TECHNICAL REPORT

# ELECTRIC MOBILITY & POWER SYSTEMS

## Impacts and Mitigation Strategies in Developing Countries

ESMAP
Energy Sector Management Assistance Program

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# Abbreviations

| | |
|---|---|
| BEV | Battery Electric Vehicle |
| DSO | Distribution Systems Operator |
| E2W | Electric Two-Wheeler |
| E3W | Electric Three-Wheeler |
| E-Mobility | Electric Mobility |
| EPM | World Bank's Electricity Planning Model |
| ESMAP | Energy Sector Management Assistance Program |
| EU | European Union |
| EV | Electric Vehicle |
| IFC | International Finance Corporation |
| FCEV | Fuel Cell Electric Vehicle |
| GDP | Gross Domestic Product |
| GHG | Greenhouse Gas |
| HDEV | Heavy-Duty Electric Vehicle |
| HEV | Hybrid Electric Vehicle |
| HVAC | Vehicle Heating and Air-Conditioning |
| LCV | Light Commercial Vehicles |
| PHEV | Plug-in Hybrid Electric Vehicle |
| PLDV | Passenger Light-Duty Vehicle |
| PV | Photovoltaic |
| ToU | Time of Use |
| TSO | Transmission System Operator |
| US | United States |
| V1G | Vehicle-to-Grid Unidirectional Charging |
| V2B | Vehicle-to-Building |
| V2G | Vehicle-to-Grid |
| V2H | Vehicle-to-Home |
| V2L | Vehicle-to-Load |
| V2V | Vehicle-to-Vehicle |
| V2X | Vehicle-to-Everything |
| VGI | Vehicle-Grid-Integration |
| WB | World Bank |
| WBG | World Bank Group |

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

# Acknowledgments

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# Key Messages

The transition to electric mobility (E-Mobility) represents a complex and multifaceted challenge for power systems that will require a range of solutions and approaches to address. Much of the literature covering this subject takes the perspective of higher-income countries. This report addresses the technical dimension of the challenge in the context of developing countries, intending to inform E-Mobility practitioners and policymakers about the impacts on power systems and potential mitigation strategies. Specifically, the research for this report provides an opportunity to clarify related questions such as the following ones.

**1. Why is the transition to E-Mobility a major technical challenge for power systems?**

**The dramatic increase in the number of electric vehicles (EV) in the coming decade will result in the formation of a unique type of electricity load.** In absolute terms, the additional demand from EV charging will most likely have only a minor impact on total electricity demand. However, EV charging may have a significant impact on the power system load profile as it will be added on top of the base hourly electricity consumption, effectively reshaping the load curve. The shape and scale of these load profiles are highly dependent on end-user charging patterns, which are influenced by a variety of social, technological, and economic factors. Furthermore, unlike conventional electricity demand, it is spatially movable: the same vehicle can draw power from different charging locations at different times, depending on a number of factors such as infrastructure availability, charging time preferences, or economics. The spatial factor will be critical as charging events will most likely be concentrated in relatively small areas, such as charging hubs and industrial parks.

**Without coordinated charging, EVs load might further amplify existing demand peaks, putting additional stress on the power system and causing substantial implications for electric utilities.** While these challenges may be of a variety of operational, financial, or socioeconomic natures, they are all deeply rooted in the technical characteristics of power systems. Without mechanisms to shift EV charging to off-peak periods, most charging events occur when people arrive at work or home, coinciding with already existing critical peaks in the power system. This effectively changes the load peak's height and duration, which are the most critical parameters in the design and operation of reliable and secure power systems and their elements at the generation, transmission, and distribution levels.

**Even at early stages of EV deployment, local clusters with a high share of penetration will most likely emerge, putting strain on power system infrastructure.** Simultaneous and uncoordinated EV charging events in low-voltage residential areas can result in significant changes in the local power load received by lines and substations, in particular transformers. Without smart charging strategies, these challenges would necessitate infrastructure investments, such as upgrading and rehabilitating transmission and distribution lines and replacing obsolete substations. As the share of EVs grows, these investment requirements are likely to increase and spread to the generation and transmission sectors.

**Electric utilities, system operators, regulators, and policymakers will need to take comprehensive steps to address a wide range of technical challenges and prepare for the upcoming EV adoption.** To minimize impacts associated with EV deployment while maximizing potential benefits, careful integrated planning and collaboration among the various actors will be required. Electric utilities, in particular, will need to strike a balance between infrastructure costs, EV owner expectations, charging time, and power grid stresses. Regulators and policy makers on the other hand will be responsible for creating a supportive and sustainable regulatory environment, incentivizing strategic investments in the power system and the charging infrastructure.

**2. Why is it particularly relevant to developing countries?**

**In some developing countries, power systems still fail to provide adequate services and remain vulnerable to external shocks.** Transmission and distribution grids, as well as the generation facilities, may not consistently meet expectations in terms of reliability and the quality of power services. This can be attributed to a variety of factors such as limited capacity, inadequate maintenance and upgrades, and various operational challenges. The distribution grid is commonly identified as a particularly vulnerable segment of the power systems mainly owing to inadequate design, aging equipment, and failure to provide sufficient maintenance. Moreover, transmission grids in developing countries are often unreliable and underdeveloped, both within national borders and across borders. These challenges are likely to exacerbate following the projected growth in energy demand in developing countries.

**The uptake of EVs may exacerbate the technical challenges facing power systems in developing countries.** The combined effects of EV charging on loading, voltages, and power quality, when coupled with poor infrastructure quality, could put significant strain on already overwhelmed grids. As a result, power grids in these countries may require significant upgrades and reinforcements to handle the increased demand caused by EVs. These upgrades need to be implemented urgently to ensure the reliable and efficient operation of these systems.

**Developing countries need to prepare their power systems, taking a comprehensive view of the current state and assessing E-Mobility challenges and opportunities in a holistic manner.** The power system impacts of the E-Mobility transition seen and assessed in mature markets can be exacerbated by specific characteristics of developing countries' systems, resulting in additional barriers to EV uptake and, as a result, stalling progress toward decarbonization goals if left unmanaged. As a result, comprehensive plans for EV grid integration must be developed, taking into account detailed technical aspects of both the grid and EVs. In a time of technological transition, it will be necessary to provide a reliable and sustainable supply. Because of the already high reinforcement needs and projected increase in base demand, there is an opportunity to leverage smart charging strategies and long-term planning to achieve significant economic, technical, and social benefits.

3. **What are the technical impacts of E-Mobility on power systems?**

**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.** In the early stages of adoption, these impacts will primarily involve increased utilization of the equipment, which may exacerbate losses, maintenance requirements, or induced aging. However, as adoption increases, these effects may escalate to overloading and equipment failures, resulting in blackouts, increased investment requirements, and significant economic and social costs. The magnitude of these impacts will be determined by the region's infrastructure, driving patterns, charger types, charging timings, and the extent of EV penetration.

**Out of all the segments of power systems, the distribution grid is undoubtedly the most vulnerable to the negative impacts of uncoordinated EV charging.** Overloading of feeders and transformers, voltage deviations, power losses, and power quality issues have been identified as primary effects and may occur even at low levels of adoption due to clustering of charging events. 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 feeders not only will be a determining factor in the scale of EV impact but also may be listed as a critical barrier to integrating EVs from a consumer perspective.

**EV deployment may also impact the transmission and generation operation and expansion planning, although it will likely be relatively minor compared to that of the distribution grid.** Incorporating additional charging load into the long-term planning exercises can result in more extensive investments in the interconnectors or peak-load generators. These effects are also likely to be more impactful in developing countries where the quality and extensiveness of transmission infrastructure, generation reserve margins, or systems' flexibility are often disruptive. Examples of technical impacts are presented in Table 1.

4. **What are the implications for electric utilities?**

**Electric utilities will need to undertake comprehensive measures to address a wide range of internal and external challenges and prepare the ground for the upcoming EV uptake.** To ensure that the power system can meet increased demand and harness the new grid resources, utilities are responsible for upgrading distribution infrastructure and adjusting operations. As EV market penetration grows, investment requirements will increase along with the number of assets connected to the grid. Without adaptation measures and appropriate support, these additional requirements could jeopardize the sustainability of utility operations.

**Electric utilities can benefit greatly from the growth of E-Mobility if they take steps to harness its development potential.** The increased demand for electricity can help electric utilities stabilize their revenue streams. Additionally, smart charging strategies can be leveraged to promote demand response programs. Furthermore, electric utilities can also explore opportunities in the EV charging market by owning and operating charging stations themselves. Through vehicle-grid-integration (VGI), electric utilities can integrate

**TABLE 1**

Technical EV Load Power System Impacts in the Context of Developing Countries

| CATEGORY | IMPACTS | DEVELOPING COUNTRY CONTEXT |
|---|---|---|
| **Power Demand** | • Increased energy consumption<br>• Altered daily load curve<br>• Modified peak load in terms of magnitude, duration, and timing<br>• Increased load profile variability and uncertainty | • Location, weather, demographics, and driving patterns may impact EV adoption, power consumption, and charging behavior<br>• Electric two- and three-wheelers may dominate in many developing countries<br>• Economic, regulatory, and geographical difficulties in establishing public charging infrastructure |
| **Generation System** | • Additional electricity generation required<br>• New capacity investments needed to ensure security and adequacy<br>• Increased power system emissions<br>• High ramping needs due to sharp power demand increase<br>• Increased need for ancillary services<br>• Increased need for energy storage | • Existing reliability and security challenges with electricity access<br>• High generation investment needs due to fast-growing demand<br>• Carbon-intensive generation capacities, often relying on inefficient fossil fuel units<br>• Poor market regulation and difficulties in providing reserves |
| **Transmission System** | • Risk of congestion and distortion of electricity prices<br>• Increased need for transmission capacity<br>• Increased need for reactive power | • Limited interconnectivity and cross-border capacity<br>• Lacking regulations for appropriate transmission system to encourage investments<br>• High investment needs to maintain adequate interconnections with growing demand |
| **Distribution System** | • Overloading feeders and transformers, necessitating capacity upgrades<br>• Increased power losses<br>• Voltage deviations<br>• Power quality issues, such as harmonic distortion. | • Weak, poorly designed distribution systems<br>• High distribution system losses<br>• High rate of transformer failures and maintenance needs<br>• Insufficient management, standards, and regulations<br>• Low awareness of power quality issues<br>• High reinforcement needs due to growing demand. |

more renewable energy sources into their grid. Finally, electric utilities can play a key role in promoting EV adoption by educating customers on the benefits of EVs and working with governments to develop policies that support EV growth.

**Planning ahead for the new role of utilities and creating a comprehensive roadmap is critical in the context of E-Mobility.** Electric utilities should identify the potential grid requirements under assumed EV shares and evaluate the least-cost way to meet the demand, keeping a high level of reliability and security. E-Mobility can also offer an opportunity for utilities to adapt their activities and stay relevant in an evolving energy sector. Adopting new innovative technologies and policies could be the most cost-effective options, such as advanced electricity metering and control technology. It is essential that utilities be prepared and proactive, especially those in developing countries that face critical shortcomings such as inadequate investment levels, low productivity, and poorly maintained grids.

### 5. How can the technical impacts on power systems be mitigated?

**Smart charging strategies could be applied to mitigate the negative impacts of the additional load from EVs while simultaneously taking advantage of the potential**

**benefits that can be reaped.** Innovative smart charging strategies provide an attractive way of avoiding expensive grid reinforcements with the large-scale deployment of EVs. The primary goal of these strategies is to shift the load to the most optimal time from the system operator's perspective, respecting the EV owner preferences and considering power system constraints. Advanced smart charging strategies as vehicle-to-everything (V2X) allow for bidirectional flow of energy between EV and their environments. This enables advanced functionalities such as vehicle-to-grid (V2G) for providing ancillary services like flexibility provision, frequency regulation, and demand response. By empowering power system operators to control and modulate EV charging, advanced smart charging strategies can foster vehicle-grid-integration (VGI), which promises the broadest scope of power grid benefits including supporting higher shares of renewables. Approaches to implementing smart charging strategies include behavioral load shift programs and technical solutions for charging control.

**Tariff designs, such as time-of-use (ToU) tariffs and real-time pricing, are key in mitigating some of the negative impacts of EVs on the power system.** These tariffs need to be dynamic and reflect the cost for power system based on time and location. They incentivize shifting of EV charging and participate in lowering the cost for the system. Local electric utilities will be key players in implementing these schemes, and they will need to strike a balance between customer satisfaction, reduced power system investments, and revenue stability.

**Strategic placement of charging infrastructure is crucial to minimizing the local grid impact.** Optimizing location in areas with abundant grid hosting capacity can reduce the need for grid reinforcements and the risk of equipment failures. Electricity utilities and grid regulators play an important role in the distribution of charging infrastructure, for example by publishing grid hosting capacity maps and adjusting connection fees according to location.

**Combining with on-site solar generation and battery storage facilities with charging infrastructure is another potential technical solution to mitigate the negative impact of EV charging while adding benefits from increased flexibility.** With the 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 photovoltaic (PV) resources, may bring additional revenues to the grid and station operator.

**Standards and interoperability requirements can facilitate aggregation and increase the flexibility potential of electric vehicles as well as improve grid safety.** The certification procedure is especially important for electric utilities to ensure that grid-connected charging equipment will perform consistently. These standards cover a wide range of certification topics such as interconnection, charging safety, vehicle functionality, and communications. Ensuring interoperability of infrastructure is also an important prerequisite for more sophisticated utilization of the EV fleet by the electric utility to provide ancillary services or balancing capacity.

**Long-term planning is critical in ensuring best mitigation of technical impacts and to achieve extensive economic, technical, and social benefits in developing countries.** It can be anticipated that when compared to EV deployment scenarios without smart charging strategies in place, benefits per EV over the long-term horizon can be far greater than estimates in high-income countries if accounting for avoided failures and reinforcements or additional capacity needs. This requires the deployment of smart grid infrastructure, well-designed electricity markets, and operational capabilities. This may pose a challenge for developing countries that are struggling with grid upgrades and investment. Carefully designed long-term plans involving pilot projects, especially in terms of innovative and emerging technologies, are crucial steps toward the broader development of smart charging frameworks.

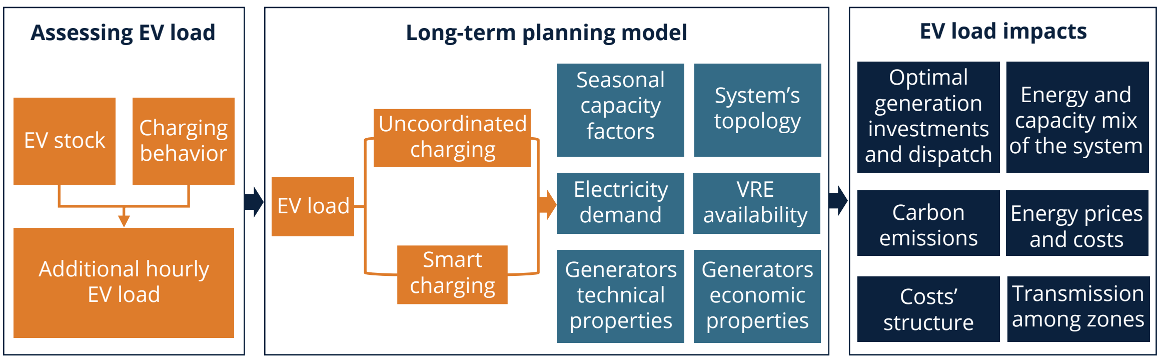
### 6. How do those impacts and mitigation options fit into broader planning considerations?

