E-Mobility on Mini Grids

with Very High Variable Renewable Energy Penetration

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This report of the Energy Storage Partnership is prepared by the Energy Sector Management Assistance Program (ESMAP) with contributions from the Alliance for Rural Electrification (ARE), Ricerea sul Sistema Energetico (RSE), Loughborough University, and the Inter-American Development Bank (IADB). The Energy Storage Partnership is a global partnership convened by the World Bank Group through ESMAP Energy Storage Program to foster international cooperation to develop sustainable energy storage solutions for developing countries. For more information visit: https://www.esmap.org/the_energy_storage_partnership_esp

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ABBREVIATIONS

AC	alternating current
ARISE	Accelerating Renewable Energy Integration and Sustainable Energy
ASEAN	Association of Southeast Asian Nations
ASPIRE	Accelerating Sustainable Private Investments in Renewable Energy
BaU	business as usual
BES	battery energy storage
BESS	battery energy storage system(s)
CO_2	carbon dioxide
DC	direct current
EU	European Union
EV	electric vehicle
FCR	frequency containment reserves
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IRENA	International Renewable Energy Agency
IRR	internal rate of return
kW	kilowatt
MTCC	Maldives Transport and Contracting Company
MW	megawatt(s)
MWh	megawatt hour(s)
PV	photovoltaic
RE	renewable energy
RES	renewable energy source(s)
V1G	control of unidirectional charging
V2G	vehicle-to-grid
VRE	variable renewable energy

All currency is in United States dollars (US$, USD), unless otherwise indicated.

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KEY MESSAGES

Growing concern over climate change has led many countries to set ambitious goals to decarbonize the transportation sector, increasing interest in electric vehicles (EVs). The electrification of transportation is particularly significant in mini grids and on islands, which, because of their relatively small size, can be used as prototypes for large interconnected systems. Several projects and initiatives promote EV charging solutions combined with the integration of renewable energy sources (RES).

The transition of isolated mini grids, such as non-interconnected islands, from fossil fuels to cleaner generation faces unique operational challenges because of their lack of connection to a stronger electrical grid. These challenges include greater uncertainty and variability in power supply and lower physical inertia, which result in more severe frequency transients and potential blackouts. Advanced control capabilities of the power electronic inverters interfacing the RES are required to support frequency and voltage. Battery energy storage plays a crucial role in regulating frequency in mini grids and providing additional services for voltage stabilization, black-start capability, and operational security.

EV charging can have negative effects on electricity grid, leading to line/transformer loading, voltage limit violations, and increased network losses; inadequate generation capacity of the system; and power quality issues, such as harmonic distortion. Voltage limits and line loading violations can be overcome by grid investments, but these problems can be avoided by applying active control strategies of EV charging. If not properly managed, EV charging demand can increase load peaks and/or create new peaks. Charging management schemes, such as valley filling (defined in section 3), can shift this load and avoid increase in the peak demand. Active filtering by the converters of the charging stations can mitigate harmonics generated by charging stations. Exploiting synergies between EVs and RES can reduce energy system costs, increase RES and EV hosting capacities, and maximize the benefits of electric mobility (e-mobility) toward a cleaner environment by reducing carbon dioxide (CO_2) emissions.

This report describes the state of the art of e-mobility in mini grids, examines the potential for synergies between EVs and variable renewable energy (VRE) sources in isolated mini grids, and formulates guidelines for e-mobility in mini grids. Real-world examples provide insights into the viability, advantages, and possible obstacles associated with integrating EVs into isolated energy systems. The analysis reveals the effect of EV–RES synergies in achieving high levels of RES penetration, the importance of funding projects to support a country’s goals for high RES penetration and electrification of transportation, the need for timely planning of the grid’s supply capacity to be able to accommodate increased penetration of EVs, and the importance of support for energy storage through multiple second-life EV batteries.

1 WHEN TRANSPORTATION AND MINI GRIDS MEET

The transportation sector relies heavily on fossil fuels and is responsible for about 20 percent of global carbon dioxide (CO_2) emissions (Ritchie 2022). Globally, emissions from the sector rose at an annual average rate of about 1.7 percent between 1990 and 2021 (Teter 2022).

Goals for decarbonizing the transportation sector have led to high interest in electric vehicles (EVs), sales of which reached 9 percent of total global vehicles sales in 2021—four times their market share just two years earlier (IEA 2022). Countries and country blocs are taking action. In the European Union (EU), the 2019 EU Green deal aims to achieve a 90 percent reduction in transport-related greenhouse gas emissions by 2050 (European Commission n.d.), and the REPowerEU plan encourages member states to consider measures such as tax reductions and exemptions from vehicle taxation for the purchase and use of EVs (European Commission 2022). In 2022, China announced its ambition to develop sufficient charging infrastructure to meet the needs of 20 million new EVs (including battery, plug-in hybrid, and fuel cell EVs) by 2025 (Office of the State Council, People's Republic of China 2020). A target of its New Energy Automobile Industry Plan (2021–35) is that 20 percent of vehicle sales will be zero-emission vehicles by 2025 (IEA 2021). As part of its Infrastructure Investment and Jobs Act, the United States set targets of 50 percent EV sales by 2030,[1] the construction of 500,000 public chargers,[2] tax incentives for plug-in and fuel cell EVs (Office of Energy Efficiency and Renewable Energy n.d.), and new funding packages of $7.5 billion for charging infrastructure (IEA 2021). Australia's Future Fuels and Vehicles Strategy aims to reduce emissions from transportation and reduce barriers to the uptake of EVs (Department of Industry, Science and Resources, Australia 2022). New South Wales' electric vehicle strategy identifies the government's commitments to increase EV sales to 52 percent by 2031 (Environment, Energy and Science Department of Planning, Industry and Environment on Behalf of Government of New South Wales, Australia 2021; Government of New South Wales n.d.).

Penetration of EVs in developing countries is still in its infancy. Developing countries are gearing up for clean mobility, however, including the use of biofuel blending and EVs. In Indonesia, for example, a roadmap includes the deployment of 13 million electric motorbikes and 2.2 million electric cars by 2030.[3] The Philippines targets 10 percent penetration of EVs, including two-wheelers, by 2040. Brunei Darussalam plans to increase the share of EVs to 60 percent of annual vehicle sales by 2035 (ASEAN Centre for Energy 2022).

Electrification of the transportation sector is a path toward achieving a cleaner environment in mini grids, including on islands, around the world. The Accelerating Renewable Energy Integration and Sustainable Energy (ARISE) project in Maldives explores the potential of new technologies such as EV charging stations and vehicle-to-grid (V2G) operation (World Bank 2020). E-mobility is also being promoted on Greek islands. The island of Astypalea, for example, plans to replace all vehicles with electric ones (e-Astypalea n.d.; Volkswagen n.d.). The ASEAN Centre for Energy modeled and evaluated the potential of integration of variable renewable energy (VRE), EVs, and smart microgrid in ASEAN member states, using Malaysia and Thailand as case studies (ASEAN Centre for Energy 2022). Similar activities that promote e-mobility are being taken by islands around the world, including the Azores (Sustainable Azores 2022); the Aran islands in Ireland (Clean Energy for EU Islands Secretariat 2019); Sanso Island in Denmark (Mathiesen and others 2015); and Porto Santo in Portugal (Torabi, Gomes, and Morgado-Dias 2021).

Exploitation of synergies between EVs and renewable energy sources (RES) in mini grids can reduce energy system costs and contribute to a cleaner environment (Karfopoulos, Voumvoulakis, and Hatziargyriou 2014). High RES penetration levels can pose technical challenges for the operation of a mini grid (Karakitsios and others 2023), but they can be overcome by applying novel control and protection schemes (Karakitsios and others 2015; Gatta and others 2019), including services offered by EVs (such as frequency control, reactive power control, and avoidance of overloads of transformers and lines) (Karfopoulos, Voumvoulakis, and Hatziargyriou 2014; Monteiro and others 2021; Carrión, Zárate-Miñano, and Domínguez 2020).

If not properly controlled, EV charging demand can make the operation of a power system more difficult (ENTSO-E 2021; Hatziargyriou and others 2021). It is therefore important to evaluate the impact of EV charging on the electricity grid and to adopt management strategies that help mitigate the negative impact (Karakitsios 2023; Nizami, Hossain, and Mahmud 2021; Karakitsios, Karfopoulos, and Hatziargyriou 2015; Muñoz and others 2016).

This report presents four case studies on the effect of e-mobility on mini-grids with high VRE penetration. It (1) overviews their characteristics; (2) identifies potential problems in isolated and remote mini grids with large shares of VRE; (3) analyzes EV charging strategies; (4) examines the impact of e-mobility on the mini grids, suggesting charging methodologies to mitigate its impact; (5) identifies synergies between EVs and RES, which lead to increased RES penetration and lower CO_2 emissions; and (6) assesses the possible contribution of e-mobility to the mitigation of technical challenges on islands. It is intended for system planners and operators as well as policy makers.

NOTES

1. White House, "President Biden Announces Steps to Drive American Leadership forward on Clean Cars and Trucks," Fact Sheet, August 5, 2021. https://www.whitehouse.gov/briefing-room/statements-releases/2021/08/05/fact-sheet-president-biden-announces-steps-to-drive-american-leadership-forward-on-clean-cars-and-trucks/.
2. White House, "The Biden-Harris Electric Vehicle Charging Action Plan," Fact Sheet, December 31, 2021. https://www.whitehouse.gov/briefing-room/statements-releases/2021/12/13/fact-sheet-the-biden-harris-electric-vehicle-charging-action-plan/.
3. Many Asian countries rely heavily on two- and three-wheelers (see ADB 2022).

2 ISOLATED MINI GRIDS WITH LARGE SHARES OF VARIABLE RENEWABLE ENERGY

Mini grids can be complex electrical systems, producing dozens of megawatts (MW) (such as a non-interconnected island with various thermal generators, VRE, and storage units serving multiple loads). They can also be small systems, providing just kilowatts of power to a few loads (Farrokhabadi and others 2020). A mini grid comprises RES, EVs, flexible loads and storage (Figure 2.1). Isolated mini grids (on non-interconnected islands and in rural communities) are usually located in remote locations with no, or only a very weak, connection to a robust electrical grid.

