charging demand in the long-term planning of an island's network.

The long-term planning in the presence of EVs for the Greek island of Astypalea has been studied in [45]. As noted in Section 2, Astypalea is one of the three Pilot Projects in Greece that have been selected to promote increased RES penetration and sustainable solutions. During recent years, Astypalea has also been selected to significantly promote e-mobility [7]. In particular, 12 publicly available charging stations have already been installed in the island, while a number of public-authority conventional vehicles have been replaced with electric vehicles. E-mobility services improving mobility on the island compared to the previous public transport system are already available, and there are plans to replace all types of private vehicles (grants towards this purpose have already been set) [7,8].

The expected EV charging demand in Astypalea (Figure 3) has been calculated in [45], taking into account the simulation tools for the estimation of EV demand in [23,24,26,27]. Different types of vehicles have been considered (two-wheelers, passenger cars of various sizes, mini buses, etc.), while also taking into account charging at various locations (home, work, publicly available stations, etc.) and various charging levels.

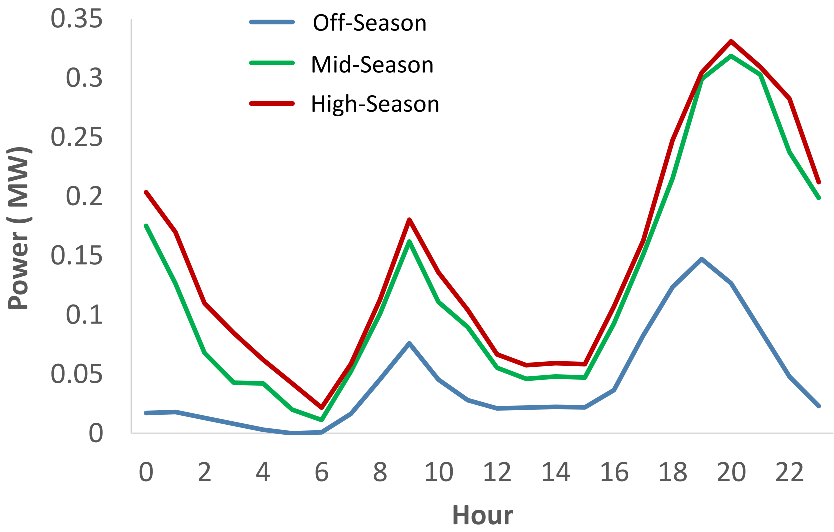


Figure 3. EV charging demand when considering the Greek island of Astypalea [45].

Due to high tourism activity during the summer months, different time-seasons are taken into account: (1) off-season (October–April), (2) high season (July–August), and (3) mid-season (May, June, and September). As depicted in Figure 3, considerable demand is introduced during the evening hours, while a significant difference is also noted when considering the different seasons. In particular, peak EV demand of 150 kW is noted during the off-season period. The demand is significantly increased during the summer months, particularly during the high-season period (peak EV demand during the high-season period is equal to around 0.33 MW).

According to the results in [45], hybrid stations in Astypalea should comprise at least 1 MW PVs, at least 2 MW from wind generation, and a battery capacity of at least 7.2 MWh in order to achieve a high IRR and a considerable RES penetration level (greater than 60%).

In this respect, two scenarios are considered for the hybrid stations in Astypalea:

- Scenario 1: PVs: 1.3 MW, wind: 2 MW, battery 7.2 MWh;
- Scenario 2: PVs: 2.3 MW, wind: 2 MW, battery 9.6 MWh.

The results in Figure 4 concern a time period of one year. As depicted in Figure 4a,b uncontrolled charging of EVs increases the RES energy injected in the grid while also increasing the IRR of the relevant investment. However, RES penetration, as a percentage of the system's demand, decreases (Figure 4c), since EV charging takes place without considering the hours with increased RES penetration. Moreover, according to Figure 4d, the average production cost of the system increases.

In order to further increase RES penetration in the island, a smart charging methodology has been developed in [45], shifting the charging demand to hours with increased RES penetration. According to Figure 4a,b, smart charging of EVs further increases the RES energy injected in the grid and the IRR of the relevant investment. As is depicted in Figure 4c, smart charging manages to increase RES penetration (as a percentage of the system's load), which is reduced in the case of uncontrolled charging.