**Integrated planning for power systems and charging infrastructure, together with aligning power sector and transportation goals, are decisive elements of successful EV integration.** Integrated planning is key to achieving a least-cost, resilient power system and is particularly crucial to reaching ambitious decarbonization targets. 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. Based on such analyses, utilities may produce comprehensive reports emphasizing the importance of utility service upgrade requirements and provide a roadmap for other actors on anticipated timelines and costs for deploying EV charging infrastructure (Figure 1).

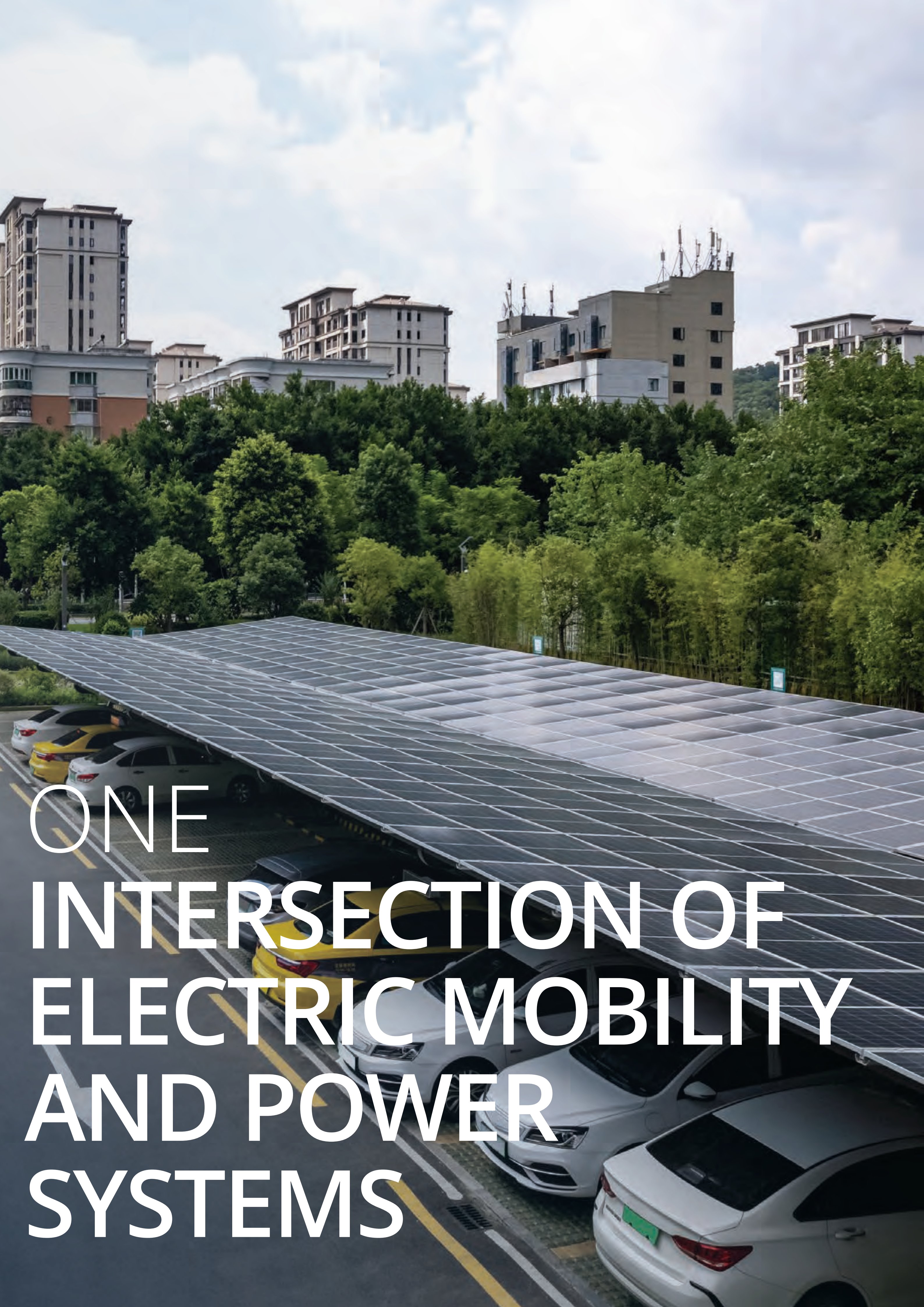
**The technical dimension is one aspect of the multifaceted challenge of the transition to E-Mobility for power systems; working on all the dimensions in a holistic manner will be necessary to ensure the sustainability of the transition to E-Mobility.**

**FIGURE 1**

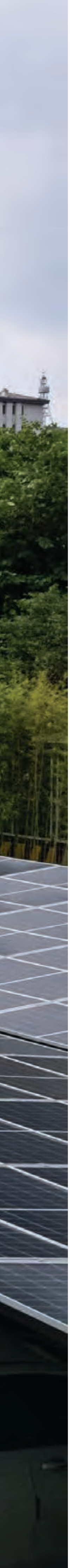
Illustrative Example of Embedding Additional EV Load in the Long-Term Capacity Expansion Planning Process



Paradigm shifts as significant as transport electrification require comprehensive planning approaches. While this report focuses on the technical dimension, other considerations such as economic, social, and environmental factors must be considered to ensure that power systems are best prepared to play their driving role. This is particularly true for developing countries seeking to meet their climate and development objectives. In this sense, enabling frameworks need to be planned and implemented to ensure that investments and efforts lead to an effective transformation of the power system, making the ground for a sustainable E-Mobility transition.



# ONE
# INTERSECTION OF ELECTRIC MOBILITY AND POWER SYSTEMS



Recent Global Electric Vehicle Outlook (IEA 2022) investigated the rapidly evolving field of E-Mobility. Electric vehicles (EVs) sales increased by more than double in 2021 compared with the previous year to 6.6 million units. Most of the increase (about 70%) was attributed to battery electric vehicles, as in previous years. The global sale share of electric cars increased fourfold in 2021, to nearly 10%. As a result, about 16.5 million electric cars are currently on the road worldwide, a threefold increase from 2018. Sales were highest in China (3.3 million), followed by Europe (2.3 million) and United States (630,000). The rest of the world has seen accumulated sales of below 1 million.

The recent and projected expansion of electric mobility (E-Mobility) is only a part of the overreaching trend of electrification as an essential strategy to reach net zero goals. Apart from the shift toward electric transport, the heating sector moves towards heat pumps and electric boilers, while industrial sectors explore opportunities to electrify existing processes with high energy consumption. Because electric technologies are often far more efficient than alternatives based on fossil fuels offering comparable energy services, electrification has a significant potential to cut ultimate energy consumption and subsequent emissions. According to the International Energy Agency's (IEA) Net Zero Scenario, electricity will account for 27% of all final energy consumption in 2030, up from its current 20% share in 2021 (IEA 2021b). However, the report emphasizes that due to technological challenges in electrifying end uses in heating and industry sectors, transportation will be primarily responsible for reducing $CO_2$ emissions due to electrification by 2030.

Electric vehicles represent a new type of load for electric utilities and system operators. Unlike traditional electricity demand, it is spatially movable: the same vehicle can draw power from different charging locations at different points in time, depending on a series of conditions, including infrastructure availability, charging time preferences, or economics. The charging power is also flexible, with its ability to be modulated (ramped up or down) or disconnected at will. Furthermore, while they are primarily viewed from a load perspective, the mentioned flexibility and integrated battery make them capable of being used as distributed resources or demand response systems.

Due to these special characteristics and the scale of the projected adoption,[1] EVs can have several significant impacts on power systems, particularly at the distribution level. These impacts might appear as extensive challenges, but with the appropriate set of policies and technological developments, they might be forged into innovative opportunities. Yet, it is crucial that countries evaluate the potential effects of EVs and prepare for their extensive integration. Assessments and integration strategies 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 operations and long-term planning. Several studies have reviewed current and potential

[1] Under IEA's Net Zero Emissions by 2050 Scenario, EV share in sales (excluding two- and three-wheelers) should reach 60% by 2050 globally (IEA 2022).

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. An earlier analysis by 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 (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 (US Drive 2019), evaluated the US EV market and associated impacts to the US 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 the stress of electrical equipment.

Another aspect is the involvement of the various stakeholders. As EVs replace conventional vehicles in the coming decades, this process can bring challenges and opportunities to various stakeholders, the most crucial from the perspective of this report include policymakers, electric utilities, and regulators. These stakeholders have varied interests and responsibilities in the adoption process and interaction with the power system. Particularly essential are electric utilities, which need to undertake comprehensive measures to address a wide range of internal and external challenges and prepare the ground for the upcoming uptake. Planning ahead and creating a comprehensive roadmap is essential in the context of transport electrification implications on utilities' financial viability. Utilities should identify the potential grid requirements under assumed EV shares and evaluate the least-cost way to meet the demand, keeping a high level of reliability and security. Being prepared and proactive is especially critical for utilities in developing countries with financially distressed institutions, insufficient investment levels, low productivity, poor maintenance, and government diversion of budget resources from other high-priority social and economic needs.

The majority of studies examining the impact of electric vehicles on power systems has focused on developed countries, where adoption rates are high and some impacts are evident. However, a comprehensive evaluation of such impacts is lacking from the standpoint of emerging and developing economies, in which large-scale integration is still in its infancy. 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, substantially affecting the adoption. 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.

The objectives of this report, therefore, 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

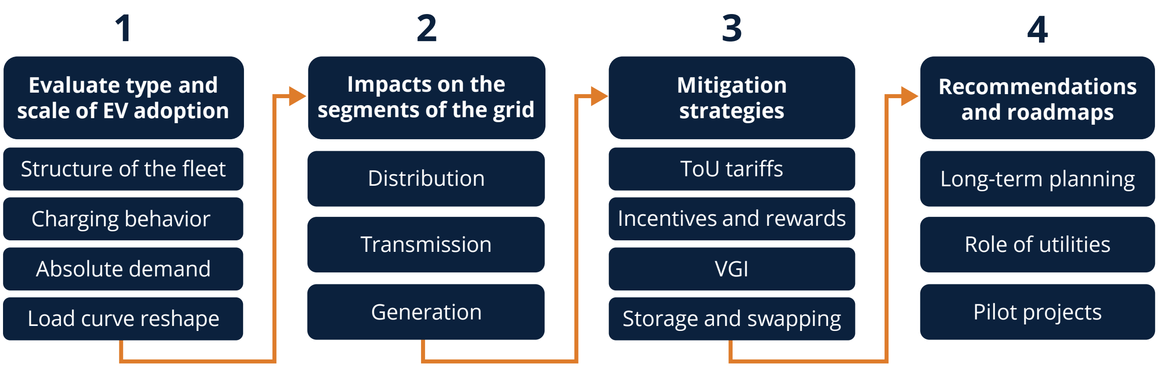
The report is written with energy sector policymakers, regulators, and utility representatives in mind. It should serve as a technical yet approachable overview of the linkages between the power sector and the deployment of electric vehicles, which are crucial to understand and consider when designing long-term decarbonization or development policies. While the technical impacts of the charging load on the electricity grid were exhaustively studied, which is presented in the comprehensive literature review in this report, the aspects of developing countries and their power systems are still relatively unexplored. This report, therefore, presents particular value for actors and professionals working on E-Mobility challenges in emerging markets.

Figure 1.1 presents a high-level representation of the assessment process of EVs impact on the power system. The procedure begins with evaluating the type and scale of EV adoption and the influencing factors, including the structure of the fleet, charging behavior, aggregate annual EV charging demand, and reshaping in the original daily load curve. Subsequently, technological, economic, and environmental impacts on various grid segments might be analyzed based on the projected level and shape of demand. Based on the scale of different impacts, specific mitigation strategies can be proposed to ease the negative impacts. Finally, based on the overall assessment, recommendations and roadmaps should be designed, including long-term planning schemes, defining the role of utilities and road-paving pilot projects.

The main technological determinants that will affect the impact of EVs on power systems include the type of electric vehicle, mode of transport, and type of charger (IRENA, 2019b). Following US Department of Transportation (2022), 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

**FIGURE 1.1**

High-Level Representation of Assessment Process of EVs Impact on Power System



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 1.1. This report focuses on BEVs and PHEVs that are used in road transport applications.

The structure of the report is as follows. The first chapter provides an introduction and context. The second chapter reviews EV technologies that are considered in this report. The third chapter includes a comprehensive review of the impacts of EVs on power systems, while the fourth chapter presents current experiences and proposals of mitigation strategies. The fifth chapter discusses the role of utilities and system planning and discusses the results of a case study done for the Maldives using the World Bank's Electricity Planning Model (EPM) (Chattopadhyay, de Sisternes, and Oguah 2018). Finally, the sixth chapter provides conclusions and recommendations.

**TABLE 1.1**

Electric Vehicle Technologies Considered in This Study

| TYPE OF ELECTRIC VEHICLE | 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** | **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 travel a high variety of roads and make a high frequency of trips. These vehicles are usually charged in the evening after work activities and are often recharged during the day using public or semi-public chargers. |
| Electric buses | Buses follow the predefined roads and each day make several short-distance trips. Charging usually occurs during the night and in the breaks between 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 usually occurs overnight, using fast public or designated depots' chargers. |

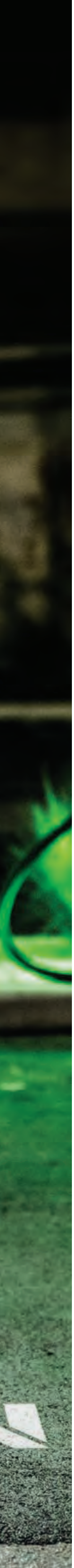
**TABLE 1.1**

Electric Vehicle Technologies Considered in This Study (*Continued*)

| VEHICLE MODE | DESCRIPTION | | |
|---|---|---|---|
| Electric two-wheelers (E2Ws),[a] electric three-wheelers (E3Ws) | E2Ws and E3Ws travel a very broad variety of roads and short distances. Their charging demand is more evenly spread in the day compared 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 shared 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. | | |
| **CHARGER TYPE[B]** | **TYPICAL LOCATION** | **VOLTAGE** | **TYPICAL POWER** |
| Residential: Level 1 | Households | 120V AC[c] | 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 |

[a] In this study, E2Ws are primarily referred to as electric scooters and motorcycles. All other small two-wheeled electric vehicles fall under the micromobility category.
[b] 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.
[c] Level 1 is not used in regions where the standard residential plug has a rated voltage of 230/240V.

# TWO
# IMPACTS ON THE POWER SYSTEM



## Highlights

- Many developing countries still lack a sufficient level of modern energy services, falling behind in energy access, reliability, or affordability.
- In absolute terms, the additional EV charging load will likely have a marginal effect on the aggregated power system demand.
- EV charging may have major consequences on the power system load profile, which will be dependent on a series of technical, social, and economic factors of the local market.
- Distribution networks in developing countries have been widely identified as the weakest part of the electricity grid.
- Overloading of feeders and transformers, voltage deviations, power losses, and power quality issues have been identified as primary effects of EV charging load in the distribution system.
- Deployment of a large-scale EV fleet will likely have a limited impact on the transmission system expansion and operation.
- In the generation system, EV deployment will primarily have an impact on the peaking units, increasing the flexibility requirements of the system and the need to supply this additional power with renewables.

Impacts from the large-scale deployment of EVs on power systems range from short-term operational issues 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 four distinctive groups in Table 2.1.

## 2.1 Power Systems in Developing Countries

The power infrastructure is vital to provide well-being as it supplies energy to residential, industrial, and commercial sectors. Reliable and affordable access to electricity embodies technological progress and capital accumulation and is directly interlinked with economic growth and development. Furthermore, adequate power system infrastructure is a crucial perquisite for unlocking effective technological transformation, especially towards decarbonized economies. Therefore, the initial state of the power system infrastructure, access rates, electricity market status, or regulation will directly have an impact on the EV adoption process and further interaction with the grid.