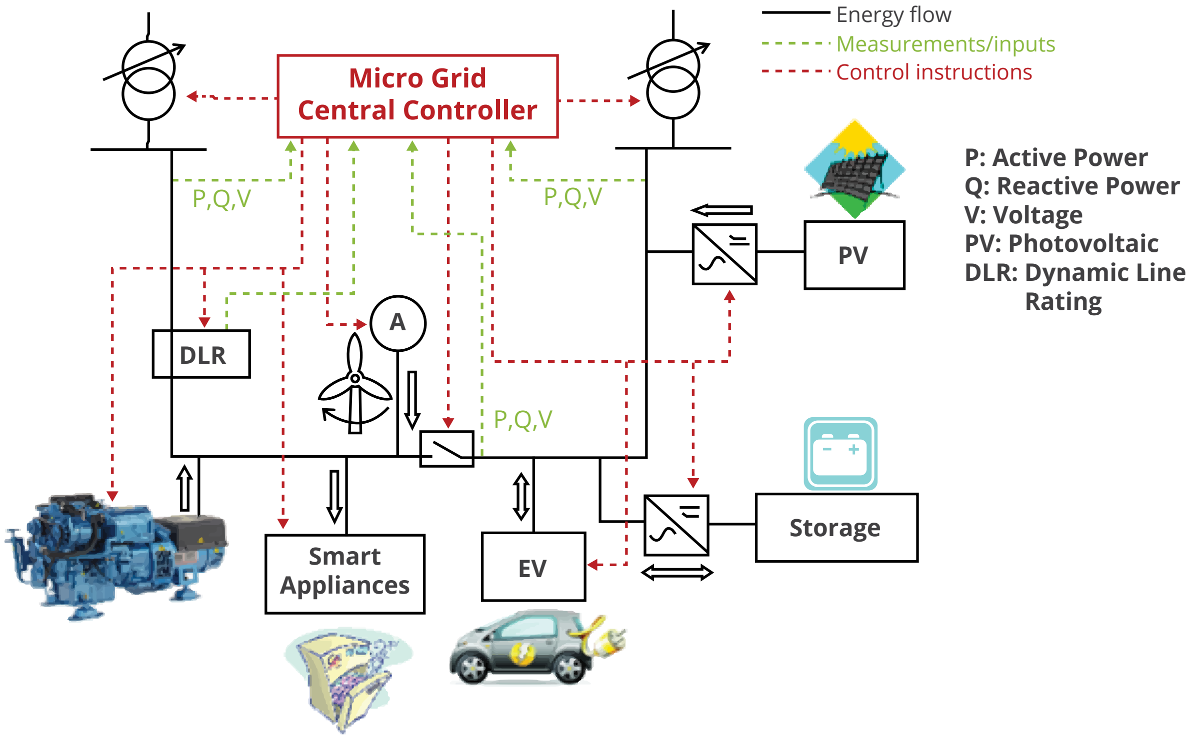
Mini grids can exist within both grid-connected and isolated distribution networks. The operational characteristics of isolated mini grids differ significantly from and are more challenging than those of larger interconnected power systems.

A small system faces greater uncertainty in power injections, because of the small number of loads and the highly correlated and rapid variations in RES production (Farrokhabadi and others 2020). In an interconnected mini grid, the grid serves as a buffer of excess RES production or demand; energy storage technologies serve that purpose in isolated mini grids. In isolated mini grids, RES production can be curtailed for several hours if the excess RES energy cannot be stored.

In existing isolated mini grids transitioning to high VRE penetration, the retirement of conventional thermal generators in the generation mix results in lower physical inertia in the system, because VRE is interfaced to the system through power electronics and thus provide no or very little inertia. As a result, the system may experience severe frequency transients, causing load curtailments by the operation of underfrequency relays,[4] generator outages caused by their own protection (Karakitsios and others 2023), and even blackouts. Inverter-based RES are able to offer several frequency support services to address this issue, including synthetic inertia and rapid frequency response. To ensure the presence of adequate frequency containment reserves, however, they have to be operated with a headroom of active power to deal with underfrequency events, which affects their economic performance. In addition, existing protection schemes are tuned to legacy thermal generators. Either a new protection scheme should be designed or proper sizing of the converters needs to be foreseen to ensure seamless coordination with existing protection devices (Gkiokas and others 2022).

Battery energy storage (BES) can help ensure safe power supply in mini grids. The ability of BES technologies to provide rapid active power makes them ideal for the provision of services related to frequency control (Aretxabaleta and others 2021). Battery inverters can be used in grid-forming mode to achieve 100 percent VRE penetration in certain periods (Rodrigues and others 2016).[5] Novel grid-forming inverters can provide black-start services and ensure seamless operation when thermal generators are disconnected (Lagos and others 2022). A central storage grid-forming inverter for frequency control is the common approach; use of the distributed storage potentially provided by EVs for frequency control can reduce the size of the central storage system and overall costs. Distribution feeders in isolated mini grids are relatively short, leading to limited voltage excursions caused by RES variability or increased demand by e-mobility. However, mini grids operated at medium and low voltage are characterized by higher resistances than high-voltage overhead networks, creating a higher correlation of voltage to active power than reactive power. In contrast, in transmission systems in which voltage (V) is controlled through reactive power (Q), typical Q(V) control at the connection point of generators can provide adequate reactive power. In mini grids, more advanced control schemes, such as virtual impedance for

FIGURE 2.1: **Indicative Concept of a Mini Grid**



Source: Strbac and others (2015).

grid-forming inverters, are required to ensure proper reactive power sharing between the generators (Li and others 2016).

Mini grids use various technologies, including power electronics interfaced (BES and VRE) and directly coupled with synchronous generators (thermal generators). The connection/disconnection of a generator alters short-circuit currents, inertia, and power sharing between generators. It requires advanced control and protection techniques (such as adaptive protection) to ensure operational security (Gatta and others 2019).

NOTES

4. Underfrequency relays are used to automatically shed a specific part of the load when the system frequency falls to a very low level, posing a threat to the power system's stability (Ahmad, Javed, and Javed 1991).
5. Grid-forming inverters provide frequency and voltage control at their connection point.

3 ELECTRIC VEHICLE CHARGING

CHARGING TECHNOLOGIES

Charging technologies can be grouped into three main categories (ENTSO-E 2021) (Figure 3.1):

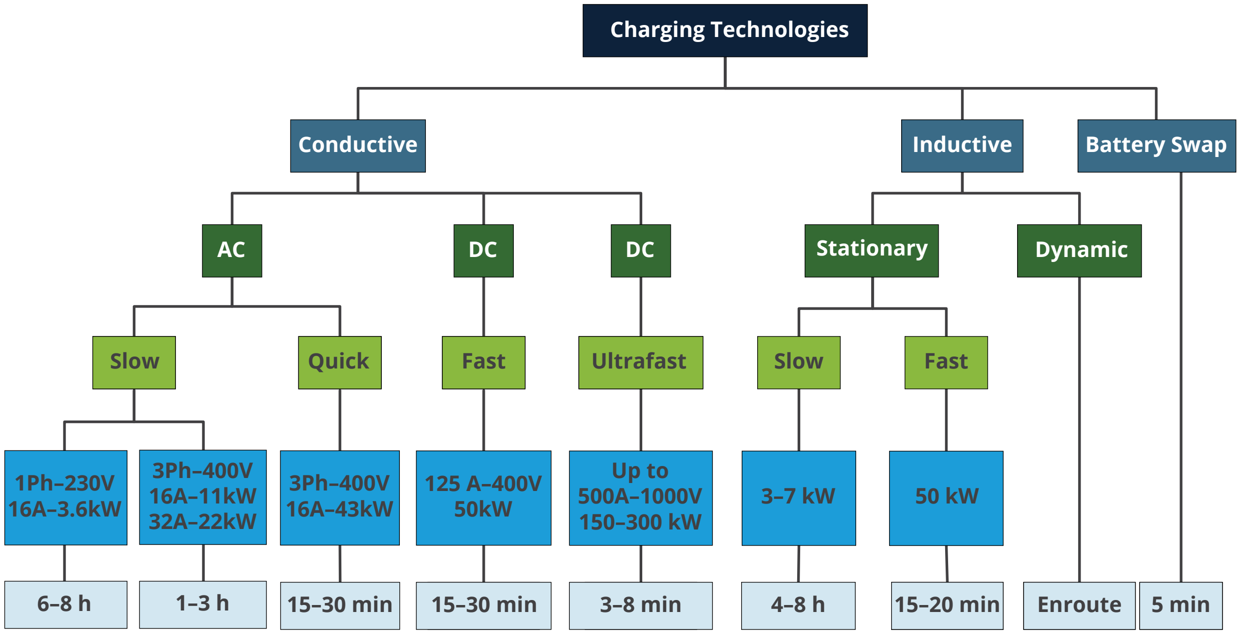
- **Conductive charging:** The EV is conductively connected to the charging station via an appropriate cable to receive power from the electricity grid. AC or DC charging options can be considered. Slow AC charging allows charging ranging from 3.6 kilowatts (kW) to 22 kW. Faster charging options (such as 43 kW) can be considered (in this case, the battery can charge in 15–30 minutes). DC charging allows fast-charging options at 50 kW or even faster; ultrafast charging options can reach 350 kW.
- **Inductive charging:** The EV receives energy from the grid wirelessly. A driver simply places the vehicle over the station without the need to plug in a charging cable. The pad for charging the vehicle is placed below the road, avoiding visually intrusive solutions for charging in public areas. The charging efficiency is more than 90 percent (Sagar and others 2023). Two main options are possible: stationary and dynamic charging. In stationary charging, the EV is charged while parked over the station (options up to 50 kW are available). In dynamic charging, the EV is charged while moving on the road.
- **Battery swap:** An EV replaces its battery with a fully charged one within five minutes.

Different approaches can be adopted regarding the potential to manage the energy required for EV charging (Table 3.1). In unidirectional charging, the EV receives energy when connected to the charging station. In bidirectional charging the EV receives energy from the charging station and has the ability to provide energy (to the grid, a building, or a home, for example).

Unidirectional charging, according to the charging strategy adapted can be further distinguished in:

- **Uncontrolled charging:** In this case the EV user simply plugs in their vehicle in a charging station and is expected to charge at the maximum available charging power. The charging process begins as soon as the user plugs in their vehicle and ends when the EV battery is fully charged.
- **Passive measures:** In this case there is no direct control of the charging process, however, signals are given to achieve a specific purpose (e.g. shift load). For instance, time-of-use tariffs can be used as a signal to encourage charging during off-peak hours. Passive measures also include the regulation of the start/stop capabilities of the chargers, as well as the chargers' capabilities for power modulation (IEA 2022). These capabilities allow simple strategies to be implemented like avoiding the peak load, spreading out the charging load until the EV leaves the station, etc.
- **Active control** (V1G [unidirectional smart charging]): Direct control is exercised by the utility responsible to control the charging process (e.g. EV Aggregator, e-mobility service provider, etc.) with the consent and participation of the EV user. When EV drivers plug in their vehicles, they set a time for departure, allowing a period of flexibility in the charging process. The drivers may also be provided the option of significantly cheaper charging, in case they allow V1G (compared with the "charge as rapidly as possible" approach). In this case, the charging process can be stopped and started remotely, while the charging power can also be modulated. Thus, more sophisticated charging strategies can be applied to achieve load shifting, valley filling, etc. Moreover, such charging strategies allow the efficient exploitation of synergies among EVs and VRE sources.

FIGURE 3.1: **Time Needed to Charge an Electric Vehicle Battery Using Different Technologies**



Source: ENTSO-E (2021).