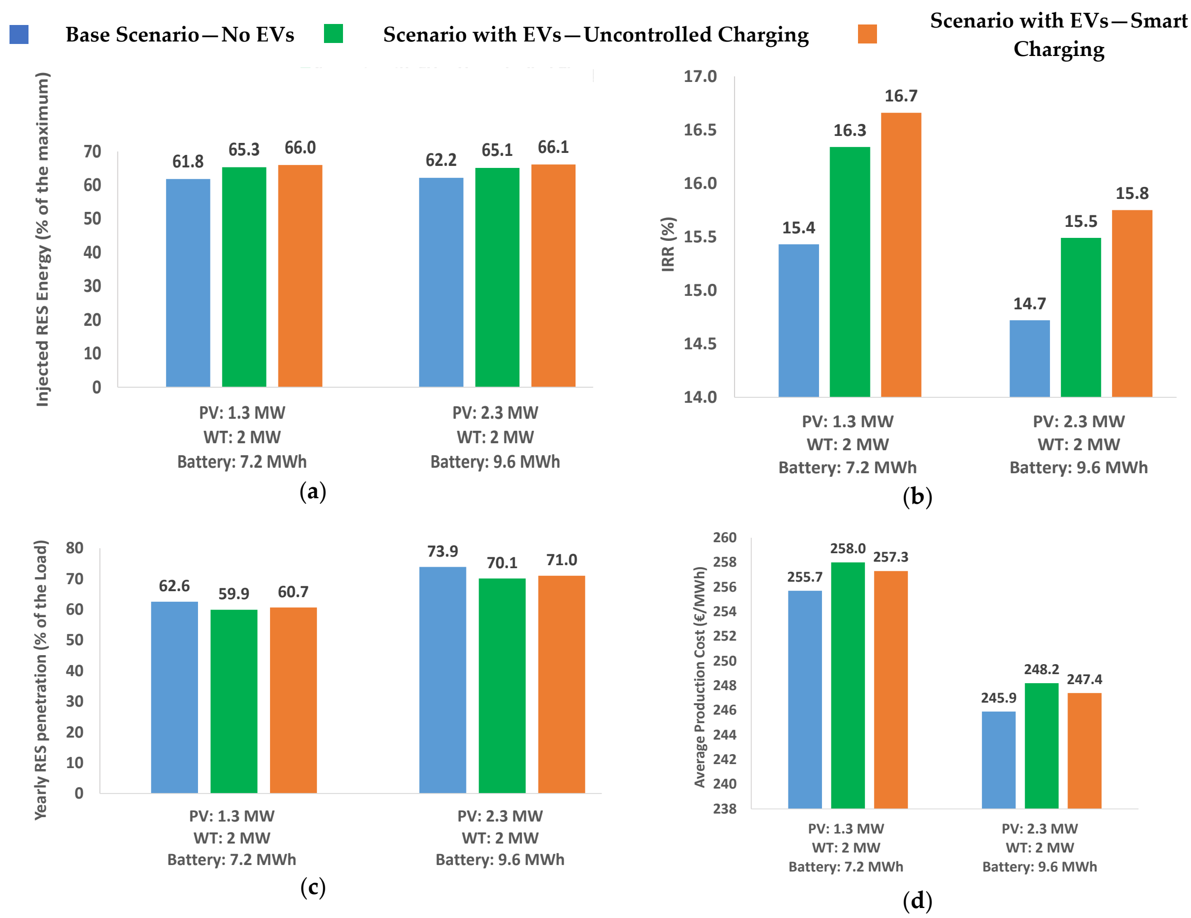


Figure 4. The impact of EV charging in Astypalea [45] regarding (**a**) injected RES energy (% of the maximum available), (**b**) IRR, (**c**) RES penetration (% of the system's demand), and (**d**) average production cost [45].

Additionally, smart charging reduces the system's cost (compared to that of the uncontrolled charging scenario), as depicted in Figure 4d. The effect of smart charging methodologies in reducing the system's cost is also evident in similar studies. For instance, the analysis of the EV load impact on the power system of Maldives has indicated that smart charging methodologies can reduce the additional system costs that should be expected in the case of uncontrolled charging by around 17% [46]. Similarly, the results in [47], indicate that the application of V2G methodologies can decrease the generation cost of the power system in the Greek islands by 10% in 2030 (compared to that with uncontrolled charging) when considering that the EV share (i.e., the percentage of EVs over the total number of vehicles) is equal to 4%. In case of an increased EV share by 2040 (equal to 20% of the total number of vehicles), the application of V2G methodologies could significantly decrease the system's generation cost by 20% (compared to the generation cost in the case of uncontrolled charging) [47].

4.2. Contribution of E-Mobility to the Mitigation of Technical Challenges in Islands

EVs can contribute to mitigating the technical challenges due to high RES penetration. For instance, interfaces that allow power quality services like reactive power compensation to be offered are described in [20], while EV chargers that allow reactive power control have been developed in [21,22].

EVs can alter their charging power to provide frequency containment reserves (FCR). More specifically, regarding underfrequency or overfrequency events, the charging power of EVs can be dynamically reduced or increased according to the measured frequency in order to provide FCR. Figure 5 depicts the provision of FCR services considering the

Astypalea island. In particular, an operating scenario is considered where the island demand is equal to 1.6 MW, and an additional demand of 0.6 MW is considered for EV charging needs. A hybrid station is considered to operate in the island comprising a wind turbine (WT) and a battery energy storage (BES) system. During the examined scenario, the wind turbine provides power equal to 2 MW, while the battery is charging at 0.4 MW. A diesel generator is also operating in the island with a power of 0.6 MW in order to cover the rest of the system's demand.