Many developing countries, however, still lack a sufficient level of modern energy services, falling behind in energy access, reliability, or affordability. The power system infrastructure especially continues to provide defective services and is vulnerable to external shocks. Grids, on both transmission and distribution levels, are, in many cases, unreliable because of inadequate capacity, lack of maintenance and reinforcement, and a host of other operational issues. It is not uncommon for power outages to occur almost daily, and many homes and businesses maintain backup diesel generators even when they have access to the grid

**TABLE 2.1**

EV Load Power System Impacts in the Context of Developing Countries

| CATEGORY | IMPACTS | DEVELOPING COUNTRY CONTEXT |
| --- | --- | --- |
| **Power Demand** | • Increased energy consumption<br>• Altered daily load curve<br>• Modified peak load in terms of magnitude, duration, and timing<br>• Increased load profile variability and uncertainty | • Location, weather, demographics, and driving patterns may impact EV adoption, power consumption, and charging behavior<br>• Electric two- and three-wheelers may dominate in many developing countries<br>• Economic, regulatory, and geographical difficulties in establishing public charging infrastructure |
| **Generation System** | • Additional electricity generation required<br>• New capacity investments needed to ensure security and adequacy<br>• Increased power system emissions<br>• High ramping needs due to sharp power demand increase<br>• Increased need for ancillary services<br>• Increased need for energy storage | • Existing reliability and security challenges with electricity access<br>• High generation investment needs due to fast-growing demand<br>• Carbon-intensive generation capacities, often relying on inefficient fossil fuel units<br>• Poor market regulation and difficulties in providing reserves |
| **Transmission System** | • Risk of congestion and distortion of electricity prices<br>• Increased need for transmission capacity<br>• Increased need for reactive power | • Limited interconnectivity and cross-border capacity<br>• Lacking regulations for appropriate transmission system to encourage investments<br>• High investment needs to maintain adequate interconnections with growing demand |
| **Distribution System** | • Overloading feeders and transformers, necessitating capacity upgrades<br>• Increased power losses<br>• Voltage deviations<br>• Power quality issues, such as harmonic distortion. | • Weak, poorly designed distribution systems<br>• High distribution system losses<br>• High rate of transformer failures and maintenance needs<br>• Insufficient management, standards, and regulations<br>• Low awareness of power quality issues<br>• High reinforcement needs due to growing demand. |

(Rentschler et al. 2019). These brownouts and blackouts are usually attributed to the poor physical condition and low capacity of the transmission and distribution network or shortfall in supply and scheduled outages (Meles 2020). In some parts of the world, strategic and unsupervised actions of utilities may limit the amount of power that reaches consumers because of the temporary rising costs of power purchases (Jha et al. 2021).

Consequently, there are already significant challenges existing in developing countries' power systems. These challenges would need to be managed with extensive infrastructural investments, upgrading and rehabilitating the transmission and distribution lines, replacing outdated transformers, installing new generation capacities, and diversifying the current mix (Meles 2020). These challenges are likely to exacerbate the projected growth in energy demand in low- and middle-income countries.

As such, one must consider the current status of the power systems and already existing challenges when evaluating the impact of EV deployment in developing countries. As presented in subsequent sections, the impacts seen and assessed in mature markets can be exacerbated because of specific characteristics of developing countries' systems and, unmanaged, might cause additional barriers to EV uptake and, consequently, stall reaching decarbonization goals. However, the already high reinforcement needs and projected increase in base demand present the opportunity to leverage smart charging strategies and long-term planning to achieve extensive economic, technical, and social benefits.

## 2.2 Impact on Power Demand and Load Profile

Increasing penetration of EVs will result in additional electricity demand in the power system. According to IEA (2022), in 2021 EVs globally used over 55 terawatt-hours (TWh) of electricity for charging purposes. While this is just over 0.2% 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 in the upcoming paragraphs.

Over 33 TWh of the recent annual electricity consumption by EVs occurred in China, primarily from the use of E2Ws and E3Ws (10% of the global consumption). 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 2022, IEA proposed three potential scenarios for global E-Mobility rollout. In the Stated Policies Scenario (STEPS), which considers current government policies, the global electricity demand from EVs will reach 780 TWh in 2030. In the Announced Pledges Scenario (APS), charging demand reaches over 1110 TWh. Finally, Net Zero Emissions (NZE) by 2050 Scenario projects electricity demand from EVs about 50% higher than in STEPS, assuming complete compliance with the Paris Agreement under enhanced global decarbonization efforts (IEA 2021a). In the APS scenario, the largest EV markets in 2030 include China, Europe, the United States, and India, accounting for 289 TWh, 263 TWh, 232 TWh, and 59 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 would be comparable to or smaller than the increased consumption caused by the electrification of other end uses, particularly residential heating (IEA, 2021c). Furthermore, it might be counterweighed with improvements in energy efficiency or a shift towards less energy-intensive sectors, for example, 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 (EEA, 2016; Taljegard et al. 2019) and much less in emerging markets at the early stages of the uptake (Kapustin and Grushevenko 2020). In the IEA estimates, in the APS, the share of electricity consumption from the EV load does not exceed 7% in the five largest markets by 2030 (IEA 2022).

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.[2] In that case, most plug-in events occur at the time of arrival in the workplace or home, coinciding with already existing morning and evening peaks in the power system, respectively. The magnitude of such 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 clustering effects in vehicle adoption might include wealthier suburban neighborhoods (Kester et al., 2020) or electric bus depots (Zagrajek et al. 2020). The examples of the aggregated EVs charging load on local and regional levels are presented in Figure 2.1. and Figure 2.2

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, the 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 could 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 for developing world areas, assessing the potential increase in electricity demand due to EV deployment. A few such studies are described in Table 2.2.

When EVs are integrated into the power systems, the resulting electricity load profiles depend on the charging patterns of final customers, which are affected by a series of social, technological, and economic characteristics. The vehicle type, the charging level, and charging location have been identified as key factors in considering the impact of an EV deployment on electricity consumption and load profiles (Grahn 2013). Nevertheless, E-Mobility trends in developing countries are driven by area-specific features 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. These factors are also presented in Figure 2.3.

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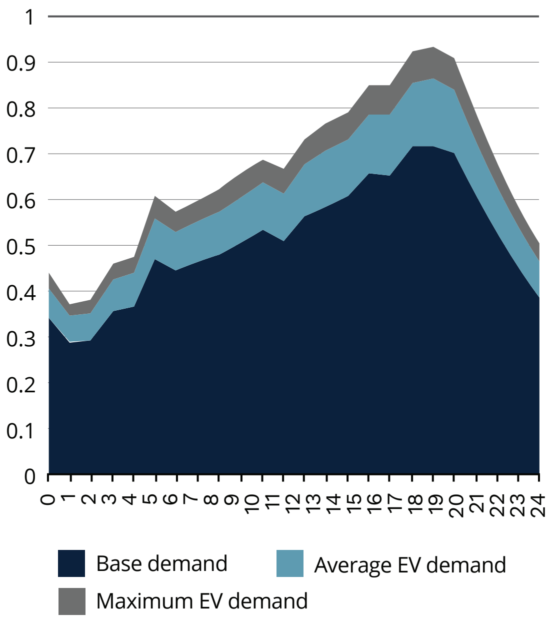
[2] Uncoordinated charging is defined as a charging process in which each EV is charged without any consideration for the grid or price of electricity (CEM, 2020).

**FIGURE 2.1**

Aggregated Load Shape for a Distribution Feeder

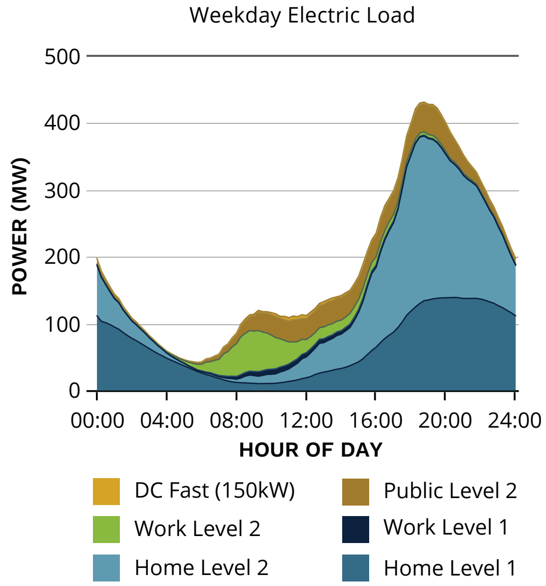
**Feeder circuit load, 150 homes with 2 vehicles per household, with 25% electric-vehicle (EV) penetration,** kilowatts




**Source:** Adopted from Engel et al. 2018.

**FIGURE 2.2**

Load Approximated by NREL's Electric Vehicle Infrastructure Projection Lite in the Los Angeles–Long Beach–Anaheim Area, Supporting a Fleet of 500,000 Plug-in Electric Vehicles




**Source:** National Renewable Energy Laboratory, California Energy Commission, and U.S. Department of Energy's Vehicle Technologies Office 2022.

Electric utilities and system operators are stakeholders, of which standard operations will be most significantly affected by changes in electricity consumption and load profiles because of EV deployment. Load forecasting is the cornerstone of long-term planning as well as short-term dispatch and is a crucial commercial issue, especially in the utility sector. It is vital for utilities to have precise load forecasts for adequate resource planning, rate cases, designing rate structures, financial planning, and other purposes. This is especially important given the extraordinary risks facing the electric utility industry because of a potentially significant shift in the technology mix as a result of EVs combined with changes in environmental regulation, aging infrastructure, the projected low cost of natural gas, and decreasing costs of renewable technologies (Hong, 2015).

Forecasting loads is a dynamic process. Therefore, utilities and decision-makers should prioritize establishment of databases and advance the most cutting-edge forecasting technologies. These processes require a lot of time and money, and, usually, the procedure needs to be enhanced and validated constantly. The complexity and essentiality of this process may create challenges for utilities and operators in developing countries with low access to institutional, human, and financial capacity.

**TABLE 2.2**

Impact on Power Demand in Selected Countries

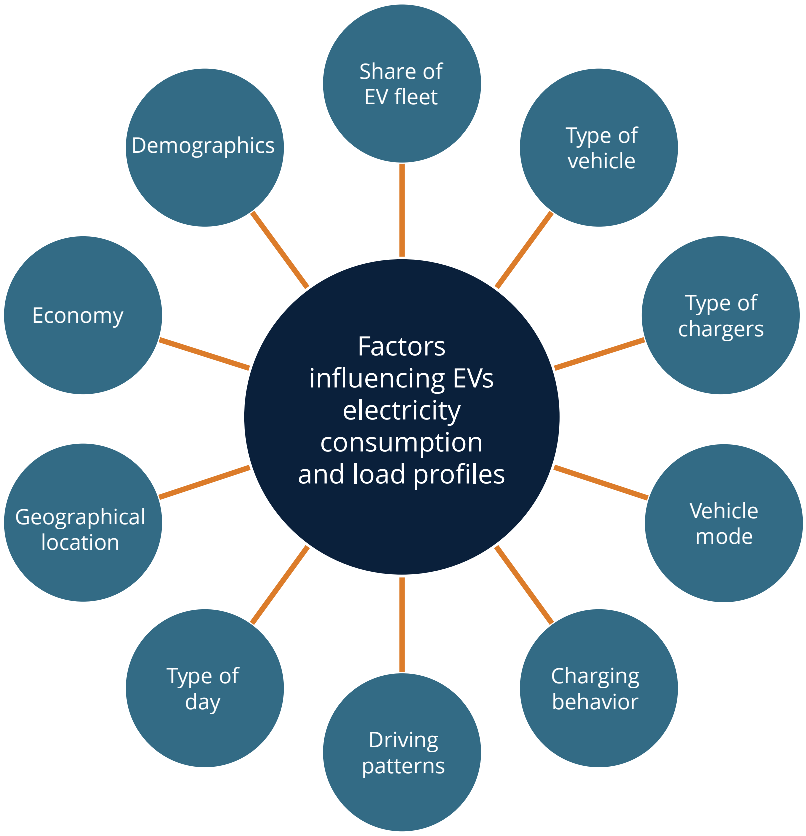
| COUNTRY | REFERENCE | ASSUMPTIONS | DEMAND IMPACT |
|---|---|---|---|
| Brazil | Dranka and Ferreira 2020 | Fleet share includes 9% of EVs (11.8 million) and 52% for hybrid vehicles (62 million) by 2050 | Electric vehicle demand is forecast to reach 38.8 TWh/yr in 2050 |
| Colombia | Unidad de Planeación Minero-Energética 2020 | 660,000 (10%) light electric or hybrid vehicles in 2030, increasing to 25% share in 2050; 82,500 EV chargers with an installed capacity of 908MW | Annual demand in 2030 amounts to 2,891 gigawatt-hours (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 15 TWh/yr in 2050 to reach full transportation decarbonization |
| India | Abhyankar et al. 2017a | By 2030 BEVs will 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 1,000 MW 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 will reach 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 |

## 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 most considerable portion of the total stock (and consequently demand) in high-income countries. Developing countries may, however, observe significantly different and more diverse mixes of EV modes. Especially on the local distribution grid level, there will be circumstances 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 travel modes. In Uganda, a majority of the region's

**FIGURE 2.3**

Factors Influencing Electric Vehicles' Load



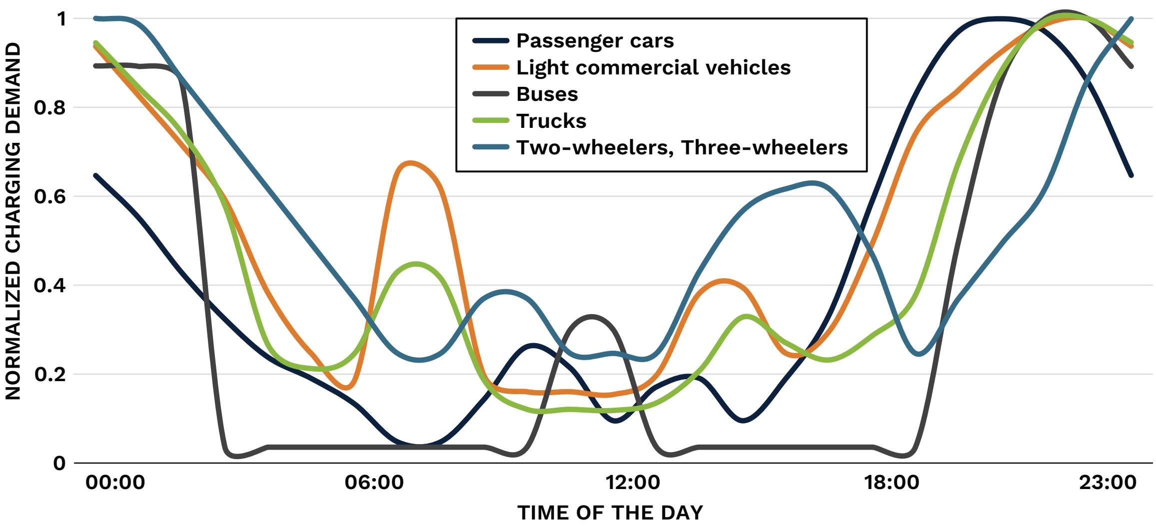

commuters use paratransit,[3] and, according to studies examining the electrification of this fleet, the dissimilar mobility characteristics of these vehicles (e.g., spontaneous stops and pauses) may result in distinct electrical requirements and power system impacts (Buresh, Apperley, and Booysen 2020). In fact, a recent commentary by (Collett and Hirmer 2021) identified data gaps in mobility patterns of different modalities, fleet volume, and geographical distribution as critical challenges in decarbonizing paratransit in Sub-Saharan Africa.