Note: A: amperes; V: voltage; 1ph: one-phase; 3ph: three-phase; kW: kilowatt; AC: alternative Current; DC: direct Current; min: minute; h: hour.

IEA (2022) distinguishes two types of bidirectional charging:

- **Vehicle to building** (V2B)/vehicle to home (V2H): In this case, active control of the charging process can be implemented with the option for bidirectional charging that can provide energy to a building or a house. When considering the potential availability of local RES production, appropriate management schemes can increase the consumption of locally produced RES energy. Energy management systems in the level of home/building can also avoid steep increase of the consumption, reducing the demand charges. This charging strategy can also provide backup electricity in case of blackouts.
- **Vehicle to grid** (V2G): This charging strategy allows active control of the charging process with bidirectional charging to/from the grid. In this case the vehicle can provide energy to the grid through the charging point (AC or DC charging stations). In this respect, the vehicle can participate in the

TABLE 3.1: **Unidirectional and Bidirectional Electric Vehicle Charging Strategies**

Type of Charging	Charging Strategy	Description
Unidirectional	Uncontrolled	EV users simply plug in their vehicle at a charging station, charging at the maximum allowed power.
	Passive measures	Signals are provided to achieve load shifting; no active control of the user's decisions to charge is possible.
	V1G[a]	Control of charging is active (it can be stopped or started remotely, and the charging power can be controlled).
Bidirectional	Vehicle to building or home	Active control of charging with two-way power flow to and from a building or house.
	Vehicle to grid	Active control of charging with two-way power flow to and from the grid.
Battery-swapping at a station	S2G (Storage to grid)	Control of charging is active; spare batteries provide bidirectional flexibility.

Source: IEA (2022b).

Note: a. V1G refers to unidirectional (one-way) smart charging with active control of the charging process. It is compared with V2G (vehicle-to-grid) and bidirectional charging. The"1" in V1G denotes the one-way power transfer (from the grid to the vehicle).

electricity market offering reserve services, frequency response capabilities, etc. Vehicles, at an aggregated level, can also allow an increased resilience level in the case of blackouts or other emergencies.

Battery swapping stations allow EVs to replace the battery (including options for the battery-replacement of two-wheelers). Such an option provides certain benefits to the end user since it reduces the CAPEX cost for the battery component of the EV. In this case the Storage-to-Grid (S2G) option allows the spare batteries of the Swapping Station to provide bidirectional flexibility. In this case the additional costs of maintaining spare batteries and the revenue from the potential participation in power system services should be taken into account.

EXPECTED IMPACT OF E-MOBILITY ON MINI GRIDS

EV charging affects the grid in several ways (Table 3.2):

- It affects line and transformer loading, can cause voltage limit violations, and intensifies network losses.
- It can affect the generation capacity of the system.
- It can reduce power quality, by affecting harmonic distortion.

Line/transformer loading, voltage limit violations, and increased network losses

Overloading can result from simultaneous home charging where EV penetration is high. Overloading is also possible, albeit with a lower probability in the case of workplace and destination charging.[6] Limited overloading issues should also be expected in battery swapping, because of the charging control applied within the battery-swapping station (IEA 2022).

If the system's limits are violated (because of increased transformer/line loading or violation of voltage limits), network upgrades may be required. In particular, stationary storage, serving as a buffer, might be required in the case of hyper-hubs or fuel station (or en route) charging. Dedicated substations might be needed in the case of bus depot charging. Depending on the station size, battery swapping may require dedicated feeders (IEA 2022).

Grid investments are generally required to overcome voltage limits and line loading violations. Such investments can be avoided when active control (V1G) strategies are applied. An example comes from the study of a rural medium-voltage distribution network on the Greek island of Ikaria (Karakitsios and others 2023; Karfopoulos 2017). Figure 3.2 shows the line loading, network losses, and voltage magnitudes for different levels of EV penetration. In the case of uncontrolled

TABLE 3.2: **Effects of Electric Vehicle Charging on the Grid**

EV Charging Use Case	Type of Access: Private Access	Type of Access: Public Access	Grid Impact
Stop-over charging		Hyper hubs 'Fuel station model'	Potential high-power draw. Depending on the power and volume required, dedicated transformer or stationary storage serving as a buffer might be required.
Collective parking and charging	Company fleets Bus depots	Park & ride facilities	Expected high-power draw due to larger volumes and numbers of vehicles served. Dedicated substation might be needed.
Individual parking and charging	Hotels Offices Home	Supermarkets, malls, theaters, parks, etc. Street parking	Overloading issues expected in the case of home charging for high levels of EV penetration with high levels of simultaneity and voltage issues for rural areas. Lower probability of overloading issues expected in the case of office charging, or destination charging, due to larger capacities typical in commercial or industrial zones. For the case of street parking, similar issues to home charging, especially with higher power draws from three-phase charging.
Battery swapping		Battery swapping stations	Limited overloading issues due to charging control within the battery-swap station. May require dedicated feeders depending on the station size.

Slow charging · Fast charging · Very predictable charging

Sources: Authors, based on information from ENTSO-E (2021), IEA (2022b), and ESMAP (2023).

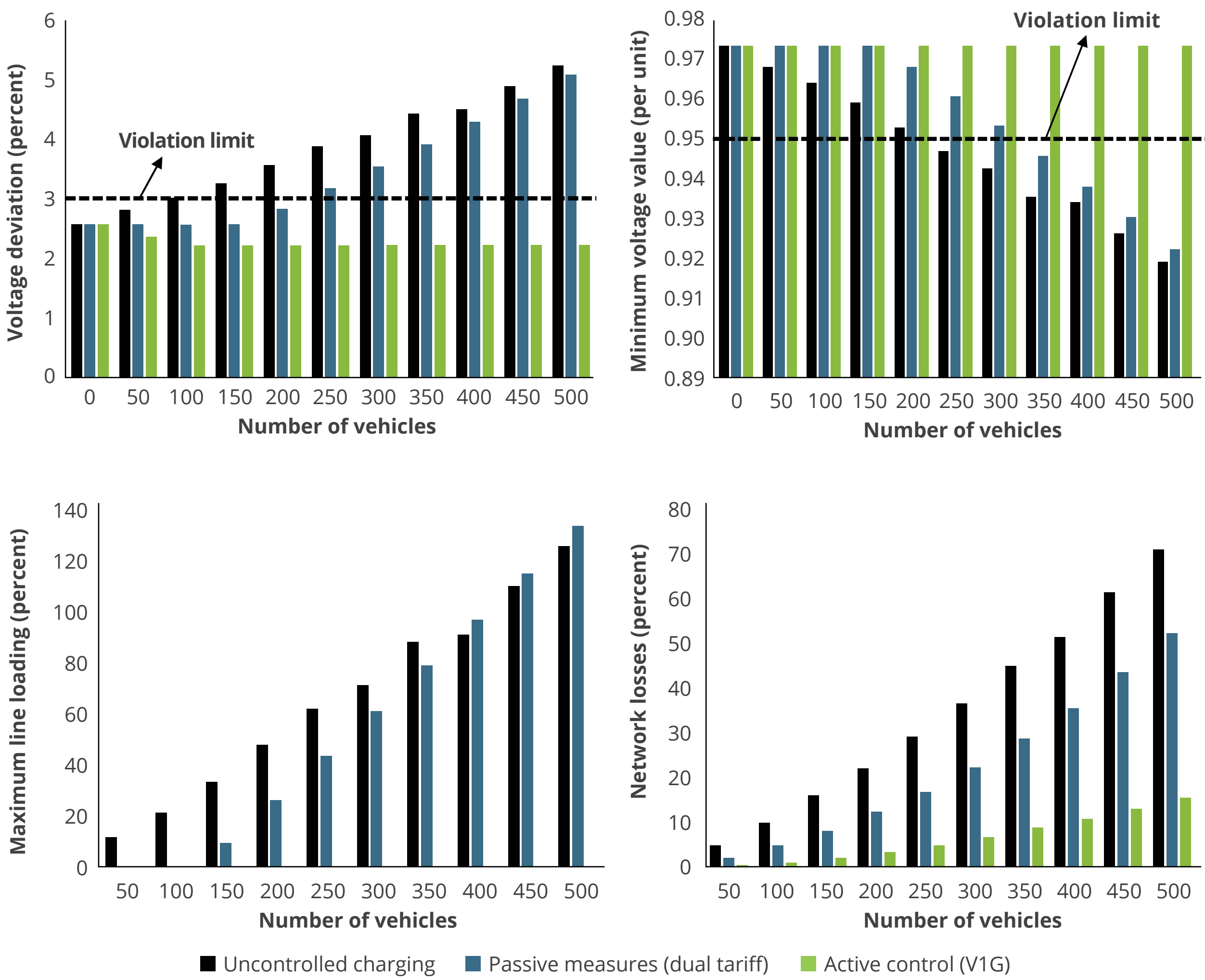
charging, just 150 EVs result in violation of the voltage limits (panel a). Similar results are observed when considering the minimum voltage value (panel b). In this case, uncontrolled charging of 200 EVs results in a violation of the voltage limit.

Increased EV deployment can also introduce high line loading and increase network losses. Uncontrolled charging of 350 EVs introduces a maximum line loading of about 90 percent (Figure 3.2, panel c) and increases network losses by about 45 percent (Figure 3.2, panel d).

A dual-tariff scheme is considered for the Greek Island of Ikaria; a lower electricity price is offered during the night hours. Passive measures do not significantly decrease the loading of the lines (Figure 3.2, panel c). They increase network losses by about 30 percent. Applying passive measures, such as dual tariff, causes voltage violations even when EV deployment is relatively low. The number of EVs that can be connected without causing voltage violation can be increased to 200.

The case study of the Greek island of Ikaria considers a valley-filling scheme (Karakitsios and others 2023; Karfopoulos 2017), distributing the EV charging demand during night-time hours in order to avoid spikes in the system's load. In this case, the EV hosting capacity of the network can be significantly increased without the need for grid investments. For instance, 500 EVs can

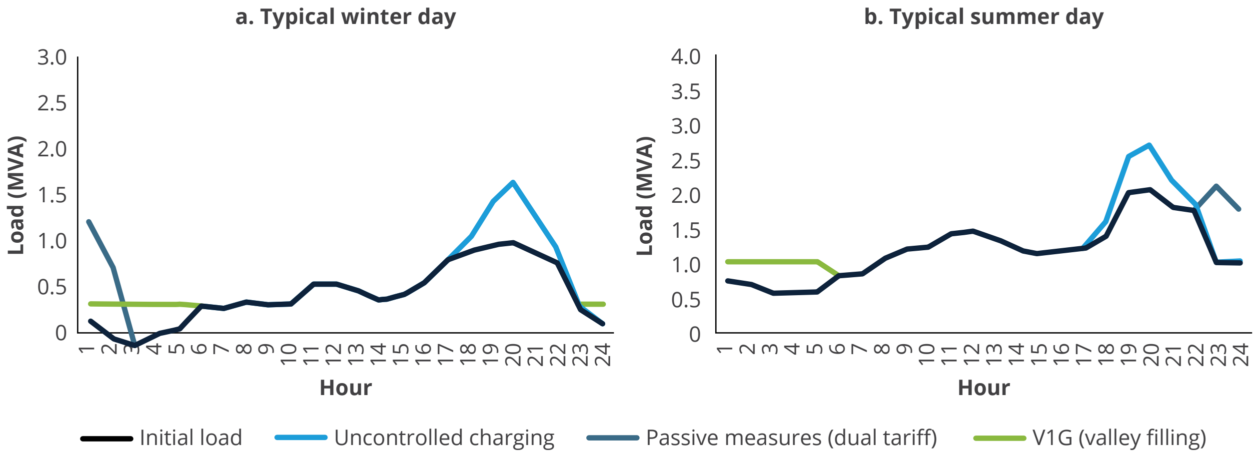
FIGURE 3.2: **Voltage Deviation, Minimum Voltage Value, Maximum Line Loading, and Network Losses for Different Levels of Electric Vehicle Penetration on Ikaria, Greece**



Sources: Karakitsios and others (2023); Karfopoulos (2017).

