E-mobility and Power Systems

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1. Introduction

Electric vehicles (EVs) represent a new type of load for utilities. Unlike traditional loads, they are movable -the same vehicle can draw power from different spatial locations at different times- and flexible -consumption is disconnected from charging. Moreover, they use electricity but can also serve as distributed resources. They can have several impacts on power systems, which countries should assess and plan for to prepare for their mass adoption. Assessments must ensure that the power system can withstand the additional demand and the potential reshape of the load profile, while continuing to provide reliable electricity services. The impact of a large-scale introduction of EVs will be reflected in all major segments of power systems including generation, transmission, and distribution, affecting both day-to-day operation and long-term planning. Several studies have reviewed current and potential future power systems impacts at various levels of penetration. Authors (Klettke and Mose 2018) conducted a comprehensive assessment of implications related to the increasing share of electric vehicles for the European Union (EU) power system. Earlier analysis in (Hedegaard et al. 2012) focused specifically on five European countries and the effect of large-scale electrification of the transport sector towards 2030. Another European-based study (W. P. Schill and Gerbaulet 2015) evaluated the case of deployment of EVs in Germany focusing on power system planning, power plant dispatch and consequent emissions deriving from EV charging load. An extensive scenario analysis was conducted in (US Drive 2019), evaluating the United States EV market and associated impacts to the U.S. power system in terms of electricity generation and capacity needed. Studies by (Lopes, Soares, and Almeida 2011) and (J. Taylor et al. 2010) focused on impacts on distribution system operation and stress of electrical equipment, indicating that with large-scale deployment of EVs, power flows, losses and voltage profiles may be subjected to substantial changes.

Most of the studies on the wide range of potential economic and technical impacts of EVs on power systems have been done for developed countries. However, there is a significant gap in a comprehensive evaluation of such effects from the perspectives of developing and emerging economies. Not only can the deployment of EVs have significantly different patterns in these economies, but their generation, transmission or distribution sectors may be characterized by distinctive features in terms of type, structure, quality, or limitations. Furthermore, the future expansion of power systems in developing countries is subjected to many uncertainties, including load patterns, population increase and economic growth. Also, their geographical and meteorological diversity affects aspects like the operation of the power system or renewable sources potential. These factors add to the complexity of assessing the integration of EVs to the grid, but ought to be considered to produce comprehensive technological, policy and regulatory recommendations.

Hence, the objectives of this chapter are the following, from the perspective of developing and emerging economies:

1) Provide a comprehensive review of the potential impacts of EVs on power systems.
2) Present proposed and implemented mitigation strategies and assess their implementation.
3) Discuss the role of electric utilities in the integration of EVs in power systems.
4) Give policy and technical recommendations on the deployment of EVs, avoiding negative impacts and promoting positive ones.

The structure of the chapter is as follows. Section 1 provides an introduction and context. Section 2 reviews EV technologies that are considered in this report. Section 3 includes a comprehensive review of the impacts of EVs on power systems, while Section 4 presents current experiences and proposals of mitigation strategies. Section 5 discusses the role of utilities and system planning, presenting the results of a case study done for the Maldives using the World Bank's Electricity Planning Model (EPM). The full case study is presented in the Appendix. Finally, Section 6 provides conclusions and recommendations.

2. Review of EV technologies considered in this study

The main technological determinants that will affect the impact of EVs in power systems include the type of electric vehicle, mode of transport, and type of charger (IRENA 2019a).

The term electric vehicle includes battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs), hybrid electric vehicles (HEVs) and fuel cell electric vehicles (FCEVs), which differ substantially in their interaction with the grid and technological properties. Furthermore, there is a common misconception to think only about personal electric cars, or more precisely passenger light-duty vehicles (PLDVs), when considering the EV market. However, electrification of road transport is happening across various other modes, including light commercial vehicles (LCVs), buses, trucks, two- and three-wheelers and micromobility vehicles. These vehicles may use various types of chargers varying in nominal power, costs, and designation. The characteristics of these categories are described in Table 1.

Table 1 EV technologies considered in this study

Type of Electric Vehicle	
Type	**Description**
Hybrid electric vehicles (HEVs)	HEVs are low-emission vehicles that use an electric motor to assist gas-powered engines. These vehicles are not charged with electricity from the grid. Instead, their batteries are charged from capturing energy when braking, using regenerative braking that converts kinetic energy into electricity.
Battery electric vehicles (BEVs)	BEVs use exclusively electricity stored in onboard batteries that are charged by plugging a vehicle into an outlet or charging station.
Plug-in hybrid electric vehicles (PHEVs)	PHEVs have both an electric motor and an internal combustion engine, but their batteries can be charged using grid electricity.

Fuel cell electric vehicles (FCEVs)	FCEVs use an electric-only motor, however, instead of recharging a battery, they may store hydrogen gas in a tank.

Vehicle mode

Mode	Description
Electric passenger light-duty vehicles (PLDVs)	PLDVs primarily include passenger cars usually used for commuting and infrequent longer trips. PLDVs are mainly charged with residential chargers, sporadically with workplace chargers or fast chargers in motorways. PLDVs usually do not have a high variety of driving patterns with the charging peaks in the morning (after arriving at the workplace) and in the evening (after returning home).
Electric light commercial vehicles (LCVs)	LCVs are used for city logistics purposes, passenger and goods transportation and various maintenance services. LCVs have a high variety of roads and a high frequency of trips. These vehicles are usually charged in the evening after work activities, often also recharged during the day using public or semi-public chargers.
Electric buses	Buses follow the predefined roads and each day several short-distance trips. Charging usually occurs during the night and in the brakes between the shifts, using fast chargers at the depots.
Electric trucks	Trucks are characterized by a moderate variety of routes, long daily distances and a low number of trips. The charging will usually occur overnight, using fast public or designated depots' chargers.
E2Ws[1], E3Ws	E2Ws and E3Ws have very broad variety of roads and short travel distances. Their charging demand is more evenly spread in the day in comparison to other modes. Battery swapping or low power chargers are used for recharging.
Electric micromobility	Electric micromobility include bicycles, mopeds or skateboard and are used for commuting, last-mile mode (often in shares mobility services). These vehicles are characterized by a high variety of road patterns They are charged using a standard outlet, often having a detachable battery.

Type of charger[2]

Charger Type	Typical location	Voltage	Typical Power
Residential – Level 1	Households	120V AC[3]	1-2kW
Residential - Level 2	Households	208-240V AC	2-5kW
Public – Level 2	Workplaces, parking lots, retail stores	208-240V AC	5-22kW
Public – DC fast charger	Designated parking lots, highway stop areas	480V DC	30-50kW
Public – AC fast charger	Workplaces, parking lots, retail stores	208-400V AC	>22kW
Public – DC UltraFast	Designated parking lots, highway stop areas	480V DC	>50kW

Since HEVs and FCEVs have very limited impact on the power system, this study focuses on BEVs and PHEVs that are used in road transport applications.

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[1] In this study as E2Ws we primarily refer to electric scooters and motorcycles. All other small two-wheeled electric vehicles will fall under micromobility category.

[2] Apart from the regular charging using electric vehicles charging stations (EVCS) listed in the table, battery swapping is another option to recharge the battery. If the battery pack of the EV is detachable, then it might be removed at the swapping station and replaced with a fully recharged unit. Currently this technology is becoming popular in the case of electric buses or small-size vehicles (E2Ws and E3Ws),but might be applicable to any mode of transportation.

[3] Level 1 is not used in regions where standard residential plug has a rated voltage of 230/240V

3. Impacts of the additional EV load on the power system

Impacts from the large-scale deployment of EVs on power systems range from short-term operational issues up to long-term energy system planning effects. Both negative and positive impacts in the context of power systems of developing countries will be reviewed in the following sections. These impacts are categorized into 4 distinctive groups as presented in Table 2.

Table 2 EV load power system impacts in the context of developing countries.

Category	**Impacts**	**Context of developing countries**
Impact on power demand	• Increase in total energy consumption • Reshaping daily load curve • Changing the magnitude, duration and potentially timing of the peak load • Changing the variability of the load profile and increasing the uncertainty of load	• E2Ws and E3Ws might be a dominant mode in many economies • Economic, regulatory and geographical difficulties in establishing public charging infrastructure • Geographical location and extreme weather might affect EV power consumption and slow down the uptake • Different demographic structure of society • Different driving patterns might impact charging behavior
Impact on the distribution system	• Overloading of feeders and transformers – increased need for capacity, including potential upgrade of feeders/transformers • Additional power losses • Voltage deviations • Power quality issues (harmonic distortion)	• Inadequately designed and weak distribution systems • High level of distribution system losses • High rate of transformer failures and maintenance requirements • Lack of appropriate management, standards, and regulations • Low awareness about power quality issues • Already high reinforcement requirements due to growing demand
Impact on the transmission system	• Risk of congestion and distortion of electricity prices • Increased need for transmission capacity • Increased need for reactive power	• Low level of interconnectivity and cross-border capacity • Lack of appropriate transmission system regulations to encourage investments • High investment requirements to provide an adequate level of interconnections with growing demand
Impact on generation	• Need for additional electricity generation • Need for new generation capacity investments to provide security and adequacy • Increased power system emissions • High ramping requirements due to sharp increase in power demand • Increased need for ancillary services • Increased need for storage	• Existing problems with providing reliable and secure access to electricity • High generation investments requirements due to rapidly growing demand • Carbon intensive generation fleet, often based on poor quality fossil fuel powered units • Poor electricity market regulation and difficulties in providing reserves

3.1. Impact on power demand and load profile

An increasing penetration of EVs will result in additional electricity demand in the power system. According to (IEA 2021), in 2020 EVs globally used over 80 TWh of electricity for charging purposes. While this is just under 0.5% of global electricity consumption, EVs are one of the fastest-growing sources of electricity demand. It is estimated that EVs will constitute up to 4% of total electricity consumption during this decade, further rising to 10% by 2040, as discussed below.

Over 50 TWh of the recent annual electricity consumption by EVs occurred in China, primarily from the use of E2Ws and E3Ws. Consumption is expected to grow as the global sales of EVs accelerate with increasing cost competitiveness, government incentive programs, and developments in battery technology that have improved efficiency and increased capacity. In its Global EV Outlook 2021, IEA proposed two potential scenarios of global e-mobility rollout. In the Stated Policies Scenario, which considers current government policies, the global electricity demand from EVs reaches 525 TWh in 2030. In the Sustainable Development Scenario, charging demand reaches 860 TWh, assuming complete compliance with the Paris Agreement under enhanced global decarbonization efforts (IEA 2021). In the more ambitious case, the largest EV markets in 2030 include China, Europe, the United States, Japan, and India, accounting for 263 TWh, 187 TWh, 153 TWh, 21 TWh and 83 TWh, respectively, of the total charging demand.

The additional electricity consumption is the most obvious impact of the widespread deployment of EVs. However, in absolute terms, the additional EV charging load will likely have a marginal effect on the aggregated power system demand. The total added yearly value will be comparable or smaller with the increased consumption caused by the electrification of other end uses, particularly residential heating (International Energy Agency (IEA) 2020). Furthermore, it might be counterweighed with improvements in energy efficiency or a shift towards less energy-intensive sectors, e.g. services (P. G. Taylor et al. 2010). In general, recent studies have shown that even at high levels of penetration, the share of electricity consumption induced by EVs will stay at acceptable levels reaching up to 10% by 2040 (Taljegard et al. 2019; EEA 2016), and much less in emerging markets at the early stages of the uptake (Kapustin and Grushevenko 2020). In the IEA estimates, even in the most optimistic Sustainable Development Scenario, the share of electricity consumption from the EV load does not exceed 6% in the 5 largest markets by 2030 (IEA 2021).

While the impact on total electricity demand may not cause substantial impediments for the electric grid, EV charging may have major consequences on the power system load profile. Charging load will be added on top of the baseline hourly electricity consumption, effectively reshaping the load curve. This is particularly significant in the initial phases of e-mobility market development when there might be no incentives to charge the vehicles during off-peak hours and there may be no technological solutions to effectively control the charging process. This implies uncoordinated charging will likely occur. In that case, most of the plug-in events occur at the time of arrival in the workplace or home, which coincides with the morning and evening peaks in the power system, respectively. The magnitude of this reshape will depend on the type and size of the EV fleet and types of chargers utilized but will likely manifest itself in changing the height and/or the duration of the daily peaks as well as increasing the variability of the load. The deeper the level of uncoordinated EV charging, the greater effect it will have on the aggregated power system load. Even if the national or regional levels of EV adoption are low, locations with higher shares of EV load are expected to emerge, significantly changing local load profiles (Mies, Helmus, and van den Hoed 2018) burdening local distribution grids. Examples of such EV load clusters might include wealthier, suburban neighborhoods (Kester et al. 2020) or electric bus depots (Zagrajek et al. 2020).

EVs are still a relatively uncommon transportation option in most developing countries. The bulk of global charging electricity consumption in the near future will come from markets where the large-scale EV adoption has already started in passenger light-duty transportation and it is accelerating for heavy-duty vehicles (Naumanen et al. 2019), including China, EU countries, United States and Japan. Nevertheless, the experience of China, where over the past two decades E2Ws became one of the dominant transportation means (Zuev 2018), showed that the uptake can be very rapid. Therefore, even an approximate assessment of the potential extra power requirements is needed to prepare systems for potential impacts. Several institutions and researchers have already conducted preliminary forecasts, assessing the potential increase in electricity demand due to EV deployment. A few such studies are described in Table 3.

Table 3 Impact on power demand in selected countries

Country	Reference	Assumptions	Demand impact
Brazil	(Dranka and Ferreira 2020)	Fleet share includes 9% of EVs (11.8 million) and 52% for hybrid vehicles (62 million) by 2050	Electric vehicle demand is forecast to reach 38.8 TWh/per year in 2050
Colombia	(Unidad de Planeación Minero-Energética 2020)	660,000 (10%) light electric or hybrid vehicles in 2030 increasing to 25% share in 2050. 82,500 electric vehicle chargers with an installed capacity of 908MW	Annual demand in 2030 amounting to 2,891 GWh which corresponds to 2.9% of total electricity demand in the country
Costa Rica	(WFC 2020)	85% of public vehicles will be emissions-free by 2050. Entire sales of light vehicles will be emissions-free by 2050.	Electricity demand increases by 15TWh per year in 2050 to reach full transportation decarbonization
India	(Abhyankar et al. 2017)	By 2030 BEVs account for 100% of all vehicle sales.	Additional EV charging load reaches 82 TWh/yr, corresponding to 3.3% of the annual electricity demand in India. Peak charging load amounts to 23 GW, which is around 6% of the total peak load in 2030 (estimated at 402 GW).
Indonesia	(Adiatma and Marciano 2020)	5% and 8.6% penetration of PHEVs and BEVs respectively in passenger cars fleet by 2050. 75% market penetration of E2Ws by 2050.	Electricity demand increases by 0.6 TWh by 2025, by 3.3 TWh by 2030, and by 18.6 TWh by 2050, primarily driven by electric motorcycles.
Pakistan	(LUMS Energy Institute 2019)	0.5 million EVs into the transportation grid by 2025	4.83 TWh of annual demand for charging that can be safely met with 1000MW of generation capacity
Turkey	(SHURA 2019)	EV fleet of 2.5 million vehicles by 2030 equaling to 10% penetration of total stock and accounting for 55% of sales	Additional 4.1 TWh electricity demand and up to 12.5% increase in peak demand in pilot regions with uncoordinated charging.
Viet Nam	(IES 2016)	Electric vehicle deployment reaches 20% across all cars and motorcycles by 2050.	Electric demand from EVs is forecast to reach 29 TWh by 2050 or 3.3% of total demand

When EVs are introduced to the power systems, the resulting electricity load profiles are dependent on the charging patterns which in turn are affected by the energy requirements and travel behavior of the final EV users. The vehicle type, the charging level and charging location have been identified as key factors considering the impact of an EV deployment on electricity consumption and load profiles (Grahn and Söder 2013). Nevertheless, e-mobility trends in developing countries are driven by special characteristics of power systems, users, and markets. Factors including vehicle mode, type of vehicle, type of day, type of charging, charging patterns, driving behavior, geographic location, climate and demographics will be described in the following sections.

3.1.1. Vehicle mode

The impact on the power grid will be highly dependent on the penetration of particular types of vehicles. Various EV modes are characterized by diverse charging patterns, energy consumption rates or battery capacities and consequently have distinctive interactions with the grid. PLDVs will most likely constitute the biggest portion of the total stock and consequently demand in high-income countries. Developing countries may however observe significantly different and more diverse modes and mix of EVs. Especially on the local distribution grid level, there will be situations when the EV market is dominated by buses (Gallet, Massier, and Hamacher 2018), E2Ws (Asian Development Bank 2009) or shared vehicle fleets (Taiebat and Xu 2019). Furthermore, different dominant transport choices for commuting might drive the electrification of particular modes. For example, while in South Africa taxis are a popular choice for a work commute (Bruce Raw and Radmore 2019), in Mexico (Harbering and Schlüter 2020) and India (N. Singh 2018) buses and motorcycles are the dominant modes.

Normalized daily charging profiles of various modes are presented in Figure 1. Buses, with their predefined routes and schedules, have easy to forecast and manageable electricity demand that will come mostly from depot overnight charging (IEA 2020a). On the other hand, loads from fast-charging battery buses, although relatively regular, are characterized by sudden spikes and large variability, substantially reshaping local load curves (Rogge, Wollny, and Sauer 2015; Zagrajek et al. 2020). Similarly to electric buses, electric taxis are another popular pilot projects for early EV implementation with examples of Benjin (Zou et al. 2016) or Latin American cities (UNEP 2019). In case of that mode, charging events usually occur at specifically designated charging stations, often equipped with fast chargers, and are likely to occur more than once during working hours, to recharge the vehicle after completing a trip. In the case of E2Ws and E3Ws, these vehicles have substantially smaller batteries, lower energy consumption per km (Weiss, Cloos, and Helmers 2020) and their users make shorter trips than PLDVs (A. Singh 2019). Additionally, their charging consumption is much more evenly spread across the day compared to other modes. All the mentioned features will affect charging profiles and the shape of the aggregated load, which should be especially considered in emerging markets, where the structure of the EV market might be very different from those of advanced economies. Nevertheless, Figure 1 suggests that regardless of the mode, peak charging time will likely occur in the evening when most of the commercial or public vehicles finish their daily service and EV users are returning from work, intensifying the already existing peak. The figure indicates how crucial it is to assess the impact of EVs on consumption, irrespective of the market location and its structure.

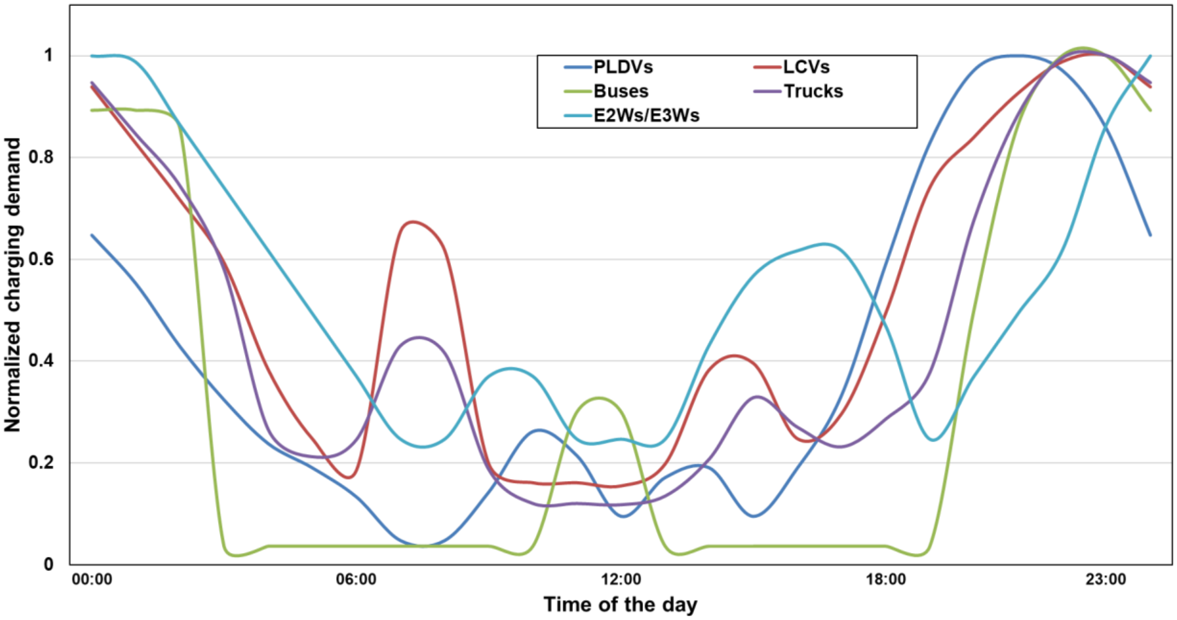

Figure 1 Normalized charging profiles of various modes (IEA 2020a)

3.1.2. Type of vehicle

The share of BEVs versus PHEVs in the market may be another factor influencing peak power requirements and load profile (Klettke and Mose 2018), considering their different charging requirements, technical differences and consequently different driving patterns. BEVs are powered by batteries with larger capacities (17–100 kWh), while PHEVs have smaller battery sizes (4-17kWh) allowing shorter electric driving ranges. BEVs with lower driving ranges generally have lower vehicle miles travelled on average, whereas PHEVs tend to have similar to ICEVs. Nevertheless, extensive development in battery technologies enhancing the range of BEVs, steadily increases their competitiveness, as observed in the UK market where sales of PHEVs have been gradually decreasing (Kane 2019a). PHEVs might be particularly attractive alternatives in developing countries with critical traffic congestion issues (Jain and Sharma, n.d.), longer commuting times, low availability of charging stations or tropical climate, where drivers' behavior and subsequent energy consumption of a vehicle is influenced by warm and humid weather (Heryana et al. 2020).