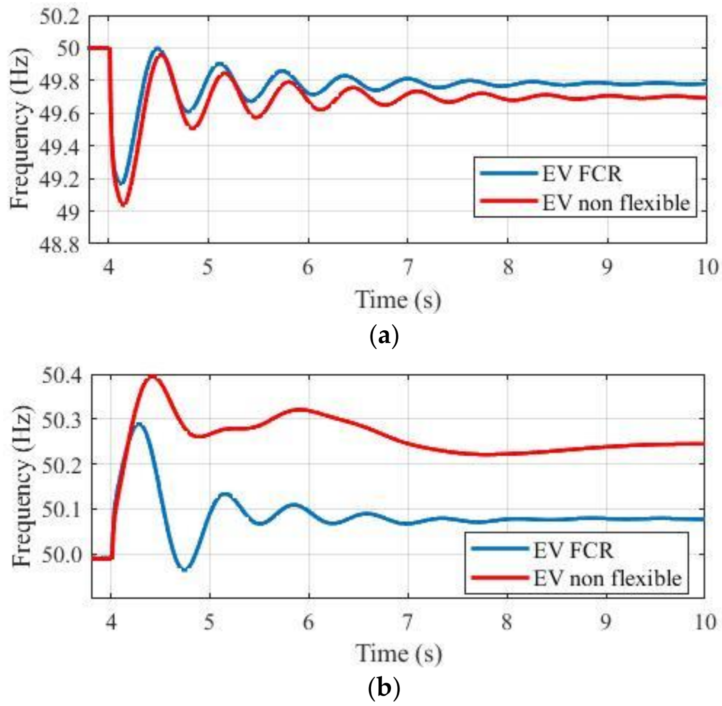


Figure 5. Contribution of EV charging in (**a**) underfrequency and (**b**) overfrequency transients.

In case the wind turbine is disconnected, an underfrequency event is evident in Figure 5a. In case EV charging demand is considered as a flexible load (blue line in the diagram), the charging power of the vehicles can be decreased, and the system's frequency can be restored to a value closer to the nominal one, compared to the case where EV charging is uncontrolled (red line in Figure 5a).

In case the central BES is disconnected, an overfrequency event should be expected, as is evident in Figure 5b. In this case, if the EVs are considered as a nonflexible load (i.e., in case of uncontrolled charging—red line in Figure 5b), the frequency is increased to values far from the nominal one. However, in case the vehicles are considered as flexible loads providing FCR, the charging power of the vehicles can be increased, allowing the system's frequency to be restored to a value closer to the nominal one.

Similar results are also evident in other studies. For instance, [16] has evaluated the potential of EVs to support the frequency in case of disturbances in the Greek non-interconnected island of Crete. Two different disturbances are evaluated in [16], as depicted in Figure 6:

- Simulation of a three-phase short circuit at a high-voltage bus;
- Simulation of a three-phase short circuit at a high-voltage bus with simultaneous loss of two generators.

In each case three, different scenarios are considered. In the base scenario, EV charging is considered as a nonflexible load. In the second scenario, EVs are considered as flexible loads with unidirectional power flow capabilities (i.e., energy can only be provided from the grid to the stations). In the third scenario, bidirectional power flow capabilities are considered, with the EVs being able to provide power to the grid when needed. The contribution of each EV to the primary frequency regulation depends on its charging energy needs (charge level—SoC) [16].