Note: Figure assumes that a 1 MW wind park operates on the island. The dotted lines represent the violation limits for the voltage deviation (which should be below 3 percent) and the voltage value (which should be above 0.95 per unit).

FIGURE 3.3: **Load Curve on Ikaria (Greece) Under Different Electric Vehicle Charging Schemes**



Source: Karfopoulos (2017).

enter the grid without causing any voltage violation issue or increasing the maximum line loading (Karakitsios and others 2023; Karfopoulos 2017). Valley-filling schemes result in only a small increase in network losses even at high EV penetration levels (see Figure 3, panel d).

Issues related to generation capacity

Issues related to the system's generation capacity can be expected when a high power draw is required for public roadside, depot, and en route charging (see Table 3.2). The change in the generation dispatch is particularly evident in the case of uncontrolled charging in island systems. If, for instance, 1,200 EVs enter the rural distribution grid on Ikaria and charging is uncontrolled, EV charging demand coincides with high demand during the evening hours and the system's peak demand increases, by 30.5 percent during the summer and 66.3 percent during the winter (Figure 3.3). More expensive peaking units need to be committed to cover this load, increasing the operating costs of the system. If the system's generation units cannot accommodate such an increase in demand, new generation capacity needs to be installed.

The introduction of passive measures—such as a dual tariff scheme, where charging occurs during hours with reduced tariffs (at night, in the case of Greek islands)—adds another peak when a significant number of EVs simultaneously charge at the beginning of the low-tariff hours. In Figure 3.3, for example, during the winter, the new peak demand is 20 percent higher than the peak demand in the initial load.

V1G management schemes, such as valley filling, can be applied to prevent a sharp increase in peak demand. In Figure 3.3, EV charging is distributed during the night hours, eliminating spikes in the system's load because of EV charging. An increase in the system's generation capacity is avoided, because the mini grid's existing generation units can meet EV demand when it is effectively distributed across the night hours. (Sections 4 and 5 describe additional charging management schemes that can shift EV demand, exploiting synergies between EV and VRE production.)

Harmonic distortion

Charging stations are responsible for harmonics. The IEEE-519 standard indicates that total harmonic distortion must not exceed 5 percent in a normal situation (IEEE 2022; Saadaoui, Ouassaid, and Maaroufi 2023). Studies related to the development of converters for charging stations take such considerations into account (Aretxabaleta and others 2021; Luqman and others 2019). Chargers that respect this limit are already commercially available (Saadaoui, Ouassaid, and Maaroufi 2023; Aghabali and others 2021).

NOTE

6. Destination charging refers to charging stations located at destinations where EV drivers are likely to park for an extended period, such as supermarkets, malls, theaters, and public parks.

4 POTENTIAL FOR SYNERGIES BETWEEN ELECTRIC VEHICLES AND RENEWABLE ENERGY SOURCES

Exploiting synergies between EVs and RES can increase the RES hosting capacity and reduce RES curtailment, the peak load, the system's cost, and CO_2 emissions (IRENA 2019; IEA (2022). RES production may be lost at certain times of the day if the system's load cannot absorb the high RES production. Simple charging schemes can shift the EV charging demand toward hours with increased RES production and/or reduce the peak load (ENTSO-E 2021).

More advanced EV management strategies can be applied to achieve a high RES penetration while also considering the system's EV hosting capacity and grid-related parameters. For instance, the flexible EV demand management strategy described in Karfopoulos and Hatziargyriou (2015) results in reduced grid losses on Ikaria (panel a of Figure 4.1). The maximum EV hosting capacity in the network can be increased by exploiting EV–RES synergies, as depicted in panel b of Figure 4.1. In particular, V1G strategies or V2G services that consider EV–RES synergies can significantly increase the number of vehicles that can enter the network.

Two other studies find similar results (Figure 4.2).

REDUCTION IN CO_2 EMISSIONS

Islands produce most of their electricity by burning diesel or heavy oil. The addition of EVs can therefore increase CO_2 emissions. RES production can reduce CO_2 emissions, but the system's demand must be effectively synchronized with RES production. Karfopoulos, Voumvoulakis, and Hatziargyriou (2014) show that valley filling reduced CO_2 emissions on Crete.

REDUCTION IN SYSTEM PRODUCTION COST

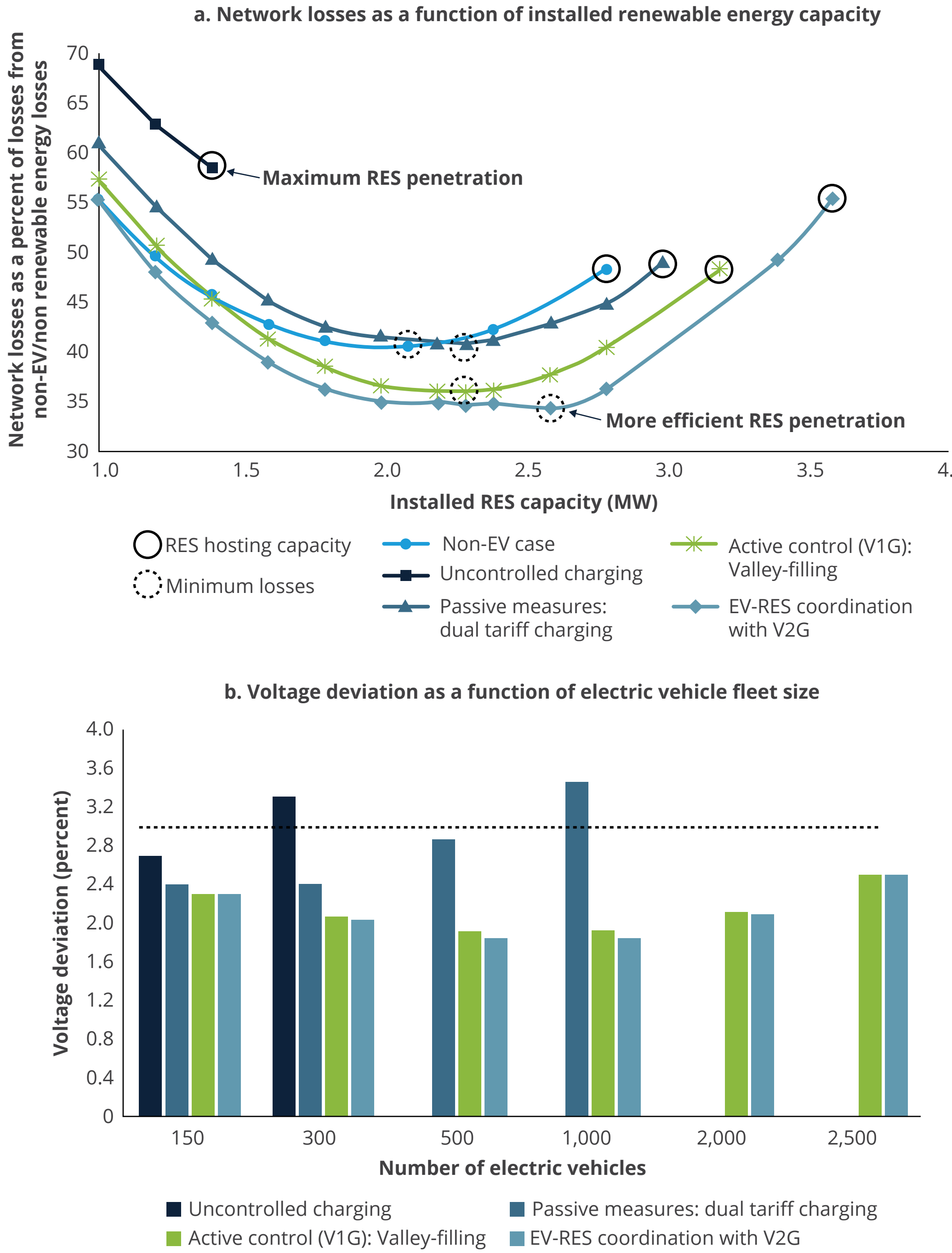
Exploitation of EV–RES synergies can reduce the cost of the system. Introduction of EVs in a mini grid increases charging demand. If this demand is met by conventional units, the production cost rises. However, charging schemes can be applied that ensure that RES covers a significant share of the newly introduced EV charging demand. In this case, the production cost of the system can fall (compared with uncontrolled charging), as there is no need to increase conventional production.

Zafeiratou and Spataru (2022) estimate that in a scenario in which the EV share rises to 20 percent of all vehicles, V2G methodologies that consider synergies with RES can reduce generation cost by 20 percent by 2040 compared with uncontrolled charging. The International Renewable Energy Agency (IRENA 2019) reports that exploitation of EV–RES synergies can achieve significant reductions in the system's cost, particularly when photovoltaic (PV) production is used and V2G methodologies applied.

CONTRIBUTION OF E-MOBILITY TO MITIGATION OF TECHNICAL CHALLENGES ON ISLANDS

EVs can help mitigate some of the technical challenges that emerge when VRE penetration on islands or remote mini grids is high. Specifically designed power electronic interfaces for EV chargers can improve power quality (Monteiro, Lopes, and others 2021) and offer reactive power control (Monteiro, Soares, and others 2021; Carrión, Zárate-Miñano, and Domínguez 2020).

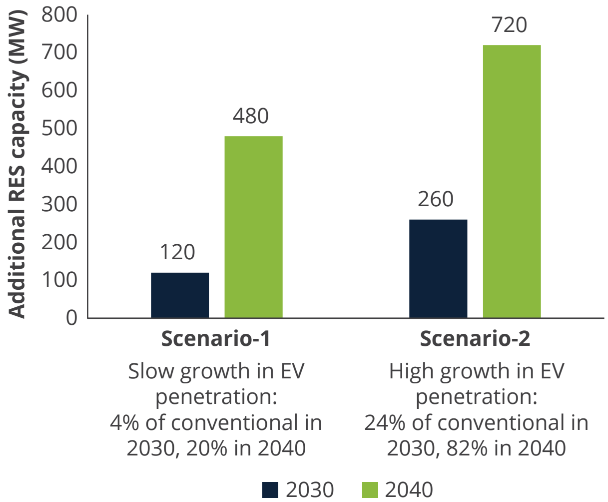
FIGURE 4.1: **Effect of Introducing 300 Electrical Vehicles (EVs) on Ikaria (Greece) on Network Losses and Electric Vehicle Hosting Capacity**



Source: Karfopoulos and Hatziargyriou (2015).