3.1.3. Type of chargers

The shape of the EV charging load will be dependent on the type of charger that is utilized. Authors (Hardman et al. 2018) conducted a comprehensive review of PLDVs consumers' charging preferences in the UK and reported that around 50–80% of all plug-in events occur at home (Level 1 or Level 2 charging), 15–25% at work (Level 2 charging), while around 5% at public and corridor charging stations (fast charging). Usage of various charging points and consequently charging levels will depend on available infrastructure, the dominant type of vehicles on the market and other socio-economic factors. Development of charging infrastructure serves primarily as an incentive for EV adoption but simultaneously allows to shift part of the load from residential evening plug-ins to mid-day public or work chargers. In the context of developing countries, some governments might be reluctant to invest in widespread public charging infrastructure due to its technical, financial, and organizational challenges. Indeed, various emerging economies including Pakistan (Jamal 2021), Mexico (Martinez 2020), Malaysia (Mustapa et al. 2020) or Bhutan (Zhu et al. 2016) identified EV infrastructure support as a main barrier for large-scale market uptake. In some cities, for example, Shenzhen, China, and Campinas, Brazil, land ownership problems and prices might be an additional barrier to establish the required infrastructure like charging depots, transformers or substations (WRI 2019). What is more, charging infrastructure can also be undeveloped in markets where E2Ws are the dominant mode as they do not require such extensive public charging capabilities (Weiss et al. 2015).

Furthermore, a socio-technical study in (Canepa, Hardman, and Tal 2019) shows that housing conditions of people living in disadvantaged communities (DACs) can affect EV charging choices. Among EV owners, there is also a higher proportion who live in apartments or do not own their home, which can make it challenging to use private or semi-private plug-in chargers and hence require the use of public charging infrastructure. In countries or regions with a high share of potential EV users living in apartments and condominiums, smart charging innovations like lampposts (Ruggedised 2018b) and car parks (Ruggedised 2018a) with integrated EV chargers might be the solutions enhancing uptake, without significant reconstruction of street infrastructure.

For example, in Egypt many households do not own or rent on-premise parking spaces, consequently limiting the availability of establishing residential chargers. On the other hand, the deployment of public chargers requires extensive regulations, incentives and coordination currently not in place in the Egyptian market. Therefore, semi-public slow charging at places like parking lots, garages, commercial centers as well as workplace parkings are expected to fill this gap. As another example, in Jordan the unavailability of public chargers induced social innovation and did not stop the rapid expansion of EV ownership (primarily second-hand). Social media groups were used to create a network of shared residential chargers, useful particularly for owners without home charging stations (The World Bank 2018).

Furthermore, developing countries are characterized by different ownership structures of electric utilities (Alkhuzam, Arlet, and Lopez Rocha 2018), which will play a critical role in the roll-out of public charging infrastructure. The case of the US shows that in the early stage of adoption, financing of this infrastructure came from national or municipal grant sources, sometimes supported by auto producers (McCormack, Sanborn, and Rhett 2013). For large-scale deployment, utilities will need to have appropriate incentives or motivation in the form of strong business cases to effectively provide the required charging infrastructure.

3.1.4. Charging behavior and driving patterns

Typically, when only fixed electricity tariffs are available, charging occurs immediately upon arrival at the charging station, work or home (Klettke and Mose 2018). In the most critical uncontrolled charging case, this can create up to 4 EV load peaks during the day (Schäuble et al.

2017). Especially in the morning and evening, charging events may correspond to existing demand peaks, increasing their height or duration (Morrissey, Weldon, and O’Mahony 2016). In the context of developing countries, metropolitan areas are often more congested and the average working hours (Lee, McCann, and Messenger 2007) are longer than in developed countries, which may affect state-of-charge (SOC) of the EV battery and subsequently residential charging hours. Empirical studies proved that stop-and-go traffic combined with vehicle auxiliary services (including lights, AC, on-board electronics) might cause efficiency losses of EVs and impact customer decisions (Florio, Absi, and Feillet 2021; Bigazzi and Clifton 2015). Other factors impacting charging behavior and driving patterns include road network configuration (Luin, Petelin, and Al Mansour 2017), distance and speed (Raykin, Roorda, and MacLean 2012) as well as cultural differences (Heydari et al. 2019).

3.1.5. Type of day

Another variable affecting EV electricity demand is type of day (weekday, weekend, holiday). On weekdays a substantial peak is apparent in the early evening caused by commuters plugging in their vehicles once they arrive home from work (Element Energy 2019a). Depending on the availability of public or work-based chargers, the second (though smaller) peak can occur in the morning when commuters arrive to work. The occurrence of the morning peak might also be dependent on the type of mode. Bike-sharing data from China indicates that the morning peak from that mode can be shorter but equally high as the one happening in the evening (Xing, Wang, and Lu 2020). On the other hand, EV consumption on weekends is considerably lower than over the week. Empirical studies of charging events show that there might be a large difference in charging demand during the weekend, and the evening peak may be shifted by several hours earlier (Uimonen and Lehtonen 2020). Furthermore, holidays can influence the utilization of specifically located chargers. For example, in China in February 2018, the level of electricity demand at highway chargers was twice as much as in the prior month because of the Spring Festival holiday (Hove and Sandalow 2019).

3.1.6. Geographical location and economy

The potential magnitude and structure of the load curve will also be determined by the type of country, its geographical location or structure of the economy. In the case of developing countries, the peak load might occur in the late evening due to a lack of extensive industries resulting in consumption driven primarily by lighting and other home appliances at night (Huda, Aziz, and Tokimatsu 2019). Developing countries, being in the midst of rapidly restructuring and evolving economies, might not follow the earlier trails that affected the demand profiles of developed nations, therefore the speed and the form of EV uptake might substantially differ. Moreover, economic growth and improvement in the well-being of the people may increase electricity demand from cooling appliances particularly in tropical regions (Adeoye and Spataru 2019), simultaneously reshaping the demand curve and changing the potential impact of EV adoption. This factor can be even more significant since emerging economies are among the most vulnerable to climate change impacts and residential space cooling is forecasted to be a central component of the net increase in final electricity consumption (van Ruijven, De Cian, and Sue Wing 2019). Similarly, demand for vehicle heating and air-conditioning (HVAC) systems driven by ambient temperature will have an impact on the power consumption of EVs. In congested traffic, annual vehicle fuel consumption for HVAC can reach up to 40%. In the case of electric vehicles, HVAC can reduce the available range by up to 50% on hot and humid days (IEA 2019). Empirical and simulation studies prove that both positive and negative deviations from rated temperature (usually 15-25°C) cause an increase in energy consumption per kilometer, reaching even 50% for the most extreme temperatures (Kambly and Bradley 2014; Liu et al. 2018; Mebarki et al. 2013). Additionally, some studies show that high road gradient may have a considerable effect on EV energy consumption, reducing the rated range by over 20% and imposing further barriers for the adoption in mountainous regions or changing the consumers' preference towards a specific type of vehicle or mode (Travesset-Baro, Rosas-Casals, and Jover 2015; Liu, Yamamoto, and Morikawa 2017).

3.1.7. Demographics

Demographic characteristics of EV users are also factors that may influence charging patterns and consequently shaping total energy consumption and impact on the local power grid. Few studies have focused on assessing the impact of demographic features like driver gender, driver age, household location (urban, rural), and household income or education level on charging behavior (J. Zhang et al. 2020; Kelly, MacDonald, and Keoleian 2012). It has been found that females usually drive fewer miles than males, while males usually start their commuting earlier and their daily travelling distances are also longer. Furthermore, older EV owners have earlier charging peaks than younger drivers. In the case of household location, drivers from urban regions usually drive fewer miles than ones in rural areas. It was also observed that the higher income group tends to have a higher and slightly delayed charging peak in comparison to lower-income drivers. Considering these demographic factors should support utilities and decision-makers in planning the distribution of charging stations and overall integration of EVs to the grid. It may have particular importance in terms of developing countries’ demographic characteristics which tend to have younger societies, higher shares of the population living in rural areas or higher income disparity.

3.2. Impact on the distribution system

During the early stages of EV deployment, the potential impact on the distribution grid has been ignored by some utilities and decision-makers, assuming that there is sufficient capacity or that adoption will occur very slowly, giving utilities enough time to reinforce and adjust their networks (Green, Wang, and Alam 2011). Nevertheless, alongside a growing number of empirical studies and technological advancements, this subject has become the center of the EV-grid integration discussion. Overloading of feeders and transformers, voltage deviations, power losses, and power quality issues have been identified as primary effects of EV charging load (Crozier, Morstyn, and Mcculloch 2020). The magnitude of these impacts will depend on the adequacy of infrastructure, driving patterns, charger types, charging timings as well as the scale of the local EV penetration (Green, Wang, and Alam 2011). In the context of developing countries, where the distribution system usually constitutes the weakest and most defective part of the power grid, the quality of the distribution transformers and lines will be determining factors in the scale of EV impact.

The local infrastructure factor is particularly significant, considering that even with low nationwide levels of EV deployment, local hot spots with a high share of penetration will likely emerge due to various socio-economic or cultural aspects (Kahn and Vaughn 2009). In low-voltage, residential areas, even a few simultaneous and uncoordinated EV charging events can cause considerable changes to the local power load received by lines and transformers (Muratori 2018). An individual EV with a fast charger at its peak might use as much power as 20-households (Hensley, Knupfer, and Pinner 2018), and even more in low-income communities. Strong clustering patterns have been confirmed by several studies evaluating early EV adoption in Ireland (Mukherjee and Ryan 2020), California (Kahn and Vaughn 2009), Beijing (Z. Lin and Kang 2020) and Nordic countries (Kester et al. 2020), presenting EV concentrations in neighborhoods with high levels of income, education and homeownership. Additionally, EV concentration may lead to the formation of streets or parking lots that cluster parking spaces with fast public charging facilities (International Energy Agency (IEA) 2018).

3.2.1. Impact on feeders and transformers

Each network is connected to the higher-voltage system using distribution transformers and distribution feeders. With EV clusters and uncoordinated charging, where there is an increased number of plug-in events within a narrow time and area, the residential load can exceed the designed capacity of these transformers and feeders leading to severe stresses and overloads (J. Taylor et al. 2010). Authors in (EA Technology 2016) indicated that 312,000 low-voltage UK feeders (around 30%) will need to be upgraded by 2050 to manage the clustering effect of EV deployment. Consequently, distribution systems could experience reliability and security issues including failures, load shedding or power losses. Especially in the case of transformers, frequent and prolonged overloading can result in higher internal temperature, effectively reducing the lifetime of the equipment even by 20% (Rutherford and Yousefzadeh 2011). The issue becomes even more relevant when considering the current state and age of distribution grids. Examples from developed countries show that distribution systems often contain an ageing fleet of transformers, with a large share of units exceeding design lifetime (U.S. Department of Energy 2015; JARMAN et al. 2009). Ageing equipment makes assets prone to failures and maintenance requirements, which combined with future charging loads could result in the need for far-reaching and expensive infrastructure upgrades. Such system modernizations include replacing existing feeders and transformers feeding into the distribution networks with more resilient versions with larger rated capacities. Low-voltage distribution transformers serving residential neighborhoods are found to be most vulnerable to increased EV loads and depending on their rating may cost between $1,000–$55,000 (U.S. Department of Energy 2015). Together with the costs of distribution feeders, these expenses comprise the largest portion of necessary grid upgrades. The review of some case studies and required distribution system upgrades are presented in Table 4.

Table 4 Review of distribution system upgrades in selected studies

Country/region	Authors	Assumptions and findings
Auckland, New Zealand	(Element Energy 2018)	Converting 15 bus depots to a fully electric fleet would require up to NZ$32 million investments in the local electricity grid
Denmark	(Calearo et al. 2019)	100% penetration in a local distribution grid, corresponding to 127 EVs would require investments of 52,000€ for transformer and cables.
European Union	(DNV-GL 2014)	150 TWh of incremental EV charging demand by 2030 increases overall reinforcements investments in distribution grid by nearly 180 B€
France	(Eurelectric 2015)	Without smart charging total, low-voltage distribution grid reinforcement per million EV was estimated as 200 M€ for charging in single houses, 650 M€ for multiple charging in multi-dwelling or business buildings and 240 M€ for public charging spots on the streets
General	(Pieltain Fernández et al. 2011)	For a scenario with 60% of total vehicles being PEV, DSO investment costs can increase up to 15% of the total actual distribution network
Ireland	(ESB 2018)	At 20% EV penetration, necessary grid upgrades are estimated at the level of €350 million. Out of that €150m account for urban areas, while €127m for rural areas. Smart meters for home chargers require an additional €68m.
Kartal region, Turkey	(SHURA 2019)	To accommodate load with 9,636 EVs by 2030, the Kartal region would need to install 3 distribution transformers, increasing required grid investments by nearly $28,000.
Madrid, Spain	(Martínez et al. 2021)	Electrification of 500 vehicles among 25 postal hubs, assuming fast 22 kW peak time charging, would result in €121,624 of distribution network reinforcements and €7,117 of power losses costs.
New Zealand	(Vector 2019)	At a 10% penetration level with 2.4 kW home charging, the distribution grid would require $22 million of reinforcements, rising to $154 million with 40% penetration and the same charging scheme.
New Zealand	(Strbac et al. 2012)	With 50% of heating and transport electrification by 2030 and 100% by 2050, distribution network reinforcement costs amount to $1.9b in 2030 and $4.9b in 2050.
Norway	(Eurelectric 2019)	2.4 GW increase in load during peak hours due to EV charging would require 1.5 B€ to reinforce grid until 2040, with the third of that used to replace older elements.

Sacramento, California	(Deora 2017)	240,000 electric cars by 2030 (together with other assumptions regarding solar PV, energy efficiency and demand response) could cause voltage violations in 26% of substations and the need for replacement of 17% of transformers at an approximate cost of $89 million.
Switzerland	(Gupta et al. 2021)	With over 130,000 EV charging points and 1,350 MW of charger capacity in 2035, grid reinforcement costs would amount to 129 million CHF. 44% of the transformers would require upgrades. Rural areas would require the highest specific reinforcement costs per kW of charging power.
United Kingdom	(Vivid Economics 2019)	Electric cars and vans achieving a 60% share of new vehicles by 2040, translated into a total of 22 million EVs by 2035 increase distribution network reinforcement costs by £40.7 billion
United Kingdom	(EA Technology 2015)	Two low-voltage feeders have been analyzed. The first one, serving 149 customers, would require reinforcement investments of £5,600 at 50% EV penetration (reaching in 2034). The second one, serving 106 customers, would require £4,800 of reinforcement investments at 70% EV penetration (in 2038).
United States	(A. Sahoo, Mistry, and Baker 2019)	15% EV penetration in 2030. $5,800 of distribution investments per EV in the nonoptimized charging scenario

3.2.2. Impact on power losses and voltage deviations

EV penetration can also affect power losses and voltage deviations in the distribution system. These issues are critical for distribution system operators and ought to be always minimized. Usually, safety requirements of appliances set the safety range of the deviations in a bus voltage to 10% in low voltage distributions grids (IEC 2009). Nevertheless, a series of studies show that uncoordinated charging of EVs can get very close to this limit during the daily peaks even at relatively low penetration levels (Clement-Nyns, Haesen, and Driesen 2010). Substantial voltage drops in the system must require intervention from the system operator and will call for the replacement of transformers if their rated capacity is exceeded (Crozier, Morstyn, and Mcculloch 2020). Additionally, power system losses associated with EVs might reach levels that force DSOs to increase tariffs (Clement-Nyns, Haesen, and Driesen 2010). Also, system losses and voltage impacts due to EV integration are correlated with each other, and minimizing one will also reduce the effect of the other.

3.2.3. Impact on power quality – harmonic distortion

EV chargers have power electronics to safely connect the vehicle's battery with the grid. Since the chargers require a large amount of power and their controllers produce nonlinear time-varying loads (R. B. Bass, Donnelly, and Zimmerman 2014), charging events might result in considerable harmonic voltages and currents injected into the distribution system. Such variations, called harmonic distortions, are the main reasons of power quality issues and might influence the network operation violating standards for public power supply (Lucas et al. 2015). Other, though less significant, power quality issues caused by EV charging include DC offset[4], phase imbalance[5] or phantom loading[6] (R. Bass and Zimmerman 2013).

Harmonic distortion describes how the wave shape of current or voltage differs from the perfect sinusoidal shape in a power system. It may be caused during conversion from AC to DC power in the EV charging process and have adverse effects on critical distribution equipment including transformers, power cables, capacitors, meters, relaying or switch gear, as well as neighboring loads like power electronics devices or motors (R. Bass and Zimmerman 2013). Several studies have assessed the harmonic impact of EVs on distribution systems operation and specifically power quality levels. Some researchers focused on the effects in small-scale residential networks, where impact can be more severe (Masoum, Moses, and Deilami 2010; Jiang et al. 2014), while others assessed the grid harmonic impact of public fast-charging stations (Lucas et al. 2015; Basta and Morsi 2021). Since residential grids will likely have high levels of rooftop solar PV capacities, assessment of harmonic distortion with the presence of EVs and PVs was also a subject of recent studies (Ceylan et al. 2018; De Oliveira, De Godoy Antunes, and Leborgne 2019). These studies found that because of the wide range of chargers and inverter types, harmonic cancellation[7] can take place to a certain extent, but in general deep penetration of PVs and EVs can create considerable harmonics problems in local distribution grids. Furthermore, depending on the infrastructure of the studied grid, accepted standards or charging levels assumptions, some authors declare that harmonic distortion can reach dangerous concentrations even at low levels of EV penetration (Angelim and De M Affonso 2019), while others state that low EV shares produced undamaging harmonic levels in the distribution systems (P. Richardson et al. 2012). Moreover, it was also found that chargers might generate harmonics sufficient to produce negative effects to low voltage distribution grids, while still complying with the official standards (Carter et al. 2012).

3.2.4. Distribution systems in developing countries

Distribution networks in developing countries have been widely identified as the weakest part of the electricity grid, due to inadequate design, aged equipment, and lack of appropriate maintenance, consequently causing poor reliability and quality of the electricity service. Figure 2 presents the relationship between GDP per capita and quality of electricity supply index, calculated annually by the World Economic Forum as a part of the Global Competitiveness Index

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[4] DC offset is an asymmetrical response of the voltage or current to a sudden fault

[5] Phase imbalance is a magnitude of the inequality in the phase voltages

[6] A phantom load occurs in electrical devices when an appliance or electrical equipment consumes power even when it is turned off.

[7] Due to various manufacturers of EV chargers and PV inverters, this equipment may produce different phase angles and magnitudes which lead to harmonic cancellations.

(World Economic Forum 2018). These characteristics might intensify the negative impacts of EV charging load on local power systems.

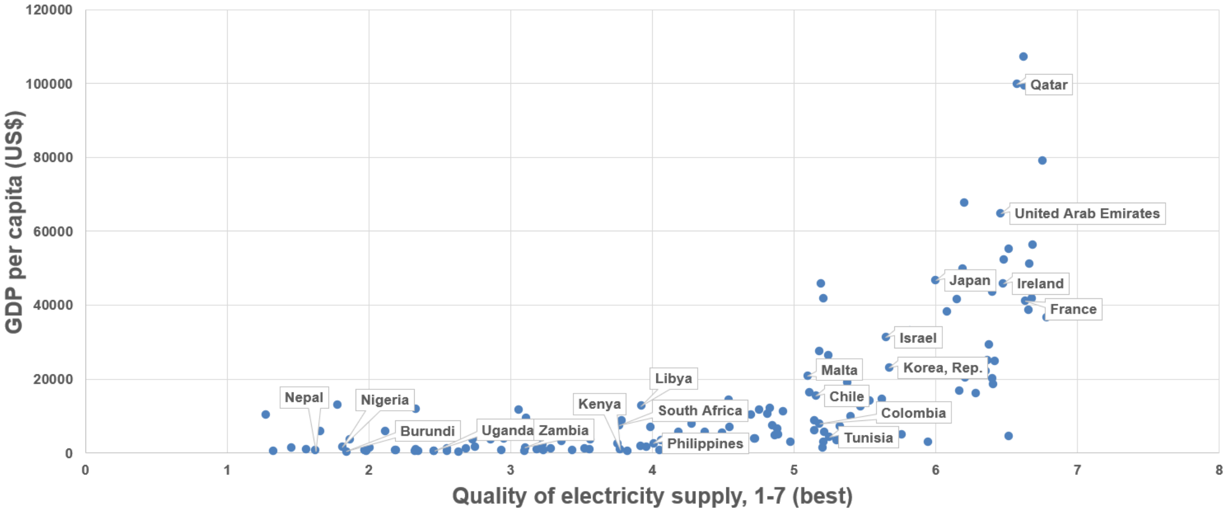

Figure 2 GDP per capita vs quality of electricity supply indicator (based on (World Economic Forum 2018))

Frequent and prolonged outages are one of the main power reliability problems in developing countries and their negative effects take several technical, economic and social forms. In Sub-Saharan Africa and South Asia, business owners indicated reliable electricity access as being the second biggest difficulty for their economic activity (World Bank Group 2016). Furthermore, households and firms may be subjected to additional costs in the form of spending on alternative sources of energy (e.g. candles, charcoal, LPG) (Meles 2020) or investing in diesel-powered standby generators which are much more expensive and polluting (Rentschler et al. 2019). Next to physical damages to the feeders or short and open circuits, transformer overloads are recognized as the primary source of unplanned outages in many developing countries. Studies from Nigeria (Musa 2015) and India (R. Singh and Singh 2010) have shown that transformer failure rates could reach up to 15% compared to less than 1% in developed countries, many of which occur at an early age, due to frequent and extended overloading combined with high ambient temperature, which accelerates ageing process (Hilshey, Hines, and Dowds 2011). The inadequately planned introduction of the EVs fleet might intensify the existing reliability issues, slowing down the overall adoption.

Figure 3 presents the percentage of distribution and transmission losses around the world, indicating that power loss is another critical issue in the distribution networks of developing countries. In Latin America and the Caribbean 17% of generated electricity is lost every year, (Jiménez, Serebrisky, and Mercado 2014), in India grid losses on average equal to 26%, reaching 60% in some regions (Acharjee 2010), while in Africa on average losses amount to 17% (African Development Bank Group 2020). With the rapidly progressing electrification, lack of appropriate planning, poor regulation and limited financial resources, utilities tend to design thin, high-strength distribution lines risking severe voltage drops and consequently high losses (ESMAP 2006). Such situations may occur especially in rural, agricultural zones where feeders are used over long distances to serve loads in remote areas, e.g. for water pumps (Asian Development

Bank, n.d.). Longer low-voltage feeders allow to provide service to a larger number of customers with a limited budget but simultaneously result in larger voltage drops, often sufficient to violate voltage limits, causing brownouts and excessive energy losses, especially for the end-users furthermost from the transformer. On the other hand, feeders and transformers in urban networks can be subjected to more frequent usage than the rural ones or have less spare capacity, increasing the potential grid reinforcement requirements (Mancini et al. 2020). Furthermore, power flow simulations indicate that the meshed grid may be more suitable for high EV penetration levels, without overloading distribution lines. This might be particularly significant in the small island developing states (SIDS), in which power systems are characterized by small and weakly meshed structures (International Renewal Energy Agency 2018).