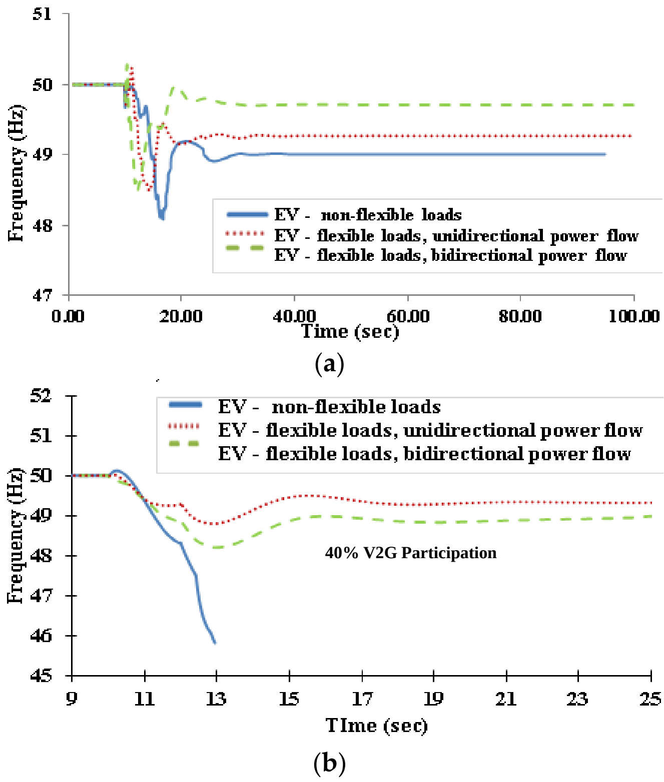


Figure 6. Simulation of (**a**) a three-phase short circuit at a high-voltage bus and (**b**) a three-phase short circuit at a high-voltage bus with simultaneous loss of two generators in the Greek non-interconnected island of Crete [16].

Regarding the base scenario in Figure 6a (simulation of a three-phase short circuit at a high-voltage bus), EVs are considered as nonflexible loads, and the frequency after the disturbance and the activation of the primary reserves is stabilized in the value of 49 Hz (the lowest value among the scenarios examined). The best results are achieved when adopting a management scheme that exploits the bidirectional exchange of energy with the EVs [16].

In case of a three-phase short circuit at a high-voltage bus with simultaneous loss of two generators (Figure 6b), when EVs are considered as nonflexible loads (blue line in Figure 6b), the frequency drops to unacceptable levels. In this case, relay protections of conventional units are tripped, and the system collapses. This blackout can be prevented when EVs offer frequency support, either by curtailing their charging demand or by injecting power to the grid [16] (red and green lines in Figure 6b).

4.3. Impact of EV Charging on Line Loading and Voltages Values

EV charging can affect the loading of lines as well as the voltage values in the island system's buses. The voltage values and the loading of the lines have been studied for the case of the Greek island of Astypalea. In particular, the distribution grid of Astypalea, which comprises three feeders, has been simulated in Dlgsilent-Powerfactory. Simulations for the time period of one year were performed, and two scenarios were examined:

- Scenario 1: Normal operation of the system;
- Scenario 2: Operation in case of a fault requiring the interconnection of two lines.

Considering a penetration level of EVs that will increase the island's peak demand by 5% and energy requirements by 15%, the maximum loading of the lines, as obtained from hourly simulations for one year, is depicted in Figure 7. It is evident that when the normal operation of the system is considered, the lines are loaded well below their thermal limits, even when EV charging is taken into account. A fault that requires the interconnection of two of the system's lines results in increased line loading, since the loads of two lines are only supplied by a single line. In this scenario, as depicted in Figure 7, a maximum line loading of 71% is noted when considering that no EVs are present. When EV charging is taken into account, the maximum line loading is increased to 74%.

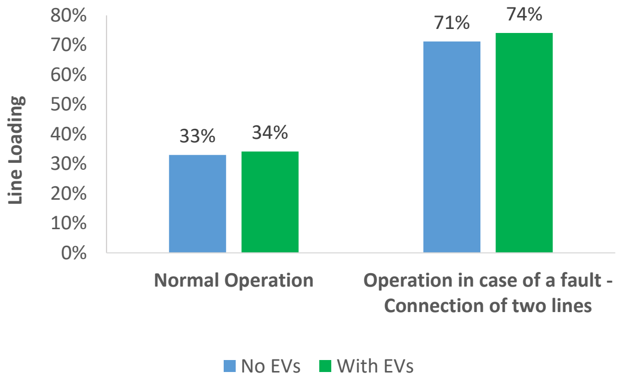


Figure 7. Maximum loading of the lines in Astypalea when considering the presence of EVs.

The minimum voltage values that were noted when applying simulations for the time period of one year are depicted in Figure 8. Due to the small length of the lines and the relatively small increase in peak demand (~5%), no issues should be expected with minimum voltages. In particular, EV charging reduces voltages; however, the relevant values remain within the required limits.