Note: The dotted line represents the limit for voltage violation. RES = renewable energy source. V1G = control of unidirectional charging. V2G = vehicle-to-grid.

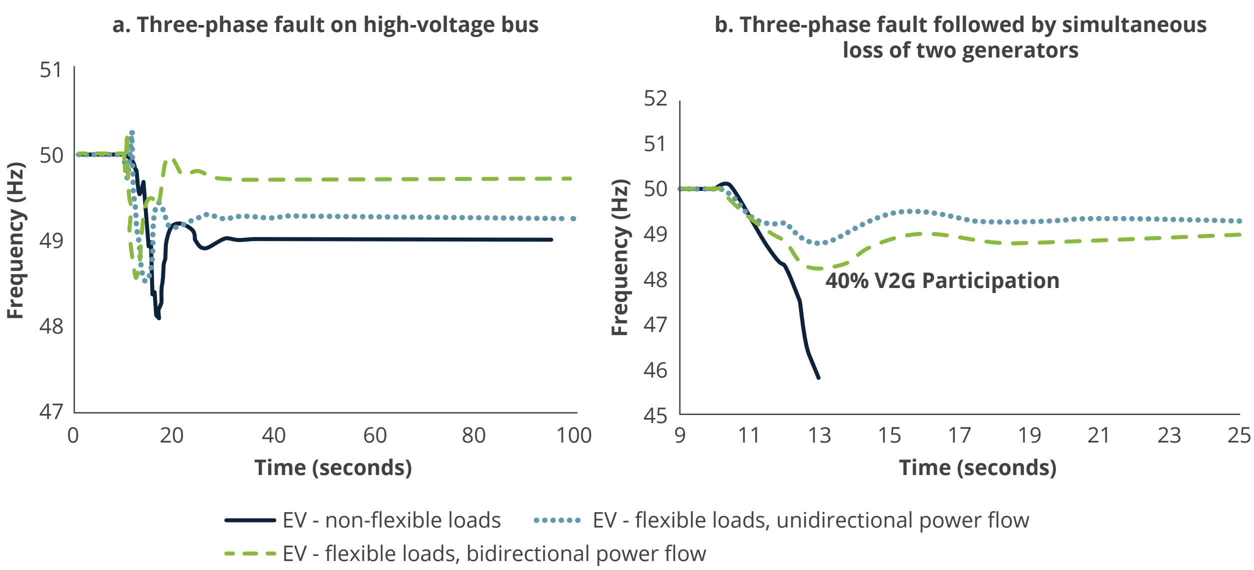
FIGURE 4.2: **Increase in Renewable Energy Hosting Capacity on All Greek Islands as a Result of Vehicle-to-Grid Strategies**



Sources: Zafeiratou and Spataru (2022); Karakitsios and others (2023).

EVs can also alter their charging power to provide frequency reserves. Karfopoulos, Voumvoulakis, and Hatziargyriou (2014) study the provision of services in case of disturbances on Crete. They examine two types of disturbances: a three-phase fault on a high-voltage bus (Figure 4.3, panel a) and a three-phase fault followed by the simultaneous disconnection of two generators (Figure 4.3, panel b). In both cases, charging schemes that consider the EVs as flexible loads can either restore the frequency at a value close to the nominal one (panel a) or prevent a system blackout (panel b).

FIGURE 4.3: **Simulation of a Three-Phase Fault on a High-Voltage Bus and a Three-Phase Fault Followed by the Simultaneous Loss of Two Generators in Crete**



Source: Karfopoulos, Voumvoulakis, and Hatziargyriou (2014).

5 REAL-WORLD EXAMPLES

Real-world examples and case studies allow the feasibility, benefits, and challenges of integrating EVs into isolated energy systems with high VRE penetration to be evaluated. This section looks at the following cases:

- the Greek island of Astypalea, which exploits EV-RES synergies to increase the level of RES penetration
- the World Bank's ASPIRE and ARISE projects in Maldives, which support the country's goals for high RES penetration and the electrification of transportation
- the uYilo E-Mobility Programme in South Africa, which uses V2G for ancillary services and energy storage support through multiple second-life EV batteries
- projects on the Obong-ri, Udo, and Jeju-do Islands, in the Republic of Korea, which highlight the need for timely expansion of grid supply capacity to serve the growing number of EVs.

ASTYPALEA, GREECE

Law 4495 in Greece promotes the development of three special pilot projects on non-interconnected island systems (Stavropoulou 2018). The main objective of these projects is to achieve high RES penetration (beyond 60 percent) through sustainable solutions. Projects should provide attractive investment opportunities and not increase total energy costs. Solutions should ensure the security of the power supply, minimize the impact on thermal production, and be replicable on other non-interconnected islands. Based on criteria such as the size of the island, the installed RES, the operational cost, and existing RES penetration, the islands of Astypalea, Megisti/Kastelorizo, and Symi were selected.

Astypalea was also selected to promote e-mobility. Several public conventional vehicles have been replaced with electric ones, and publicly available charging stations have been installed on the island. Smart and sustainable mobility solutions have been developed and financial incentives provided, with the aim of replacing all types of private vehicles with electric ones (e-Astypalea n.d.; Volkswagen n.d.).

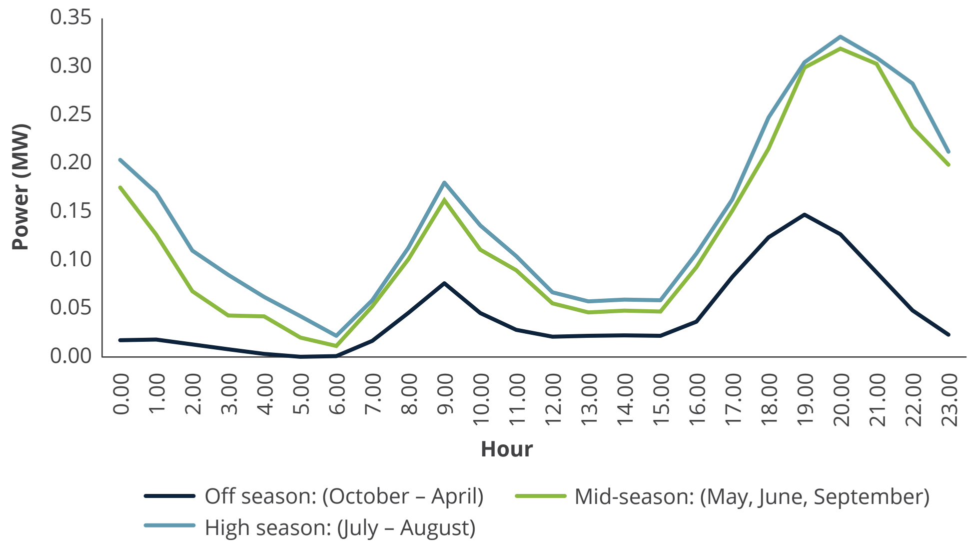
Figure 5.1 shows the expected EV charging demand once the ambitious e-mobility targets are achieved. Because tourist activity is high in the summer, demand during the mid- and high-season months is more than twice as high as demand in the off season.

Islands with high RES penetration must install hybrid stations that include RES units and energy storage systems. A combination of at least 1 MW of PV, 2 MW of wind turbines, and 7.2 megawatt hours (MWh) of battery capacity can provide an internal rate of return (IRR) above 8 percent and an annual RES penetration level close to 70 percent (Karakitsios and others 2023).

A hybrid station with 2.3 MW of PV, 2 MW of wind, and 9.6 MWh of battery capacity is considered.

Installation of such a station on Astypalea significantly increases RES penetration (Figure 5.2, panel a) and reduces the system's production cost (Figure 5.2, panel d). In all cases with EVs, production cost rises, as additional load is served. Comparing the three hybrid scenarios reveals that the additional EV load is served mainly by conventional generation, because technical constraints prevent RES penetration from increasing significantly. The higher EV demand in the case of uncontrolled charging (the green bar in Figure 5.2, panel a) can increase the RES energy

FIGURE 5.1: **Demand for Electric Vehicle Charging on Astypalea (Greece), by Season**



Source: Karakitsios and others (2023).

supplied to the grid while also increasing the IRR on the hybrid station investment. A smart charging scheme that exploits EV–RES synergies (the orange bars in Figure 5.2) can further increase RES penetration and the IRR on the hybrid station investment and reduce the system's production cost compared with uncontrolled charging.

The charging flexibility that EVs offer can be considered for the provision of frequency containment reserves (FCR). In this case, an operating scenario is considered in which island demand is 1.6 MW, to which EV charging adds 0.6 MW. The hybrid station operates with a wind turbine providing 2 MW, and the BES charges at 0.4 MW. A diesel generator operating at 0.6 MW covers the rest of the system's demand.

Panel a of Figure 5.3 depicts the case in which the wind turbine is disconnected, causing an underfrequency event. The provision of FCR services from EVs (when considering EV charging as a flexible load) allows the frequency to be restored at a value close to the nominal one. Results are similar when the central BES is disconnected and an overfrequency event occurs (panel b). If no FCR services are provided from EVs, the frequency of the system increases significantly; when EV charging is used as flexible load offering FCR services, the frequency transient is reduced and is eventually restored closer to the nominal value (Karakitsios and others 2023).