Reasons for both frequent equipment failures and high losses, are multifold. First, distribution systems in developing countries may suffer from a lack of appropriate planning and management strategies. These would include conducting comprehensive simulation studies, allowing for appropriate sizing and location of transformers in distribution lines, considering prediction of changes in load levels. Furthermore, lack of regulation regarding grid connection rules as well as poor supervision and financial adequacy cause the installation of incorrectly sized equipment, collapsing particularly during peak times. Additionally, already installed lines and transformers are inappropriately maintained and secured causing malfunctions and reduction of life expectancy. Finally, poorly designed regulation frameworks, weak control over utilities and inappropriately subsidized electricity prices cause disincentives for infrastructure upgrades (Mcrae 2015).

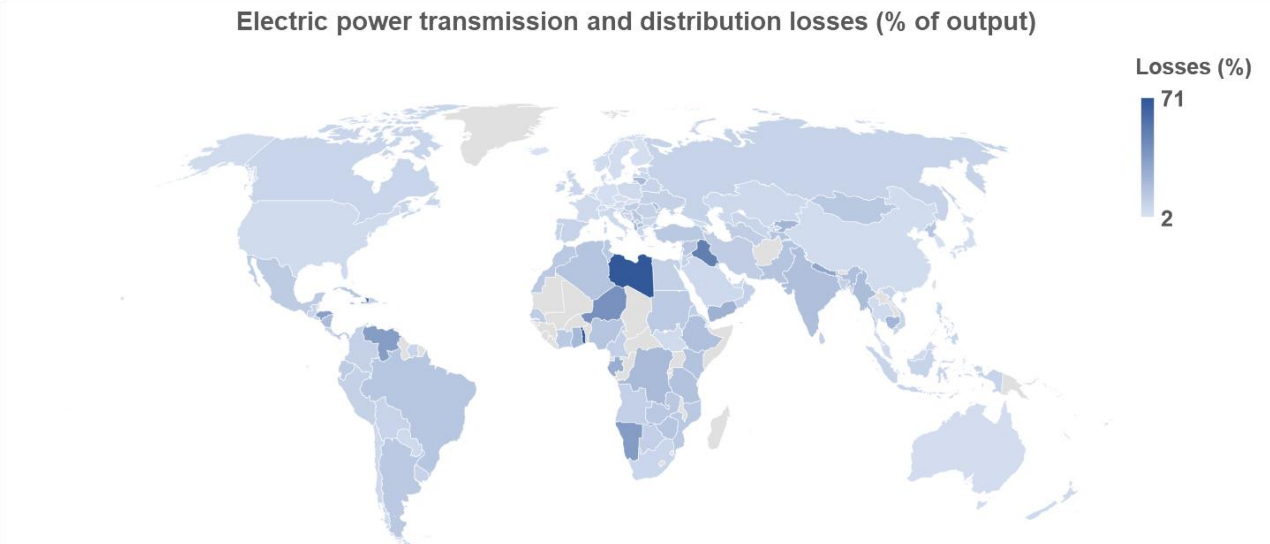

Figure 3 Electric power transmission and distribution losses (World Bank Group and International Energy Agency 2021)

In addition, poor power quality is another distribution network issue widely present in developing countries. This is caused by several factors. First of all, there is a lack of management strategy to cope with power quality issues, which often results from the multifaceted group of end-users connected to one distribution network including residential, agricultural, industrial or commercial customers (Sultan and Darwish 2012). Furthermore, power quality standards that ought to be followed by the utilities and manufacturers are often inadequately defined, outdated and not consistent with international standards (Minnaar et al. 2015). In addition, some authors reported that there might be a lack of awareness of power quality issues among customers and utility employees leading to disturbances and failures (Paracha General Manager and Aftab Qureshi 2007).

There are numerous case study examples from developing countries that report on power quality issues. Analyses from India (Forum of Regulators India 2015), Indonesia (Kunaifi and Reinders 2018) and Mexico (Binz et al. 2019) show that poor power quality results in decreased reliability of electricity supply and increases the likelihood of disturbance events. These are especially relevant in South-East Asian countries where lightning strikes are responsible for many of the failures and incidents (Zoro and Mefiardhi 2006). The Power Quality Loss Survey prepared for Indonesia, Vietnam and Thailand (International Copper Association Southeast Asia 2012) illustrated that voltage dips and harmonics accounted together for over 40% of all power quality disturbances. Both might be particularly damaging for medical devices used in developing countries (Kibiti and Stachel 2020), as this equipment is especially sensitive to voltage fluctuations.

With the extensive spread of low voltage distribution networks, especially in remote areas, developing countries are facing an immense challenge to maintain quality and reliable supply. The aforementioned impacts on loading, voltages, and power quality combined with poor asset quality, might pose significant pressure on the already burdened grid and increase the requirement for urgent, far-reaching upgrades and reinforcements in distribution grids. Furthermore, the distribution system issues, and at the same time upgrade requirements, are expected to deteriorate in the future due to an increase in electricity demand with pro-poor development and ongoing provision of electricity access. In 2017, IEA reported that universal provision of electricity access would require additional investments of $391 billion up to 2030, $115 billion of which will be needed for transmission and distribution upgrades and new grid-connected generation capacities. Upgrading requirements can be even greater when considering the widespread deployment of renewables and smart grid infrastructure, which will be crucial not only for the efficient managing of future electricity grids but also for the implementation of smart charging technologies. For example, South American and South Asian economies plan to invest $25.9 billion and $18.1 billion, respectively, in smart grid infrastructure over the next decade (T&D World 2020a; 2020b).

Furthermore, although overloading and voltage deviation issues are particularly relevant in rural areas, with the deployment of public chargers or a large share of modes that do not require charging infrastructure, these stresses might be expected to occur in urban centers. For example, E2Ws and e-bikes are easy to charge in dense urban locations due to their limited sizes, while some of models come with portable battery packs that are feasible to carry and charge anywhere (A. Singh 2019). Even with small battery capacities, clustering of such plug-in events within a limited area in dense city centers might cause a local increase in load that should be considered by the system operator.

The negative effect of EV charging might deepen in emerging cities with chaotic transportation systems and without urban planning, where uncontrolled traffic and spatial deployment of charging infrastructure can cause potential overloads in distribution feeders and transformers. Examples of case studies with public fast-charging station installations have been performed for cities in Brazil (Melo, Carreno, and Padilha-Feltrin 2014) and Ecuador (González, Siavichay, and Espinoza 2019), which concluded that an appropriate management strategy for charger deployment is critical in city centers to avoid distribution system failures. Furthermore, since electric buses (Ayetor et al. 2021) and taxis (Gómez-Gélvez, Mojica, and Kaul 2016) are most likely to emerge as the first types of larger types of EVs deployed in emerging markets, their fast-charging stations and charging clustering effect might substantially burden local sections of distribution systems. In South Africa, taxi minibuses account for 75% of commuting to work and schools (Transaction Capital 2019), and the potential electrification of such a massive fleet of nearly 300,000 vehicles (Booysen and Apperley 2020), could require substantial infrastructure upgrades. In Chile, the operator of a depot with 75 buses requested 6 MW of power needs, forcing reinforcements in the local distribution system including constructing new feeders (The World Bank, Steer, and NDC 2020). A study from India estimates that depending on the type of bus depot charger ancillary equipment including transformers, switchgear, cables, protection system and SCADA may cost over $150,000 per charger (Shyamasis Das, Chandana Sasidharan 2019).

In the longer term, regions and countries with a high significance of road freight industry like Latin America, China or India, might experience distribution system stresses due to deployment of heavy-duty electric vehicles (HDEVs) and their high-power charging stations, especially alongside major highways (The Brattle Group 2019). Additionally, local EV clusters are likely to emerge in popular touristic destinations, driven both by the popularity of sustainable tourism (Bigerna, Micheli, and Polinori 2019) and providing local transportation services (Csiszár et al. 2019), which can further burden local grids and the impact may be seasonal. An example of such patterns is substantial deployments of e-rickshaws in Asian countries (Saxena 2019).

All the aforementioned characteristics of developing countries call for the preparation of suitable plans for EV integration into local electric power systems, necessary to provide reliable, secure, and sustainable systems. Such evaluations should not only consider potential levels of EV penetration but also the spatial disposition of chargers, the actual state of the grid and the future increase in other non-EV-related loads. Ideally, multi-scenario simulations with a detailed representation of the distribution grid and its elements should be conducted. An example of such an impact assessment study is presented in Box 1.

Furthermore, the potential technical impacts like loading of lines, voltage deviations or harmonic distortions might be effectively limited by strong power system regulation and enforcement of the standards specified for reliability parameters. While many countries introduced internationally acknowledged power quality standards and regulations (Bollen 2003), nevertheless these standards are often not strictly monitored and implemented (Forum of Regulators India 2015), causing issues and failures. Even with the increase in power usage after widespread EV implementation, many potential risks in the distribution system can be mitigated with proper design of electrical equipment, particularly EV chargers, including the selection of components, measurement techniques and control standards.

BOX 1. Example of a comprehensive impact assessment of large-scale EV integration on the distribution system – case study of India

India, with its growing economy, and massive consumption capacity, will likely become one of the biggest and most diverse EV markets in the world. Nevertheless, India's extensive power distribution system struggles with many economic and technical issues (Holmukhe 2016), that may escalate with large-scale EV uptake and consequently slow down EV adoption. Therefore, careful assessment of EV implementation in India's distribution system is a crucial step for effective and widespread integration.

A comprehensive evaluation has been recently conducted by Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ 2019). The study started by selecting 10 existing distribution feeders for general data collection, which included load and voltage profiles, information on distribution transformers, consumer mixes and energy consumption. The data collected was used to shortlist 3 specific feeders for exhaustive technical simulation studies. The selection process aimed at choosing feeders with diverse characteristics in terms of voltage profiles, charging station existence or locational importance. Networks of designated feeders were carefully modelled to analyze the impact of charging stations on the load flow, loading, voltage and harmonics. To appropriately simulate charging demands, five subsystem models were combined: travel patterns, energy consumption, power consumption, EV penetration levels and EV charging strategies. Finally, for each feeder, various scenarios were analyzed, differing in EV penetration levels, installation of public chargers, the addition of storage facilities or solar PV integration.

This study found that with the appropriate balance of network improvements and time-of-use tariffs, the DSO will be able to manage any level of EV deployment. Furthermore, it was advised that the DSO ought to precisely follow grid connection standards and practices to avoid equipment failures. Additionally, it was suggested to penalize commercial charging stations which violate the adopted harmonic standards.

Such comprehensive studies simulating existing parts of the networks bring multifold advantages. First, they provide full quantification of the potential impact of EV integration. Second, they allow for flexible manipulation with the analyzed scenarios and system designs. Third, they provide decision-makers valuable information regarding the location of the charging station or required network upgrades.

3.3. Impact on the transmission system

The deployment of EVs may also impact the transmission power system operation and expansion planning. Transmission expansion aims to determine what class of new grid facilities will be required, considering various technological and socio-economic indicators. Investment decisions, similarly to generation capacity ones, are crucial to ensure adequacy to supply the load at all times, avoiding excessive congestions, bottlenecks and failures. For the appropriate impact assessment, it is essential to assess the spatial distance between the largest EV load spots and critical power units, especially for systems in extensive geographical areas, with heavily centralized generation.

Several authors have developed and assessed the impact of EV charging on national and regional transmission systems. (Graabak et al. 2016) analyzed an effect of 100% EV penetration on the Nordic transmission system by 2050. Uncoordinated charging resulted in 2.8GW of additional transmission capacity needed in the region, which corresponded to a 60% increase in comparison to the reference scenario with no electrification of the transport sector. (Sarid and Tzur 2018) conducted transmission and capacity expansion research based on a large-scale IEEE-8500 test node feeder. It has been shown that in the most extreme case of uncoordinated charging, investment requirements rose by 30% relative to the base case without EV, translating into 20 new transmission lines. On the other hand, in a recent Chilean study, no significant differences in transmission expansion were found, even for the high penetration scenarios (Manríquez et al. 2020). However, sensitivity analysis of 100% EV penetration, reveals 4 additional lines that needed to be installed. A study conducted by BCG on the US market estimates costs of transmission investments at $420 per vehicle through 2030 with 15% EV penetration in the US market in 2030 (A. Sahoo, Mistry, and Baker 2019). Authors in (M. Li et al. 2020) analyzed the impact of large scale EV deployment on the operation and expansion of the Australian power grid. With a 100% penetration rate and uncontrolled charging scenario, transmission line capacity needed to increase by 90GW (by 17%) on a national scale, causing a 6% growth in transmission costs. (Crozier, Morstyn, and McCulloch 2020) evaluated the impact of deep EV penetration on the UK transmission system. Although none of the modelled lines exceeded their rated limit, areas with lower voltage were seen with concerning high levels of loading in case of failure of one of the other lines.

Analogously to generation and distribution assets, in terms of developing countries, some distinctive characteristics need to be considered when analyzing the sensitivity of transmission system planning and operation to EV loads in emerging markets. First, transmission networks in developing countries are often unreliable and underdeveloped, both within the individual country borders as well as for cross-country transmission (Levin and Thomas 2016), resulting in frequent failures and a high level of losses. In Sub-Saharan Africa, transmission and distribution losses cause additional costs of $5 billion annually, with levels far exceeding the world average of 10% (Adams et al. 2020). Power grids in emerging economies may experience significant burden and investment requirements not only due to the urgent need for modernization and improvements, but also because of rapidly growing electricity demand, which in some regions may double by 2050. India expects over $24 billion in investments in the transmission grid by 2025 (The Economic Times 2020). The African Development Bank estimated already existing annual investments in 2015-2040 needed for transmission expansion between $3.2 billion and $4.3 billion (African Development Bank Group 2019). Other technical difficulties may include frequency control on the tie lines or the risk of slow oscillation when main generation units go off-line. For example in Nigeria, tightening frequency control and avoiding deviations is crucial for successful deregulation of the electricity market (Vanfretti et al. 2009). Furthermore, the lack of a legal framework for electricity trading, lack of regulation of the transmission system (Leeprechanon et al. 2001), or poor involvement of private investments (World Bank Group 2011) are also relevant when considering impacts on transmission expansion and operation. Spatial and temporal availability of renewable sources might also have an impact on the transmission system and ought to be appropriately included to account for EV-induced electricity demand or supply shocks across regions. For example, in hydro-based systems dams are often constructed in remote locations and power must be transmitted over significant distances. In addition, in the long-term hydro generation is subjected to a high level of uncertainty caused by multiple inflow scenarios (Pereira et al. 2005) that may affect the transmission system operation and planning under deep EV penetration levels. Finally, the impact on transmission system planning might be fundamentally different given various geographical and meteorological factors, like a latitudinal extension (e.g. Chile (Manríquez et al. 2020) or isolation and lack of interconnectivity between regions (e.g. SIDS (Agenc 2018)).

3.4. Impact on power generation

As discussed earlier, the deployment of EVs will cause an increase in electricity consumption that will need to be accommodated by the power system's generation resources. With the accelerating level of integration and in the absence of coordinated management and planning, additional demand may put considerable stress on the generation infrastructure. The burden might be even greater when considering concurrent electrification in other segments of the economy and high expectations of rapidly progressing power sector decarbonization. Furthermore, in the context of developing countries, there are several challenges that already exist in the power generation sector that may make the integration of EV loads even more problematic, including growing demand, ageing and inefficient units or extensive investment requirements. In this section, the impacts and challenges of additional EV loads in the power generation sector will be described.

3.4.1. Power generation and capacity

Additional loads from EVs need to be accommodated by increasing electricity generation from the power system units, discharging stored energy, or importing power from another region. The timing and place of the charging load determine what type of generation resources are used to recharge the vehicles and will drive subsequent economic, technical and environmental impacts. Most of the national and regional power systems have appropriate generation capacities to accommodate load at the early adoption stages when the number of EVs is low. Nevertheless, in the long-term, especially in the absence of coordinated charging strategies, EV demand may induce needs for additional capacity. Charging electricity consumption should be incorporated in long-term power system planning studies, to assure security, adequacy and sustainability while considering economic and technical characteristics of power technologies as well as the system itself.

Several authors have deployed long-term power system planning models to analyze the impact of EV charging loads on the dispatch of generation units, CO_2 emissions, capacity investment decisions, peak demand and subsequent costs. A review of such studies is presented in Table 5. There are a few key conclusions that may be drawn from these evaluations. First, uncontrolled charging enhances peaks in the daily electricity load, making the peak generators the main providers of a charging load. Most of the times, the marginal electricity generating unit satisfying EV load will be gas- or oil-fired units, characterized with flexibility, but also high variable costs. This in turn will cause growth in overall operational expenses of the system and subsequently may lead to an increase in electricity prices and end-user costs. Furthermore, it may happen that already existing and planned capacities will not be sufficient to satisfy the increase in peak demand. In such cases, new capacity investments (especially in the peak units) will be needed to provide security and adequacy.

Table 5 Review of studies evaluating power generation impacts of EV load

Country/region	**Source**	**Assumptions**	**Power generation impacts**
Alberta, Canada	(Doluweera et al. 2020)	5% EV penetration in 2020 raising to 20% in 2031 corresponding to 2,500 GWh of additional demand	EV charging demand is met with natural gas and imports. With uncoordinated charging, the contribution of the electricity sector to power system emissions decreases from 32.6% to 30.6%. 350 MW of new generation capacity is needed in 2031.
Barbados	(Taibi, Fernández del Valle, and Howells 2018)	26,600 EV on the road by 2030	In case of uncontrolled charging, 25% of extra production costs added to the power system. Over 30% increase in the yearly average marginal cost of electricity.
Chile	(Manríquez et al. 2020)	150,000 electric PLDVs, 28,000 taxis and 360 electric buses	Compared to a scenario without EV deployment, generation investments increase by $18 million (2.8%), while operational costs by $18 million (1%).
China	(B. Li et al. 2021)	174 million EVs on the roads in the moderate scenario and 349 million EV in the aggressive scenario by 2050 + 70% reduction in power sector emissions by 2050	10%, 13% and 6% increase in gas, storage and solar capacity respectively between moderate and aggressive scenario. $55.5 billion (4.4%) increase in annual total power system costs by 2050. Even in the uncontrolled charging scenario the average CO_2 emissions of the power system in 2050 decrease from 90.16 kg/MWh in the moderate scenario to 87.37 kg/MWh.
Chongqing, China	(B. Li et al. 2020)	2 million electric PLDVs and unmanaged charging strategy	Evening peak increases by 6.7% causing operating costs of the power system (including fuel, O&M, reserves, curtailment and trade) to increase by $6.5 billion (7.8%).
Germany	(Hanemann, Behnert, and Bruckner 2017)	6 million EVs in 2030 with various CO_2 price scenarios	With uncoordinated charging, the production from lignite, hard coal and natural gas plants is higher for all CO_2 price scenarios in comparison to the case with no EVs. With a CO_2 price of 20 EUR/t system operating costs increase by 0.2 billion EUR (2%) and emissions increase by 5 Mt (3.5%)
India	(N. Abhyankar at el. 2017)	367 million E2Ws and 89 million electric PLDVs by 2030	The total peak EV charging load exceeds 30GW, which is about 6% of the total peak load by 2030 (480 GW). The demand might be fully met with already planned capacity expansion

New York, US	(Weis, Jaramillo, and Michalek 2014)	10% penetration of PHEVs, corresponding to 900,000 vehicles	System costs increase by \$0.15 billion per year (3.7%) with a capacity expansion scenario in comparison to a scenario without EVs. There is an increased investment into Gas Combined Cycle units.
Texas, Finland, Germany, Ireland and Sweden	(Shortt and O'Malley 2014)	Evaluation of generation portfolio impacts with penetration between 0-5%	Net-costs of the power system supplying the EV charging load ranges between 200-400 EUR/year per vehicle for 0.5% penetration, but costs vary significantly depending on RE penetration or CO_2 costs. Without CO_2 costs the coal and CCGT capacity increases with deeper levels of integration.
United Kingdom	(Heuberger, Bains, and Mac 2020)	14.6 million EVs in 2040, translating to a demand of 34.1 TWh increasing daily peak demand by 9.4 GW.	Total capacity requirements in 2050 are 9.2 GW (5%) greater than in the base case without EV demand driven by flexible capacities of CCGT, OCGT, battery storage or transmission capacities.

Many developing countries face power generation issues, causing difficulties in providing constant, reliable, and affordable electricity supply and consequently impacting economic growth and competitiveness (Eberhard et al. 2008). A rapidly rising electricity demand stimulated with economic expansion and population growth, stresses the power system to provide appropriate generation capacity levels. Due to extensive investment requirements and lack of financing, many developing countries are prone to regular power crises caused by inadequate power capacity (Afful-Dadzie et al. 2017). Nigeria (Roche et al. 2019), Pakistan (National Transmission and Dispatch Company (NTDC) 2018), and Brazil (Minister of Mines and Energy 2020) serve as examples of regions with significant projected increase in electricity consumption and consequently massive capacity installations and investment requirements. A large-scale deployment of EVs, especially when combined with rising electricity demand from other sectors, can cause additional economic and technological stresses. Moreover, developing countries are often characterized by poor electricity conversion efficiency, deriving from ageing and inefficient power units or bad quality fuel input. Furthermore, emerging economies can have an abundant potential of renewable resources, which should be comprehensively considered when assessing the EV load impact in regions dominated by wind (Kiviluoma and Meibom 2010), solar (Carrión, Domínguez, and Zárate-Miñano 2019) or hydro (Keller et al. 2019) energy. Finally, climate and geographical features should also be considered as a factor influencing EV impact on capacity expansion. Residential space cooling is expected to cause a significant increase in final electricity consumption of developing countries (van Ruijven, De Cian, and Sue Wing 2019) and when combined with EV fleets, it may increase investments and generation requirements. A particularly characteristic case is power system planning in SIDS where a lack of interconnections, limited capacity possibilities and heavy reliance on diesel generation can cause substantial economic and environmental impacts in the power system from large-scale EV deployment. Such a case is described in Box 2.

3.4.2. Peak and flexibility

One of the most noticeable effects of large-scale EV deployment with uncoordinated charging will be an increase in peak electricity consumption. Changes in the level of the peak load increase the capacity adequacy requirements, which is defined as the ability of the generation capacities to meet the peak load, considering uncertainties in the availability and demand level of the generation units. Additionally, the peak load is needed for a shorter period and requires a high level of flexibility, therefore should be provided by transmission or units with appropriate ramp rates, i.e. gas turbines, internal combustion engines and pumped or battery storage (International Renewable Energy Agency 2019). The concept of flexibility is critical since increasing penetrations of variable renewable energy (VRE) needed to reach decarbonization targets, drastically intensify the requirement for flexibility (Lannoye, Flynn, and O'Malley 2012). The magnitude of this requirement and consequent appropriate grid management strategy will be heavily contingent on the type of renewable energy included in the electricity mix, but also on already existing conventional generators.