Normalized daily charging profiles of various modes are presented in Figure 2.4. Buses, with their predefined routes and schedules, have easy to forecast and manageable electricity demand that will come primarily from depot overnight charging (IEA 2020). 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). Similar to electric buses, integrating electric taxis is another popular pilot project for early EV implementation, with examples of Benjin (Zou et al. 2016) or Latin American cities (UNEP 2019). In case of that mode, charging

[3] In Africa context *paratransit* "refers to demand-driven, unscheduled public transport provided by small operators, typically in mini- to medium-sized buses" (Jennings and Behrens 2017).

**FIGURE 2.4**

Normalized Charging Profiles of Various Modes




**Source:** IEA, 2020.

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 distance (Weiss, Cloos, and Helmers 2020), and their users make shorter trips than PLDVs (A. Singh, 2019). In addition, their charging consumption is much more evenly distributed throughout the day compared to other modes of transportation. Each of the features mentioned will affect charging profiles and the shape of the aggregated load, which should be taken into account, especially in emerging markets where the structure of the EV market is likely to differ from that of advanced economies. While this may be the case, Figure 2.5 also indicates that no matter which mode of transportation is used, the peak charging time is likely to occur in the evening when most commercial or public vehicles have completed their daily duties and EV users return from work, intensifying the already existing peak. The discussion highlights the importance of assessing the impact of EVs on consumption, regardless of the location and structure of the market.

## 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 (4–17 kWh), 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).

## Type of Chargers

The shape of the EV charging load will be dependent on the type of charger that is utilized. Hardman et al. (2018) conducted a comprehensive review of PLDVs consumers' charging preferences in the United Kingdom and reported that around 50% to 80% of all plug-in events occur at home (Level 1 or Level 2 charging), 15% to 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 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 for shifting 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), and Bhutan (Zhu et al. 2016) identified EV infrastructure support as the main barrier to 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 establishing the required infrastructure such as 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 by 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 homes, making it challenging to use private or semi-private plug-in chargers and, hence, require 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-site 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, and workplace parking 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 (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 United States 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 provide effectively the required charging infrastructure.

## 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 four 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 the state-of-charge (SOC) of the EV battery and subsequently, residential charging hours. Empirical studies proved that stop-and-go traffic combined with the vehicle's auxiliary services (including lights, air conditioning, and onboard electronics) might cause efficiency losses of EVs and have an impact on customer decisions (Bigazzi and Clifton 2015; Florio, Absi, and Feillet 2021). Other factors affecting charging behavior and driving patterns include road network configuration (Luin, Petelin, and Al Mansour 2017), distance and speed (Raykin, Roorda, and MacLean 2012), and cultural differences (Heydari et al. 2019).

## Type of Day

Another variable affecting EV electricity demand is the 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 indicate 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 during the work 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 several hours earlier compared with weekdays (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).

## Geographical Location and Economy

The potential magnitude and structure of the load curve will also be determined by the high-level characteristics of the country or region, including its geographical location or the economy's structure. In the case of developing countries, the peak load might occur in the late evening because of 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 because 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, the 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 EVs, 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 adoption in mountainous regions or changing the consumers' preference towards a specific type of vehicle or mode (Liu, Yamamoto, and Morikawa 2017; Travesset-Baro, Rosas-Casals, and Jover 2015). For example, a recent simulation study (Bhatti et al. 2021) conducted in Islamabad, Pakistan, revealed that road slope profile has a substantial influence on EV operation, and only appropriate capture of this effect will allow an appropriate analysis of electric grid impacts.

### Demographics

Demographic characteristics of EV users are also factors that may influence charging patterns, 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 (Kelly, MacDonald, and Keoleian 2012; Zhang et al., 2020). Females usually drive fewer miles than males, while males usually start their commuting earlier, and their daily traveling distances are also longer. Furthermore, older EV owners have earlier charging peaks than younger drivers. As for household location, drivers from urban regions usually drive fewer miles than those in rural areas. It was also observed that the higher income group tends to have a higher and slightly delayed charging peak compared to lower-income drivers. Considering these demographic factors should support utilities and decision-makers in planning the distribution of charging stations and the overall integration of EVs to the grid. It may have particular importance for developing countries' demographic characteristics, which tend to have younger societies, higher shares of the population living in rural areas, or higher income disparity.

## 2.3 Impact on the Distribution System

During the early stages of EV deployment, the potential impact on the distribution grid was ignored by some utilities and decision-makers, assuming that there is a sufficient capacity or that adoption would 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 the determining factor in the scale of EV impact.

The local infrastructure factor is particularly significant, considering that even with low nationwide levels of EV deployment, local clusters with a high share of penetration will likely emerge as a result of 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 constitute a significant share of the momentary household load (Hensley, Knupfer, and

Pinner 2018), especially 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 (IEA 2018). The schematic representation of the electric vehicles ecosystem and connection with wider grid is presented in Figure 2.5.

## 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 limited 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 & Yousefzadeh 2011). The example of EV impact on transformer loading is presented in Figure 2.6.

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 aging fleet of transformers, with a large share of units exceeding the nominal lifetime (Jarman et al. 2009; U.S. Department of Energy 2015). Aging 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

**FIGURE 2.5**

Example of Embedding Additional EV Load in the Long-Term Capacity Expansion Planning Process

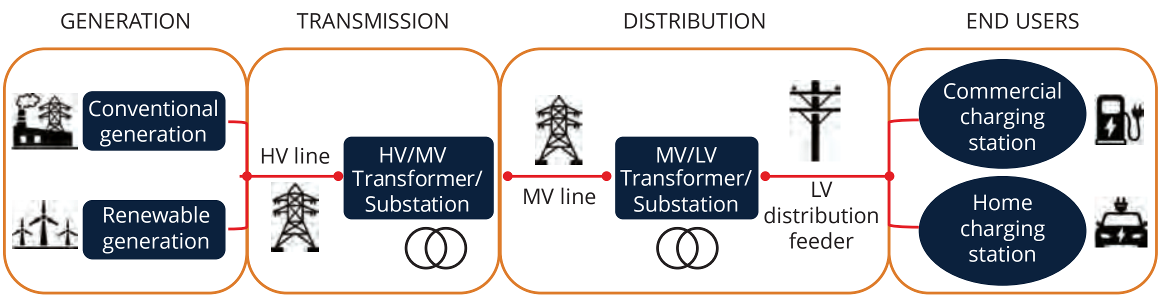
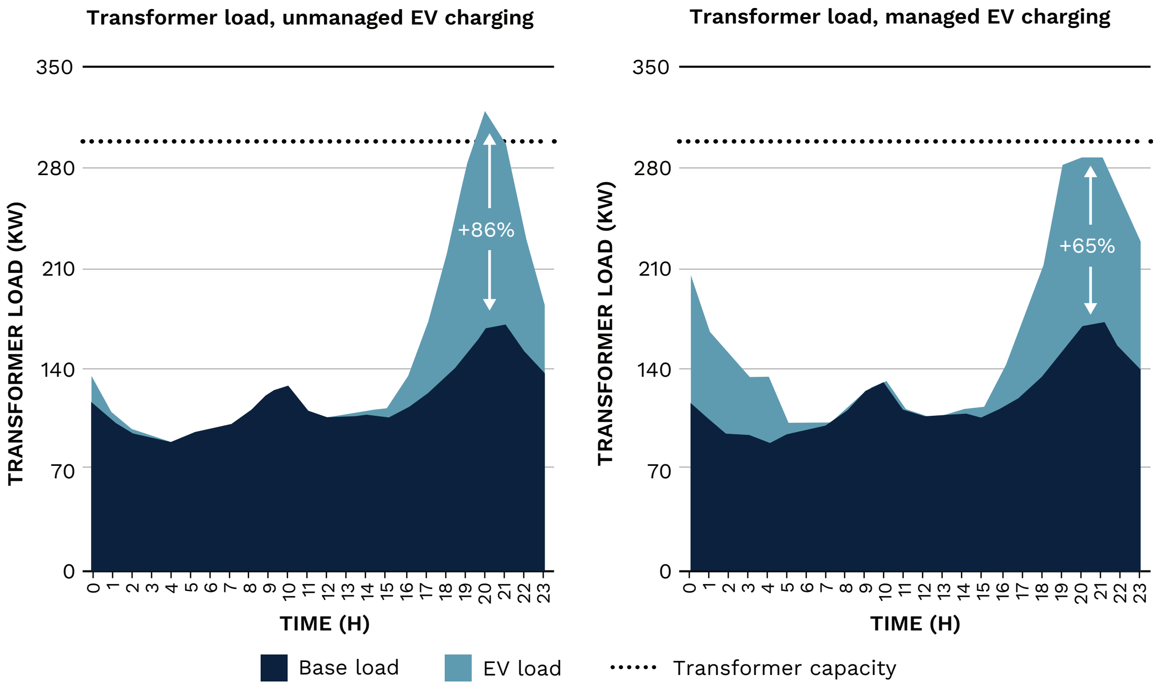


**FIGURE 2.6**

Impact of Uncoordinated and Coordinated Charging on the Distribution Transformer Load




**Source:** Adapted from EY, 2022.

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 and $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 2.3.

## 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 should always be minimized. Usually, safety requirements of appliances set the safety range of the deviations in a bus voltage to 10% in low-voltage distribution grids (IEC 2009). Nevertheless, a series of studies shows 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

**TABLE 2.3**

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 investment in the local electricity grid. |
| Denmark | Calearo et al. 2019 | 100% penetration in a local distribution grid, corresponding to 127 EVs would require investment of €52,000 for transformer and cables. |
| European Union | DNV-GL 2014 | 150 TWh of incremental EV charging demand by 2030 increases overall reinforcements investment in distribution grid by nearly €180 billion. |
| France | Eurelectric 2015 | Without smart charging total, low-voltage distribution grid reinforcement per million EVs was estimated as 200 M€ for charging in single houses, €650 million for multiple charging in multi-dwelling or business buildings,and €240 million for public charging spots on the streets. |
| General | Pieltain Fernández et al. 2011 | For a scenario with 60% of total vehicles being PEV, distribution systems operator (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 €150 million account for urban areas, while €127 million for rural areas. Smart meters for home chargers require an additional €68 million. |
| 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 2018 | 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 $1.9 billion in 2030 and $4.9 billion in 2050. |
| Norway | Eurelectric 2019 | 2.4 GW increase in load during peak hours due to EV charging would require €1.5 million to reinforce grid until 2040, with a 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 Swiss francs (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 2019a | 15% EV penetration in 2030. $5,800 of distribution investments per EV in the nonoptimized charging scenario. |

associated with EVs might reach levels that force distribution systems operators (DSOs) to increase tariffs (Clement-Nyns, Haesen, and Driesen 2010). Also, system losses and voltage impacts as a result of EV integration are correlated; minimizing one will also reduce the effect of the other.

## Impact on Power Quality—Harmonic Distortion

Electric vehicle chargers have power electronics to safely connect the vehicle's battery with the grid. Because the chargers require a large amount of power and their controllers produce nonlinear time-varying loads (R. B. Bass, Donnelley, 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 for 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 occur 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, specifically power quality levels. Some researchers focused on the effects in small-scale residential networks, where the impact can be more severe (Jiang et al. 2014; Masoum, Moses, and Deilami 2010), while others assessed the grid harmonic impact of public fast-charging stations (Basta and Morsi 2021; Lucas et al. 2015). 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, 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

[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 that lead to harmonic cancellations.

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 on low-voltage distribution grids while still complying with the official standards (Carter et al. 2012).

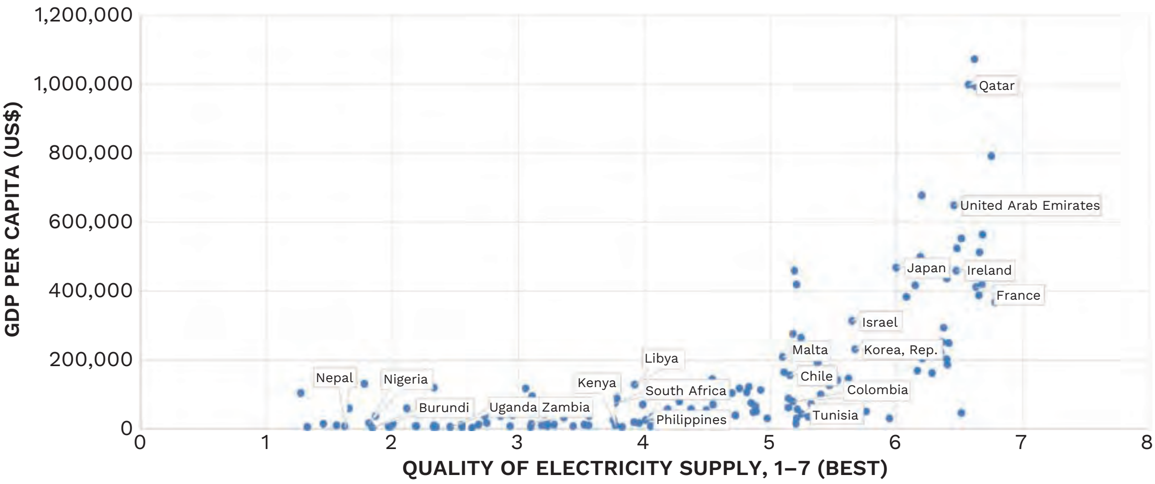
## Distribution Systems in Developing Countries

Distribution networks in developing countries have been widely identified as the weakest part of the electricity grid because of inadequate design, aged equipment, and lack of appropriate maintenance, consequently causing poor reliability and quality of the electricity service. Figure 2.7 presents the relationship between GDP per capita and the quality of electricity supply index, calculated annually by the World Economic Forum as a part of the Global Competitiveness Index (World Economic Forum 2018). These characteristics might intensify the previously mentioned negative effects of EV charging load on local power systems. Furthermore, poor quality of supply may be listed as a critical barrier to integrating EVs from a consumer perspective, which, in many cases, needs to addressed before advancing EV adoption (Dioha et al. 2022).