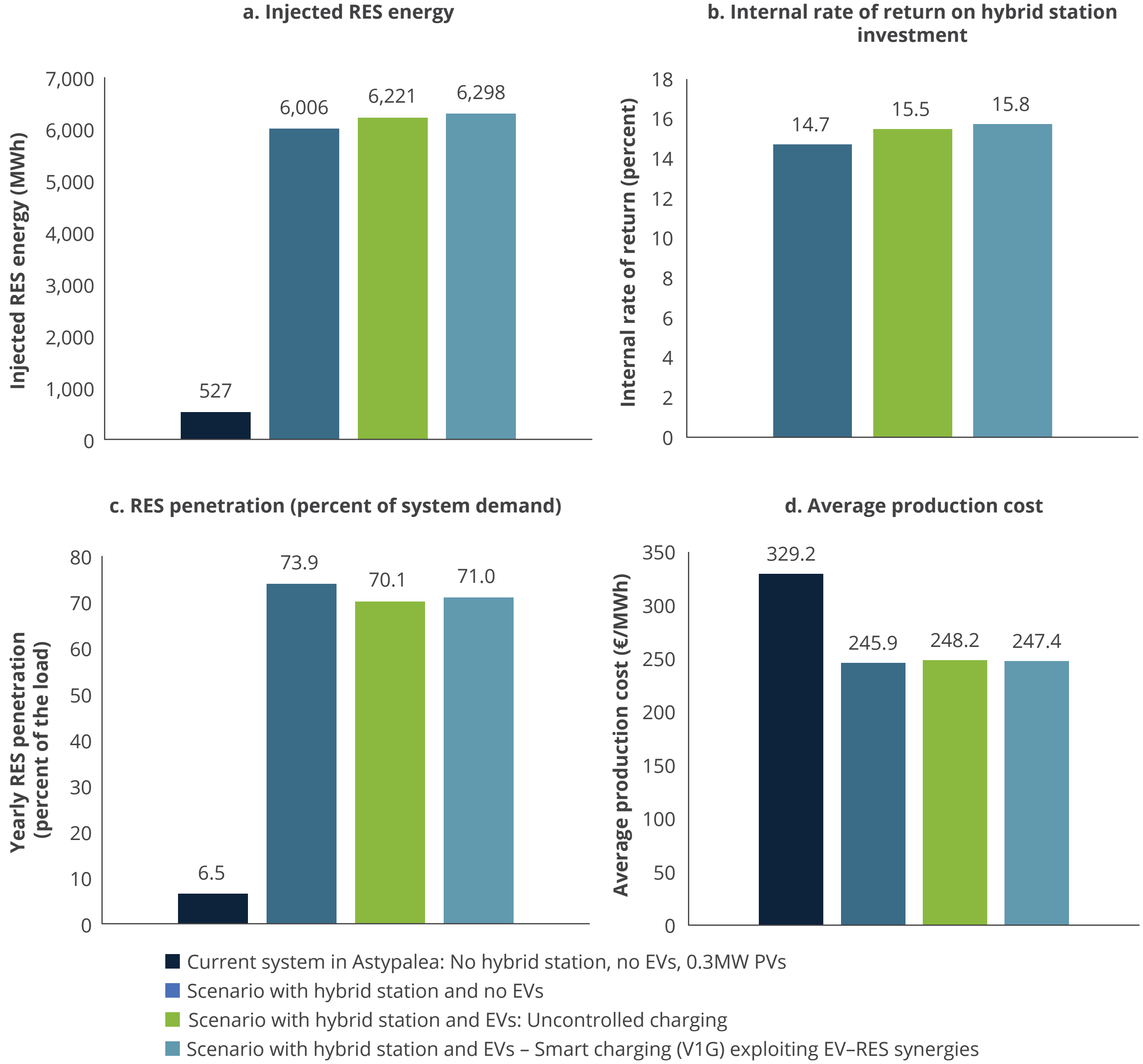
Karakitsios and others (2023) study the impact of EV charging on the loading of the lines and the voltages of the system's buses in Astypalea for a penetration level of EVs that increases the island's peak demand by 5 percent and energy demand by 15 percent. Their results suggest that during normal operation of the system, the lines are loaded well below their thermal limits, even with the presence of EVs. In the case of a fault that requires interconnection of two of the system's lines, a maximum line loading of 71 percent is noted for the non-EV case, which EV charging increases to 74 percent. EV charging reduces the voltage magnitudes. Because of the relatively small increase in demand and the short length of the lines, however, the voltage limits are not significantly affected.

MALDIVES

Maldives comprises nearly 1,200 coral islands, 15 percent of which are inhabited. The population of about 521,000 as of 2022 (according to the population census) is spread out over 185 islands, although around 41 percent live in Greater Male. Eighty percent of the total land area of less than 300 square kilometers is lower than 1 meter above mean sea level. The country's exposure to natural hazards and climate variability poses a threat to lives and the economy.

Maldives achieved universal access to electricity in 2008 (Macrotrends n.d.). The biggest challenge it now faces is transitioning toward clean energy to meet its climate change targets and commitments.

FIGURE 5.2: **Impact of Electric Vehicle Charging on Astypalea (Greece)**



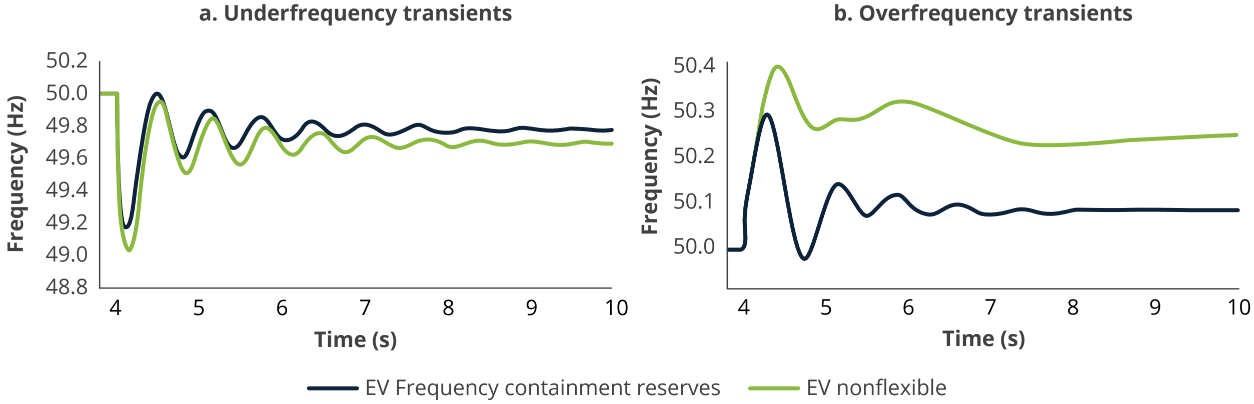
Source: Karakitsios and others (2023).

Maldives relies heavily on expensive fuel imports for its energy needs. Until 2022, 91 percent of its installed capacity for electricity generation was from oil, and 9 percent was from renewable sources (IRENA n.d.). Of the 762 MWh of electricity it generated in 2022, only 6 percent came from renewable sources; 94 percent came from fossil fuels (IRENA 2022). Maldives now has about 600 MW of installed capacity, of which 6 percent comes from RE (95 percent from solar) (IRENA 2022).

Maldives faces many challenges in the power sector. Some of its power stations are more than 20 years old, and its mini grid system consists of multiple dispersed diesel-powered units, contributing to the grid's instability and lack of flexibility (Shumais and Mohamed 2019). The geographic spread of its many islands makes it difficult to achieve economies of scale in the power sector. This challenge, alongside the global supply chain crisis and the worldwide pandemic, has made it difficult to reduce the costs of RE and energy storage in recent years.

Reducing dependence on imported fuel and investing in RE is a key priority of the government of Maldives. Over the past decade, it launched several strategies and initiatives to scale up the application

FIGURE 5.3: **Contribution of Electric Vehicle Charging to Underfrequency and Overfrequency Transients**



Source: Karakitsios and others (2023).

Note: Underfrequency transients occur when the wind turbine is disconnected. Overfrequency transients occur when the central battery energy system is disconnected.

of RE technologies. To accelerate power sector decarbonization and increase access to electricity, it approved the Maldives Energy Policy and Strategy in 2016. The National Strategic Action Plan for Maldives 2019–23 includes actions that promote the energy transition. Its Clean Energy Pillar aims to "(a) increase the share of renewable energy by 20 percent as compared to 2018 levels, (b) reduce fuel usage for electricity generation by 40 million liters, (c) increase renewable energy storage capacity to 30 MWh, and (d) install a minimum of 10 MW of solar PV under net metering regulations by 2023" (World Bank 2022a).

The ASPIRE and ARISE projects

Maldives is accelerating its energy transition and increasing the flexibility and robustness of its grid, including through two World Bank Group projects, the Accelerating Sustainable Private Investments in Renewable Energy (ASPIRE) Project and the Accelerating Renewable Energy Integration and Sustainable Energy (ARISE).[7] ARISE provides over $65 million of public sector financing through grants and loans, alongside a $40 million guarantee from the Multilateral Investment Guarantee Agency (MIGA) and $45 million in private sector investments leveraged for the solar PV investments.

Since 2014, ASPIRE has been helping Maldives de-risk private investments through $11.68 million of concessional finance. Its main objective is to increase PV generation in Maldives through private sector investments (World Bank 2020a). The operation has three components: technical assistance to support the government, the structuring and delivery of tariff buy-downs for currently planned and subsequent subprojects, and a risk-mitigation structure consisting of escrow accounts to cover payment defaults by the off-taker under the subproject power purchase agreements (PPAs) and International Development Association (IDA) guarantees to partially backstop the payment by the government of subproject termination payments (World Bank 2022a). This risk mitigation framework was developed to build the required confidence for the private sector to invest in renewable energy projects in Maldives.

ARISE builds on ASPIRE to further increase RE capacity in Maldives by applying innovative approaches such as the deployment of battery energy storage systems (BESS) to enhance the integration of renewables. Together, the two projects will install more than 50 MWh of battery storage to support the installation of 36 MW of ground-mounted plus floating solar PV. ARISE is expected to reduce Maldives' import bill by about $30 million a year, saving $750 million over 25 years.[8] ARISE is also contributing to VRE deployment through grid modernization investments that complement the BESS installations. These investments include the deployment of grid modernization and smart grid applications, such as Supervisory Control and Data Acquisition (SCADA), smart meters, and site development for installing and integrating solar PV. Like the ASPIRE project, ARISE includes a solar PV risk mitigation package through two financial tools: a tariff buy-down grant and a secured payment mechanism. The government is currently working with the World

Bank to expand the scope of ARISE to include investments that would support the government's ambitious net-zero commitments, including investments in e-mobility.

E-mobility and Vehicle Grid Integration

More than 60 percent of Maldives' energy-related CO_2 emissions come from the transportation sector—far more than the 20 percent from industrial use and 5 percent from residential use (IRENA 2022). About 75 percent of final energy consumption is from the transportation sector, including 59 percent from road transport, 37 percent from domestic navigation,[9] and 4 percent from domestic aviation, according to the UN Statistics Division (n.d.); residential use accounts for 11 percent and manufacturing 6 percent. Rapidly increasing the number of EVs powered by greener electricity sources is therefore urgent. As of 2022, Maldives' total fleet of land-use vehicles numbered 131,000, only 1 out of 25 of which was an EV (mostly tricycles and e-bicycles) (World Bank 2022). About 80–85 percent of Maldives' vehicle fleet are two-wheeler motorcycles, none of which is electric. The main challenges remain lack of access to charging infrastructure and parking constraints (World Bank 2022).

Although the country has no formal e-mobility framework, Maldives has included e-mobility in some of its power sector and RE national strategies in recent years. For instance, the 2015 Maldives Climate Change Policy Framework included as one of its objectives "to achieve a balanced shift toward environmentally friendly transportation modes to bring about a sustainable transport and mobility system" (UNISDR n.d.). The Maldives Strategic Action Plan 2019–2023 Strategy 2.4 includes enabling the transportation industry "to adopt vehicles that use renewable energy" as one of its main ambitions. It calls for support of the Ministry of Transport and Civil Aviation in introducing solar-powered and/or battery-operated taxis and buses and charging stations for the public transport network.