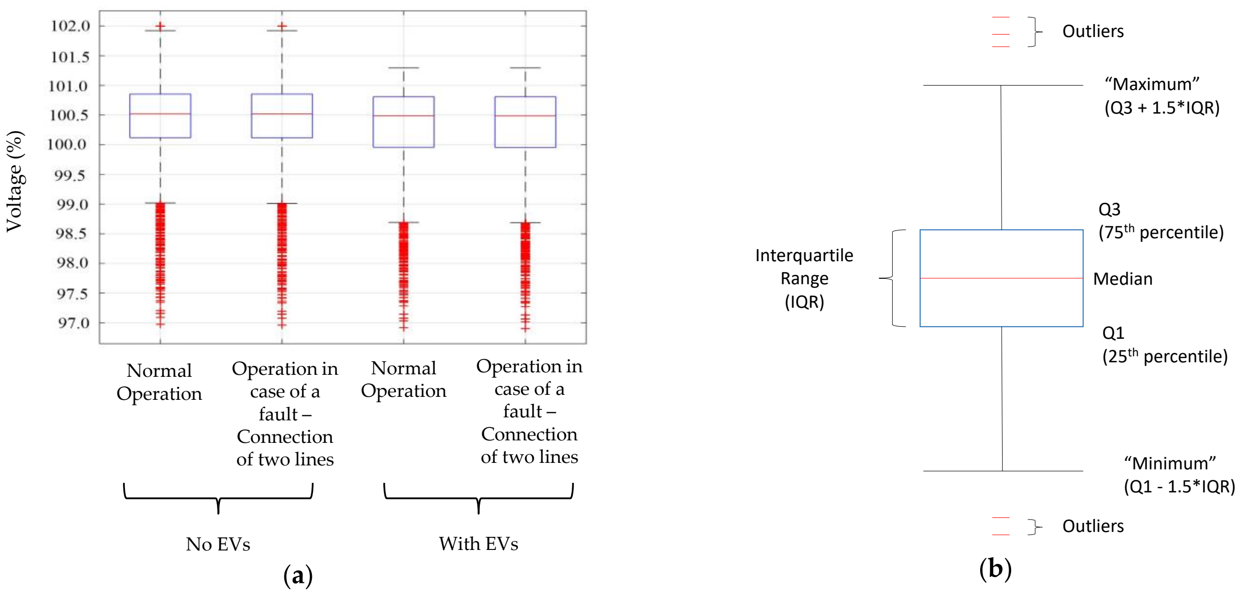


Figure 8. (**a**) Boxplot for the minimum voltage values in Astypalea when considering the presence of EVs, (**b**) Explanation of the boxplot.

However, higher EV penetration can introduce higher peak demand, particularly in the case of uncontrolled charging. For instance, according to Figure 9a, when considering the island of Ikaria [48], uncontrolled charging of EVs results in a violation of the minimum voltage limit in case more than 200 EVs enter the island. The number of EVs that can enter the island can be increased to 300 when considering the application of dual tariff schemes (red bars in Figure 9a). Similar results are observed when considering a voltage deviation (Figure 9b). In this case, uncontrolled charging of 150 EVs results in a violation of the voltage deviation limit. In this respect, penetration of EVs greater than the maximal number of EVs that the system can support will require additional grid investments.

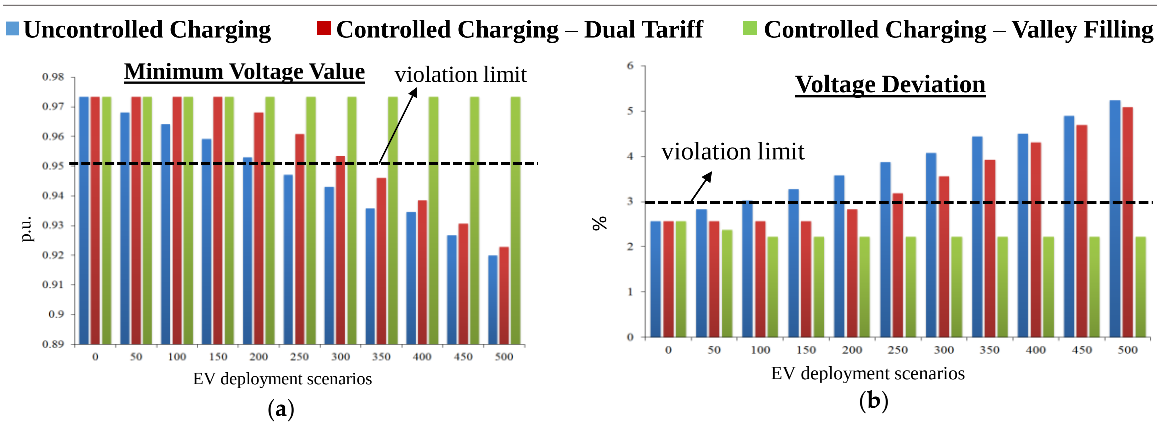


Figure 9. Voltage values for various EV penetration scenarios in the island of Ikaria (a 1 MW wind generator is considered to operate in the island for the scenarios examined): (**a**) minimum voltage value and (**b**) voltage deviation [48].

However, such investments can be avoided with smart charging strategies. For instance, when considering the application of a valley filling scheme (i.e., EV charging is distributed during the night hours in order to avoid spikes in the system's load) in the case of Ikaria [48] (green bars in Figure 9a,b), an increased number of EVs can enter the grid without causing any voltage violation issue.