Frequent and prolonged outages are one of the main power reliability problems in developing countries, and their negative effects take several technical, economic, or social forms. In Sub-Saharan Africa and South Asia, business owners indicated reliable electricity access as being the second most significant 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,

**FIGURE 2.7**

GDP per Capita versus Quality of Electricity Supply Indicator



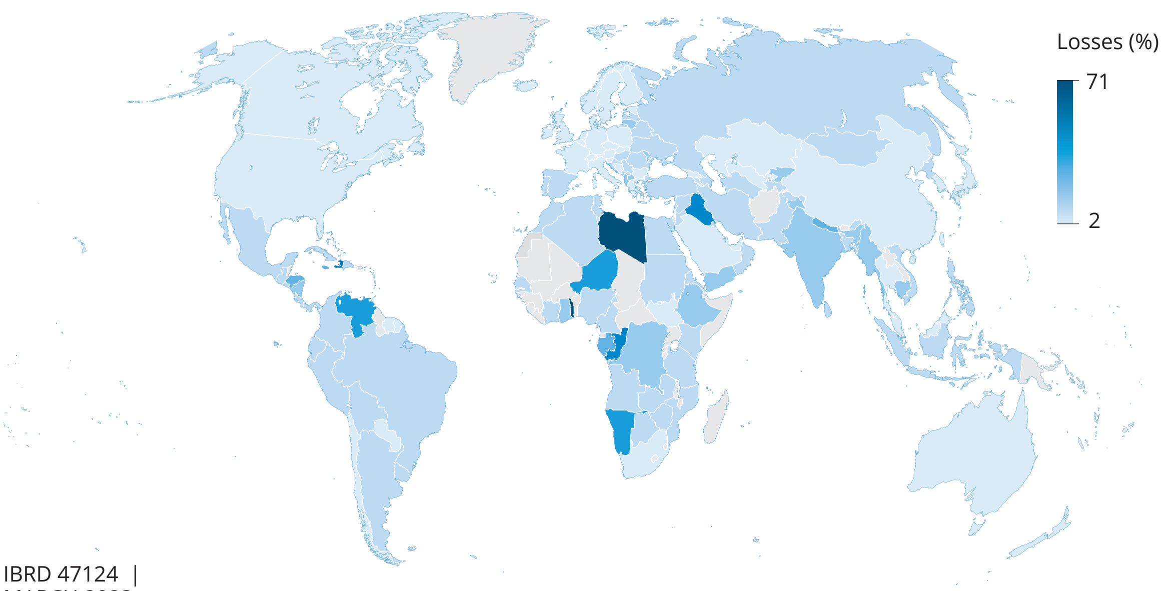

**Source:** Based on World Economic Forum, 2018.

liquefied petroleum gas [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 & Singh 2010) have shown that transformer failure rates could reach up to 15% compared with 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 aging process (Hilshey, Hines, and Dowd 2011). The inadequately planned introduction of the EV fleet might intensify the existing reliability issues, slowing the overall adoption.

Figure 2.8 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, 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

**FIGURE 2.8**

Electric Power Transmission and Distribution Losses

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MARCH 2023

**Source:** World Bank Group & International Energy Agency, 2021 zones where feeders are used over long distances to serve loads in remote areas, for example, for water pumps (Asian Development Bank n.d.). More extended low-voltage feeders provide service to a larger number of customers with a limited budget but simultaneously result in more significant voltage drops, often sufficient to violate voltage limits, causing brownouts and excessive energy losses, especially for the end-users furthest 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, and considering the 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 a reduction in life expectancy. Finally, poorly designed regulation frameworks, weak control over utilities, and inappropriately subsidized electricity prices cause disincentives for infrastructure upgrades (Mcrae 2015).

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 disturbances (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 face an immense challenge in maintaining quality and reliable supply. The impacts mentioned earlier 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 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 (IEA & World Bank 2017). 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).

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 instance, E2Ws and e-bikes are easy to charge in dense urban locations due to their limited sizes, while some models come with portable battery packs that can be carried and charged 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 the system operator should consider.

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, as electric buses (Ayetor et al. 2021) and taxis (Gómez-Gélvez, Mojica, and Kaul 2016) are most likely to emerge as the first kinds 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's ancillary equipment, including transformers, switchgear, cables, protection system, and SCADA, may cost over $150,000 per charger (Sasidharan and Ray 2019). Recent India-based study from the World Bank (World Bank Group 2021) indicates that disrupting impacts on the distribution network are projected to be confined and focused mostly in metropolitan areas. Distribution utilities will need to enhance their technical planning abilities and equipment, as well as employ digital technology to monitor the network. Investments in planning tools, training, and network upgrades would be required.

In the longer term, regions and countries with a high significance of the road freight industry like Latin America, China, or India, might experience distribution system stresses due to the 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 by 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 these 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 consider not only 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 2.1.

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), 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 the proper design of electrical equipment, particularly EV chargers, including the selection of components, measurement techniques, and control standards.

## BOX 2.1

# EXAMPLE OF A COMPREHENSIVE IMPACT ASSESSMENT OF LARGE-SCALE ELECTRIC VEHICLE 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 crucial 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 three 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 modeled to analyze the impact of charging stations on the load flow, loading, voltage, and harmonics. Five subsystem models were combined to appropriately simulate charging demands: 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 distribution systems operator (DSO) will be able to manage any level of EV deployment. Furthermore, it was advised that the DSO should precisely follow grid connection standards and practices to avoid equipment failures. Additionally, it suggested penalizing commercial charging stations that violate the adopted harmonic standards.

Such comprehensive studies simulating existing parts of the networks bring multi-fold 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 with valuable information regarding the location of the charging station or required network upgrades.

## 2.4 Impact on the Transmission System

EV deployment may also have an impact on 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. Transmission investment decisions, similar to generation capacity ones, are crucial to ensure adequate supply of 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 2.8 GW of additional transmission capacity needed in the region, which corresponded to a 60% increase compared to the reference scenario with no transport sector electrification. Sarid and Tzur (2018) conducted transmission and capacity expansion research based on a large-scale IEEE-8500 test node feeder. 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 four 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 2019b). 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 90 GW (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 modeled 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 developing countries, some distinctive characteristics must 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 burdens and investment requirements not only because of 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 that already existing annual investment in 2015 to 2040 needed for transmission expansion is 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 the impacts on transmission expansion and operation. Renewable sources' spatial and temporal availability might also impact the transmission system and should 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., IRENA 2018).

## 2.5 Impact on Power Generation

As discussed in previous sections, 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 integration level and absence of coordinated management and planning, additional demand may put considerable stress on the generation infrastructure. The burden might be even more significant when considering concurrent electrification in other segments of the economy and high expectations of rapidly progressing power sector decarbonization. Furthermore, in developing countries, several challenges already exist in the power generation sector that may make the integration of EV loads even more problematic, including growing demand, aging inefficient units, or extensive investment requirements. This section will describe the impacts and challenges of additional EV loads in the power generation sector.

### 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 charging load's timing and place determine what 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 the need for additional capacity. Charging electricity consumption should be incorporated in long-term power system planning studies to assure security, adequacy, and sustainability while considering the economic and technical characteristics of power technologies and 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 2.4. 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 time, the marginal electricity generating unit satisfying EV load will be gas- or oil-fired units, characterized by flexibility and 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.

Many developing countries face power generation issues, causing difficulties in providing constant, reliable, and affordable electricity supply and consequently affecting economic growth and competitiveness (Eberhard et al. 2008). A rapidly rising electricity demand stimulated by 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 a significant projected increase in electricity consumption and consequently massive capacity installations and investment requirements. Large-scale EV deployment, 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 aging and inefficient power units or bad quality fuel input. Furthermore, emerging economies can have an abundant potential for 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 in 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 2.2.

**TABLE 2.4**

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, rising 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 electricity sector's contribution 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 are added to the power system—over a 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 | Generation investments increase by $18 million (2.8%) compared to a scenario without EV deployment, while operational costs increase by $18 million (1%). |
| China | B. Li et al. 2021 | 174 million EVs on the roads in the moderate scenario and 349 million EVs in the aggressive scenario by 2050 with 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 (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 will 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, operation and maintenance, 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 compared 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 | Abhyankar at el. 2017a | 367 million E2Ws and 89 million electric PLDVs by 2030 | The total peak EV charging load exceeds 30 GW, 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, United States | 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 range between 200 and 400 EUR/yr per vehicle for 0.5% penetration, but costs vary significantly depending on renewable energy (RE) penetration or $CO_2$ costs. Without $CO_2$ costs, the coal and combined cycle gas turbine 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 combined cycle gas turbines, open cycle gas turbines, battery storage, or transmission capacities. |

## BOX 2.2

# POWER SYSTEM PLANNING IN SMALL ISLAND DEVELOPING STATES WITH LARGE-SCALE ELECTRIC VEHICLE 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 because of 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 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 peak times 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, to comply with emission targets, uncontrolled EV charging can increase investment requirements in storage technologies needed for sufficient reserves and flexibility. In the most extreme cases, without adequate reserves in the form of storage or generation capacities, EV load can lead to a 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 deploying 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 (United Nations ESCAP 2019) identified government light vehicle fleets, 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.

The development process of the new generation capacity involves a myriad of stakeholders, ranging from the policymakers, through regulators, system operators, and utilities, up to final power producers. It begins at the earliest stages of long-term power system planning, where it is crucial to appropriately represent the shape and magnitude of the EV charging load. This process determines the type, capacity, and location of new generation units, simultaneously considering policy, technical, or security constraints. Subsequently, policymakers should shape policies, incentives, or regulations to direct the power producers into developing the optimal capacity mix. Due to the complexity and dimensionality of this process, developing countries might face tremendous challenges in providing an adequate level of generation capacity. Risk and uncertainty are of particular concern, as the degree of uncertainty surrounding power investment decisions is very high, especially during the time of technological transition. Consequently, particular focus should be put on the planning and analyzing process to weigh and consider all the aspects of different risks, infrastructure development costs, policy goals, or uncertainties. Careful, comprehensive, and proactive planning may allow for meeting all these goals even with the strictly limited financial or institutional capacity present in emerging economies.

## 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, it should be provided by transmission or units with appropriate ramp rates, that is, gas turbines, internal combustion engines, and pumped or battery storage (International Renewable Energy Agency 2019). The concept of flexibility is critical because increasing penetrations of variable renewable energy (VRE) required to reach decarbonization targets drastically intensifies 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 and already existing conventional generators.

For developing countries, reshaping the peak load and consequent flexibility requirements induced by 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 and supply balance and frequent load shedding events as a result of 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 VRE sources characterized by short-term uncertainties. This is true, especially in terms of solar power, which is expected to be the backbone of the 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. 2017b), 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 2022) 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 a 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.

## Power System Emissions

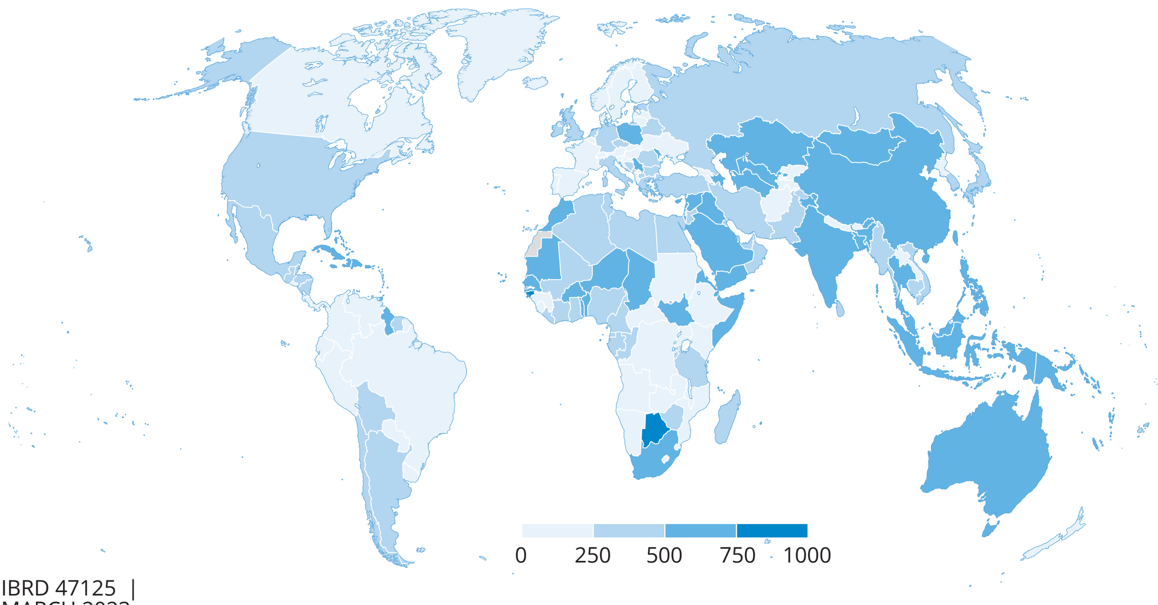
With deeper penetration of EVs, rising charging demands will put greater pressure on regional power generation systems. Considering that transport electrification is one component in the fight against global warming, the critical issue is the source of the electricity used to power EVs and, consequently, the extent of the green-house-gas (GHG) emissions from this generation. This question is valid not only from the perspective of power system operation but also from 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 make up 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 $CO_2$e/MWh) (Kim & 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 by coal thermal power plants, marginal carbon intensity will be higher during off-peak hours when these units are under-utilized (e.g., Germany [Schill and Gerbaulet 2015]) 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 nuclear or hydro. Furthermore, as 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 coal. With growing E-Mobility penetration, this reliance can cause an increase in power sector emissions and challenge the sustainability of EVs. This is even more critical when considering poor fuel quality (N. R. Sahoo, Mohapatra, and Mahanty 2018), aging 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; Wu et al. 2012), calculating well-to-wheel emissions and incorporating an average emission intensity indicator. This indicator is presented in Figure 2.9, showing that certain developing countries tend to have higher average electricity intensity. Nevertheless, as previously discussed, using an average intensity value disregards important spatial and temporal characteristics of power systems, which might be critical in assessing EVs' sustainability 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 2.9**

Average Power System Emission Intensity

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**Source:** Pavarini and Mattion 2019

# THREE
# MITIGATION STRATEGIES

## Highlights

- With smart charging, EV load can be scheduled and modulated to shift the load to the most optimal time and space from the system operator's perspective, respecting the end-user preferences and power system constraints.
- Innovative smart-charging strategies provide an attractive way of avoiding expensive grid reinforcements with the large-scale deployment of EVs.
- Smart-charging strategies might be divided into two groups: (1) behavioral load shift programs, which encourage EV users to shift plug-ins to avoid peak times using direct or indirect monetary incentives and rewards programs; (2) technical solutions that may be used to control the charging process or deploy storage technologies.
- With existing issues in developing countries' power systems, including blackouts, brownouts, equipment failures, and power quality issues, innovative charging strategies will be needed to avoid or reduce capacity additions and grid reinforcements with growing demand.
- However, benefits of deploying smart-charging strategies over the long-term can be far greater than estimates in developed markets if accounting for the avoided failures and reinforcements in distribution grids or additional capacity needs and opportunities from providing ancillary services to the power system.
- Pilot projects, especially innovative and emerging technologies like V2G, are crucial steps towards the broader development of smart-charging frameworks within public and private environments.

Several strategies have been proposed to mitigate the negative impacts of the additional load from EVs while simultaneously taking advantage of the potential benefits. As 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, EV load can be scheduled and modulated to shift the load to the most optimal time and space from the system operator's perspective, respecting end-user preferences and power system constraints. In general, this shift can be obtained through two main methods. The first is behavioral load shift programs, which encourage EV users to shift plug-ins 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. It may also involve strategic planning of charging infrastructure to unlock location-based load shifting and move load towards more reinforced or underutilized locations. The second one is technical solutions that may be used to control the charging process or deploy storage technologies. This group includes various vehicle-grid integration (VGI) schemes, co-locating battery storage, and 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 3.1 exemplifies how smart charging is part of a more comprehensive strategy to develop the EV ecosystem in South Africa.