E-mobility for road transportation will be the most impactful in reducing the country's emissions. The greatest potential is from electric two-wheeler motorcycles, with over 105,000 of them currently on the market and with market estimates of significant annual scale-up until 2040. Measures that could incentivize the adoption of electric two-wheelers include relief from applicable taxes, guidelines for charging private vehicles through residential connections, measures to achieve adequate e-vehicle supply equipment at public and private parking facilities, and a scrappage policy for internal combustion engine vehicles more than 15 years old (EY 2023).

Policies on e-buses and micro-mobility options would also be useful. The five main bus routes in Male and Hulhumale (known as Greater Male) are served by 23 diesel-fueled buses. E-buses to replace them should have batteries of either 186 kWh or 325 kWh; they would use 33,601–105,592 kWh of electricity a year. Installing rooftop solar PVs at the eight Maldives Transport and Contracting Company (MTCC) terminals would be required to ensure zero-emission charging operations. To date, the MTCC has procured six electric buses, which are now operational in Male, with one charging station in Male and another in Hulhumale.

Micro-mobility options include cargo bikes, rickshaws, skateboards, e-scooters, and e-bicycles under a hub-to-hub model are the ones that have been showing more results in other island cities. Results from Barbados, Bonaire (Dellissen 2023), and Crete (Lime Micromobility 2019) show that e-scooters and e-bicycles under a hub-to-hub model are the most promising.

E-ferries also hold promise. Maldives has 13 commercial and cargo ferries. A 2023 evaluation by EY recommended that cargo ferries be replaced with solar e-ferries, which would require 349 MWh–1.4 GWh annually. An estimated 11–14 percent of this energy could be provided by the ferries' own 25 kW rooftop solar PVs; the rest would have to come from the grid. Motor power consumption increases exponentially with cruising speed, the customization of the battery size could add weight, implying additional motor power.

To assess the potential impact on Maldives' grid if EV penetration reached 30 percent by 2030, Suski and others (2021) use a modelling methodology that combines annual forecasting of electricity demand on EV penetration, charging profiles, and multiple variables associated with the power system, resulting in four potential scenarios:

- Scenario 1: EV penetration remains the same as it was in 2021 (business as usual [BaU)]
- Scenario 2: Uncoordinated (or uncontrolled) EV charging; most EVs are charged after 6 pm, with different distributions between the level of charging for two-wheelers, electric cars, and e-buses.[10]

- Scenario 3: Optimized EV charging (V1G) with no CO_2 limits; the EV charging load is optimally distributed throughout the day to minimize costs and additional grid-load.
- Scenario 4: Optimized EV charging scheme (V1G), which limits the CO_2 emissions to 2021 level.

The capital expenditure and net present value of the system are tiny compared with the environmental impact of progressively electrifying vehicles (Table 5.1). Although the only scenario in which CO_2 emissions are reduced is the fourth one, the new VRE capacity installed and the electrification of the transportation sector have a multiplying effect on the greenhouse gas emissions of other sectors, which could increase the environmental benefits.

The fourth scenario is the hardest to achieve. The second and third scenarios still show the large benefits of electrifying vehicles and the marginal investment required to do so. Most scenarios require the installation of BESS to ramp up VRE installation (through rooftop PV and/or utility PV) and deal with their load shedding and peak management. These results reaffirm that it is always necessary to consider the consequences of integrating VRE into the grid.

Other challenges

In order to identify the impact of the increased deployment of EVs in Maldives, EY (2023) compares two scenarios. The first is BaU, which assumes a progressive annual increase in EV sales from 3 percent in 2022 to 21 percent in 2039. The second is an optimistic scenario in which EV penetration increases from 7 percent in 2022 to 85 percent in 2039. It includes six variables: applicable tax on vehicles, EV charging cost, availability of public charging infrastructure, provision for charge point collocated at the parking facility, scrappage policy for internal combustion engine vehicles, and a ban on sales of new one. In the optimistic scenario, annual electricity consumption by EVs in Maldives could be twice that under BaU in 2025, four times as much in 2030, and more than eight times as much in 2040 (Figure 5.4). The peak load for EV charging in the optimistic scenario is 67 percent more than under BaU in 2025, four times more in 2030, and eight times more in 2040. Both scenarios present a significant increase in the size of the power sector. The planning of the grid should take into consideration the need to manage a higher peak load.

E-mobility efforts should include an end-of-life strategy. One option is a battery-swapping scheme as the main EV charging model. Batteries in swapping stations can be charged during surplus RE generation, resulting in better load distribution on the grid. Efficiency in terms of the number of vehicles leaving the station with charged batteries can rise by a factor of up to five versus a charging station. Battery swapping also provides shorter downtime for consumers, virtually no replacement cost of batteries, lower upfront costs, and less stress on the grid and space requirements.

To continue to scale up e-mobility, the MTCC would need to continue to support an enabling regulatory

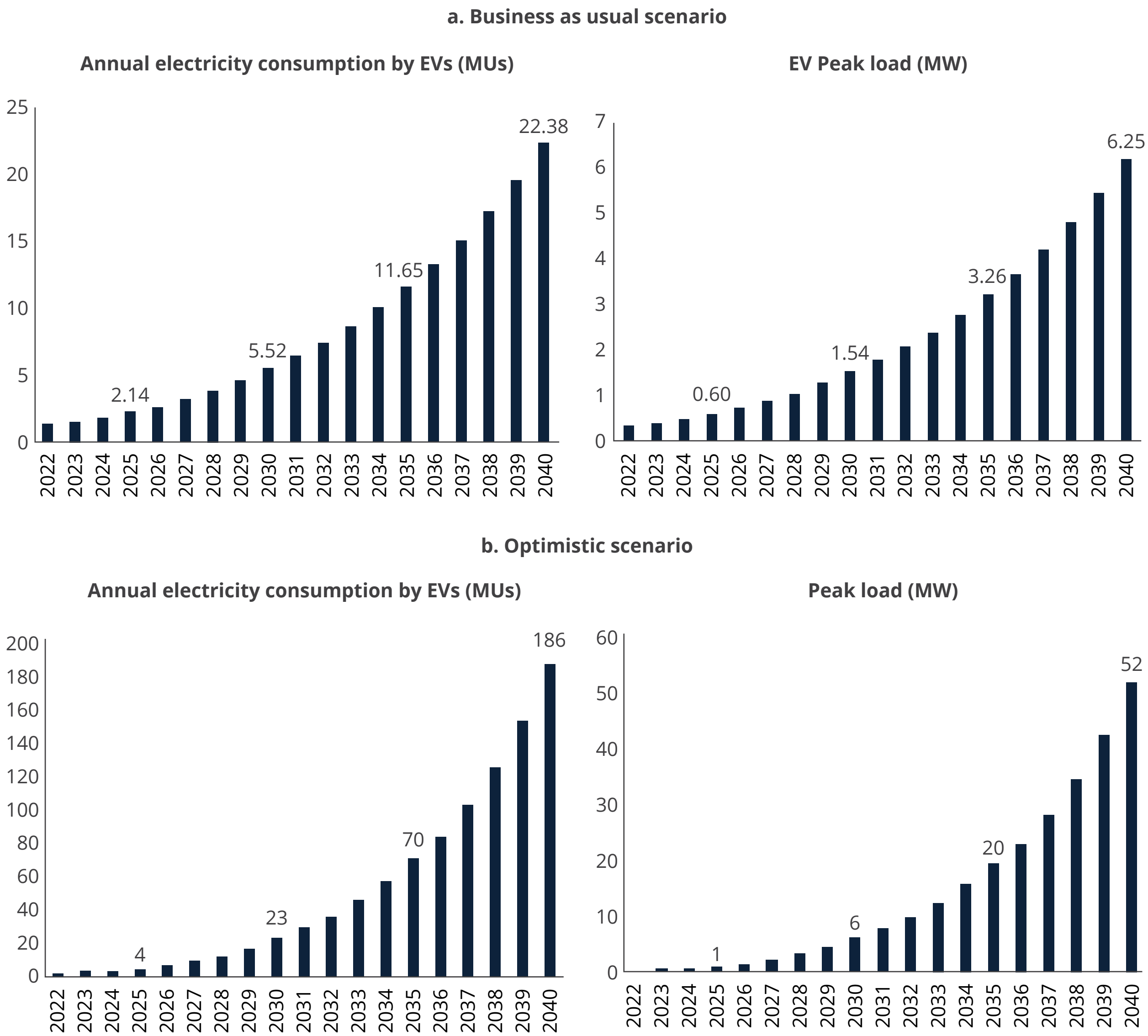
TABLE 5.1: **Estimated Costs and Benefits of Four Electrical Vehicle Charging Scenarios in Male**

Result	Baseline	Uncoordinated EV Charging	Optimized EV Charging	Optimized EV Charging with CO_2 limits
Demand (GWh)	5,299	5,465 (+166)	5,465 (+166)	5,465 (+166)
Net present value of system costs[a] (million dollars 2021)	867	897 (+30)	892 (+25)	919 (+52)
Investment CAPEX (million dollars)[b]	229	265 (+36)	231 (+2)	255 (+26)
New capacity (MW)	111	140 (+29)	113 (+2)	131 (+20)
Unserved demand (GWh)[c]	10	11 (+1)	10 (-)	79 (+69)
Emissions (kton CO_2)	3,173	3,244 (+87)	3,287 (+114)	0 (–3,173)
Production	5,351	5,542 (+191)	5,518 (+166)	5,436 (+85)
Diesel	4,677	4,788 (+138)	4,846 (+169)	4,750 (+73)
Rooftop PV	594	626 (+31)	591 (–3)	613 (+19)
Utility PV	73	73 (–)	73 (–)	73 (–)
BESS	7	28 (+13)	7 (–)	0 (–7)

Source: Suski and others (2021).

Note: a. Discount rate is 10%.
b. Total capex. Please note that the planning model considers capital costs in annualized terms for 2021–2030 which is below the total capex.
c. Unserved energy penalized at 1000 USD/MWh following [69]

FIGURE 5.4: **Estimated Impact of Electric Two-Wheelers on the Grid, 2022–40**



Source: EY (2023).

environment. Its funding efforts need to be accompanied by a national-level program to promote e-vehicle adoption that defines the maximum incentives available per vehicle and fleet owner, eligibility guidelines for e-mobility options, the total funds available, and the horizon over which the incentives would apply, among other features. Procurement of EVs and charging stations must follow the specifications that technical studies are proposing, and procurement of applicable permitting and licensing has to be expedited. Economic barriers—such as tariffs on EVs and solar panels—should be removed and remuneration options, optional ownership schemes, and reduced quotas on stationary energy storage systems correlated with the increase in EVs and the deployment of RE should be considered. Other noneconomic concerns that should be addressed include refining the technical and specific legal definitions and standards, and allocation of guarantees and insurances, which should be flexible and ambitious enough to consider most of the e-mobility options mentioned above.