4.4. Exploiting EV–RES Synergies towards Increasing the RES Penetration

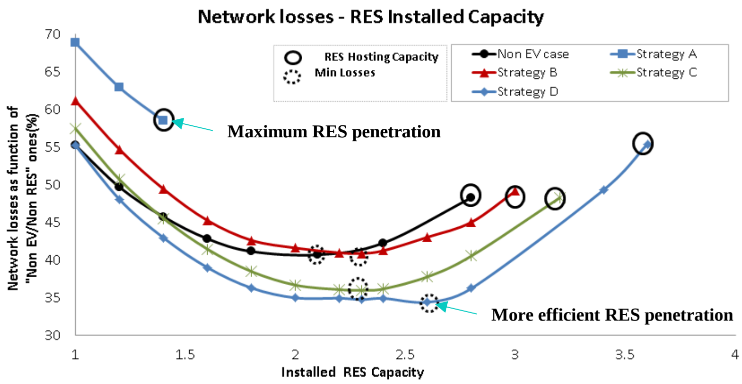
Simple charging schemes can be applied to shift EV charging demand towards hours with increased RES penetration [25]. In this respect, EV charging exploits the available RES production that otherwise would not be utilized.

Advanced EV management strategies can be applied to achieve maximal RES penetration, taking into account the EV hosting capacity alongside grid-related parameters (grid losses, voltage fluctuations, etc.) [37]. For instance, the flexible EV demand management strategy in [37] results in reduced grid losses in the island of Ikaria, as is depicted in Figure 10a. Three hundred EVs are considered to enter the network of Ikaria in the case examined in Figure 10a. The maximum allowable RES penetration that can be achieved in each charging strategy examined in [37] is determined by the maximum voltage fluctuation and is represented by the continuous cycle in Figure 10a. The intermittent circles in Figure 10a indicate the more efficient RES penetration in the examined network (i.e., the maximum RES penetration that can be achieved with the minimum system losses). It is evident that the exploitation of EV–RES synergies alongside V2G capabilities (Strategy D in Figure 10a) allow for increased RES penetration alongside reduced system losses.

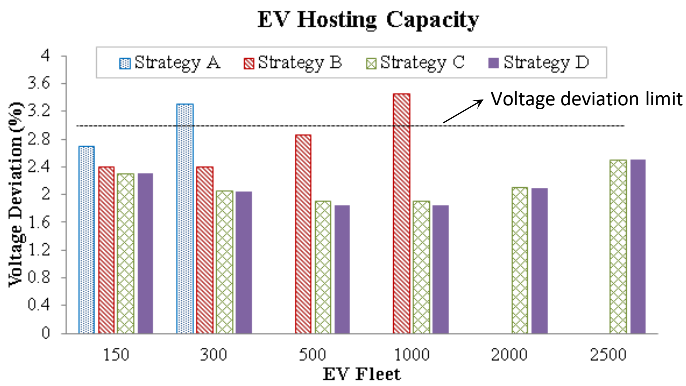
The maximal EV hosting capacity in the network can also be increased when exploiting EV–RES synergies, as is depicted in Figure 10b. More specifically, Figure 10b depicts the voltage deviation for various levels of EV penetration when considering that 2.1 MW RESs are installed in the island of Ikaria [37]. The maximal EV hosting capacity for the examined network of the island of Ikaria is determined by the maximum voltage deviation [37]. According to Figure 10b, the management strategy that exploits EV–RES synergies allows an increment in the grid's EV hosting capacity without violating technical network restrictions.

Similar results are shown in [47], where the application of V2G methodologies results in increasing the RES hosting capacity in the Greek islands, as indicated in Figure 11. More specifically, in case of slow growth in EV penetration in 2030, where EV shares as a percentage of the total number of vehicles are equal to 4%, 120 MWh of additional RES capacity will be available when considering the application of V2G methodologies. The additional RES capacity can be further increased in 2040 when considering an EV share equal to 20%. A considerable increase in RES capacity can be achieved if high growth in EV penetration (24% of vehicles are EVs in 2030) is considered (orange bars in Figure 11).

Strategy A: Uncontrolled charging
Strategy B: Dual tariff charging
Strategy C: Valley-filing
Strategy D: EV–RES coordination with V2G



(**a**)



(**b**)

Figure 10. (**a**) Network losses for various cases of RES penetration when considering the introduction of 300 EVs in the island of Ikaria; (**b**) voltage deviation for various levels of EV penetration when considering that 2.1 MW RESs are installed in the island of Ikaria [37].