BOX 2. Power system planning in small islands developing states with large-scale EV fleets

Despite deep reliance on fossil fuels in the power and transportation sector, various SIDS have ambitious and rapid decarbonization strategies to transition into a system with high shares of VRE sources and EVs. Long-term power system planning is a challenging task in SIDS due to the remote geographical locations, limited capacity to host energy technologies, environmental constraints on network expansion, heavy dependence on fossil fuels, high uncertainty in electricity demand growth and the small size of the overall system. Therefore, any change to the system has a great impact on the overall operation.

Achieving appropriate levels of system reserves and flexibility to guarantee system security and reliability are the most crucial aspects of EV integration in SIDS. Uncontrolled evening charging may lead to a substantial increase in daily peak and cause short- and long-term consequences in a VRE-based system with limited interconnection. First, it may lead to firing diesel generators to meet the demand in times of peak or VRE unavailability, consequently delaying achieving decarbonization goals. Additionally, inducing fossil fuel-fired generators would increase marginal generation costs in the system, which in many competitive markets later is translated into higher electricity prices charged to customers. Furthermore, in order to comply with emission targets, uncontrolled EV charging can increase investment requirements in storage technologies needed for sufficient levels of reserves and flexibility. In the most extreme cases, without adequate reserves in the form of storage or generation capacities, EV load can lead to the drastic decrease of reliability indexes caused by non-supplied energy. On the other hand, with low levels of demand, leveraging flexibility from EVs can provide a big advantage in the deployment of VRE reducing curtailment and providing storage services.

Some studies have assessed strategies for introducing EV fleets into SIDS power systems. (Gay, Rogers, and Shirley 2018) analyzed the suitability of Barbados for EV penetration. The authors emphasized dependence on fossil fuels and the need for alignment between the power sector and transportation sector targets to ensure efficient decarbonization. Furthermore, it was argued that depending on the development of wind or solar resources, various charging strategies will be most suitable for the best interaction of the power and transportation sector. A study conducted in Fiji (GGGI 2019), identified government light vehicle fleet, airport taxis, tourism rental vehicles and waste management trucks as the most suitable for early EV adoption. Authors indicate the risk of creating local EV clusters and advice considering it in local development plans of feeders and transformers.

In the context of developing countries, reshaping the peak load and consequent flexibility requirements induced with EV charging may coincide with issues that are already in place and severely stress existing power systems. First, many developing countries are already experiencing a tight demand/supply balance and frequent load shedding events due to inadequate power systems. Studies of Nepal (Timilsina, Sapkota, and Steinbuks 2018), South Africa (CSIR Energy Centre 2021) and Kenya (Abdullah and Mariel 2010) show that load shedding might cause a substantial decrease in industrial output, trade volumes and subsequently GDP output. Furthermore, flexibility requirements that occur due to wide-ranging EV deployment will accord with the increasing share of variable renewable energy sources characterized by short-term uncertainties. Especially in terms of solar power, which is expected to be the backbone of power systems of many developing countries on their way to sustainable transformation (Shahsavari and Akbari 2018). Given that the peaks for PV production and uncoordinated EV charging in the evening do not coincide (Abhyankar et al. 2017), significant flexibility in the power system will be required to ensure reliable and secure service (Kondziella and Bruckner 2016). For example, in a Nigeria-based study (Eni and Akinbami 2017), the peak-valley demand difference provided with the conventional plants doubles at 20% PV penetration. In addition, many developing countries' power systems are now heavily based on inflexible generation units, increasing the need for building a more robust portfolio, modernizing existing plants or unlocking other innovative sources of flexibility, like storage and demand response. South Africa (Leino 2017) and India (Shrimali 2021) are the primary examples of such systems. Additionally, considering often underdeveloped transmission system infrastructure or lack of it in terms of island systems, there might be limited potential of deploying system reserves located in other regions, placing an even greater burden on peak and reserve plants. In Indonesia, where the power system heavily depends on the transmission between islands, violating the stability limit of power plants leads to dispatching more expensive generation units or load shedding during peak hours. Finally, appropriate designs of electricity markets are critical for efficient short-term disposition of flexibility options, as well as long-term planning of flexibility resources (Veerakumar 2020). Taking that into account, poorly defined regulatory frameworks and undeveloped markets (Kessides 2012) might pose another obstacle for achieving an appropriate level of flexibility in developing countries.

3.4.3. Power system emissions

With deeper penetration of EVs, rising charging demands will put greater pressure on regional power generation systems. Considering that transport electrification is one component in the fight against global warming, the critical issue is the source of the electricity used to power EVs, and consequently the extent of the GHG emissions from this generation. This question is valid not only from the perspective of power system operation but also life cycle assessment and actual sustainability of the vehicles themselves. Power systems are not homogenous and there are spatial and temporal differences in fuels or technologies that comprise their energy structure. Various types and volumes of emissions might result in different areas at different points in time, depending on whether oil, coal, gas or renewable sources are used as primary energy input and what generation technologies are deployed for energy conversion.

An appropriate analysis of EV charging impact on emissions requires consideration of marginal grid carbon intensity, which is the emission intensity resulting from the additional power generation (usually represented in kg CO_2e/MWh) (Kim and Rahimi 2015). Marginal intensity will vary hourly depending on the type of generator unit used for supplying additional demand. This, in turn, will be contingent on the installed capacity mix, available renewable resources, and technical properties e.g. ramp capabilities. In the regions where the base load is served with coal thermal power plants, marginal carbon intensity will be higher during off-peak hours when these units are under-utilized (e.g. Germany (W. Schill and Gerbaulet 2020) or the Los Angeles region (Kim and Rahimi 2015)). On the other hand, carbon intensity can be lower in systems with high shares of solar PV or where base generation is composed of nuclear or hydro units. Furthermore, as it was discussed, most of the uncoordinated EV charging tends to coincide with morning and evening electricity peak load. Consequently, depending on the characteristics of a specific power system, a peak might be provided with units fundamentally differing in emission factors like gas turbines, diesel engines, pumped-storage plants or batteries.

Although the overall global electricity generation is still heavily based on fossil fuels, this dependence is particularly strong in developing countries, especially in terms of coal. With growing e-mobility penetration, this reliance can cause an increase in power sector emissions and challenge sustainability of the EVs. This is even more critical when considering poor fuel quality (N. R. Sahoo, Mohapatra, and Mahanty 2018), ageing thermal units causing low conversion efficiencies (Oberschelp et al. 2019) or using oil-fired generators for peak load provision (Watson and Rodgers 2019). Several researchers have focused on assessing the impact of EV charging on power system emissions (Dias et al. 2014; Doucette and McCulloch 2011; Y. Wu et al. 2012), calculating well-to-wheel emissions and incorporating an average emission intensity indicator. This indicator is presented in Figure 4, showing that certain developing countries tend to have higher average electricity intensity. Nevertheless, as discussed above, using an average intensity value disregards important spatial and temporal characteristics of power systems, which might be of critical importance in assessing the sustainability of EVs in developing countries. Such characteristics include seasonal and daily variability of renewable resources, technologies and fuels used for satisfying the peak load or differences in regional energy mixes.

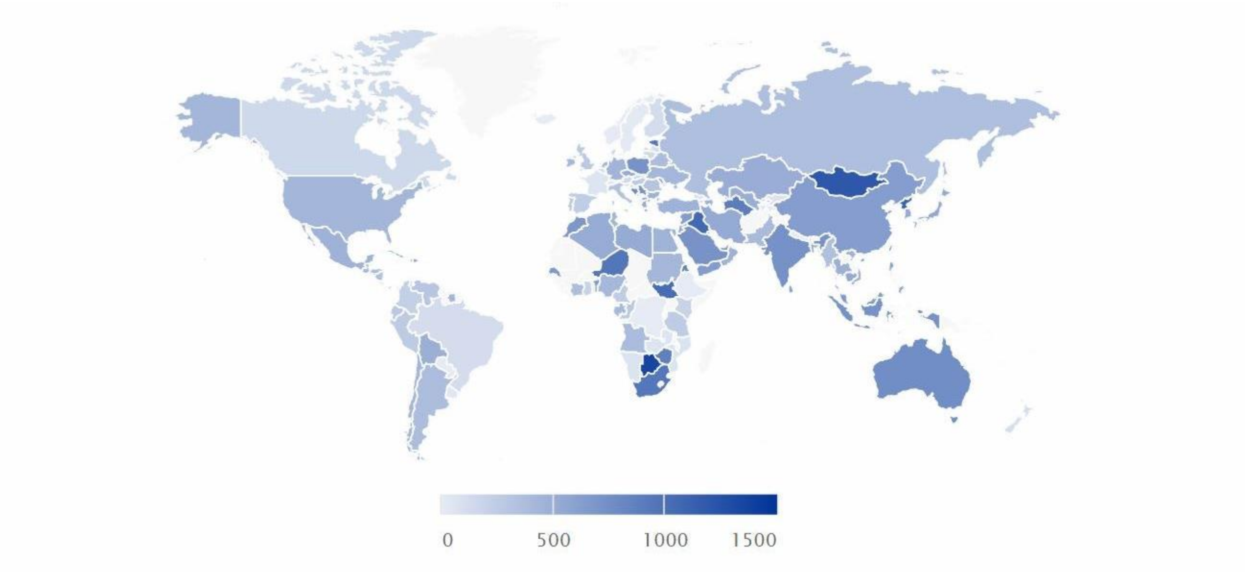

Figure 4 Average power system emission intensity [gCO_2/kWh] (Pavarini and Mattion 2019)

4. Mitigation strategies

Several strategies have been proposed to mitigate the negative impacts of the additional load from EVs, while simultaneously taking advantage of the potential benefits that can be reaped. Since the charging scheme directly influences the magnitude of these impacts, most of the strategies that have been developed can be summarized with the concept of smart charging. With smart charging, part of the EV load is scheduled and modulated over the day. The primary goal is to shift the load to the most optimal time from the perspective of the system operator, respecting the end-users' preferences and power system constraints. In general, this shift can be obtained through two main methods. The first one is based on behavioral load shift programs, which encourage EV-users to shift plug in to avoid peak times using direct or indirect monetary incentives and rewards programs. This form usually deploys time-of-use (TOU) electricity tariffs, which can be either static or dynamic. The second one is based on technical solutions that may be used to control the charging process or deploy storage technologies. This group includes various vehicle-grid integration schemes (VGI), co-locating battery storage or battery swapping. In practice, these two categories often function together, complementing each other. TOU tariffs and rewards programs enable and popularize the implementation of technical solutions, while technical solutions provide the foundation for participation in load shift programs (CAISO 2014). Box 3 exemplifies how smart charging is part of a more comprehensive strategy to develop the EV ecosystem in South Africa.

BOX 3. uYilo Electric Mobility Program

South Africa’s national e-mobility program, called uYilo (uYilo 2013), serves as a prominent example of successful pilot projects in the area of smart charging and e-mobility advocacy. uYilo is more than just the EVs themselves. It is focused on developing the entire ecosystem for a successful e-mobility implementation, all the way from sustainable energy generation through skills development up to circular economy. In 2013 uYilo established the Smart Grid EcoSystem facility to analyze EV-Grid interoperability and determine the future challenges regarding the control of the entire e-mobility system. The facility includes integrated PV panels, storage through second-life EV batteries, vehicle-to-grid ancillary services, energy management systems, and various types of chargers. With that infrastructure in place, uYilo tests energy optimization techniques to provide reliable and undisturbed service to the connected loads under various available grid capacities (including blackouts or brownouts) or availability of renewable energy and level of integrated energy storage. The system is tested with the primary goal of maintaining resilience, shifting to alternative and available sources of energy in terms of disturbance of any other sources, making sure that the EV is always charged. The facility is also used to test smart grid remote communications standards between various players in the system and the grid operator. uYilo uses the outcomes of the ongoing field experiments to campaign for e-mobility benefits in the region. Furthermore, the experience and insights gained are used in conversations with decision-makers, regulators, and utilities to promote smart charging strategies implementation alongside transport electrification.

Source: Interview with Mr. Hiten Parmar, Director of the uYilo Programme

4.1. User behavior-based methods

4.1.1. Time-of-use (TOU) tariffs

TOU tariffs often called price-based demand response programs (IRENA 2019b), are based on time-varying electricity prices, incentivizing end-users to adjust their electricity consumption and shift it to off-peak times. TOU programs might be designed in the form of static or dynamic programs. In the static case, tariffs are determined by utilities in advance, based on the historical consumption and price profiles while in dynamic pricing, tariffs may vary based on temporary wholesale electricity market conditions. The benefits of these schemes are bilateral. From the perspective of the system operator, these schemes allow for better management of supply-demand balance, providing power system flexibility reducing investments in grid upgrades and new capacity, while customers may save on household electricity expenses.

Several researchers assessed the potential of TOU tariffs as a method to mitigate the negative impacts of EVs on the power system. (Gao et al. 2012) demonstrated that TOU tariffs are effective means for peak load shifting, as a significant portion of the EV owners decides to adjust the time of plugging in their vehicles. An increase in peak power demand after integration of the EV fleet was 64% smaller with the TOU tariff (Ibid). (Chen et al. 2018) presented regional TOU tariffs as an effective mechanism to shape EV charging load, and subsequently minimize the peak valley difference and overall charging cost. With 8,000 EVs operating in the selected urban zone, the peak-valley difference and charging costs decreased by 16% and 4%, respectively, after introducing the peak price, valley price and flat price tariffs (Ibid). From the distribution system perspective, (Assolami and Morsi 2015) show that TOU tariffs may reduce loading and subsequent ageing of distribution transformers. Charging at midnight can reduce the yearly loss of life of transformers from 30.68% down to 23.85%, assuming Level 2 charging at 6.6 kW (Ibid). (Suyono et al. 2019) have found that power losses, voltage deviations and overloadings were substantially reduced when TOU pricing was applied. With 63% EV penetration, power losses decreased by 31% while charging costs were reduced by 16% compared to uncoordinated charging (Ibid). Furthermore, other studies quantified system benefits from avoided grid upgrades and lower energy costs, both in terms of the entire system and per EV (MJ Bradley & Associates 2017; Citizens Utility Board 2017; Klettke and Mose 2018). On the other hand, some studies indicate that TOU might cause the creation of new peaks in periods when prices are low (CEER 2017; Ramchurn et al. 2011). Moreover, the tariff setting procedure may be a lengthy regulatory process with multiple stages, causing significant lag in its implementation (European Commission 2015b).

4.1.2. Indirect incentives and rewards programs

While dynamic pricing schemes, like TOU tariffs, have been popular demand-side management policy in developed EV markets (Amin et al. 2020), several other indirect incentives and reward programs have been proposed to modulate the charging load and meet specific system operator's objectives. The most fundamental strategy might be simple information from the utility, in the form of messages or push-notifications, with a request to shift or reduce the user's consumption, whenever the grid is under strain. This has proven to be an effective approach with smart thermostats (EirGrid 2018) in the case of an Irish utility and similarly can be applicable for EV charging. As an extension, utilities may provide various types of rewards for a cumulative number of fulfilled load shifting requests. For example, FleetCarma company equips electric utilities with a smart charging reward program, allowing customers to shift EV charging load and collect points that can be exchanged for a reduction in the electricity bill, while the electric utility benefits from the user data collected. ConEdison, the New York-based energy company, allows its customers to collect rewards for charging at off-peak times, which can later be exchanged for discounts on electricity bills, without requiring smart meters installation, but rather an inexpensive device that is connected to the cellular network and is installed in the vehicle's on-board diagnostics port (ConEdison 2021). Long Island Power Authority (PSEG Long Island) started the Smart Charge Rewards program allowing eligible customers to receive $0.05/kWh cash back when charging the vehicle during off-peak hours between 11 PM and 6 AM (PSEG Long Island 2021). Jedlix application provides smart charging services, creating intelligent charging plans based on SOC goals, power grid stress, power system emission intensity, and the electricity price (Jedlix 2021). Furthermore, a German-based study indicates that non-monetary incentives can play a significant role in encouraging participation in smart charging programs and their effectiveness will depend on factors like local culture, social attitude, or education (Schmalfuß et al. 2015).

4.2. Technical solutions

4.2.1. Vehicle-grid integration (VGI)

Vehicle-to-grid unidirectional charging (V1G) is the most basic scheme out of VGI mechanisms. V1G refers to the charging process in which the charging duration and rate can be controlled and modulated by the power system operator, depending on electricity system needs. The simplest version of this mechanism may deploy on/off switching of charging power, delaying or bringing forward the charging process to the more suitable time from the perspective of the power system operator. Such controllability brings a series of opportunities to mitigate negative charging impacts in the power system. The most significant benefits include congestion management (Moorman, Van 't Wel, and Van Beek 2019), frequency regulation (Glavic 2016) and reducing the risk of overloading in peak hours (Pratt and Bernal 2018). Authors in (California Energy Commission 2019) have estimated that assuming high-frequency regulation prices, relative annual net grid benefits of the V1G scheme compared to unmanaged charging equals $253 per vehicle. (Heinisch et al. 2021) evaluated V1G smart charging strategies in a city energy system with sector coupling. Charging costs determined as a local marginal cost of the system decreased by 34% with V1G in comparison to an inflexible charging strategy. In a study considering the British Columbia setting (Ivanova et al. 2017), smart unidirectional charging reduces operational charging station costs between 14% to 96% depending on season and PV availability. (García-Villalobos et al. 2016) analyzed smart charging impacts on a Danish low voltage distribution network. With 50% EV penetration (corresponding to 52 vehicles and 0.584 MWh of demand), charging cost, peak load, energy losses and voltage unbalance factor[8] were reduced by 17%, 29%, 6% and 26% respectively compared to the uncontrolled case. (Element Energy 2019b) estimated the average revenue from a V1G strategy in UK distribution networks to be £57/EV per year. Many public chargers are equipped with V1G control capabilities (IRENA 2019a) and successful pilot projects have been already introduced with examples in California (BMW Group 2021), Australia (Pratt and Bernal 2018) and the EU (European Commission 2015a).

While V1G provides an opportunity to modulate the charging process, bidirectional controlled charging (V2X) additionally allows discharging stored energy when it is most needed in another system. This system can be load (V2L), home (V2H), building (V2B) or grid (V2G), however, only the latter may significantly affect broader system performance (IRENA 2019a). V2G has been in the center of the political, scientific and industrial debate, since it may fundamentally change the impact of charging load on the power system, transforming EV batteries into a clustered power storage. In the recent Global EV Outlook 2020 (IEA 2020a), IEA estimates that across China, India, the EU and the US, V2G technologies have the potential to provide almost 600 GW of additional flexible capacity during peak time by 2030. It can translate to 470 TWh of saved electricity, otherwise provided by fossil fuels, and consequently reducing

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[8] Voltage Unbalance Factor is the ratio between percentage of the negative sequence voltage and the positive sequence voltage.

CO_2 emissions by 330 million tonnes. Although V2G is in a relatively early stage of deployment and a limited number of pilot projects have been implemented, several authors evaluated V2G in the context of providing broad power grid benefits. These services include peak shaving (X. Li et al. 2020), frequency regulation (Lam, Leung, and Li 2016), minimizing congestion (Staudt et al. 2018), voltage regulation (Choi, Lee, and Sarlioglu 2016), minimizing overloading (Ramos Muñoz et al. 2016), minimizing power loses (Deilami et al. 2011) and supporting integration of renewables (D. B. Richardson 2013). (Oldfield et al. 2021) estimated that a fleet of 50,000 V2G-enabled EVs in the UK's power system can generate operating savings by up to £12,000 per year per EV. The annual financial benefits from participation in flexibility services can reach £700-£1,250 per vehicle. (Park, Yoon, and Hwang 2016) evaluated annual benefits from EV participation in frequency regulation with time-varying prices to be between $8,000 and $22,000 per vehicle. (Peterson, Whitacre, and Apt 2010) assessed the grid benefits from V2G services with perfect information and no battery degradation to be between $140 and $250 per year for a 16 kWh battery pack for three cities in the U.S. (Noel and McCormack 2014) investigated the value of electric school buses providing V2G services and have found the net present benefit to be $5,700 per seat, considering fuel cost, electricity price, battery costs and frequency regulation revenue. (Noori et al. 2016) evaluated the cumulative benefit from V2G services for five US Independent System Operators (ISOs) and Regional Transmission Organizations (RTOs). The net revenues ranged from $26,000 to $62,000, considering uncertainty in capacity payments, electricity prices and battery costs. (Haddadian et al. 2015) concluded that the EV fleet with V2G integration could reduce operational costs of the grid by 3% of revenues, from a reduction and shift of the power load.

4.2.2. Storage and battery swapping solutions

Co-locating battery storage facilities with public or semi-public charging infrastructure and battery swapping strategies is another potential technical solution to mitigate the negative impact of EV charging, while adding benefits from increased flexibility. With rapidly decreasing costs of battery packs, on-site storage is becoming an attractive option for station owners. Battery storage may be charged with a fast DC charger coupled with a large inverter at times when electricity costs are low or renewable energy is available, and then discharged when EV demand peaks. Optimized charging, as well as coupling with local solar PV resources, may bring additional revenues to the grid and station operator (Feng et al. 2020). In the literature, the key variables explored were the optimal battery swap station location considering grid capacity, EVs routes and area constraints (M. Lin et al. 2021; Yang and Sun 2015). Furthermore, such battery storage could also provide frequency containment reserves for the system operator (Shi et al. 2017) as well as peak shaving options. Authors (Richard and Petit 2018) evaluated the operation of a fast-charging station coupled with a battery storage system in grid services. The study found that the provision of grid services does not negatively affect the performance of the station and allows to increase revenues by 10%. (Ding, Hu, and Song 2015) investigated the value of energy storage in an electric bus fast charging station. Compared to the case without an energy storage system, annual overall costs were reduced by 23%, mainly deriving from savings on feeders and transformer capacity.

On the other hand, battery swapping is characterized by high CAPEX for the operators, lack of standardization across vehicle models, or difficulties with infrastructure establishment (Ahmad et al. 2020). These drawbacks might be a reason that battery swapping is still not mainstream in e-mobility strategies, despite its long history of application in certain cases. Nevertheless, recently there has been an uptake of battery swapping when market circumstances allow it. Several market outlooks indicate battery swapping technology as one that could boost EV adoption (Xin 2021), especially within public and commercial vehicle use (Edelstein 2021)(Furnari et al. 2021).