Many institutions and researchers have recently evaluated the comprehensive monetary and operational benefits of smart VGI. Thompson and Perez (2020) conducted a comprehensive

## BOX 3.1

### UYILO ELECTRIC MOBILITY PROGRAM

South Africa's national E-Mobility program, called uYilo (uYilo 2013), is a prominent example of successful pilot projects in 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 the 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 (V2G) 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 energy sources in terms of disturbance of any other sources, and ensuring 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 ongoing field experiments' outcomes to campaign for the region's E-Mobility benefits. 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 the director of the uYilo Programme.

analysis of the value streams and services associated with VGI and concluded that power-associated services are more valuable than energy-associated services in the overall context of VGI. RACE for Networks Program (2021) investigated the benefits of EVs integration with the grid in the Australian market, emphasizing that appropriate technological and regulatory solutions can convert the potential adverse impacts on the grid into significant opportunities. IRENA (2019a) lists unlocking demand-side flexibility and EV services as crucial components enabling power sector transformation. Eurelectric (2022) investigated smart grid mechanisms, enabling them to reduce grid reinforcements (such as transformer loading), through EV flexibility solutions. Anwar et al. (2022) recently reviewed the potential value of managed

**TABLE 3.1**

Division of Demand-Side Flexibility Benefits of Vehicle-Grid Integration

| POWER SYSTEM APPLICATION | GENERATION CAPACITY AND TRANSMISSION/ DISTRIBUTION PLANNING | RESILIENCE TO EXTREME EVENTS | COMMITMENT AND DISPATCH DECISIONS | BALANCING AND POWER QUALITY | SUPPORT END CONSUMERS |
|---|---|---|---|---|---|
| Time Scale | Multi-year | Years (planning), hours (real-time response) | Days to hours and sub-hours | Seconds to sub-seconds | Years (planning), hours (real-time |
| Vehicle-Grid Integration Value | Ability to reduce peak load and capacity requirements and defer distribution systems upgrades if reliable EV charging flexibility is available | Load response to natural events (heat waves, tornados) or human-driven disasters, load postponement over days, and support microgrid management and grid restoration (V2G) | Leverage EV charging flexibility to support supply dispatch and load-supply alignment (tariff management), variable renewables integration, operating reserves, energy arbitrage (V2G) | Provide voltage/ frequency regulation and support distribution system operations | Tariff management (e.g., mitigate retail demand charges), complement other distributed energy resources (smart load, generation and storage), and minimize equipment aging/ upgrades |

**Source:** Adapted from Muratori et al. 2021.

smart charging. A study aimed to provide an overview of how electric vehicles and the grid could interact in the future as the electric and transportation sectors become increasingly intertwined (uYilo 2013). It argued that although advantages might be broad and far-reaching, the costs of deploying these services must be weighed against the benefits they can potentially provide. Finally, Muratori et al. (2021) highlighted the importance of conducting comprehensive research on the value creation for VGI as well as the expanding advantages of managed charging, particularly in situations of insufficient grid resources and significant system strain. Table 3.1, adapted from the Muratori et al. article, shows the range of benefits of unlocking VGI.

# 3.1 User Behavior-Based Methods

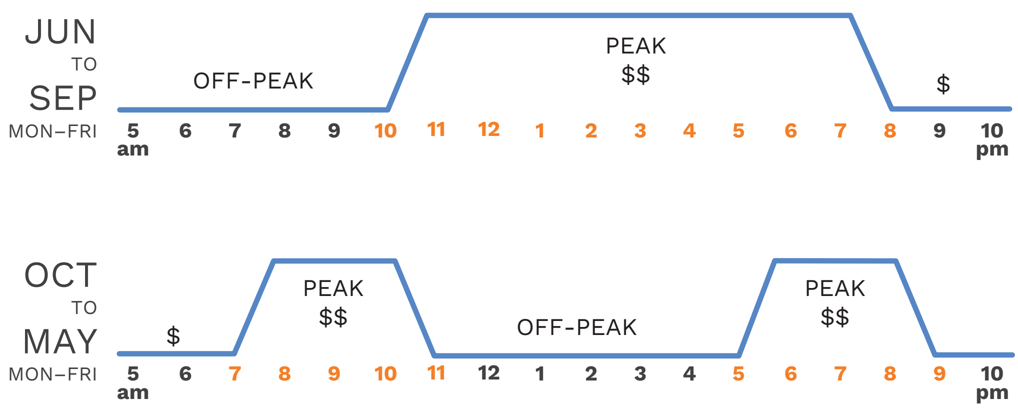
## Time-of-Use Tariffs

Time-of-use (ToU) tariffs, often called price-based demand response programs (IRENA 2019c), 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 as static or dynamic. In the static case, utilities determine tariffs in advance, based on the historical consumption and price profiles, while in dynamic pricing, tariffs may vary based on temporary wholesale electricity market conditions. Figure 3.1 provides an example of static ToU. The benefits of these schemes are bilateral. From the system operator's perspective, these schemes allow for better management of supply-demand balance, providing power system flexibility and 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 decide to adjust the time of plugging in their vehicles. An increase in peak power demand after the integration of the EV fleet was 64% smaller with the ToU tariff (Gao et al. 2012). Chen et al. (2018) presented regional ToU tariffs as an effective mechanism to shape EV charging load and subsequently to 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 (Chen et al. 2018). From the distribution system perspective, Assolami and Morsi (2015) show that ToU tariffs may reduce loading and subsequent aging of distribution transformers. Charging at midnight can reduce transformers' yearly loss of life from 30.68% down to 23.85%, assuming Level 2 charging at 6.6 kW (Assolami and Morsi 2015). Suyono et al. (2019) had 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 (Suyono et al. 2019). Furthermore, other studies quantified system benefits from avoided grid upgrades and lower energy costs for the entire system and per EV (Citizens Utility Board 2017; Klettke and Mose 2018; MJ Bradley & Associates 2017). On the other hand, some studies indicate that ToU might cause the creation of new peaks in periods when prices are low (CEER

**FIGURE 3.1**

Example of ToU Tariffs in the Context of EV Charging




**Source:** Adapted from Baltimore Gas and Electric Company 2022.

2017; Ramchurn et al. 2011). Moreover, the tariff setting procedure may be a lengthy regulatory process with multiple stages, causing a significant lag in its implementation (European Commission, 2015b).

Local electric utilities are the key actors in implementing ToU tariffs. Depending on a variety of variables, ToU rates have the ability to accomplish or contribute to several stated aims, but from the perspective of implementation, stakeholders must comprehend the effect of these rates on utility financials as it differs significantly from a fixed charge rate design proposal. A ToU rate, unlike a fixed tariff that is intended to improve assured utility revenues, is not intended to give revenue certainty or stability to the utility but rather to represent more precisely the time of cost incurrence in an effort to generate more stable utility profitability over the long term. Consequently, utilities must carefully design their tariff structures to ensure that they encourage flexibility, meet customer needs with differentiated offerings, and appropriately reflect their costs. Utilities must work with regulators to ensure that identified policy objectives are achieved, such as economic efficiency, deployment of distributed energy resources (DER) technologies, peak load reduction, emissions reduction, and more equitable cost-benefit allocation (Colgan et al. 2017).

## Spatial Load-Shifting and Charging-Stations Planning

Load shifting may be achieved not only temporally but also spatially by incentivizing charging in optimally located stations from the system operator. The optimal allocation strategies of EV charging stations play a crucial role in satisfying charging and promoting EV uptake and potentially minimizing required grid reinforcements and the risk of distribution equipment failures (Luo et al. 2018). The common allocation task involves optimal planning of workspace and public charging stations, which apart from having a positive economic effect on stations owner and EV user, can improve a series of technical aspects associated with charging station deployment, such as network losses, voltage profiles, and unburdening clustered plug-ins in residential locations (Erdogan et al. 2021).

Assessing the optimal planning of EV charging stations has been a popular research topic over recent years, resulting in many potential methodologies. Ahmad et al. (2022) and Ma (2019) presented reviews of different approaches for the placement of EV charging stations, showing that the objectives of analyzed methodologies can include minimization of power losses, voltage deviations, investment costs, installation costs, operation costs, maintenance costs, or connection costs. Zeb et al. (2020) evaluated the optimal placement of EV charging stations in the distribution network, reporting 44% reduction in cost, 64% reduction in distribution losses, and 62% reduction in transformer congestion as a result of deployed planning methodology. Sadeghi-Barzani, Rajabi-Ghahnavieh, and Kazemi-Karegar (2014) showed that accounting for grid reliability in optimal placing exercises, including failures of grid components such as lines and transformers, may considerably affect the capacity and position of the stations. Simorgh et al. (2018) mentioned that overloading may occur in substations if the placement of charging stations is suboptimal and adequate locating and sizing can reduce energy losses and voltage deviations.

Again, as in the case of ToU tariffs, electric utilities and governmental utility regulators play crucial roles in the implementation of charging infrastructure in an effective and fair manner. Utilities' involvement in the development of charging infrastructure might bring numerous benefits to utilities and customers, including maintaining reliability and minimizing grid impacts, improving the ability to communicate with customers, providing more equitable access to charging infrastructure, and building on utility experience with infrastructure development. On the other side, regulators will have to weigh these aspects, which may not always arise from every project, against other risks and concerns. Regulators have a crucial role in ensuring that utility initiatives addressing these problems are well-designed and efficiently executed (Allen et al. 2017). Importantly, regulators, utilities, and local authorities should work together to decide how charging investment programs should be structured, how can regulators ensure more equitable access by all customers to charging infrastructure, and how should utilities allocate and recover the costs of investment.

## Indirect Incentives and Rewards Programs

While dynamic pricing schemes, like ToU tariffs, have been popular demand-side management policies 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 proved to be a practical 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 (RISE 2020). 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 state-of-charge (SOC) goals, power grid stress, power system emission intensity, and the electricity price (Jedlix 2021). Furthermore, a German-based study indicates that nonmonetary 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, and education (Schmalfuß et al. 2015).

# 3.2 Technical Solutions

## Vehicle-Grid Integration

Vehicle-to-grid unidirectional charging (V1G) is the most basic scheme out of vehicle-grid integration (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-and-off switching of charging power, delaying or bringing forward the charging process to a more suitable time by the power system operator. Such controllability brings a series of opportunities to mitigate negative charging impacts on the power system. The most significant benefits include congestion management (van't Wel 2019), frequency regulation (Glavic 2016), and reducing the risk of overloading during peak hours (Pratt and Bernal 2018). Authors in the 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 in British Columbia (Ivanova et al. 2017), smart unidirectional charging reduced operational charging station costs between 14% and 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 United Kingdom distribution networks to be £57/EV per year. Many public chargers are equipped with V1G control capabilities (IRENA 2019b), and successful pilot projects have already been introduced with examples in California (BMW Group 2021), Australia (Pratt and Bernal 2018), and the European Union (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), vehicle (V2V), or grid (V2G); however, only the latter may significantly affect broader system performance (IRENA 2019b). V2G has been in the center of the political, scientific, and industrial debate as it may fundamentally change the impact of charging load on the power system, transforming EV batteries into a clustered power storage. IEA (2020) estimates that across China, India, the European Union, and the United States, V2G technologies have the potential to provide almost 600 GW of additional flexible capacity

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

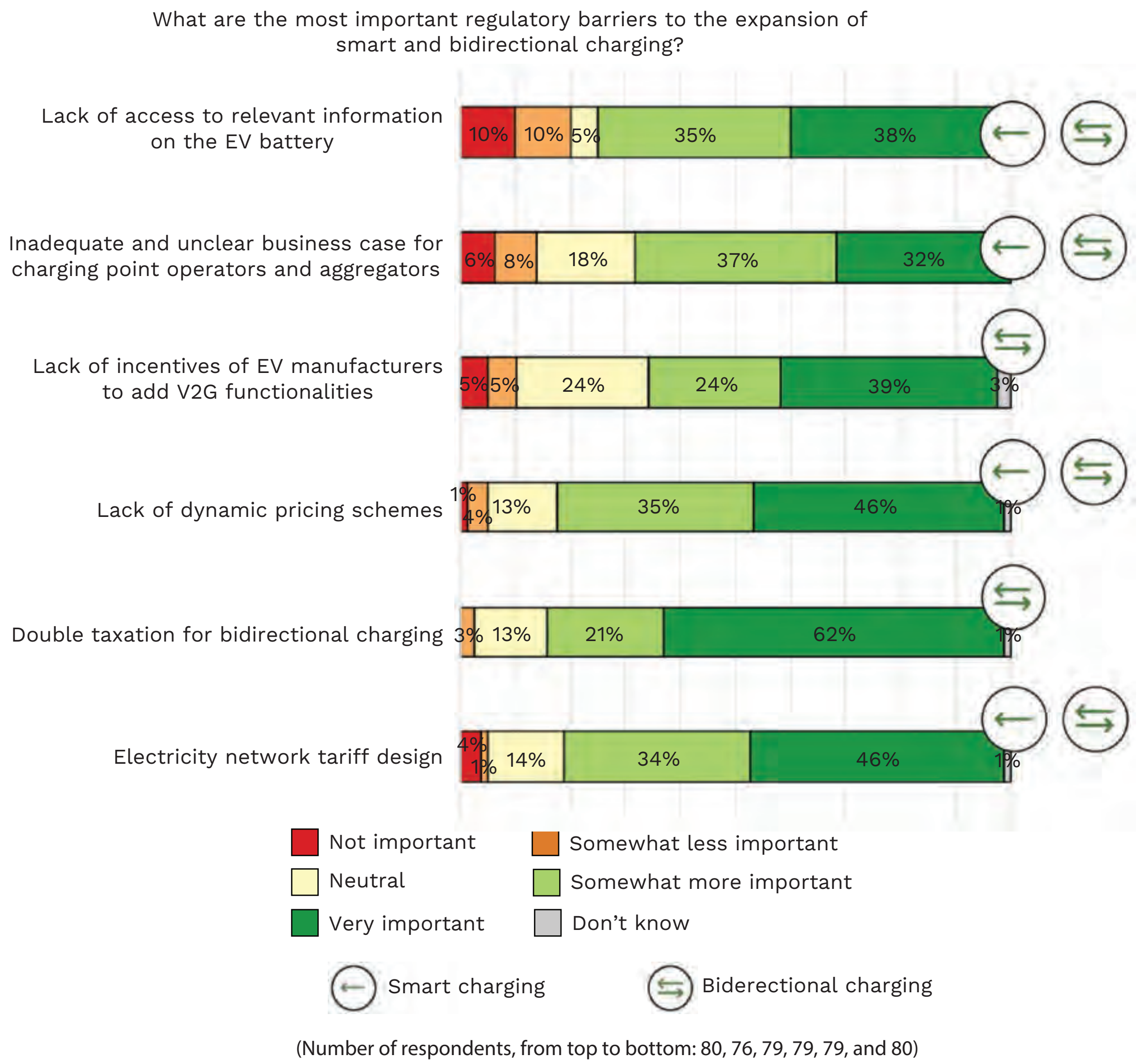
during peak time by 2030. It can translate to 470 TWh of saved electricity, otherwise provided by fossil fuels, and, consequently, reduce $CO_2$ emissions by 330 million tonnes. Although V2G is in a relatively early stage of deployment and a limited number of pilot projects have been implemented, several authors evaluated V2G for 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 United Kingdom'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 to £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 United States. 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.

In order to expand the electrification of transportation through smart charging, regulators, electric utilities, the EV sector, and other stakeholders will need to address a variety of technological and regulatory concerns. Particularly, the different technical requirements governing the integration of smart-charging-enabled EVs through the interconnection process must be included into state-level regulations. Given the importance of the power and transportation sector, these regulations are crucial to ensure its safe operation on the grid, especially in the emerging economies where the system is prone to failures or contingencies. The certification procedure is particularly essential for electric utilities and distribution system operators, who must have confidence that any equipment linked to the grid will perform in a consistent manner (Mafazy 2022). These standards cover a broad variety of certification subjects (such as interconnection, charging safety, vehicle functioning, and communications), and there is no one standard that comprehensively encapsulates all the ways in which smart charging systems will interface with the grid.