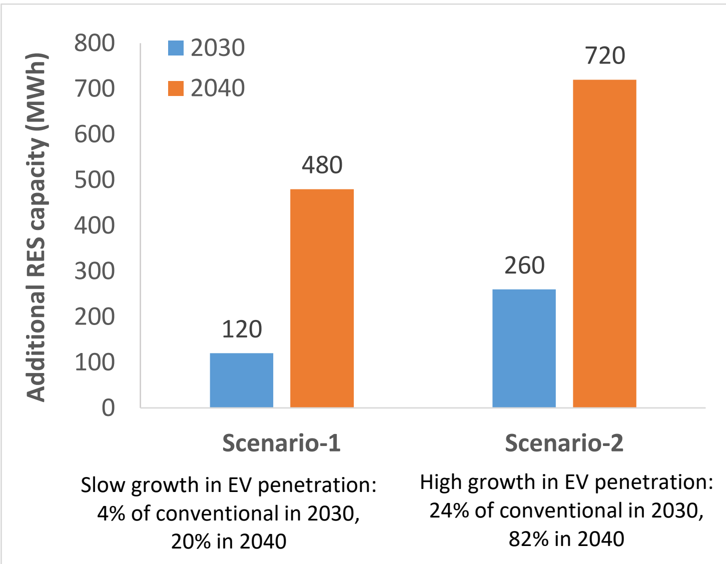


Figure 11. Increase in RES hosting capacity in the Greek islands with the application of V2G methodologies [47].

It should be noted that in the case of uncontrolled charging, increased RES penetration can limit the number of EVs that the grid can support, particularly due to violations in voltage deviation [49]. As depicted in Figure 12, when the RES installed capacity is increased, the number of EVs that can enter the island of Ikaria without causing any grid-related issue is reduced for uncontrolled (dumb charging) and valley filling charging (blue and red lines in Figure 12). However, more efficient smart charging schemes that also consider the maximum system load and RES penetration (green line in Figure 12), can increase both the grid's RES hosting capacity as well as the number of EVs that can enter the grid. More specifically, in this case, EV charging demand is shifted towards hours with low load or large wind power production, achieving increased EV hosting capacity in addition to increased RES penetration.

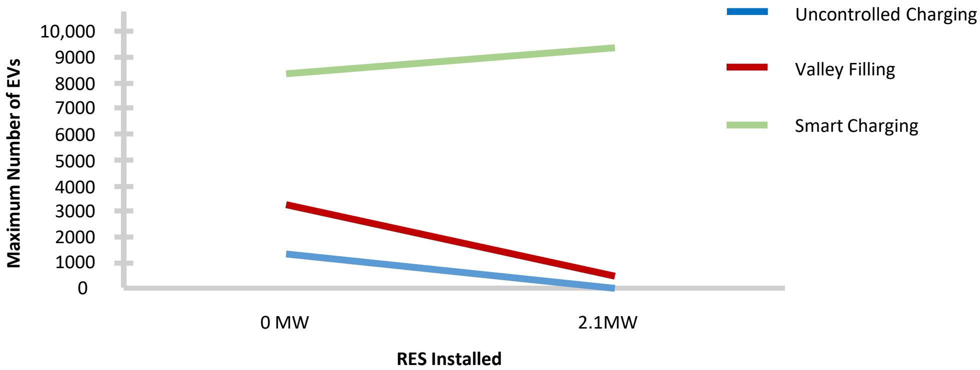


Figure 12. Relation between the maximum allowed number of EVs and the RESs installed in the network of Ikaria (based on the results of the Merge EU project) [49].

4.5. Reduction in CO_2 Emissions

Smart charging schemes can also reduce the CO_2 emissions related to the conventional energy production in an island. In particular, according to [16], an increase in the load of the system due to uncontrolled EV charging demand in the Greek island of Crete results in increased CO_2 emissions of conventional production (Figure 13). CO_2 emissions are slightly decreased when applying dual tariff schemes, as is depicted in Figure 13. However, valley filling schemes can significantly decrease the CO_2 emissions (green bars in Figure 13).

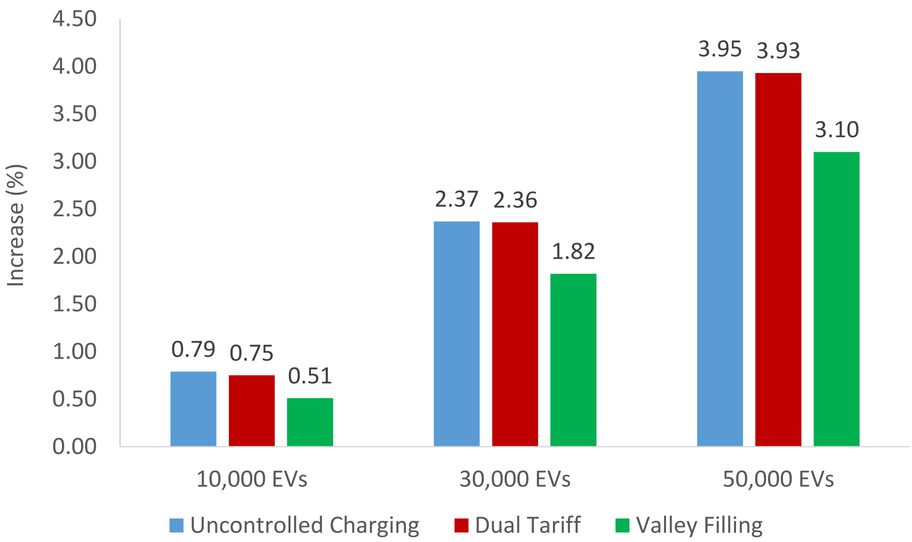


Figure 13. Generation CO_2 footprint in Crete, considering different charging schemes [16].