Battery swapping allows EV owners to quickly replace the discharged battery with a fully charged unit and continue driving. Battery swapping stations are becoming popular in markets with a large share of small EVs, like E2Ws, E3Ws or micro-mobility solutions due to their limited range and simple construction. In India, the swapping market is expected to have a cumulative average growth rate (CAGR) of 31.3% in the 2020-2030 period (Kumar, Bhat, and Srivastava 2021). China's State Administration for Market Regulation (SAMR) recently approved the mandatory National Standard for Battery Swap Safety Requirements for Electric Vehicles (GB/T 40032-2021) that will go into effect at the beginning of November 2021 and will include safety requirements, test methods, and inspection rules for battery swappable EVs (P. Zhang 2021). In Indonesia several industry firms in collaboration with government introduced battery swapping trials for two-wheelers (Deloitte 2021), installing swapping stations and operating swappable vehicles (Post 2021). Furthermore, the Indonesian Ministry of Energy and Mineral Resources introduced a battery swapping incentive scheme (Saputra and Simanjuntak 2021), where the cost of batteries can be reduced, given that a potential investor is going to invest and open a swap station.

4.3. Challenges and opportunities in developing countries

There are key obstacles to introducing the above-mentioned mitigation strategies in the electricity systems of developing countries. First, is the cost of grid infrastructure needed to implement smart methods. To control the charging and discharging process, either in public, semi-public or home chargers, the system operator needs an extensive amount of real-time data and control capabilities. The main infrastructure equipment needed to allow smart charging procedures includes numerous smart meters, battery-management software and hardware which allow bidirectional exchange of power, communication technologies, and electric vehicle supply equipment. This requires a massive deployment of smart grid infrastructure, which in the context of developing countries that are already struggling with significant grid upgrades and investment requirements, may be a challenging task. To a certain degree this investment can be sidestepped, as shown by the case of FleetCarma with conEdison in New York.

Second, the implementation of smart charging strategies requires appropriately designed electricity markets. Market designs will need to be adjusted and new regulation needs to emerge to provide well-functioning, competitive and efficient frameworks for EV grid services. This may be another important challenge in emerging economies, where electricity markets are already poorly designed and require fundamental reforms.

Nevertheless, as it was mentioned, developing countries face many power systems challenges that will drive significant infrastructure investments and policy regulations. Enabling the flexibility of EVs and their widespread deployment can be an instrument in addressing challenges while providing long-term technological and economic benefits. Examples of pilot projects of various smart charging strategies in developing countries are presented in Table 6 while examples of theoretical and simulation studies are listed in Table 7.

Pilot projects, especially in terms of innovative and emerging technologies like V2G, are crucial steps towards broader development of smart charging frameworks within public and private environments. Successful pilots, either based on government policy programs or a companies' innovative product or service, incentivizes other market participants and stakeholders to take action and implement similar programs or extend existing ones. The pilot projects reviewed showed substantial economic, environmental, and social benefits, allowing for a clear and more confident outlining of long-term e-mobility plans. As an example, initial battery swapping pilots in India combined with ministry announcements regarding E2Ws and E3Ws, led to a significant increase in the number of battery swapping providers within the country.

Studies presented in Table 7 showed extensive benefits coming from the adoption of smart charging strategies in developing countries. The projected increase in electricity demand, induced vehicle ownership rate, poor condition of transmission and distribution grids, and fossil fuel-based power systems make the described smart charging strategies far more attractive and profitable when taking all the potential costs and benefits into account. Although the precise estimates per EV were not conducted, it can be anticipated that when compared to EV deployment scenarios without smart charging strategies in place, as in (Manríquez et al. 2020) or (SHURA 2019), benefits per EV over the long term horizon can be far greater than estimates in developed markets if accounting for the avoided failures and reinforcements in distribution grids or additional capacity needs. Potential market opportunities from providing ancillary services to the power system operation increase this profitability even more.

Table 6 Smart charging pilot projects in developing countries

Country/region	**Source**	**Mitigation strategy**	**Description**
Barbados	(James 2018)	Delayed charging	A Barbados based firm, Megapower, electrified fleets of the telecommunication firm Flow and of delivery companies DHL and UPS. With the use of smart meters, DHL facilitated overnight charging of their vans and was able to charge the vehicles without increasing the electricity tariff demand charge.
Chile	(Kane 2019b)	V2G	Nissan, in cooperation with ENEL X and the Chilean Energy Sustainability Agency, developed the first V2G system in Latin America.
India	(ETAuto 2021)	Battery swapping	Indian startup Zypp has installed 15 battery swapping stations in the city of Gurugram. Zypp offers electric scooter ride-sharing services, with an option of fast battery swapping at dedicated stations.

India	(BatterySmart 2021)	Battery swapping	Battery Smart provides battery swapping services for E2Ws and E3Ws on a membership basis. Subscribers can stop at any of the company's partner swapping stations and replace discharged battery packs with a fully charged unit.
India	(Das and Tyagi 2020)	TOU	Eighteen Indian states and five utilities have introduced designated tariffs for EV charging to promote EV adoption and manage charging demand. Customers are categorized as non-residential, commercial, nonindustrial, or bulk supply
Jamaica	(Office of Utilities Regulation 2019)	TOU	Jamaica's vertically integrated utility, JPS, is planning to introduce a rate case for EVs, considering TOU tariffs to develop a more favorable environment for EV deployment. The regulatory changes are planned to be implemented alongside infrastructure development, including installation of 60 public charging stations by the end of 2021.
Namibia	(UNDP 2019)	V2G	UNDP in Namibia Vehicle-Grid-Integration (VGI) project at United Nations House in Windhoek. When there are disruptions in the electrical grid, due to planned or unplanned outages, charged EVs located in the parking lot may be utilized as a backup power source.
South Africa	(uYilo 2013)	V2G/storage	Smart Grid Ecosystem was established at Nelson Mandela University. It consists of AC and DC chargers, integrated PV arrays, stationary battery bank, energy management system and V2G services.
Thailand	(Thananusak et al. 2021)	TOU	In 2018, Thailand's National Energy Policy Commission favored the introduction of the TOU tariff for residential users and charging station operators. This tariff aimed to incentivize EV owners to charge their vehicles during off-peak periods.

Table 7 Smart charging strategies studies in developing countries

Country/region	**Source**	**Mitigation strategy**	**Description**
Brazil	(Drude et al. 2014)	V2G	The study indicates that the V2G strategy, combined with rooftop PV deployment, proves to be a valuable approach to provide higher grid stability in the Brazilian setting. With an allowable vehicle depth of discharge of 40%, the annual revenue from grid stabilization exceeds $1,000.
Brazil	(Bitencourt et al. 2019)	Static and dynamic TOU	This study analyses EV charging load impact on distribution transformer loading, with TOU tariffs. Results proved that both types of TOU tariffs reduced or entirely removed the negative impact of EV charging on distribution transformer loads, substation load and transformer charging level.

Chile	(Manríquez et al. 2020)	V1G	The authors evaluated Chilean power system expansion planning under a smart charging strategy. The availability of smart charging enables a larger capacity of solar power to be installed compared to a scenario without EV. Higher capacity investments are outbalanced with a reduction of operational and emission costs.
India	(Das and Deb 2020)	V1G, V2G	Extensive assessment of challenges and opportunities for vehicle-grid integration, with a comprehensive review of regulatory needs and techno-economic analysis. Authors argue that smart charging strategies should be gradually introduced starting with TOU tariffs, followed by V1G, aggregated smart charging and finally V2G. Each step requires separate technological and regulatory advancements.
Indonesia	(Aziz and Huda 2019)	V2G	The authors discuss the deployment of EV charging strategies for load levelling and frequency regulation, considering rapidly increasing energy demand.
Mexico	(Khan and Castillo 2017)	V2G	Authors evaluate V2G technology on a distribution feeder in Mexico City. It showed that with 2,500 EVs connected with available V2G services, voltages improved especially at nodes near the connection of the vehicle fleet. Power losses decreased by 69.3% as compared to the case without EV fleet.
South Africa	(Change Pathways 2018)	TOU	Authors present an extensive review of EV tariff opportunities for the city of Cape Town and list recommendations to incentivize EV adoption and mitigation of negative power system impacts
Turkey	(SHURA 2019)	TOU	The authors evaluated a smart charging mechanism in the form of midnight shifting in residential chargers. The increase of the peak load due to EV deployment was reduced from 12.5% down to 3.5%.

5. Role of utilities and system planning

According to market projections, EVs are expected to replace conventional vehicles within the coming decades, first in sales and then in total stocks. As discussed above, this process can bring challenges and opportunities to all stakeholders, ranging from EV users, to manufacturers and charging station operators, to utilities and TSOs. Particularly the two latter ones need to undertake comprehensive measures to address a wide range of internal and external challenges and prepare the ground for the upcoming uptake. Being prepared and proactive is critical for utilities and TSOs, especially in developing countries with financially distressed utilities, insufficient investment levels, low productivity, poor maintenance, and government diversion of budget resources from other high-priority social and economic needs (Ichord 2016). Recent publications of the Smart Electric Power Alliance (SEPA) (SEPA 2019) and the European Network of Transmission System Operators for Electricity (ENTSO-E) (ENTSO-E 2021) indicate that careful integrated planning and collaboration between the various actors are the keys to minimize infrastructure and economic challenges related to EV deployment and to maximize the potential benefits.

(SEPA 2019) outlines good practices and key messages for utilities preparing their assets, staff, and clients for EV uptake. First, utilities ought to identify strategies and frameworks in advance to avoid certain costs for EV charging infrastructure installations, including reducing labor hours necessary to perform system upgrades and works. Furthermore, special attention should be paid to appropriate sizing of EV charging infrastructure including chargers and auxiliary electrical equipment. Utilities should aim to achieve the balance between infrastructure expenses, EV owners' expectations, charging time and power grid stresses. Next, utilities and other relevant stakeholders must ensure that charging and power system infrastructure meet safety and functionality standards, to avoid potential failures and continue providing reliable and safe services. SEPA advices to make the investments in the power system and charging infrastructure strategically, anticipating the potential future service requests (e.g. including deployment of electric heavy-duty vehicles or business opportunities from smart charging strategies).

(ENTSO-E 2021) explores how a proper environment for the optimal integration of the EV fleet can be set from technological, regulatory and market perspectives. First, smart charging strategies are a critical solution to minimize potential costly grid reinforcements or generation capacity additions and to enable new opportunities of providing ancillary services to the power system. The implementation of smart charging technologies ought to be preceded by a comprehensive analysis to select an optimal mix and capacity of the system. Furthermore, the development and implementation of common technological and regulatory standards, as well as transparent data management and access are key enablers of e-mobility. Finally, on market designs and rules, ENTSO-E argues that prices of wholesale markets and tariffs for final customers should be dynamic to stimulate the integration of e-mobility and mitigate potential negative charging impacts in the power system. TOU tariffs or locational prices can be established to provide the necessary market signals. Moreover, regulators, market operators and utilities should cooperate to bring down the barriers preventing EV owners (or their representatives) from participation in energy and ancillary services markets. To do that, a long-term strategy for various players should be created to allow and subsequently manage the services offered by EVs in electricity markets.

Both the SEPA and ENTSO-E reports identify integrated planning for power systems and charging infrastructure as decisive elements of successful EV integration. Researchers have been emphasizing the importance of integrated planning (e.g. (F. Yao et al. 2018) or (W. Yao et al. 2014)) indicating the significance of aligning power sector and transportation goals. This is key not only to achieve a least-cost, resilient power system, but particularly crucial to reach ambitious decarbonization targets. Charging infrastructure planning should consider urban planning, private household electricity demand, distribution system needs and quality of power system assets. Such a planning exercise should be performed with the use of sophisticated models, capable of capturing the stress imposed on the distribution system equipment, power flow principles and variability of the load. Furthermore, integrated planning should be conducted through a careful scenario definition, usually involving various scenarios to better inform decision makers about the potential implications under different projections. (SEPA 2019) highlights the importance of data and transparency to improve integrated system planning at all levels. Planning tools should be used by various system players to identify optimal locations that minimize grid impacts. Based on the analyses using such tools, utilities may publish comprehensive reports emphasizing the importance of utility service upgrade requirements and to provide a roadmap for other actors on anticipated timelines and costs for deployment of EV charging infrastructure.

The implementation of these measures can be subjected to political, financial and technological challenges in many developing countries, where power sector actors operate in unfavorable and distorted environments. Therefore, the priority should be to create a policy, legal, and regulatory environment for the various actors to provide stability, attract investments and deploy more efficient technologies. An appropriate market design structure, achieved by a carefully planned sequence of reforms for clear, fair, realistic market rules, will be a key to effective power system transformation, making the ground for the e-mobility deployment (The World Bank 2018). Once these technical and regulatory hurdles are solved, utilities and other stakeholders will be able to prepare for an e-mobility future, unbundling the business and technical opportunities it may provide.

The Maldives case study conducted for this report provides interesting insights on the impact of EVs on power systems under different scenarios. EVs can have massive benefits for the energy sector, especially for a small island country like the Maldives that imports oil with high transportation costs while power could have been generated from abundantly available local renewable resources. However, EV charging may also impose significant investment requirements for the power system that needs to be analyzed carefully, including the capacity of the existing distribution network system, investments needed in solar PV together with battery storage and additional diesel capacity to meet the incremental demand from EVs. The analysis explores an EV adoption scenario for the Maldives for 2030 with 30% of all vehicles including two-wheelers that dominate the transport on the island under two different charging regimes: uncoordinated and optimized coordinated mode. The latter is achieved through a system wide optimization using a modified version of the World Bank Electricity Planning Model (EPM) that optimizes charging load subject to a range of constraints on allowable timing for different categories of vehicles. If charging from the fleet is uncoordinated, a relatively small increase in energy requirement of 3.1% due to EV may lead to a 26.1% increase in generation capacity requirement and hence 15.7% additional investment. While the optimized charging regime helps to drastically cut down on generation capacity requirements to just 1.8% increase and also considerably eases feeder loading, it may also lead to higher emissions as more EV load during off-peak hours leads to an increase in diesel-based generation. Hence, an additional scenario was explored wherein the annual emissions from the power sector are constrained to the baseline (``No EV'') scenario. The analysis shows the importance of focused modeling analysis to understand the ramifications of EV load impact on the power system, including a significant increase in generation capacity and potential increase in power sector emissions in a fossil-fuel dominated system. Details of this case study are presented in the Appendix.

6. Conclusions and key recommendations

The large-scale deployment of EVs will likely impact all sectors of power systems in developing countries. These effects can be technical, economic, or environmental and affect a wide range of actors. Though the uptake of EVs is still in its initial stages in most countries, the following conclusions and recommendations can already be made based on the experience of both developing and developed economies:

- In absolute terms, the additional EV charging load will have a marginal effect on the annual power system demand. However, it will likely reshape the daily electricity load curve, amplifying evening peak loads, when most of the residential charging happens.
- The EV charging load curve will strongly depend on the vehicle stock, the mix of various modes in the total fleet, and the charging behavior of the EV owners. These, in turn, might be substantially different in developing countries, where local culture, demographics, geography, climate and economy determine what kind of vehicles are in use and how they are operated.
- The availability of public charging infrastructure and the possibility of installing residential chargers, are two key determinants of consumer decisions, affecting the shape of the charging load.
- The impact of the EV charging load will be most noticeable in the distribution segment of the power system. Even if national adoption levels remain low, clustering effects might occur, significantly increasing the peak demand at the local level.
- Numerical studies indicate that with uncoordinated charging in place, most of the costs from capacity additions and reinforcements will be at the distribution level.
- Local impacts will affect distribution transformers and feeders, requiring reinforcements. This effect will likely be even more significant in developing countries, where local transformers and feeders are already subject to frequent failures and high losses. When evaluating the impact of the charging load at the local level, it is critical to consider the actual quality of the distribution assets to assess the potential risks and required reinforcements appropriately.
- EV charging can lead to notable power quality issues at the distribution level, which can be harmful in the developing country context, with underdeveloped power quality standards, lack of appropriate maintenance and of specialized human capacity.
- Least-cost distribution system planning analyses combined with an optimal installation of public chargers are needed to provide reliable service with increasing vehicle electrification. Furthermore, detailed power flow analyses should be conducted to ensure that existing or planned power system assets are appropriately sized and do not experience overloads, failures or accelerated ageing.
- Deployment of a large-scale EV fleet will likely have a limited impact on the transmission system expansion and operation. Nevertheless, detailed power flow studies should be

conducted in systems with heavy congestion, frequent failures, or underdeveloped transmission systems. Special attention should be paid to the transmission system's potential congestion during peak hours.

- In the generation system, EV deployment will primarily impact the peaking units, increasing the flexibility requirements of the system and the need to supply this additional power with renewables. If these peaking units are powered by fossil fuels, then emissions will increase. With uncoordinated charging, new gas plants or storage facilities, characterized with high ramping capabilities, may be needed to provide energy during the evening peaks.
- In most developing countries, electricity demand is forecast to heavily increase over the following decades, requiring extensive capacity additions in all segments of the power system.
- Innovative charging strategies focused on modulating charging demand provide an attractive way of avoiding expensive grid reinforcements with the large-scale deployment of EVs.
- With already existing issues in the power systems of developing countries, including blackouts, brownouts, equipment failures or power quality issues, innovative charging strategies will be needed to avoid or reduce capacity additions and grid reinforcements with growing demand.
- Innovative charging pilot projects are usually successful initiatives, helping in introducing a new technology and paving the way for large-scale implementation. Governments, companies, and regulators in developing countries should be more active in the area of pilot projects to convince stakeholders about their benefits. Vehicle-grid integration technologies are still emerging even in well-established EV markets. Developing countries can pursue their implementation to show the full potential of these technologies in inducing EV deployment, mitigating negative grid impacts, managing the grid and providing new services for customers and utilities.
- To prepare their assets and operations for the upcoming EV deployment, electric utilities should conduct comprehensive long-term planning exercises at the generation, transmission, and distribution levels of the power system. These analyses should include the forecasted increase in base load demand as well as the additional demand from the electrification of other sectors of the economy, focusing on the hourly distribution of the latter.

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APPENDIX

Analyzing Electric Vehicle Load Impact on Power Systems: Modeling Analysis and a Case Study for Maldives[9]

I. INTRODUCTION

A. CONTEXT

Electric vehicles (EVs) together with cleaner forms of power generation technologies present a formidable option to decarbonize the transport sector. Countries, institutions, companies and international development communities have been stepping up, introducing electric mobility (e-mobility) targets, strategies and funds, fostering innovation and deployment [1], [2]. In many advanced economies, e-mobility markets are already well-established and EVs started to constitute a substantial share of annual vehicles sales [3]. Nevertheless, transport decarbonization still remains a particularly significant issue in many developing countries with fossil fuel dominated power systems, crowded and polluted cities with heavy traffic, where unsustainable transport poses a threat for urban communities [4].

Small Island Developing States (SIDS) like the Maldives, which generates almost all its electricity from expensive imported diesel fuels, presents a good example of potential challenges and the need for aligning transportation with power system targets. Nearly half of the population lives in the crowded capital of Malé, covering an area of less than 10 km^2. Maldives, located in the equatorial Indian Ocean, has an abundance of available solar energy to generate power that can charge a good share of more than 80,000 currently unelectrified two-wheelers [5]. Nevertheless, economic and land constraints are slowing down the uptake of residential and utility-scale renewable energy installations [6], consequently leaving the country nearly entirely dependent on imported fossil fuels.

There are a few studies that examined the nature and magnitude of the impacts of EV deployment on power systems. For example, De Quevedo [7], Shortt [8], Mousavi Agah [9] and Pieltain Fernández [10] review and model impacts of EV charging on distribution, transmission and generation in the operational and planning context. However, the literature on quantifying the current or projected impacts in the existing EV markets is still relatively limited. The investment requirement to upgrade the grid, additional generation capacity requirements, increase in operational costs and changes in emissions profile, are important metrics to understand the full array of impacts. Some of these assessments are available mostly for developed countries where EVs have been introduced. EV impact assessment is limited for the developing world though even for cases like India that has announced its intent to do rapid electrification of its transport sector. Although the estimates for the developed countries cannot directly be applied for the developing counterparts given the substantially different nature of the physical systems, they still constitute a set of useful indicators of the nature and orders of increase in cost, capacity and emissions. This information can be of value to decision makers, utilities and regulators in the emerging EV markets, especially in developing countries with typically more resource constrained power systems.

Furthermore, the modelling literature on power system planning for developing countries to assess EV impact is practically non-existent. This gives an incomplete overview of the technical, economic and environmental impacts of EV integration in power systems characterized by low flexibility, excessive level of backouts and failures, poor power quality or high share of fossil fuel generation. Additionally, the charging behavior of the EV owners in developing countries and the resultant aggregated load can vary significantly from the one observed in developed EV markets due to different demographics [11], climate [12], the share of the transportation modes [13] or availability of charging infrastructure [14]. Consequently, rapid EV deployment in developing countries, similar to the one observed in China [2], might result in impacts considerably different from those reported for developed countries. There may, for instance, be a significantly higher need to boost peaking capacity in the developing world with sharper peak demand growth compounded by demand from EV that may coincide with system peak.

These considerations provided the motivation for detailed long-term planning analysis. This forms part of a wider EV Flagship study undertaken by the World Bank. We have used a capacity expansion and dispatch model to explore the technical and economic viability of converting 30% of all vehicle modes to EVs by 2030. A sharp increase in peak demand and hence peaking generation and network investments are some of the fundamental power system challenges that are addressed as part

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of our technical analysis. This work underlines the importance of long-term modelling in achieving decarbonization targets. The rest of this paper is organized as follows:

- First, it provides background information on the Maldives power sector. Subsequently, it presents a comprehensive review of the international experience regarding EV impacts on the power system, including relevant case studies and modelling approaches. The review focuses on the quantification of reinforcement costs and capacity additions in the country-specific case studies.
- Second, it proposes a methodology to incorporate EV fleet charging load in the long-term electricity planning framework based on already existing and well-established planning models. It includes a detailed description of mathematical formulations, together with a comprehensive explanation of EV load assumptions and projections. We have also enhanced a standard planning model to consider optimization of EV load and further simulated a carbon-neutral EV load addition scenario.
- Third, it presents a comprehensive techno-economic case study to assess the impacts of EV fleet introduction on the power system of Maldives, with a detailed representation of the distribution system and two distinct charging strategies. Results of this study might be extrapolated to other SIDS countries as well as urban/peri-urban distribution areas with fossil fuel dominated power systems and limited land availability.