Additionally, to the need for technical standards previously described, the present legal and regulatory framework, mostly based on the conventional purpose of the electrical grid, might be suboptimal for the VGI idea. Therefore, for VGI to materialize as envisioned, certain legal and regulatory modifications are required. Some of these challenges are strongly associated with substantial technological barriers, while others are associated with

**FIGURE 3.2**

Regulatory Barriers to the Expansion of Smart Charging




**Source:** Adapted from European Commission Directorate-General for Energy, 2022).

the socioeconomic impacts of increased EV adoption. Figure 3.2 illustrates the relevance, as seen by survey respondents, of the most significant regulatory obstacles to the growth smart charging. The findings of the poll show that double taxation in the case of bidirectional smart charging, the absence of dynamic pricing schemes, and the design of energy network tariffs are the most significant obstacles. Similar conclusions were drawn by the Smart Electric Power Alliance (2020), where utilities indicated a lack of legislative VGI understanding as one of the top three hurdles to creating VGI programs and a lack of regulatory assistance as the top organizational barrier to authorizing and implementing a VGI program.

## Storage and Battery Swapping Solutions

Co-locating battery storage facilities with public or semipublic 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 the 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, EV 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. Richard and Petit (2018) evaluated the operation of a fast-charging station coupled with a battery storage system in grid services. They found that the provision of grid services does not negatively affect the performance of the station and allows revenues to increase 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, overall annual costs were reduced by 23%, mainly deriving from savings on feeders and transformer capacity.

On the other hand, battery swapping is characterized by high capital expenditure for the operators, lack of standardization across vehicle models, or difficulties with infrastructure establishment (Ahmad et al. 2020). These drawbacks might be why battery swapping is still not mainstream in E-Mobility strategies, despite its long history of application in some instances. 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 micromobility 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 to 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 went into effect at the beginning of November, 2021, and includes safety requirements, test methods, and inspection rules for battery swappable EVs (P. Zhang 2021). In Indonesia, several industry firms, in collaboration with the 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.

# 3.3 Challenges and Opportunities in Developing Countries

There are critical obstacles to introducing the previously mentioned mitigation strategies in the electricity systems of developing countries. The first, is the cost of grid infrastructure needed to implement smart methods. The system operator needs an extensive amount of real-time data and control capabilities to control the charging and discharging process, either in public, semi-public or home chargers. The main infrastructure equipment needed to allow smart-charging procedures includes numerous smart meters, battery-management software, and hardware that 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 (2021) 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 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 3.2 while examples of theoretical and simulation studies are listed in Table 3.3.

Pilot projects, especially in terms of innovative and emerging technologies like V2G, are crucial steps towards the broader development of smart charging frameworks within public and private environments. In a recent publication focused on vehicle-to-grid solutions, Sachan et al. (2022) indicated pilot projects as a critical stage on a future roadmap for implementing recommended technological solutions. Successful pilots, either based on government policy programs or a companies' innovative products or services, incentivize 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 3.3 showed extensive benefits coming from the adoption of smart-charging strategies in developing countries. The projected increase in electricity

**TABLE 3.2**

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 | In cooperation with ENEL X and the Chilean Energy Sustainability Agency, Nissan 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 nonresidential, 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 were implemented alongside infrastructure development. By July 2022, eight EV charging stations were opened. |
| 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, a stationary battery bank, an 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. |

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, one can anticipate 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 3.3**

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 providing 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 analyzes 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 levels. |
| 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 an EV. Higher capacity investments are outbalanced with a reduction of operational and emission costs. |
| India | Das and Deb 2020 | V1G, V2G | The authors discuss extensive assessment of challenges and opportunities for VGI with a comprehensive review of regulatory needs and techno-economic analysis. They 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 leveling 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. They 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% compared with the case without an EV fleet. |
| South Africa | Change Pathways 2018 | ToU | The 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 peak load increase due to EV deployment was reduced from 12.5% to 3.5%. |

# FOUR
# UTILITIES AND SYSTEM PLANNING

## Highlights

- Electric vehicle deployment can bring a series of challenges and opportunities to all stakeholders, ranging from electric vehicle users to manufacturers and charging station operators to electric utilities.
- Being prepared and proactive is critical for utilities, especially in developing countries with financially distressed institutions, insufficient investment levels, low productivity, poor maintenance, and government diversion of budget resources from other high-priority social and economic needs.
- Integrated planning for power systems and charging infrastructure are decisive elements of successful electric vehicle integration.
- It is essential to align power sector and transportation goals to achieving a least-cost, resilient power system and particularly crucial to reaching ambitious decarbonization targets.

# 4.1 Key Stakeholders Involved

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 in previous chapters, this process can bring challenges and opportunities to various stakeholders, where the most crucial are policymakers, electric utilities, and regulators. These stakeholders have varied interests and responsibilities in the adoption process and interaction with the power system, which are worth highlighting.

Central and provincial policymakers have long considered transportation and energy sectors as strategic pillars because or their large impacts on employment, local gross domestic product, and upstream industries. Specifically, governments are widely responsible for setting up long-term targets and least-cost plans for the power sector and, consequently, should adequately reflect the potential role and impact of electric mobility. These plans are designed to guide long-term capacity procurement, such as volume, type, and timing of investments into power generation technologies and transmission assets. These investments, as described in Chapter 3, have substantial linkages with impacts and overall adoption of EVs. Depending on the level of market liberalization, they may be induced with appropriate development of energy policies and regulation, giving indicative direction as to where investments should be made (in a more liberalized market), or directly financed by governmental entities (in a more centralized structure). They can also ensure a degree of risk allocation away from resource developers, for example, towards rate- or tax-paying consumers.

State policymakers are tasked with formulating policies that encourage cost-effective investment in the grid while enabling innovative technologies and smart grid techniques to thrive and compete in a continually changing market. Nevertheless, one difficulty is evaluating the cost-benefit analysis and long-term impacts of promoting or mandating the usage of certain technologies on the network. Federal and regional governments must evaluate the optimal combination of infrastructure expenditures and technological possibilities. Given the complex nature and diversity of possible grid upgrading options, it is essential to build comprehensive planning strategies and decision-making mechanisms. These may assist in evaluating whether grid upgrades are beneficial and limit the chance of stranded investment.

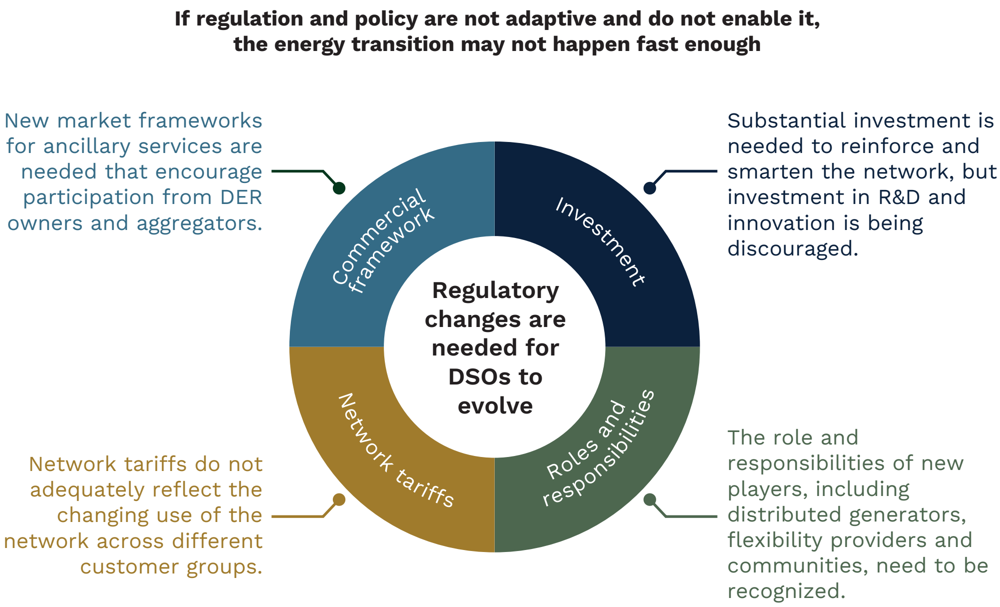
An electric utility's fundamental objective is to supply reliable and affordable electricity to its customers. One of the key means by which this goal is achieved is developing long-term plans for meeting customers' electricity needs through a forecast, analysis, and planning cycle for maintenance and development of the utility grid. In government planning and the long-term objectives of policymakers for EV deployment, the role of utilities is usually to execute plans at the local level. This may be done through specifically designed incentives or policies, influencing utility actions by predetermined processes, planning elements, rules, and regulations. Consequently, for utilities to back EV adoption, there must be a supportive regulatory environment standardizing charging station ownership, funding investments in infrastructure, restructuring the electricity market, defining connection standards, or incentivizing VGI (Hall and Lutsey 2017). Furthermore, recent reports indicate that with proper planning and regulatory adjustments, EV deployment benefits may outweigh the potential costs for utilities (even without extensive federal government incentives), which should encourage utilities to be explorative, proactive, and innovative, as well as ease the potential dialog with state policymakers.

Finally, regulators' role in planning and preparing the grid for EV adoption is diverse and may vary across jurisdictions. In order to ensure that core principles for effective planning are adhered to at all times and all applicable laws and regulations are being followed, regulators may need to supervise a planning process that is later implemented by a different entity (usually utilities). In addition, regulators may be responsible for ensuring that planning studies are reviewed and approved on a technical basis. Especially on the distribution level and in interaction with local utilities, regulators might define specific resource planning requirements and evaluate whether the plans filed by utilities address economic, social, technical, and environmental concerns and meets policy goals. In these actions, the regulator (and policy) must be adaptive and quick to respond to changing social and technological environments. Regulators should promote the transformation of utilities, incentivize innovation, reevaluate tariff design, eliminate obstacles to the development of innovative technologies, and enable adequate returns to investors. Nonadaptive regulators risk destabilizing the speed and effectiveness of the energy transition and grid reinforcement needed for EV deployment. The key aspects of the regulator's role are presented in Figure 4.1.

As described, the roles of the stakeholders and their significance in preparing the grid for EV adoption may vary depending on the market liberalization and structure (an open market or a regulated market environment). But in any market setting, effective planning and regulatory control are essential for successful EV adoption. There are, therefore, a few administrative, legal, and institutional aspects that might be highlighted as the factors facilitating the success of these processes. The first aspect is access to institutional and knowledge capacity for conducting sophisticated and detailed planning exercises. Effective planning requires a skilled and experienced team of specialists, access to adequate computational resources and models, as well as detailed data on the techno-economic properties of the system. Furthermore, in most national or regional markets, the control over the planning

**FIGURE 4.1**

Areas Where Clear Regulatory Direction Is Needed




**Source:** Adapted from Colle and Micallef, 2019.
DER = distributed energy resources; DSO = distribution systems operator; R&D = research and development.

processes is stated in foundational laws that define the responsibilities of a specific entity (primary regulator). Finally, the regulatory and political environment should encourage the active engagement of various stakeholders as well as the public through transparent access to power-system planning processes, open access to data, and debate. That might ensure a high level of trust and effective co-ordination between the actors, and, through guaranteeing regulatory stability and confidence, can encourage entry by new participants at the market or planning process.

## 4.2 Role and Good Practices for Utilities in Preparing the Grid

Utilities need to undertake comprehensive measures to address a wide range of internal and external challenges and prepare the ground for the upcoming uptake. However, there are also a series of risks for the grid and electric utilities not being adequately prepared for E-Mobility adoption. The direct ones include the technical failures extensively described in Sections 3.2 to 3.4. Yet, these issues may prompt a range of indirect consequences for utilities and other stakeholders. Every failure in the grid will need to be addressed through immediate emergency measures, which substantially increase the operating and maintenance costs for the utilities. Potential failures, including blackouts and brownouts, will also bring additional costs to final customers, especially businesses, and it is estimated it may disproportionately affect low-income communities. These additional costs may also deteriorate the financial viability of utilities to conduct preventive investments into grid reinforcements and resilience. Finally, the potential failures caused by an unprepared network might dent consumer confidence in their providers. This will also have a direct impact on consumers' intentions to purchase an EV, affecting market sales, as well as may slow down the charging infrastructure development in public or semi-public spaces.

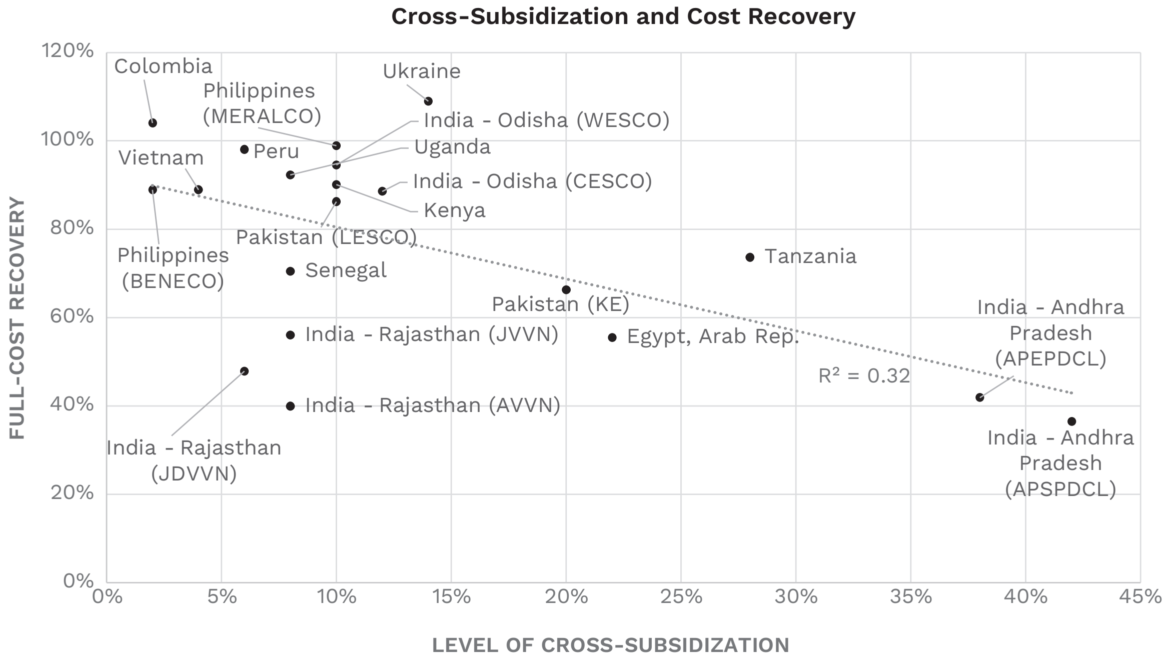
Being prepared and proactive is critical for utilities, especially in developing countries with financially distressed institutions, insufficient investment levels, low productivity, poor maintenance, and government diversion of budget resources from other high-priority social and economic needs (Ichord 2016). In a time of technological transition, utilities' financial viability and cost recovery are particularly critical in ensuring aimed EV deployment. To guarantee that the grid can accommodate increased demand, utilities are responsible for investing in new and updated distribution infrastructure to transport power from the transmission system to EV chargers (A. Sahoo, Mistry, and Baker 2019b). As market penetration expands, investment costs climb exponentially due to the requirement for more costly equipment and a greater number of new assets. Without sufficient technological innovation, cost-reflective tariffs, or state support, these additional investment requirements could jeopardize utilities' financial sustainability. Particularly in the developing world, the chronic poor financial performance of electricity utilities is pervasive as a result of underpricing, excessive losses, and ineffective bill collection and has been a primary cause of investment shortfalls, under-maintenance of infrastructure, power shortages, and poor quality of supply (Huenteler et al. 2020). In many cases, utilities are heavily based on the use of state subsidies, which have long-term macroeconomic, fiscal, and social repercussions. Figure 4.2 shows the relationship between the levels of electric utility cross-subsidization and full cost recovery, adopted from (Huenteler et al. 2020).