Similar results are evident in [46] for the case study of the Maldives islands. In particular, the optimized smart charging scheme that is applied in [46] reduces the evening spike, introduced in the system demand due to the uncontrolled charging of EVs, and distributes the EV charging load throughout the whole day. In this respect, the developed charging management scheme smoothens the load profile while also reducing the costs of the system. However, EV load is mainly covered by diesel generators in this case, resulting in increased CO_2 emissions [46]. In particular, as is depicted in Figure 14, CO_2 emissions are increased by 3.6% compared to those in the scenario where no EVs are considered in the examined network (baseline scenario). In this respect, a "carbon-neutral scenario" has been developed in [46] that successfully constrains the CO_2 emissions to be equal to the emissions in the baseline scenario (non-EV case), as depicted in Figure 14.

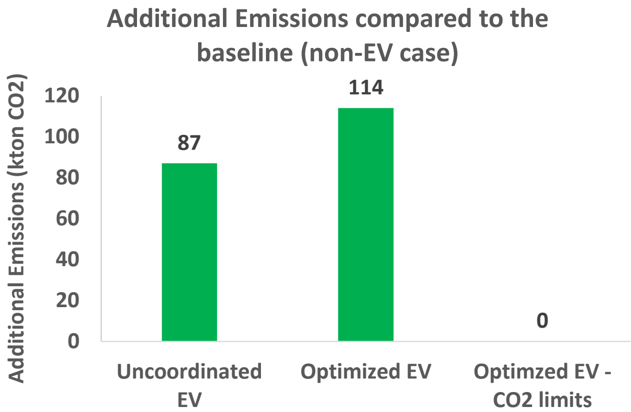


Figure 14. Additional emissions (kton CO_2) compared to the baseline scenario that considers no EVs for different charging schemes for the case study of the Maldives islands [46].

An overview of references indicating the services that can be offered by EVs alongside the smart charging strategies to mitigate the grid impact and increase RES penetration is provided in Table 1.

Table 1. References indicating the services that can be offered by EVs alongside the smart charging strategies to mitigate the grid impact and increase RES penetration.

Services Offered by EVs and Smart Charging Strategies to Mitigate the Grid Impact and Increase RES Penetration	References
Frequency support in case of grid disturbances	[16]
Power quality services like reactive power compensation and EV chargers that allow reactive power control	[20–22]
Mitigation of issues related to voltage values and line loading	[37,48]
Charging strategies to lower the peak demand	[29,35,36]
Charging strategies to avoid transformer overloading	[31,32]
EV–RES synergies to increase the RES penetration	[25,37,47,49]
Smart charging strategies to reduce CO_2 emissions	[16,46]

5. Conclusions

The effective introduction of e-mobility in NII systems can contribute to the reduction of costly and polluting operation of conventional generation units by achieving high RES penetration. Pilot studies have indicated that RES penetration greater than 70% can be achieved with the installation of hybrid stations based on centralized storage facilities. The relevant solutions also appear to be economically feasible with a high IRR related to the investments for the hybrid station.

Although e-mobility can assist in increasing the RES penetration in NII systems, technical challenges may arise. In order to overcome these challenges, new technologies like grid-forming converters are important, while novel control and protection schemes are needed to ensure secure operation. EVs can contribute to providing solutions in the technical challenges that are noted due to high RES penetration in an island. In particular, EVs can alter their charging power to provide frequency containment reserves (FCR), while solutions to offer reactive power control have also been proposed.

The additional EV charging demand in an island with hybrid stations (comprising variable RES production and an energy storage system) can increase the RES-injected energy, while an increase is also noted in the IRR of the relevant investment for the hybrid station. The application of smart charging schemes further increases the RES injected energy and the IRR while also increasing the RES penetration as a percentage of the system's demand and reducing the system's cost (in comparison to that with uncontrolled charging).

Small EV penetration that does not significantly increase an island's peak demand is not expected to introduce issues related to voltages and line loading. However, higher EV penetration would introduce higher peak demand, particularly in the case of uncontrolled charging. In this case, smart charging schemes can lower peak demand. Methodologies that manage to exploit the synergies among EVs and RESs can effectively increase the RES hosting capacity in an island while also taking into account grid-related parameters (grid losses, voltage fluctuations, etc.).

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