B. BACKGROUND INFORMATION ON MALDIVES

The Republic of Maldives is among the smallest countries in the world. The total population of nearly 550,000 people lives on 194 islands stretched out along 800 km in the central part of the Indian Ocean including around 250,000 in the capital of Malé. Tourism has become the main contributor to the country's annual gross domestic product (GDP) and allowed its graduation from a low-income country to upper-middle-income country status in 2011 [15]. However, Maldives is exposed to a high dependency on fossil fuel imports. The total fuel import in monetary terms amounted to 465 million USD in 2019, which was corresponding to 20% of the whole import and 8.7 % of the country's GDP.

The power system in the Maldives is composed of independent isolated island-based grid systems, with each island having its own powerhouse and distribution facility. Due to this, the power systems are reliant on imported diesel generation to meet almost all their power needs. In 2018, the total installed capacity was 335.5MW, where diesel generators accounted for 319 MW, while renewable energy units in the form of solar PV for only 16.5 MW. In total, 775 GWh was generated in 2018, with a 97% share from diesel generation.

There has been significant emphasis on cleaner forms of generation in future, especially solar PV, as noted in the Energy Policy and Strategy 2016 [16] and the Strategic Action Plan (SAP) 2019–2023 [17]. The most significant goals from the perspective of the power sector include a 4% share of renewable energy in the energy mix, reducing diesel consumption in the electricity generation sector by 40 million liters and scaling up energy storage capacities to 30 MWh. The Government of Maldives (GoM) aims at scaling up the initial targets and considers having a daytime peak met by solar PV with a 70% share by 2030 [18]. The commitment towards GoM's clean energy has recently been reinforced with the President of Maldives committing to net zero emissions as early as 2030 with international aid.

Apart from the power sector, transportation is another contributor to fossil-fuels dependency and greenhouse gas emissions. If the Maldives is able to transition towards a combination of sustainable power and transport systems that are based on cleaner forms of electricity generation, it would not only reduce the country's reliance on fuel imports but significantly reduce air pollution in the capital Malé, and boost the tourism industry by building a more positive image of the country [19]. EVs are expected to be the core solution towards the widespread transport decarbonization in SIDS. With the need for flexibility in the power system to deploy more renewables sources of electricity and high fuels costs, implementation of electrified passenger and public transportation systems may bring significant economic and environmental benefits for these nations by providing the required storage and grid service solutions when an appropriate EV deployment strategy is being considered [20].

II. LITERATURE REVIEW

A. EV IMPACTS AND INTERNATIONAL EXPERIENCE

Sustainable e-mobility is globally considered the most promising option to decarbonize the transportation sector and an important step towards achieving climate targets. However, quickly rising shares of EVs in sales and total stocks may pose significant technological and operational challenges for the generation, transmission, and distribution segments of the power systems. The aspects of potential techno-economic impacts of charging load have been widely studied over recent years.

The distribution part of the power system is the most prone to experience the stresses and negative impacts of EV deployment. At the local low-voltage level, a clustering effect might occur, causing spatial concentration of vehicles and consequently congregating the plug-in events [21]. Without smart charging strategies in place, allowing to shift the load towards a more favorable time, residential home charging is likely to happen right after returning from work, causing already existing evening consumption peak to amplify. In turn, distribution transformers and feeders might become overloaded, causing losses, failures, and shortening asset life [22]. Furthermore, uncontrolled EV charging can lead to power quality issues, including voltage deviations or harmonic distortions [23]. In order to accommodate the growing charging load and avoid serious reliability issues, electric utilities might be forced to make significant upgrades to the distribution system infrastructure. Boston Consulting Group (BCG) analysis [24] estimated that with uncoordinated charging and 15% penetration rate, required distribution investments through 2030 may reach up to 5,380 USD per EV in the US market.

In the remainder of this section, we present a summary of the literature that covers distribution system impacts (Table I), followed by impact on demand/generation/emission (Table II) and the modeling techniques used to capture EV impacts (Table III).

Table I reviews relevant studies presenting international assessments of distribution system impacts and the consequent reinforcement costs. The review indicates that with uncoordinated charging, EV deployment will result in substantial reinforcement costs driven by the required replacements of transformers and cables.

Changes in the daily load due to the increasing number of EVs would also impact upstream transmission and should be considered as part of grid operation and expansion planning. While at the distribution level, the clustering effects within the same section of the grid pose a substantial challenge to the system operator, the impact on the high-voltage transmission grid is generally less severe. The BCG analysis assessed required transmission infrastructure reinforcements through 2030 to reach 420 USD per EV, which is just below 8% of the distribution sector cost impact. Nevertheless, at deeper EV penetration levels, or in systems with already congested transmission lines, uncoordinated charging can lead to high loading levels [25], more severe congestions and consequently increase wholesale electricity prices [26]. Furthermore, incorporating the EV load in the transmission expansion planning can result in additional investments or upgrade requirements to assure reliability and prevent load shedding or system failures in the future [27].

Charging of the EV fleet will have a direct impact on the dispatch of the generation units, power system emissions, operation costs and, in the long term, capacity expansion decisions. As the preceding discussions alluded to, without appropriate load shifting incentives, residential charging load is likely to be allocated to evening hours with high demand levels, subsequently being met with peak power plants. In most systems, peaking capacities comprise gas turbines or gas engines fueled with natural gas or liquid fuels such as heavy fuel oil, characterized by high variable costs. A sharper peak, especially in a small system, therefore, not only calls for adding disproportionately more capacity but also increases operational expenses and emissions in the power sector. Since the charging load in the Maldives may occur during the evening peak that may be typically highly uncertain and variable, it may also call for a new capacity that is highly flexible to ensure security and adequacy of the grid. Table II presents the relevant studies evaluating the short and long-term impact of EV charging load on the generation fleet. These studies reveal flexible peaker plants (gas turbines and engines) to be required in the capacity mix with the uncoordinated charging in place, subsequently increasing the system's emissions and total costs.

While reinforcing the grid and expanding the asset's capacity is one way to cope with growing charging demand, smart charging and battery swapping strategies may be potentially good alternatives to partially mitigate the negative impacts. Smart charging allows controlling a specific part of the EV charging load through technological and incentive programs introduced by electric utilities. The simplest and currently most popular smart charging approach is the introduction of time-of-use (TOU) tariffs, incentivizing EV owners to plug in their vehicles during times of lower electricity prices. TOU schemes have been proven to be an effective way of peak shaving and mitigating major EV-related capacity investments in distribution, transmission and generation segments [28], [29]. Battery swapping to provide significant flexibility around when depleted batteries can be recharged enhances the prospect of utilizing cheaper renewables and/or surplus capacity to avoid an addition to peaking capacity, albeit at additional expenses for spare battery capacity and infrastructure that is needed for swapping. Furthermore, vehicle-grid integration (VGI) allows EV owners and system operators to control, modulate and shift charging load. VGI schemes range from turning on and off the charging power through unidirectional charging load control (V1G) to bidirectional vehicle-to-everything (V2X) technologies. VGI technologies, apart from mitigating the most severe impacts of EVs to the power systems, may bring a series of additional benefits, including frequency control, auxiliary services, short-term storage services, and supporting the integration of variable renewable energy (VRE) [29]. As the full array of technologies around smart charging, battery swapping and VGI unfold, it may be possible to use the flexibility these entail to minimize the impact of EV load on the power system. Moreover, the introduction of an appropriate energy management system linked with distributed energy resources can further reduce charging costs and maximize benefits from the exchange with the grid [30]. These benefits can be fully unlocked only if the charging infrastructure and energy management systems are carefully designed and operated [31][32]. The availability of these technologies in a developing country power system like Maldives would however take significant time, effort, and investments. A full cost-benefit analysis of such flexibility also requires further exploration and methodology development – an issue that is not covered in the scope of the current paper.

TABLE I:

EV IMPACT ON DISTRIBUTION SYSTEM: SUMMARY OF INTERNATIONAL STUDIES

Country/region	Assumptions and findings
United States [24]	15% EV penetration in 2030. 5,800 USD of distribution investments per EV in the nonoptimized charging scenario
France [33]	Without smart charging total, low-voltage distribution grid reinforcement per million EV was estimated as 200 million EUR for charging in single houses, 650 million EUR for multiple charging in multi-dwelling or business buildings and 240 million EUR for public charging spots in the streets
United Kingdom [34]	Electric cars and vans achieving a 60% share of new vehicles by 2040, translated into a total of 22 million EVs by 2035, increase distribution network reinforcement costs by 40.7 billion GBP
Norway [35]	2.4 GW increase in load during peak hours due to EV charging would require 1.5 billion EUR to reinforce grid until 2040, with the third of that used to replace older elements.
Auckland, New Zealand [36]	Converting 15 bus depots to a fully electric fleet would require up to 32 million NZD investments in the local electricity grid
European Union [37]	150 TWh of incremental EV charging demand by 2030 increases overall reinforcements investments in distribution grid by nearly 180 billion EUR
Denmark [38]	100% penetration in the local distribution grid, corresponding to 127 EV, would require investments of 52,000 EUR for transformer and cables.
Sacramento, California [39]	240,000 electric cars by 2030 (together with other assumptions regarding solar PV, energy efficiency and demand response) could cause voltage violations in 26% of substations and the need for replacement of 17% of transformers at an approximate cost of 89 million USD.
New Zealand [40]	At a 10% penetration level with 2.4 kW home charging, the distribution grid would require 22 million USD of reinforcements, rising to 154 million USD with 40% penetration depth and the same charging scheme.
General [10]	For a scenario with 60% of total vehicles being PEV, DSO investment costs can increase up to 15% of the total actual distribution network
Ireland [41]	At 20% EV penetration, necessary grid upgrades are estimated at the level of 350 million EUR. Out of that, 150 million EUR account for urban areas, while 127 million EUR for rural areas. Smart meters for home chargers require an additional 68 million EUR.
Switzerland [42]	With over 130,000 EV charging points and 1,350 MW of chargers' capacity in 2035, grid reinforcement costs would amount to 129 million CHF. 44% of the transformers would require upgrades. Rural areas would require the highest specific reinforcement costs per kW of charging power.
Madrid, Spain [43]	Electrification of 500 vehicles among 25 postal hubs, assuming fast 22 kW peak time charging, would result in 121,624 EUR of distribution network reinforcements and 7,117 EUR of power losses costs.
Kartal region, Turkey [44]	To accommodate load with 9,636 EVs by 2030, the Kartal region would need to install three distribution transformers, increasing required grid investments by nearly 28,000 USD.
United Kingdom [45]	Two low-voltage feeders have been analyzed. The first one, serving 149 customers, would require reinforcement investments of 5,600 GBP at 50% EV penetration (reaching in 2034). The second one, serving 106 customers, would require 4,800 GBP of reinforcement investments at 70% EV penetration (in 2038).
New Zealand [46]	With 50% of heating and transport electrification by 2030 and 100% by 2050, distribution networks reinforcement costs amount to 1.9 billion USD in 2030 and 4.9 billion USD in 2050.

TABLE II:

EV IMPACT ON DEMAND, GENERATION AND EMISSIONS: SUMMARY OF INTERNATIONAL STUDIES

Country/region	Assumptions	Power generation impacts
Chongqing, China [47]	2 million electric cars and unmanaged charging strategy	Evening peak increases by 6.7%, causing operating costs of the power system (including fuel, O&M, reserves, curtailment and trade) to increase by 6.5 billion USD (7.8%).
China [48]	174 million EVs on the roads in the moderate scenario and 349 million EV in the aggressive scenario by 2050 + 70% reduction in power sector emissions by 2050	10%, 13% and 6% increase in gas, storage and solar capacity respectively between moderate and aggressive scenarios. 55.5 billion USD (4.4%) increase in annual total power system costs by 2050. Even in the uncontrolled charging scenario, the average CO2 emissions of the power system in 2050 decrease from 90.16 kg/MWh in the moderate scenario to 87.37 kg/MWh
United Kingdom [49]	14.6 million EVs in 2040, translating to the demand of 34.1 TWh, increasing daily peak demand of 9.4 GW	Total capacity requirements in 2050 are 9.2 GW (5%) greater than in the base case without EV demand driven by flexible capacities of gas turbines, battery storages or transmission capacities.
Texas, Finland, Germany,	Evaluation of impacts generation portfolio impacts with penetration between 0-5%.	Net-costs of the power system supplying the EV charging load range between 200-400 EUR/year per vehicle for 0.5% penetration, but the costs vary significantly depending on RE penetration or

Country/region	Assumptions	Power generation impacts
Ireland and Sweden [8]		CO2 costs. Without CO2 costs, the coal and gas turbines capacity increases with deeper levels of integration.
India [50]	367 million electric-two wheelers and 89 million electric passenger cars by 2030.	The total peak EV charging load exceeds 30GW, which is about 6% of the total peak load by 2030 (480 GW). The demand might be fully met with already planned capacity expansion
Barbados [51]	26,600 EVs on the road by 2030	In case of uncontrolled charging, 25% of extra production costs are added to the power system—over 30% increase in the yearly average marginal cost of electricity.
New York, US [52]	10% penetration of passenger cars, corresponding to 900,000 vehicles.	System costs increase by 0.15 billion USD per year (3.7%) with a capacity expansion scenario in comparison to a scenario without EVs. There is an increased investment in gas units.
Chile [27]	150,000 electric passenger cars, 28,000 taxis and 360 electric buses.	Compared to a scenario without EV deployment, generation investments increase by 18 million USD (2.8%), while operational costs by 18 million USD (1%).
Germany [53]	6 million EVs in 2030 with various CO2 prices scenarios	With the uncoordinated charging, the production from lignite, hard coal and natural gas plants are higher for all CO2 price scenarios in comparison to the case with no EVs. With a CO2 price of 20 EUR/t, system operating costs increase by 0.2 billion EUR (2%) and emissions increase by 5 Mt (3.5%)
Alberta, Canada [54]	5% EVs penetration in 2020 raising go 20% in 2031 corresponding to 2500 GWh of additional demand	The EV charging demand is met with natural gas and imports. With uncoordinated charging, the contribution of the electricity sector to power system emissions decreases from 32.6% to 30.6%. 350 MW of new generation capacity is needed in 2031.

TABLE III:
REVIEW OF THE EV MODELLING STUDIES

Ref.	Year	Model/methodology/solution method	Modelling horizon	Case study	Charging schemes
[55]	2019	Integration of EVs is evaluated with Electricity Systems Investment model (ELIN) and an Electricity System Dispatch model (EPOD)	Up to 2050	Sweden, Norway, Denmark and Germany	Optimization and optimization with V2G
[56]	2007	ORCED (Oak Ridge Competitive Electricity Dispatch)	Up to 2020	Southeast United States	Uncoordinated charging
[57]	2008	National Energy Model System (NEMS)	Up to 2030	United States energy markets	Uniform, charging; home-based charging; off-peak charging, V2G charging
[58]	2016	MILP economic dispatch and unit commitment model	Single year optimization	United Kingdom system	Inflexible EV operation and smart charging of part of the fleet
[27]	2020	MILP capacity expansion model	Up to 2030	Chilean power system	Uncoordinated and coordinated charging
[59]	2019	Three-stage stochastic program with Benders decomposition	Up to 2050	The power system of Lanzarote-Fuerteventura in Spain	Uncoordinated and coordinated charging
[52]	2014	MILP capacity expansion model with hourly unit commitment and dispatch	Single year, 20 representative days	NYISO system	Uncoordinated and coordinated charging with hourly and 15-min resolution
[60]	2015	Monte-Carlo-Based portfolio modeling tool coupled with economic dispatch model	Single year optimization	The Australian National Electricity Market (NEM)	Residential charging unmanaged, universal charging unmanaged and universal charging managed
[8]	2014	Integrated capacity expansion algorithm with unit commitment model	Single year optimization	Power systems of Texas, Sweden, Finland, Germany, and Ireland	Controlled and uncontrolled charging
[61]	2012	Brazilian MESSAGE model	Up to 2030	Brazil energy system	Uncontrolled charging
[62]	2020	Iterative short- and long-term capacity expansion algorithm	6-year horizon	Generic microgrid case	Optimized operation of electric vehicle charging station
[7]	2019	MILP with scenario generation by k-means methodology	15 years in 3-year stages	Generic case study	Uncoordinated charging

[63]	2020	Adaptive robust optimization problem, solved with column-and-constraint generation algorithm	Single year optimization	69-bus test distribution system	Optimized charging
[64]	2018	MILP model with the robust multistage joint expansion planning and uncertainties in load	15 years in 5-year stages	18-node test distribution system	Uncoordinated charging with uncertain EV load
[65]	2020	Particle swarm optimization and tabu search hybrid approach	24-hour period	PG&E 69-bus test system	Optimized charging
[66]	2020	Chance-constrained programming coupled with genetic algorithm	24-hour period	33-bus test distribution system	Uncoordinated charging with various charging scenarios

B. OVERVIEW OF EV MODELING LITERATURE

Recent studies show that the impact of large-scale EVs deployment on absolute electricity demand might be limited to an increase reaching up to 10% of the total consumption [55], which is likely to be accommodated by the power system without causing undue stress. Over the years, numerous researchers incorporated EV load into the dispatch and capacity expansion models, determining impact on the operation costs, investments decisions, and environmental factors under various charging approaches. In 2007, Oak Ridge Competitive Electricity Dispatch model was used to evaluate the charging impact of Plug-in Hybrid Electric Vehicles (PHEVs) on the Virginia-Carolinas electricity grid, showing that peak charging leads to intensified use of combustion turbines and combined cycle plants [56]. In [57], the National energy modelling system (NEMS), used by US Energy Information Administration (EIA), was adjusted to investigate the impact of four different charging strategies on the power capacity expansions. A long-term capacity expansion model based on the mixed-integer linear programming (MILP) approach is used in [58] to evaluate the value of EVs flexibility. Two inflexible charging strategies were proposed, supported with vehicle-to-grid (V2G) services, assessed for the case study of the UK power system. MILP model was also deployed in [27] to analyze the impact of different EV charging strategies on the power system expansion in Chile, considering co-optimization of transmission and generation investments. In [59], the MILP-based optimization model was expanded to include day-ahead and real-time markets stages in the decision process, creating the multi-stage stochastic program used to analyze the impact of EVs controllability on the investment decisions. Hourly MILP capacity expansion model with unit commitment and economic dispatch was also utilized in [52] to evaluate the benefit from PHEVs controlled charging strategy in the NYISO system's expansion planning. In [60], the sensitivity of the generation portfolio investments on the EV and PV deployment was evaluated using Monte-Carlo based scenario modelling with the case study of the Australian National Electricity Market. In [8], the power systems of Texas, Sweden, Finland, Germany, and Ireland were represented and analyzed with unit commitment and capacity expansion models under uncoordinated and coordinated charging schemes. Some of these studies focused on the cooperation of EV fleet with other generation technologies and their potential to support VRE integration in power systems. Borba et al. [61] assessed the suitability of a controllable electric vehicle fleet to integrate and balance the large-scale wind power capacity deployment in northeastern Brazil. Mehrjerdi [62] analyzed the microgrid multistage capacity expansion problem with integrated electric vehicle charging station, solar PV, and battery energy storage. Furthermore, some of the models also included a detailed representation of the distribution system's assets in the modelling framework. In [7] the MILP model of power system expansion planning was deployed to evaluate the impact of EVs on the distribution system with charging stations, storages, and distributed energy resources. An adaptive robust optimization model, formulated as MILP, was used in [63] to determine the least-cost investment planning of charging stations, solar units, and battery storage, considering long-term uncertainty and short-term meteorological variability. Banol Arias et al. [64] focused on the small scale local distribution system expansion planning, co-optimized with the least-cost allocation of the charging stations. The model was formulated as MILP and considered the uncertainties of conventional loads as well as EV demand. Distribution level expansion planning was also analyzed in [65]. A combination of particle swarm optimization and tabu search was deployed to evaluate the system's operational costs, losses, and emissions, while integrating renewable energy sources, storage facilities and EVs. In [66], planning of the PV capacities and charging stations is performed with stochastic chance-constrained programming coupled with genetic algorithm. A summary of the modeling studies is presented in Table III.

A review of the modeling literature indicates that long term optimization models based on the MILP approach are the most popular tool to evaluate the impact of EV load on the power system. These models are characterized with easy to formulate (linear) form, a wide range of available solvers and guarantee to obtain global optimum. Considering a wide range of advantages similar approach has been applied in this study.

III. METHODOLOGY

Figure 1 illustrates the key methodological steps undertaken in this study. The analytical process started with obtaining annual forecasts of electricity demand for each EV mode over the investigated horizon. Subsequently, the typical charging profiles were assumed for each mode under various charging strategies. Afterwards, the annual charging demand and normalized profiles were combined to generate EV load curves for typical days that are incorporated in the planning model. Then, least-cost generation and expansion plans were developed considering detailed technological, economic and environmental parameters of the power system. Finally, the key incremental parameters were calculated using outcomes of the modelling process to evaluate the critical impacts of the EV deployment. Key steps of the methodological process are described in the subsequent sections.

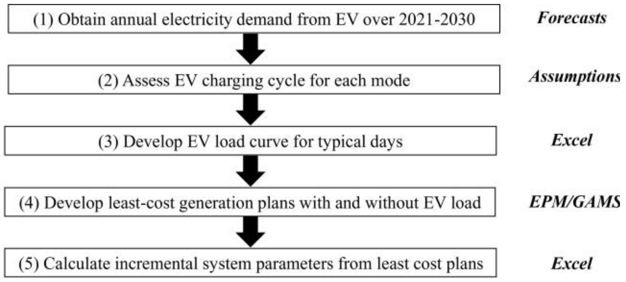

FIGURE 1. Key methodological steps

A. EV LOAD AND CHARGING SCENARIOS

The first step in generating hourly EV load involves estimating annual electricity demand from each mode and type of vehicle. At this stage, two key inputs include a forecast number of EVs by mode and assumed battery capacity per vehicle type (in kWh). Annual electricity demand for EV charging depends on the structure of the market and dominant mode in the EV stock. Passenger light-duty vehicles, light commercial vehicles, buses, trucks as well as electric two- or three-wheelers will have not only distinct battery capacities and designated chargers, but also their daily charging schemes will change depending on the intended use, charging solution (wired, wireless or battery swapping) or charger availability.

To assess the impact of the additional demand on the daily peak and load profile, the annual demand needs to be converted into hourly load cycles based on a series of assumptions. First, charging cycles and levels must be defined for each mode. This includes defining the powers of the various types of chargers as well as the percentage of vehicles using specific chargers. Finally, the charging scenarios are constructed to develop final EV load cycles. In this study, two EV charging scenarios are considered: uncoordinated and optimized. In all EV charging scenarios, the total demand is derived from the baseline scenario without any transport electrification (henceforth referred to as the "No EV Load" scenario, plus the incremental addition from EV deployment.