Consequently, planning ahead and creating a comprehensive roadmap is essential in transport electrification implications on utilities' financial viability. Utilities should identify the potential grid requirements under assumed EV shares and evaluate the least-cost way to meet the demand, keeping a high level of reliability and security. Studies show that the adoption of new innovative technologies and policies could be the most cost-effective option to limit the strain that EVs put on the grid and on utilities' finances. They should especially foster the uptake of digital and technological long-term solutions, such as advanced electricity metering and control technology, to reduce the potential investment requirements, reduce exposure to reliability issues, or not create bottlenecks in EV uptake. Nevertheless, even with a high level of ingenuity, still many areas managed by utilities will need to be reinforced, and part of these investments will need to be recouped through higher retail rates. Therefore, regulated utilities should be prepared not only for infrastructural but also administrative upgrades, submitting early regulatory claims that will enable updating retail tariffs and recouping expenditures.

Recent publications indicate that careful integrated planning and collaboration between the various actors are the keys to minimize infrastructure and economic challenges related

**FIGURE 4.2**

Cross-Subsidization Levels and Full-Cost Recovery of Selected Electric Utilities in Developing Countries




**Source:** Adapted from Huenteler et al., 2020.

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 the appropriate sizing of EV charging infrastructure, including chargers and auxiliary electrical equipment. Utilities should aim to achieve a 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 to continue providing reliable and safe services. SEPA advises strategically investing in the power system and charging infrastructure, anticipating future service requests (e.g., deployment of heavy-duty electric vehicles or business opportunities from smart charging strategies).

ENTSO-E (2021) explored 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 enable new opportunities to provide 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 to the success of E-Mobility. Finally, on market designs and rules, ENTSO-E argued 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 reduce the barriers preventing EV owners (or their representatives) from participating 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.

An EY (2022) report described the scale of the E-Mobility challenge and the available or in development technologies for reducing peak load on electric vehicle batteries and capturing the benefits of their flexibility. It outlined that in order to reach defined decarbonization goals, E-Mobility practitioners must engage with the network of enablers in associated fields. The involvement of various layers and actors in a collaborative, integrated, and cohesive manner promotes interoperability and unlocks value. Report discusses, that the rollout of EVs and supporting infrastructure is frustrated by operational and administrative barriers. Thus, for the road transportation system to be truly successful, it needs to be properly designed today so that it can serve for many years to come.

Huether, Cohn, and Jennings (2022) recommended that the planning process be transparent, consistent, and ongoing in order to ensure that stakeholders are able to provide high-quality input. As part of the planning process, plans should cover a wide variety of scenarios, including the use of personal and service vehicles, provide indicators and targets pertaining to a myriad of potential outcomes, incorporate equity, and provide meaningful outreach to parties and communities affected by the plan.

Hall and Lutsey (2017) conducted a literature review on power utility best practices in EVs. They showed that with a lack of appropriate planning or preparation, deep EVs rates uptake could put significant stress on the grid and increase operation and investment costs. With adequate planning, however, E-Mobility can bring substantial benefits to utilities, even outweighing the potential costs of adoption. Careful preparation might result in reliable and cost-effective system operation, provide ancillary services, reduce electricity rates for final consumers, and facilitate integration of variable renewable energies (VREs).

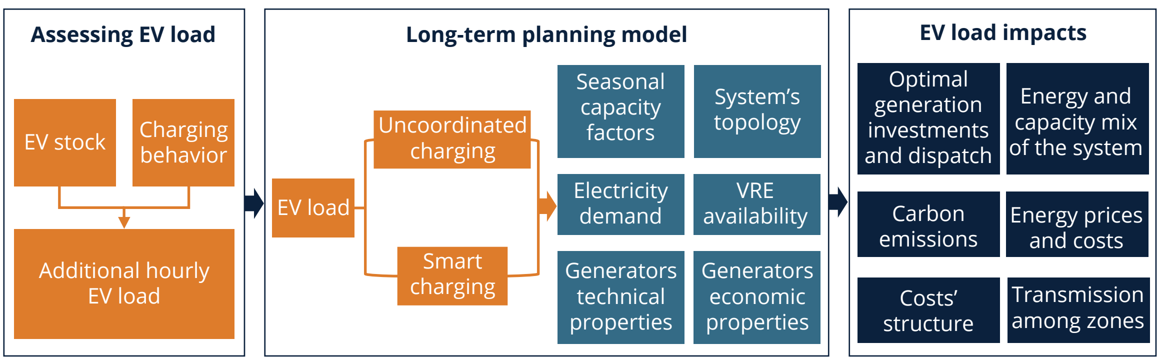
## 4.3 Incorporating Electric Vehicle Load in Power System Planning

These reports identify integrated planning for power systems and charging infrastructure as decisive elements of successful EV integration. The lack of an appropriate charging structure may cause the customers' reluctance, called "range anxiety" (Melliger, van Vliet, and Liimatainen 2018), which EV drivers' worry about the limited range of their vehicle or the availability of charging stations in driving patterns (Thananusak et al. 2021). 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 to achieving a least-cost, resilient power system and particularly crucial to reaching 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. Figure 4.3 illustrates an example of embedding additional EV load in the long-term capacity expansion planning process. Box 4.1 also outlines key insights from a Maldives long-term study conducted for this report.

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 transparent, fair, realistic market rules, will be key to effective power system transformation, setting the ground for the E-Mobility

**FIGURE 4.3**

Illustrative Example of Embedding Additional Electric Vehicle Load in the Long-Term Capacity Expansion Planning Process



## BOX 4.1

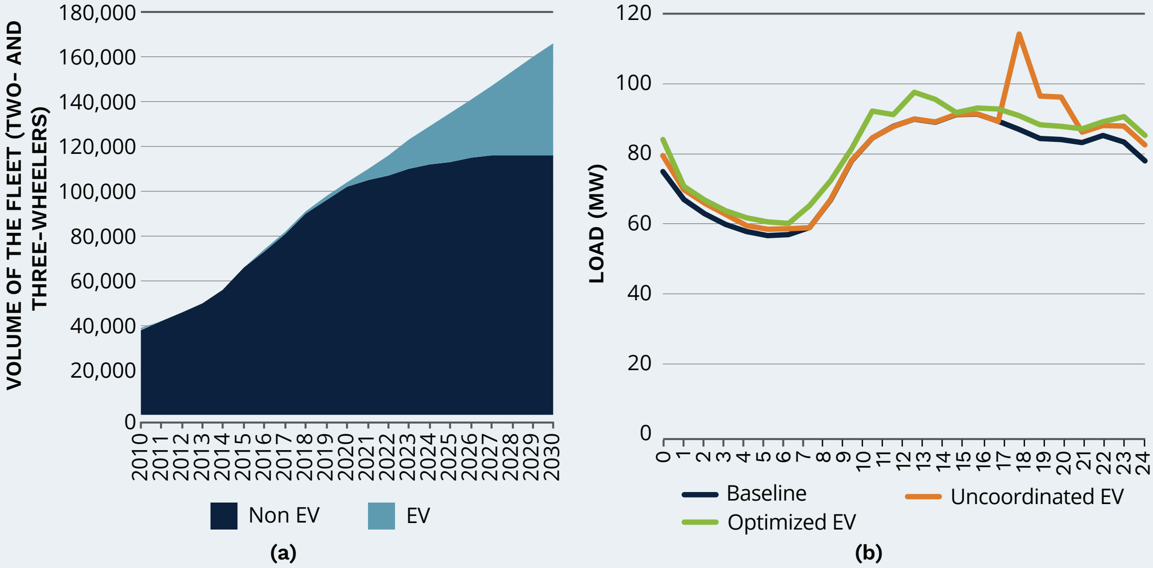
# LONG-TERM POWER SYSTEM PLANNING, INCLUDING ELECTRIC VEHICLE LOAD—A CASE STUDY OF MALDIVES

The Maldives case study conducted for this report provides interesting insights into 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 a 1.8% increase and 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 a potential increase in power sector emissions in a fossil-fuel-dominated system.

## BOX 4.1 (*Continued*)

Key Electric Vehicle Development Metrics from Maldives Case Study.

Figure A Shows the Projected Deployment of Electric Two- and Three-Wheelers up to 2030. Figure B Shows the Reshaped Load Curve in 2030 under the Uncoordinated and Coordinated Scenario.




deployment (World Bank 2018). Once these technical and regulatory hurdles are overcome, utilities and other stakeholders will be able to prepare for an E-Mobility future, unbundling the business and technical opportunities it may provide.

## 4.4 Planning Nexus Across the Sectors

Recent developments in innovative technologies and sophisticated and automatized management techniques led to increased interdependence between the power system and other sectors of the economy. With electrification being a key factor in reaching ambitious climate goals, the nexus becomes particularly strong between the power system and the transport sector. On the one hand, the future distribution of passenger EV traffic flows will be restricted not only by the dimensions of the transportation infrastructure but also by the grid's capacity. On the other hand, these traffic flows will not only have an effect on the performance of the transportation network, such as the travel time, but it will also affect the power distribution system and, as a result, the economic efficiency of the coupled power grid (H. Zhang, Hu, and Song 2020). Consequently, EV integration started to play a significant role in power system–focused planning studies, through the spatio-temporal representation of charging load, as well as transportation studies through the appropriate representation of mobility features of EVs on transportation networks.

While nexus between power and transportation systems is most apparent, the integrated system planning and operation can involve interdependencies between more sectors. For example, there is a clear nexus between urban infrastructure planning and development and energy-transport. Conventional metropolitan and regional planning has a strong connection with transport and infrastructure planning, as seen by the zoning of cities and the placement of jobs or services in areas well serviced by major transport linkages (Buckwell 2016). These relations are particularly essential in terms of planning of charging stations network, as well as appropriate distribution grid reinforcement. For example, nexus with infrastructure might be crucial to develop E-Mobility hubs, with spatially aggregated public and semi-public chargers, providing a more efficient approach to planning in urban and peri-urban regions and will also facilitate the transition to more computerized forms of mobility-energy management (Burdet 2020). In another case, infrastructure planning might democratize EV uptake and usage through appropriate location of charging infrastructure. For instance, inhabitants of multiunit dwellings have often restricted access to home charging, resulting in greater running expenses and less flexibility, and could benefit from equitably distributed infrastructure (Kontou 2022). Furthermore, as presented on the Nordic example (Noel et al. 2020), there might be an extensive socio-technical nexus worth exploring by planers and policymakers. It could include factors like consumer perception on price and range, correlation of rates and charging network with acceptance of transitioning to E-Mobility, or consumer knowledge and experience with EVs.

Developing countries, with rapidly expanding metropolitan areas, changing demographics, and evolving markets, can particularly benefit from long-term planning nexus between various economy sectors. For example, Mauritius, as a representative of small islands developing states, is working towards an innovative strategy to decarbonize its economy through renewable energy and transport planning nexus (Soomauroo, Blechinger, and Creutzig 2021). Dioha et al. (2022) presented that VRE sources in Nigeria supplying the EVs charging demand combined with V2G technologies could substantially reduce cost level below which EVs become cost competitive. Bamisile et al. (2021) presented comprehensive research of the relationship between electrification and deployment of renewable energy sources in emerging nations and recommended EV integration to optimize the usage of surplus power generation from VREs. Portugal-Pereira et al. (2013), using India and Japan as examples, presented the vicious cycle of transport, which indicates that increasing motorization leads to poorer quality of life, and that implementing an integrated co-benefit approach can simultaneously reduce global greenhouse gases and local air pollutant emissions and tackle urban congestion and promote social equity and economic prosperity.


Rapid Charge Point

# FIVE
# CONCLUSIONS AND RECOMMENDATIONS

The large-scale deployment of EVs will likely have an impact on all sectors of power systems in developing countries. These effects can be technical, economic, or environmental and affect a wide range of stakeholders. 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.

## EV Load

| CONCLUSIONS | RECOMMENDATIONS |
| --- | --- |
| • In absolute terms, the additional EV charging load will have a marginal effect on the annual power system demand. However, it will likely significantly reshape the daily electricity load curve, amplifying evening peak loads if not managed.<br>• 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.<br>• 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. | • In order to evaluate the impact of EVs on power systems, a comprehensive assessment of predicted uptake should be performed, taking into consideration fleet details and local characteristics affecting charging demand and behavior.<br>• Planners and decision-makers, in particular those in developing countries, need to consider the local social, economic, infrastructure, and cultural factors as these factors may influence not only the scale and type of adoption but also the operation of and charging of vehicles.<br>• Clustering effects of plug-ins might occur in cities, charging depots, or specific neighborhoods; therefore, the distribution of EV load should be assessed not only temporally but also spatially. |

## Power System Impacts

| CONCLUSIONS | RECOMMENDATIONS |
| --- | --- |
| • 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.<br>• Numerical studies indicate that with uncoordinated charging in place, most of the costs from capacity additions and reinforcements will be at the distribution level.<br>• 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.<br>• EV charging can lead to notable power quality issues at the distribution level, which can be harmful in the developing countries with underdeveloped power quality standards, lack of appropriate maintenance, and specialized human capacity.<br>• Deployment of a large-scale EV fleet will likely have a limited impact on the transmission system expansion and operation.<br>• In the generation system, EV deployment will primarily have an impact on the peaking units, increasing the flexibility requirements of the system and the need to supply this additional power with renewables. If fossil fuels power these peaking units, then emissions will increase. With uncoordinated charging, new gas plants or storage facilities, characterized by high ramping capabilities, may be needed to provide energy during the evening peaks.<br>• In most developing countries, electricity demand is forecasted to increase heavily over the following decades, requiring extensive capacity additions in all power system segments. | • 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.<br>• 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 aging.<br>• 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.<br>• As the generation assets in developing countries are often constrained by their technical limitations, these characteristics should be appropriately represented in the planning and simulation models to account for potential failures, uncertainties, maintenance periods, and security evaluations. |

## Mitigation Measures

| CONCLUSIONS | RECOMMENDATIONS |
|---|---|
| • Innovative charging strategies focused on modulating charging demand provide an attractive way of avoiding expensive grid reinforcements with the large-scale deployment of EVs.<br>• With existing challenges in developing countries' power systems, 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. | • In order to fully exploit the benefits of smart charging strategies, a combination of mitigation measures should be considered and implemented.<br>• Mitigation strategies could be introduced gradually, starting with the most mature ones (e.g., ToU tariffs or incentives programs), which can simultaneously play a substantial role in incentivizing uptake, up to the most technologically sophisticated (e.g., V1G solutions).<br>• The mitigation of the negative impacts might be partially achieved through the optimal setting of charging stations. Therefore, the potential role of the locational load distribution should be considered already at the stages of infrastructure planning.<br>• Due to administrative, financial, or infrastructure limitations, not all the potential mitigation measures can be feasible in developing countries. Therefore, the smart-charging strategies should be selected not only on the basis of the theoretical performance but also by considering local context and chances of success. |

## Role of Utilities and Planning

| CONCLUSIONS | RECOMMENDATIONS |
|---|---|
| • Being prepared and proactive is critical for utilities, especially in developing countries with financially distressed institutions, insufficient investment levels, low productivity, poor maintenance, and government diversion of budget resources from other high-priority social and economic needs.<br>• Careful integrated planning and collaboration between the various entities are the keys to minimize infrastructure and economic challenges to EV deployment and to maximize the potential benefits.<br>• Integrated planning aligning power sector and transportation goals is crucial to achieving a least-cost, resilient power system and reaching ambitious decarbonization targets. | • To prepare their assets and operations for the upcoming EV deployment, electric utilities should conduct comprehensive long-term planning exercises at the power system's generation, transmission, and distribution levels. 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.<br>• Innovative charging pilot projects are usually successful initiatives, helping to introduce new technology and paving the way for large-scale implementation. Governments, companies, and regulators in developing countries should be more active in 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. |

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