SOUTH AFRICA

South Africa depends heavily on coal for electricity generation. The use of smart mini grids would support the grid integration of EVs and reduce the impact of EVs on energy demand.

The uYilo e-Mobility Programme, South Africa's national electric mobility program, has been active since 2013. It hosts facilities and projects across the e-mobility ecosystem. Its smart mini grid outdoor testing facility focuses on the resilient and sustainable integration of EVs with embedded generation through a solar PV array.

The use of smart grids increases the efficiency of power distribution across the grid network, by integrating renewable sources, managing EV demand, and using EVs to provide energy to the grid through vehicle-to-everything (V2X) capabilities. In the vehicle-to-grid use cases the program has implemented, EVs use the vehicle's battery pack for ancillary grid services, including behind-the-meter services and frequency regulation, generating additional revenue for EV fleets.

Energy storage is supported through multiple second-life EV batteries used within stationary applications. Increased EV penetration produces more retired battery packs as vehicles reach the end of their first lives as driving range declines. When no longer fit for mobility applications, the batteries start their second lives, in stationary applications.

The distribution network consists of multiple AC and DC chargers as well as V2G for ancillary services from EV fleets (Figure 5.5). The AC charging stations include one station with two socket outlets (3.7 kW and 3.7 kW), another station with two socket outlets (3.7 kW and 7.4 kW), and one station with one socket outlet (7.4 kW). DC charging stations include 10 kW station with V2G functionality and one station with three socket outlets (one 50 kW DC outlet supporting either CHAdeMO or CCS2, and one 43kW AC outlet). The total capacity of the stationary battery systems is 87 kWh. A local autonomous energy management system provides dynamic load management of the charger network. Smart grid communication is achieved through IEC 61850 for remote monitoring and control of the mini grid, which provides energy resilience and sustainability for the grid integration of EVs.

OBONG-RI, UDO, AND JEJU-DO ISLANDS, REPUBLIC OF KOREA

The micro grid examined in the Korean case study includes various types of power generation, including RE, gas turbines, diesel generators, small cogeneration, and various demand resources. EVs can be used as a demand resource by managing their charging demand or as a supply resource through V2G. The grid's supply capacity should therefore be capable of handling the additional EV charging load. It must be expanded in a timely manner, however, taking into account projected increases in EV use.

Figure 5.6 shows the simulation results for EV home charging with 3.1 kW for 660 houses, based on real data for electricity demand and EV charging patterns. It assumes that EV users charge their vehicles when they arrive home after work.

FIGURE 5.5: **Electric Vehicle (EV) Charging Hub and Second-Life EV Batteries Used for Stationary Applications at the uYilo Outdoor Testing Facility in the Eastern Cape, South Africa**

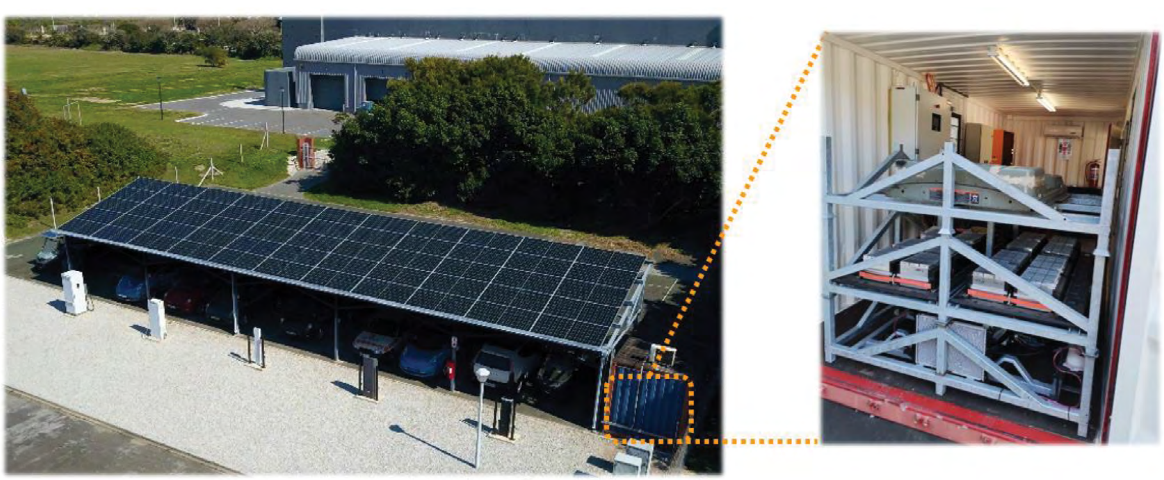
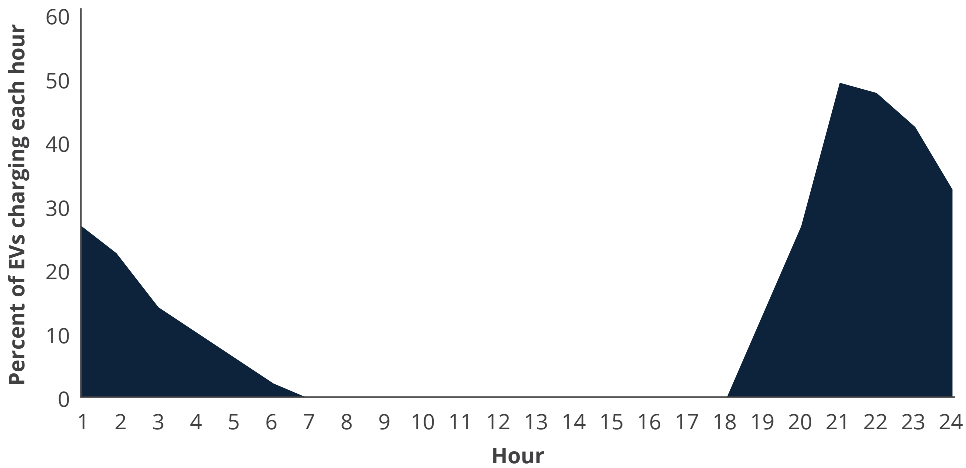


FIGURE 5.6: **Hourly Charging Ratio of Electric Vehicles**



Source: Hwang and others (2015).

The optimal generation composition was evaluated taking into account the introduction of EV scenarios considering only the existing diesel generators as well as scenarios considering the new micro-grid supply following the introduction of EVs in non-interconnected islands. Four cases were evaluated for domestic independent special island A.

The reference case (Case 1) assumes an average monthly load of 90 kW and a maximum monthly load of 167 kW that is supplied by two diesel generators of 100 kW; it does not consider EVs (Table 5.2). Case 2 introduces EVs. Case 3 considers the operational concept of a microgrid, which introduces solar PV and energy storage, in addition to the diesel generators. Case 4 considers both the micro grid and EVs. Cases 2 and 4 are subdivided based on the level of EV penetration.

An important factor when designing the operation modes of solar PV, BESS, and EVs on islands is the end of life of the products. The lifespan of solar PVs is currently 20–25 years; a BESS and an EV last 10 years. The levelized cost of electricity (LCOE) should therefore be designed based on a 20-year period. Cases 1 and 3 assume 20 years of operation. Case 3 consists of 300 kW of solar PV, 200 kW of diesel, a 1 MWh lithium-ion battery, and a 250 kW power converter system (PCS). It is more economical than Case 1.

Case 2 supplies power to the system's load only with diesel generators; Case 4 assumes that the penetration rate of EVs is 50 percent. The analysis finds that including a micro grid is more economical than supplying the system's loads only with diesel. For a 100 percent RE supply, larger battery capacity is required, because of unstable output.

TABLE 5.2: **Parameters of Case Studies**

Case	PV (kW)	Diesel Generation Set (kW)	Battery Energy Storage System (kWh)	Power Converter System (kW)	Net Present Cost ($, thousands)
1: Diesel generators only	None	200	None	None	8,043
2: Diesel generators and EVs only	None	300	None	None	11,456
3: Micro-grid (diesel generators, storage, and/or PVs) without EVs	300	200	1,000	250	6,907
	200	200	None	None	7,840
	None	200	1,000	250	8,113
4: Micro-grid (diesel generators, storage, and/or PVs) with EVs	300	200	1,000	250	6,821
	800	300	None	None	8,875
	None	200	1,000	250	9,310

Source: Hwang and others (2015).

Micro grid concepts have economic advantages, but RE–related BESS and EV charging infrastructure for island systems should be approached step by step. Initially, it is necessary to reduce the proportion of diesel power generation by integrating RE generation and BESS with diesel power generation. Demand management utilizing EVs is also necessary. In order to achieve a 100 percent penetration of renewables, mini grids must be used in certain areas of the island and expanded to implement 100 percent RE for the entire island.

NOTES

7. ARISE is funded partly by support from the Clean Technology Fund and the Asian Infrastructure Investment Bank.
8. Project Brief Results Maldives Energy Program (January 12, 2023).
9. According to the United Nations Economic and Social Commission for Western Asia (UNESCWA), domestic navigation in this context refers to vessels transporting goods or people and undertaking a domestic voyage.
10. The three levels of charging are level 1, charging at about 1 kW peak power (for up to three hours); level 2, charging at about 6kW peak power (for up to one hour); and level 3, at about 25 kW peak power (for up three hours). Charging of e-buses was assumed to be about 45 kW peak power for eight hours.

6 CONCLUSIONS

This report addresses the impact of EV charging on the electricity grid and suggests management strategies to mitigate potential negative effects. It emphasizes the potential synergies between EVs and RES that can increase RES hosting capacity and reduce RES curtailment, system peak load, and CO_2 emissions. Charging control can shift EV charging demand toward hours with increased RES production and/or reduce peak load. Battery-swapping stations, which increase the convenience to EV owners, allow active control of battery charging, providing bidirectional flexibility to the grid operator. More advanced EV management strategies can increase RES penetration and EV hosting capacity (V2G services are particularly useful). V1G charging schemes can further reduce CO_2 emissions. Synergies between RES and EVs can reduce the operating cost of the system, which will otherwise increase to cover the additional charging demand of EVs. Charging schemes that consider V2G capabilities can help ensure that RES cover a significant part of the additional EV charging demand, thus reducing production costs.

Integrating EVs and RES in mini grids is one way to achieve a cleaner environment. Isolated mini grids face unique operational challenges because of their lack of connection to a stronger electrical grid. These challenges include greater uncertainty in the power supply; lower physical inertia, resulting in frequency transients and potential blackouts; and demanding voltage and frequency control. Advanced control of the power electronic converters interfacing with EV chargers can support system operation on islands or remote mini grids with very high VRE penetration. Specifically designed EV chargers can improve power quality and provide reactive power control or frequency reserves. In the case of faults, the flexibility of the charging schemes can be used to restore the frequency at nominal values or prevent a system blackout.

Increased use of e-mobility improves air quality and diminishes reliance on fossil fuels. By reducing the carbon footprint of the transportation sector, EVs help prevent global temperature from rising above critical thresholds.

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