In the uncoordinated scenario, most of the charging occurs during the evening hours, representing the typical time with the highest frequency of such events according to historical data. Specifically, we have assumed that:

- Most two-wheeler owners will plug in their EV after coming home from work. Therefore, the uncoordinated scenario considers 20% of electric two-wheeler fleet to perform level-1 charging at ~ 1 kW peak power (for up to 3 hours) and 10% level-2 charging at ~ 6kW peak power (up to 1 hour) every day starting at 6 pm
- 10% of electric cars will charge daily at level-2 (~7 kW peak power for up to 10 hours) and 10% at level-3 (~ 25 kW peak power up to 3 hours) starting at 6 pm
- The entire EV bus fleet is recharged every day through fast charging (~ 45 kW peak power for 8 hours), with half of them starting at 6 pm and the other half at 11 pm.

Figure 2 shows the baseline (before EVs load) and incremental EVs load for 30% of the vehicles for a typical working day in 2030, estimated as part of our work. While the additional volume of electricity consumption is relatively small (~3%), an increase in evening peak for an uncoordinated charging regime can be an order of magnitude higher.

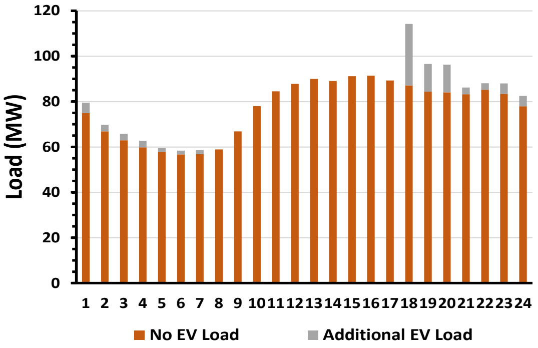

FIGURE 2. Load in Malé on a typical working day for 2030: Baseline (No EV) and EV load

As shown in Figure 2, the additional electricity demand from EVs can shift the daily peak from noon to the evening in the uncoordinated scenario.

In the optimized scenario, the model optimally distributes part of an EV load among hours to achieve the least-cost outcome. The optimization of the load is unidirectional, similar to the application of V1G technologies. The goal of the optimized scenario is to estimate the benefits of centralized charging by allowing the model to shift load not only across the hours but also balance it across the zones of the system. The EV charging optimization needs to observe the following three additional constraints in addition to observing restrictions on the timing of charging for different categories of different EV categories:

1. The daily energy demand in the optimized EV scenario is equal to the daily energy demand in the uncoordinated EV

charging scenario, i.e., the total charging load for the day remains the same as uncoordinated charging regime;

2. The hourly electricity consumption from EV charging must be larger than 1% of the daily required electricity for EV charging which sets a minimum charging requirement; and
3. The hourly electricity consumption from EV charging must be lower than 50% of the daily required electricity for EV charging, which sets a maximum charging load for any hour.

Finally, we also consider an optimized EV-CO₂ limits scenario, where the model optimizes the EV charging load but applies a CO₂ emissions limit for each year of the modelling period. The yearly CO₂ emissions in this optimized EV-CO₂ limit scenario cannot be higher than for the baseline (No EV Load). In other words, we explore a carbon-neutral case in which the additional EV load does not increase emissions to understand the system cost and investment implications.

B. OPTIMIZATION MODEL

In this study, the Electricity Planning Model (EPM) is deployed as a least-cost planning optimization framework for assessing the impact of additional EV load. EPM is formulated as a single mixed integer linear programming model for all years and implemented in GAMS [67] environment. It performs a systemwide multi-year planning optimization to determine:

- The optimal generation and transmission capacity addition for the system over the next 10-20 years.
- How generators should be dispatched including solar/wind subject to their availability profile and dispatchability.
- Flows among the nodes/zones, subjected to transmission limits.
- Optimal capacity of storage and how storage units should be operated to provide energy arbitrage and reserve services; and
- Allocation of spinning and capacity reserves to ensure adequacy and security of the system.

EPM is used to develop a baseline least-cost generation plan without further transport electrification and alternative generation plans with incremental EV load for the period from 2021 to 2030 for uncoordinated and optimized EV charging scenarios. Key outputs from the model include the net present value (NPV) of the system costs, annual CO₂ emissions, required capacity additions and associated investments, and fuel costs.

Equations 1-8 present the key formulations of the EPM model that are relevant for the present EV analysis. A complete formulation of the model is available in reference [68]. The objective function of the model constitutes NPV of all generation related costs discounted by the discount factor DF. First, the NPV covers $CAPEX$ costs applicable to newly build thermal, renewable and storage units. $CAPEX$ value is annualized with the capital recovery factor (CRF). Second, it comprises $OPEX$ costs, which include both operation and maintenance (O&M) expenses and fuel costs. Finally, NPV covers penalties θ^{USE} and $\theta^{Surplus}$ for unserved and surplus energy in each zone z.

$$\begin{aligned} NPV = &\sum_{g,y}\left(DF_y \cdot CRF_g \cdot CAPEX_g \cdot Cap_{g,y}\right) \\ &+ \sum_{g,y,q,d,t}\left(DF_y \cdot OPEX_{g,y,q,d,t} \cdot Gen_{g,y,q,d,t}\right) \\ &+ \sum_{z,y,q,d,t}\left(DF_y \cdot USE_{z,y,q,d,t} \cdot \theta^{USE}\right) \\ &+ \sum_{z,y,q,d,t}\left(DF_y \cdot Surplus_{z,y,q,d,t} \cdot \theta^{Surplus}\right) \end{aligned} \tag{1}$$

Equation 2 imposes the limit on the generation output $Gen_{g,y,q,d,t}$ of each unit g in every hour t, day d, season q and year y. Output is constrained by the product of installed capacity $Cap_{g,y}$ and capacity factor $CF_{g,y,q,d,t}$.

$$Gen_{g,y,q,d,t} \le Cap_{g,y} \cdot CF_{g,y,q,d,t} \qquad \forall\, g, y, q, d, t \tag{2}$$

Equation 3 restricts the hourly transfer of power $Trans_{z,z',y,q,d,t}$ between two adjacent zones z and z' with parameter $TransLimit_{z,z',y,q}$ based on the technical limitations of lines in the system.

$$Trans_{z,z',y,q,d,t} \le TransLimit_{z,z',y,q} \qquad \forall\, z, z', y, q \tag{3}$$

Demand supply balance in each zone and timestep is represented by Equation 4. It includes the generator's output (mapping between zones and generators is represented with a set ψ^z), surplus and unserved power, storage outputs and injections as well as transmission connectivity between the zones. Demand (total load) comprises two parts: base demand $Demand_{z,y,q,d,t}$ and additional EV charging load $EVLoad_{z,m,y,q,d,t}$.

$$\begin{aligned} &\sum_{g\in\psi^z} Gen_{g,y,q,d,t} - Surplus_{z,y,q,d,t} \\ &+ \sum_{g\in\psi^z, g\in\psi^B} BStorOut_{g,y,q,d,t} \cdot \eta^B \\ &- \sum_{z'} Trans_{z,z',y,q,d,t} + \sum_{z'}\left(Trans_{z,z',y,q,d,t} \cdot \eta^T\right) \\ &- \sum_{g\in\psi^z, g\in\psi^B} BStorIn_{g,y,q,d,t} + USE_{z,y,q,d,t} \\ &\le Demand_{z,y,q,d,t} + \sum_m EVLoad_{z,m,y,q,d,t} \qquad \forall\, z, y, q, d, t \end{aligned} \tag{4}$$

$EVLoad_{z,m,y,q,d,t}$ is an input parameter for each transport mode m (two-wheelers, cars, and buses) in the uncoordinated scenario. We assume centralized charging of electric buses in all scenarios with further EV deployment. Therefore, the additional load required to charge electric buses remains an exogenously defined parameter in all scenarios with further EV roll-out. However, the additional charging load $EVLoad_{z,m,y,q,d,t}$ is a *variable* for electric two-wheelers and cars when considering optimized EV charging. Our study assumes charging of these two-wheelers and cars across the entire network that can be spread out (and thus optimized) to avoid overly concentrating the load from charging these vehicles around the peak hour. In other words, under optimized charging the model will determine the optimal balance between centralized charging and distributed charging of the two-wheeler and cars.

Equations 5-7 represent EV load specific constraints under optimized charging. Equation 5 ensures that the sum of optimized load across all zones is equal to the predefined value of daily EV demand in the system $EVLoad^{daily}_{m,y,q,d}$. Equation 6 imposes the lower bound on the hourly EV load in each zone z and hour h. Minimum optimized load is proportional to the base electricity demand $Demand_{z,y,q,d,t}$ using the scalar δ^{EVmin}, which for this study is defined as 0.01. Finally, Equation 7 imposes the upper limit on the amount of load allocated to one zone in each hour, proportional to the product of daily EV load $EVLoad^{daily}_{m,y,q,d}$ and factor δ^{EVmax} (set to 0.5 for this study).

$$\sum_{z,t} EVLoad_{z,m,y,q,d,t} = EVLoad^{daily}_{m,y,q,d} \qquad \forall\, m,q,d,y \qquad (5)$$

$$EVLoad_{z,m,y,q,d,t} \geq \frac{Demand_{z,y,q,d,t}}{\sum_z Demand_{z,y,q,d,t}} \cdot EVLoad^{daily}_{m,y,q,d} \cdot \delta^{EVmin} \qquad \forall z,m,q,d,y,t \qquad (6)$$

$$EVLoad_{z,m,y,q,d,t} \leq EVLoad^{daily}_{m,y,q,d} \cdot \delta^{EVmax} \qquad \forall z,m,q,d,y,t \qquad (7)$$

Equation 8 provides the capacity balance of each technology g in year y, excluding the first year of the planning horizon (represented as $FirstYear$). The capacity in the specific year is defined as a sum of capacity in the preceding year $Cap_{g,y-1}$ and newly constructed capacity $Build_{g,y}$.

$$Cap_{g,y} = Cap_{g,y-1} + Build_{g,y} \qquad \forall\, g, y \neq FirstYear \qquad (8)$$

Equation 9 constrains the amount of energy stored in each timestep $BStorage_{g,y,q,d,t}$ in-unit $g \in \Psi^B$ (where set Ψ^B includes the storage units). Equations 10 and 11 define the balance of the storage considering the output of storage unit $BStorOut_{g,y,q,d,t}$ and storage charging $BStorIn_{g,y,q,d,t}$. All storages are considered to be empty in the first hour of each day d mainly because the planning model works with non-adjacent representative days, and the storage optimization is restricted to each daily cycle independent of other days.

$$BStorage_{g,y,q,d,t} \leq Cap_{g,y} \qquad \forall\, g \in \Psi^B, y,q,d,t \qquad (9)$$

$$BStorage_{g,y,q,d,t} = BStorIn_{g,y,q,d,t} - BStorOut_{g,y,q,d,t} + BStorage_{g,y,q,d,t-1} \qquad \forall\, g \in \Psi^B, y,q,d,t \neq FirstHour \qquad (10)$$

$$BStorage_{g,y,q,d,t} = BStorIn_{g,y,q,d,t} - BStorOut_{g,y,q,d,t} \qquad \forall g \in \Psi^B, y,q,d,t = FirstHour \qquad (11)$$

For network stability reasons, in Equation 12, the total installed capacity of rooftop solar PV is limited to 50% of the yearly peak load in any load zone $Demand^{max}_{z,y}$.

$$\sum_{g\in\Psi^z, g\in\Psi^{RoofPV}} Cap_{g,y} \leq 0.5 \cdot Demand^{max}_{z,y} \qquad \forall\, z,y \qquad (12)$$

IV. CASE STUDY FOR MALDIVES (MALÉ)

A. KEY INPUTS

1) EV PENETRATION

The study focuses on the impact of EV fleet located in the system of Malé, the capital and most populous city in Maldives where 50% of each type of EV is located and charged. Table IV summarizes the number of EVs by type and the associated electricity demand for both the whole Maldives and Malé up to 2030.

The projected number of two-wheelers in the Maldives split between fossil-fueled two-wheelers (non-EV) and electric two-wheelers (EV) up to 2030, as shown in Figure 3. The number of electric two-wheelers is expected to increase from 5,377 in 2021 to 49,977 in 2030. The study assumes an average 2.5 kWh battery capacity for the electric two-wheelers.

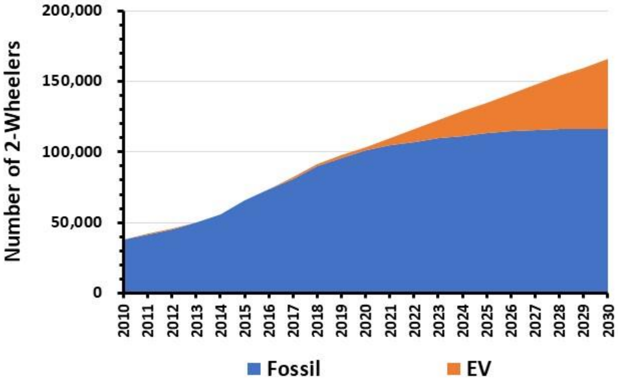

FIGURE 3. Historic (up to 2018) and forecast number of two-wheelers in the Maldives.

Note: Historic data is from Maldives Ministry of Transport.

The number of electric cars in the Maldives is forecasted to grow from 546 in 2021 to 3,444 in 2030 (Figure 4). Electric cars are assumed to have batteries with an average storage capacity of 60 kWh.

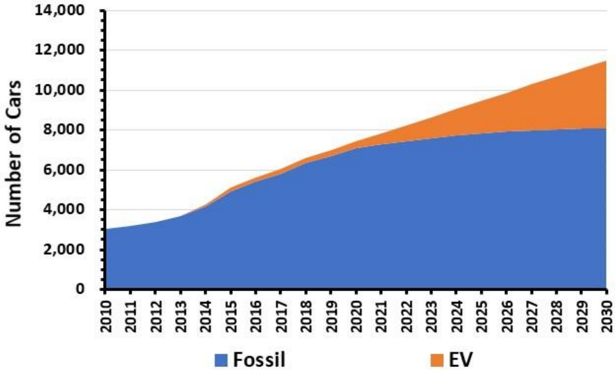

FIGURE 4. Historic (up to 2018) and forecast number of cars in the Maldives.

Note: Historic data is from Maldives Ministry of Transport.

We assume 15 new electric buses per year in Malé as of 2021, yielding a total electric bus fleet of 150 buses by 2030 since currently there are no electric buses in the Maldives. These buses are expected to have an average battery capacity of 350 kWh and are being recharged through fast charging (peak power of 45 kW) every evening or night.

TABLE IV
EV PROJECTIONS FOR THE MALDIVES AND MALÉ BY VEHICLE TYPE (NUMBER AND TOTAL CAPACITY IN KWH).

	2021	***2022***	***2023***	***2024***	***2025***	***2026***	***2027***	***2028***	***2029***	***2030***
Maldives										
Electric two-wheelers										
Number (-)	5,377	8,935	12,843	17,100	21,707	26,662	31,967	37,621	43,625	49,977
Capacity (kWh)	14,285	22,338	32,108	42,751	54,267	66,656	79,918	94,054	109,062	124,943
Cars										
Number (-)	328	546	784	1,043	1,324	1,625	1,947	2,290	2,654	3,038
Capacity (kWh)	19,680	32,735	47,044	62,607	79,423	97,492	116,816	137,393	159,223	182,307
Buses										
Number (-)	15	30	45	60	75	90	105	120	135	150
Capacity (kWh)	5,250	10,500	15,750	21,000	26,250	31,500	36,750	42,000	47,250	52,500
Malé										
Electric two-wheelers										
Number (-)	2,857	4,468	6,422	8,550	10,853	13,331	15,984	18,811	21,812	24,989
Capacity (kWh)	7,143	11,169	16,054	21,375	27,134	33,328	39,959	47,027	54,531	62,472
Cars										
Number (-)	273	392	522	662	812	973	1,145	1,327	1,519	1,722
Capacity (kWh)	16,368	23,522	31,303	39,711	48,746	58,408	68,696	79,611	91,153	103,322
Buses										
Number (-)	8	15	23	30	38	45	53	60	68	75
Capacity (kWh)	2,625	5,250	7,875	10,500	13,125	15,750	18,375	21,000	23,625	26,250

2) PEAK POWER AND ELECTRICITY DEMAND IN MALÉ

Baseline peak demand for Malé in the absence of further transport electrification is expected to grow at 4.4% per year from 71 MW in 2021 to 105 MW in 2030 (Figure 5). The associated electricity demand grows from 427 GWh in 2021 to 630 GWh in 2030 (Figure 6).

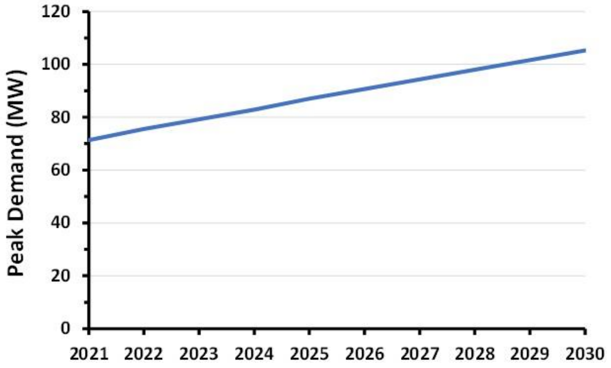

FIGURE 5. **Baseline peak demand projection for Malé**

Gradual electrification of vehicles up to 30% of the fleet or ~ 26,800 EVs out of a total fleet of 89,000 vehicles in Malé by 2030 increases the incremental EV energy requirement from 4 GWh in 2021 to 31 GWh in 2030 (Figure 6, labelled as EV). Total electricity demand is therefore expected to grow from (427+4=) 431 GWh in 2021 to (630+31=) 661 GWh in 2030.

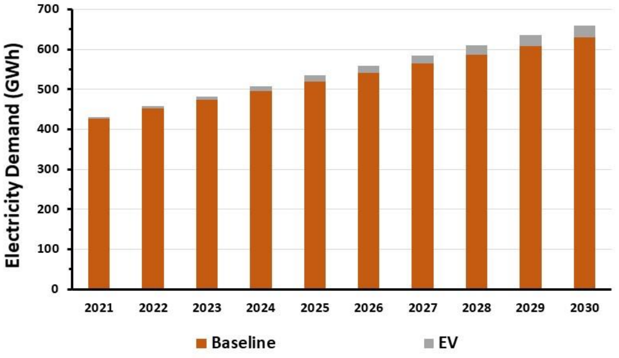

FIGURE 6. **Energy requirement projection for Malé – Baseline and incremental EV demand**

Annual electricity demand is modelled with 12 representative days with 3 days per quarter (1 peak day, 1 minimum day and 1 average day) in hourly resolution. The model assumes a constant load profile for each representative day of the next ten years (2021-2030) at each distribution node (substation). The load profile for each node for each of the three representative days in the second quarter (April to May) is based on the recorded hourly loads of April 2019. Load profiles in the other quarters (quarters 1, 2, and 4) were scaled based on the ratio of total generation in that quarter to the total generation in Malé for quarter 2. Peak demand at each distribution node has the same growth rate as the entire system. The study assumes that the additional EV load at each distribution node is split proportionally to each distribution node's contribution to the system peak demand in the absence of any further electrification.

3) NETWORK REPRESENTATION

The schematic representation of Malé's medium voltage distribution network is based on STELCO's Malé single line diagram from October 2019. Out of the 13 feeders, 3 feeders (feeders 2, 7, and 14) were split into subsections with the associated distribution transformers to investigate the possible overloading of transformers and feeder section capacity constraints. The assumed power transfer limit of each feeder subsection (labelled as F_xS_y in Figure 7) is 8 MW (Figure 7). STELCO also provided power transfer limits in MW for the distribution transformers (labelled as DTzz in Figure 7) along with these 3 feeders. The remaining 10 feeders were modelled as single nodes with a feeder power transfer limit of 8 MW (Figure 7). The model is allowed to deploy new rooftop solar PV and grid connected batteries at each distribution node. Existing diesel gensets and solar PV capacity are connected to all feeders. Connection to all feeders is schematically represented by placing existing diesel units and solar PV in the zone labelled as GENZONE (Figure 7). New candidate diesel or utility solar units are assumed to be deployed in the same GENZONE. We assume that network constraints are absent between the GENZONE and the first subsection of each feeder (F_xS_1). Incremental load from EV buses charging is connected to GENZONE to represent centralized charging of these vehicles. Total load, including base demand and the incremental EV load from two-wheelers and cars, is connected to each distribution node. This incremental load is a fixed parameter in the uncoordinated scenario and a variable in the optimized scenario. In the optimized charging scenario, the two-wheelers and cars can be charged through both decentralized charging in the distribution network and centralized charging. The centralized charging is represented as an additional load in GENZONE.

4) GENERATOR CHARACTERISTICS

Table V lists the cost and operational characteristics for both existing and candidate diesel gensets (DG) and utility-scale solar PV taken from the Energy Storage Roadmap for the Maldives [69]. Rooftop solar PV is assumed to have a capital cost of 3.0 million USD per MW in line with recent IRENA projections [70] and economic life of 20 years. CAPEX of the battery energy storage systems (BESS) is assumed to be 250 USD per kWh with an economic life of 15 years. For candidate generators, the column "Capacity" shows the maximum capacity limit by 2030. The maximum utility PV deployment of 5 MW by 2030 is based on a previous PV potential assessment [69]. Diesel prices are assumed to increase in line with the latest WB Commodity Market Outlook starting from the reported 2019 diesel price of 21.5 USD/GJ [70]. The solar availability profile in Malé for both utility-scale PV and rooftop PV is taken from the Global Solar Atlas (2020 data). The average solar capacity factor in the model is 18%. Table VI summarizes four key scenarios in terms of EV load and associated constraints.

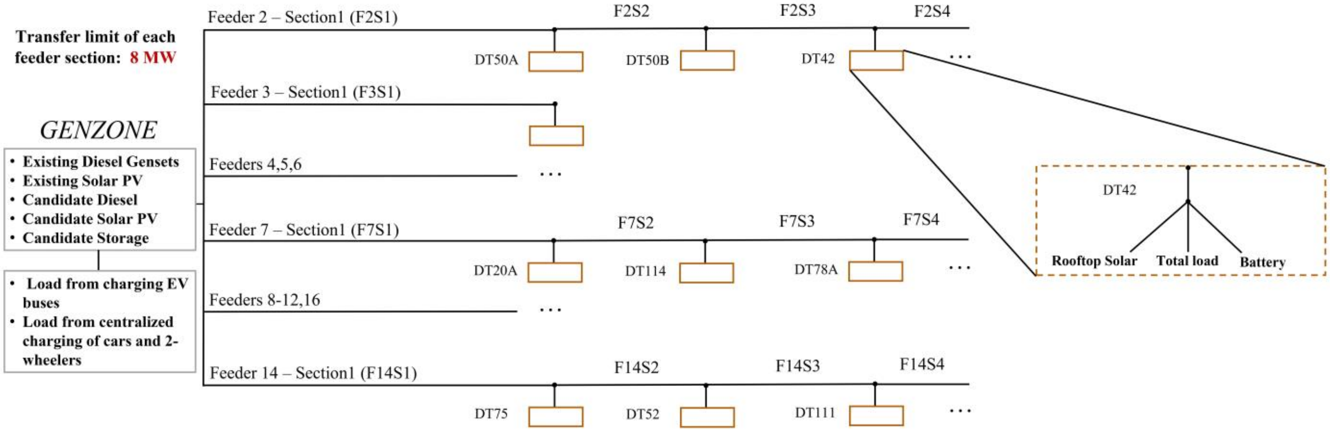

FIGURE 7. **Schematic representation of the Malé distribution network with candidate additions of rooftop solar PV and battery energy storage systems at customers sites. Feeders 2, 7, and 14 were split into their different subsections. The remaining 10 feeders are modelled as single nodes. The power transfer limit of each feeder section is 8 MW.**

Note: * Load from centralized charging of cars and two-wheelers in GENZONE is only considered in the optimized scenario.

TABLE V

GENERATOR OPERATING AND COST CHARACTERISTICS

Plant	**Status**	**Zone**	**COD**	**Capacity (MW)**	**Heat rate (MMBTU/MWh)**	**FOM (USD/MW/year)**	**VOM (USD/MWh)**	**CAPEX (mUSD/MW)**
DG	Existing	GENZONE		82	9.37	38,000	7.0	-
SolarPV	Existing	GENZONE		0.67	-	10,000	-	-
Generic DG	Candidate	GENZONE	2021	100	9.0	76,000	7.0	1.20
Utility PV	Candidate	GENZONE	2023	5	-	5,000	-	1.20
Rooftop PV	Candidate	Each distribution node	2021	20	-	10,000	-	3.0
BESS (non-battery costs)*	Candidate	Each distribution node/ GENZONE	2021	10	-	14,000	-	0.3

Note: *Capex for battery pack is taken as 250 USD/kWh – the table shows only the non-battery costs component of the battery energy storage system in million USD per MW; efficiency of 85%. The World Bank report "Economic Analysis of Battery Energy Storage Systems" explains the difference between the battery pack and non-battery pack costs in detail [71]. COD = Commercial Operation Date; FOM = Fixed Operation and Maintenance Cost; VOM = Variable Operation and Maintenance Cost.

TABLE VI.

OVERVIEW OF SCENARIOS (2021-2030)

Scenario	**EV Load**	**EV Charging Constraints**
Baseline	No further transport electrification: $\mathrm{EVLoad}_{z,m,y,q,d,t} = 0.$	N/A (no further EV roll-out)
Uncoordinated EV charging	• Deterministic calculation of EV charging load across all transport modes • Centralized charging for buses • Decentralized charging for two-wheelers and cars	N/A (EV load is an input parameter for each transportation mode)
Optimized EV charging	• Centralized charging for buses (same load as for uncoordinated EV charging) • ***Optimized charging for two-wheelers and cars across the entire network (optimal mix of centralized and decentralized charging)***	For optimized charging of two-wheelers and cars: • Same daily energy demand as for uncoordinated EV charging scenario • Hourly consumption from charging must be larger than 1% of the daily energy demand for charging • Hourly consumption from charging must be smaller than 50% of the daily charging requirement

Optimized EV charging – CO_2 limits	• Same methodology as for optimized EV charging	Same assumptions as for optimized EV with the following additional constraint: • CO_2 emissions in each year of the forecast cannot be higher than the corresponding emissions for the baseline

Note: All scenarios are subject to the constraints in Equations (2) - (4), (8)-(12).

B. DISCUSSION OF RESULTS

The optimal generation plan in the baseline scenario without further EV deployment yields a total net present value of 867 million USD in system costs at a 10% discount rate over the 2021 to 2030 period (Table VII). Total power sector generation emissions stand at 3,173 kton CO_2. The combined existing and new capacity will be able to meet almost the entire demand by 2030 but for a relatively small part of it (< 0.2% of total demand over the 2021-2030 period). The deployed capacity to meet increased demand by 2030 includes 54 MW of rooftop PV and 2.5 MW of BESS (14 MWh) in the distribution network together with 5 MW of utility-scale PV and 4 MW of new diesel units (Figure 8). Most of the new rooftop PV (47 MW out of 54 MW) is built in the first six years of the modelling period.

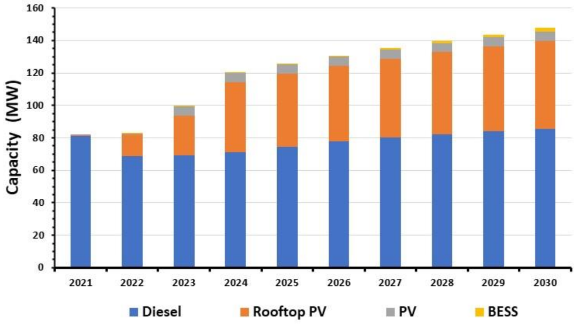

FIGURE 8. **Optimized Baseline Generation Capacity for Malé (2021-2030)**

The expected contribution of renewables (rooftop and utility-scale PV) will increase over the next 10 years up to 14% of the generation mix by 2030 (Figure 9. The contribution from batteries to energy mix is marginal and is about 1% of the annual output by 2030.

Uncoordinated EV charging increases the total electricity demand by 3.1% (+166 GWh) relative to the baseline scenario over the 2021-2030 period. The increased electricity demand causes a 3.5% increase in system costs (+30 million USD).

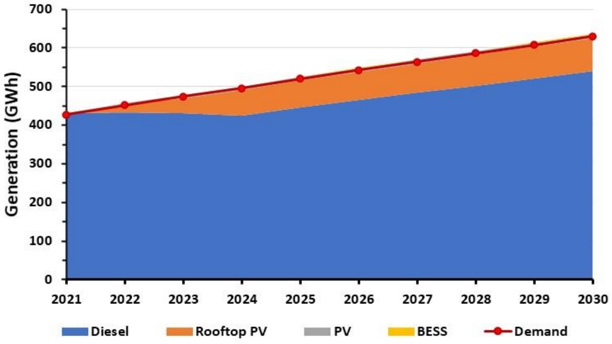

FIGURE 9. **Baseline Generation Mix for Malé (2021-2030)**

The increase in system costs mainly stems from increased fuel costs due to increased diesel generation and, to a lesser extent, increased capital investment (Table VII). The additional demand is met through a combination of diesel, rooftop PV and BESS generation. The increased electricity generation from diesel units causes a 2.7% (+87 kton) increase in greenhouse gas emissions over the next 10 years. The higher capital expenditure results from the additional deployment of 8 MW rooftop PV, 15 MW BESS (34 MWh), and 6 MW diesel (Figure 10). Uncoordinated charging increases the evening peak by up to 12 MW in 2025 (+17%) and 27 MW (+31 %) in 2030. The higher peak demand is met through a combination of increased diesel and BESS output (Figure 11). BESS is charged through overproduction of rooftop PV during the day (7h – 16h) and diesel units during the night (Figure 11).

TABLE VII

COMPARISON OF DIFFERENT EV CHARGING SCENARIOS FOR MALÉ (2021 – 2030).

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)
NPV of System Costs* (million USD 2021)	867	897 (+30)	892 (+25)	919 (+52)
Investment CAPEX (million USD)**	229	265 (+36)	231 (+2)	255 (+26)
New Capacity (MW)	111	140 (+29)	113 (+2)	131 (+20)
Unserved Demand (GWh)***	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)

Note: *Discount rate is 10%.

** Total capex. Please note that the planning model considers capital costs in annualized terms for 2021-2030 which is below the total capex.

*** Unserved energy penalized at 1000 USD/MWh following [69]

Optimized EV charging reduces the incremental cost of EV deployment relative to the baseline scenario for the power sector from 30 million USD in the uncoordinated EV charging scenario to 25 million USD, i.e., a 2.9% increase in system costs over the baseline NPV estimate. The optimized EV charging case incurs larger fuel costs than the uncoordinated scenario due to increased diesel generation (Table VII). The increase in fuel costs (+5 million USD) in the coordinated charging scenario compared to the uncoordinated scenario is more than offset by a reduction in capital cost (-7 million USD) and operating costs (- 2 million USD), leading to a net 5 million cost decrease relative to the uncoordinated case (Figure 12).

The optimized charging scenario has a similar capacity expansion plan as the baseline. The only difference is the 2 MW higher diesel deployment over the 2021-2030 period (Figure 13). Put differently, the optimized scenario flattens the EV load sufficiently to warrant very little increase in capacity relative to the baseline and uses more diesel generation to meet this load.

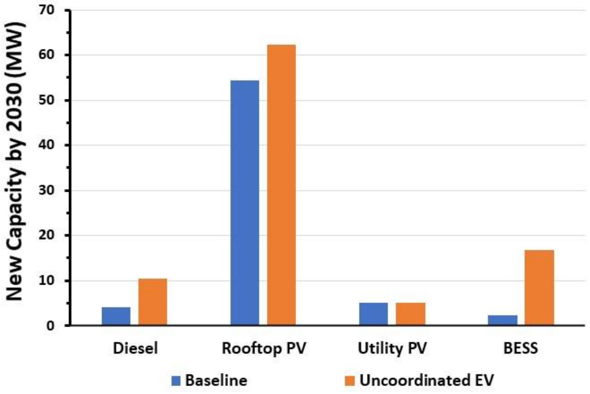

FIGURE 10. Comparison of the optimized capacity mix for Malé: Baseline vs. Uncoordinated EV.

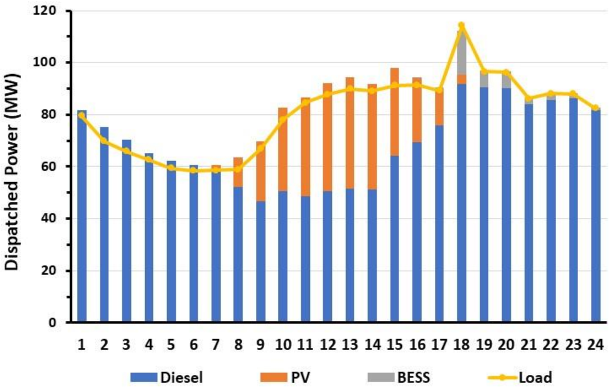

FIGURE 11. Hourly dispatch for Malé in 2030 for an average day in the uncoordinated EV charging scenario.

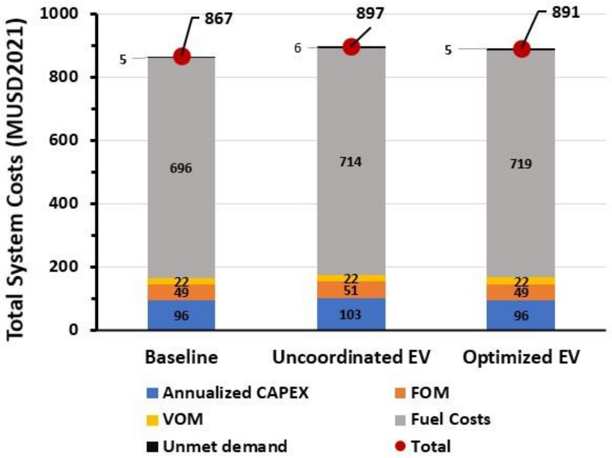

FIGURE 12. Comparison of total system costs (2021-2030) under different EV charging scenarios for Malé.

This is evident from Figure 14 that shows optimized EV charging removes the evening spike from concentrated EV charging in the uncoordinated scenario by distributing the EV charging load throughout the day. Optimized charging smoothens the load profile and reduces systems costs due to reduced CAPEX needs. On the flipside, the incremental EV load is mainly met by previously unused diesel capacity, especially during periods of high solar availability (11h – 15h) where even more idle diesel capacity is available to meet incremental EV load (Figure 14). The increased diesel capacity and generation in the optimized charging scenario further increase CO_2 emission up to 3,287 kton over the 2021-2030 or a 3.6 % increase vs. the baseline.

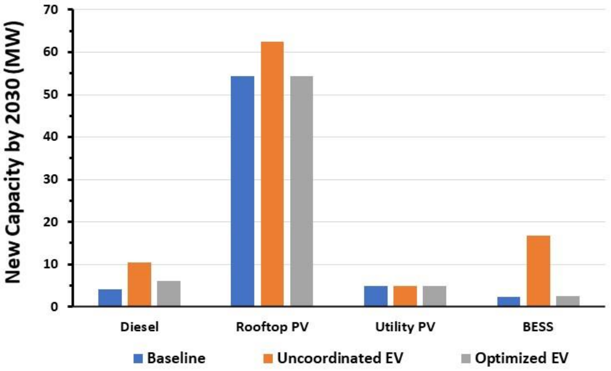

FIGURE 13. New capacity by 2030 under different EV charging scenarios for Malé.

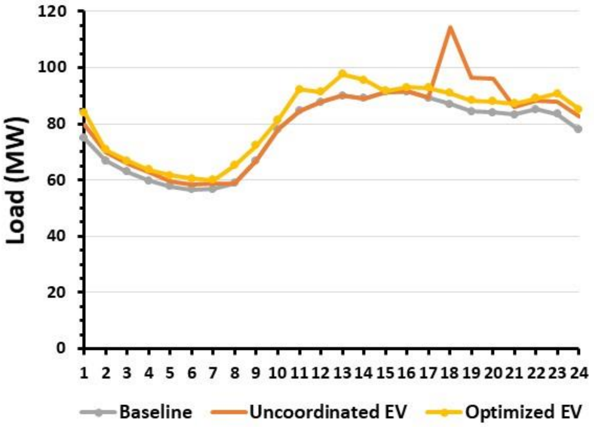

FIGURE 14. Hourly load for an average day in Malé during quarter 2 in 2030 under different EV charging scenarios.

We, therefore, also explored a carbon-neutral scenario by constraining the optimized EV scenario CO_2 emissions limits to the baseline emissions. This proved to be an expensive constraint that doubles the incremental cost to 52 million USD over the baseline (Table VII). Limiting the CO_2 emissions in the optimized EV scenario not only results in increased solar PV deployment in the distribution network but also increases unmet demand during high load hours in the evening. The combination of both effects increases the total system cost by 6.0% over the 2021-2030 period. However, it is interesting to note that even with the carbon neutrality criterion imposed, optimized charging of EV leads to distributing the load more evenly and eliminates the need for BESS, albeit at the expense of increasing (economic) load shed (Figure 15). Although we do not explore the demand response options as part of this study, such options for cooling loads etc., may be a highly potent option to manage other loads.

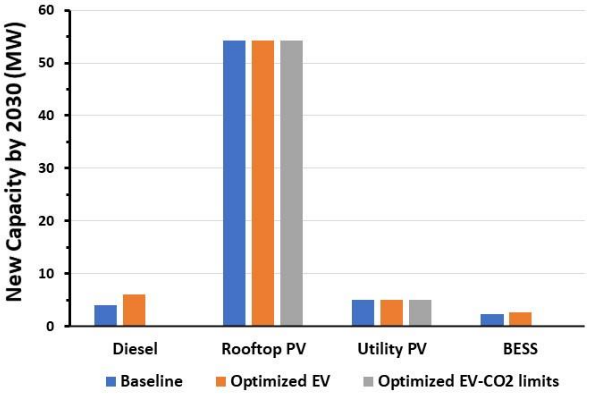

FIGURE 15. New capacity by 2030 under different EV charging scenarios for Malé.

VI. CONCLUDING REMARKS

Electrification of transport is one of the critical planks of decarbonization and is a welcome addition in many other terms too for oil-importing countries with heavily polluted cities. It is, however, going to place an additional burden on power systems requiring more generation, storage, transmission and distribution capacity, more generation from expensive peaking plants and potentially more emissions from the power sector. There is a serious need for planning ahead so that these impacts can be minimized through measures like optimized/coordinated charging of EV loads and intensifying RE and storage programs.

In this paper, we present the methodology to incorporate the EV charging demand in the long-term capacity expansion model and evaluate the impact of the additional load on the power system operation, costs, emissions and investment decisions. We have firstly surveyed the academic and industry literature that mostly discuss the experience with EV in the developed world to provide an understanding of the nature and magnitude of EV impacts on generation, transmission and distribution. Some of the studies do point to a substantial need to upgrade the distribution network that may add in excess of 5000 USD per EV. Furthermore, capacity expansion studies indicate that investments in new flexible gas units are needed in the system after large scale EV introduction with uncoordinated charging. In the developing world, these impacts may be even more serious because of the dilapidated nature of the distribution system, rapidly growing electricity demand, a lack of sufficient peaking capacity and inadequate level of RE penetration to meet the added load without increasing emissions. Nevertheless, literature review confirms that smart charging strategies, including TOU tariffs, coordinated unidirectional charging and V2G technologies, are effective ways of mitigating the power system stresses, reducing required investments to provide reliable electricity supply and avoiding CO2 emissions from a new load. Especially in the systems with already high investments requirements, due to increasing demand and poor infrastructure, load management approaches can be substantially more cost-effective compared to typical capacity expansion and grid reinforcement.

We have undertaken a planning study for the city of Malé in Maldives to explore these issues and inform a strategy around distributed RE, EV and BESS to augment the existing generation system in a way that does not require a massive upgrade to the distribution network. We have used the Electricity Planning Model (EPM) developed at the World Bank with some enhancements made to it to optimize EV charging load. There are three key questions we have tried to answer for Maldives: (a) what are the additional capital and operating cost and emissions implications of adding EV to the system? (b) does it help to plan for an optimized charging regime to contain some or all of these impacts sufficiently? and (c) can the Maldives system be made carbon-neutral for the additional EV load, and at what cost?

We have considered a moderate EV scenario that assumes 30% of the vehicles (primarily two-wheelers) will switch to EV by 2030, adding a modest ~3% to energy requirement on average over 2021-2030. However, the addition to evening peak hour load can be an order of magnitude higher if a substantial part of these vehicles is to be charged during the evening in an "uncoordinated" regime. This regime is compared and contrasted with a coordinated/optimized regime wherein the model distributes the EV load across the hours while observing constraints on minimum and maximum charging that is feasible and on timing requirements for different modes of transport.

Uncoordinated EV charging will increase total power system costs by ~3% (+ 30 million USD 2021) over the 2021-2030 period resulting from increased CAPEX for generation units and diesel fuel costs. Total undiscounted generation CAPEX will increase by 36 million USD (or 16% relative to a baseline of No EV load) as the system will require an additional 29 MW capacity by 2030 (8 MW rooftop PV, 15 MW BESS, 6 MW and diesel). Given that the 36 million USD additional generation investment is needed to electrify approximately 50,000 two-wheelers, 3,400 cars and 150 buses, about 500-600 USD in new generation investment is needed for every new EV (primarily two-wheelers) on the road over the next ten years in the Maldives. This is in fact a significant cost for a small system and represents around 50% of the cost of a new EV two-wheeler in the country.

Optimized EV charging will reduce the incremental cost to 25 million USD in discounted terms over 2021-2030. The incremental cost from Optimized EV is mainly due to increased fuel (diesel) costs, but it will cause an additional 114 kton CO_2 emissions compared to the baseline case. Optimized EV charging also causes 27 kton more CO_2 emissions than the uncoordinated EV charging scenario. New and emerging technologies such as smart charging, battery swapping, and VGI can enable/support the Optimized EV scenario and potentially expand its scope and limit the negative emissions impacts. However, these issues would require significant enhancements to the methodology and that data that do not exist at present and hence have not been explored.

Uncoordinated EV charging causes increased rooftop PV and BESS deployment together with increased RE generation to manage a sharp increase in the evening peak, whereas optimized EV favors increased diesel generation and capacity (+2 MW vs. baseline). The increased evening load under uncoordinated EV charging improves the business case for BESS or PV+BESS as local rooftop PV, and BESS avoids overloading feeders. The distribution network is able to cope with the EV load without requiring an upgrade of the feeders that we have studied. A thorough load flow analysis will still be needed to confirm this finding for the full network.

In summary, the study provided us with a number of useful insights. While it provided some comfort that the additional EV load can be accommodated within the limitation of the 11 kV feeders studies, it also revealed a severe increase in generation capital requirement to meet the peak load. Optimized charging can contain this impact but presents a challenge of increasing emissions too. Although these conclusions are somewhat idiosyncratic to the Malé generation and network systems, the underlying issues are symptomatic to many cities in the developing world. The planning model and the framework around which these issues are addressed may need to be applied for a carefully planned development of EV penetration, including a fuller exploration of new and emerging technologies that can minimize potential ill-effects of EV load on the power systems.

These conclusions and insights lead to a few key recommendations for the key stakeholders involved in policy making, regulations and system planning and operation, namely:

- Policy making on EV should explicitly consider integrated energy sector-wide studies including decarbonization target for the sector as a whole. As the Maldives case study clearly demonstrate, the impact of additional EV demand on the power system is significant that requires careful planning, investment and operational changes that will require a long lead time.
- Power system planning should be used to exploit any flexibility that may be available in optimizing the EV load to minimize system cost, investment and emissions impacts. Bringing the EV roll out plan and power system plan closer is essential to understand the benefits of a more flexible EV charging and devise necessary incentive mechanisms. Given the resource constraints that typically prevail in developing countries, it is important not to overburden an already stressed system or extenuate investment requirements that are usually quite challenging to meet organic load growth.
- The impact on distribution system can be particularly severe that may in the limit require a complete overhaul of the system, e.g., to upgrade a substantial part of the 11 kV system to 22 kV. If this transition is not managed well, it may lead to a substantial increase in outages. Long-term planning analyses should be complemented with detailed load flow studies to evaluate the suitability of distribution and transmission system assets and uncover potential risks of overloading or failures.
- Theoretical studies prove that smart charging strategies provide an attractive way of avoiding expensive grid reinforcements with the large-scale deployment of EVs. Piloting new technologies is a useful way to check if some of the costly upgrades can be avoided and the planning analysis also provides a means to test the cost-benefit of these technologies.

VII. REFERENCES

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