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Electric Power & Natural Gas Practice

The impact of electromobility on the German electric grid

Estimates indicate that eight million electric vehicles could be on the roads in Germany by 2030. Investing in fast-charging stations and managed charging will be key to upgrading infrastructure.

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With a share of almost 20 percent, the global transport sector is the third-largest contributor to CO_2 emissions after electricity generation and industry. Despite vast improvements in the energy efficiency of vehicles, greenhouse-gas (GHG) emissions in the sector have more than doubled since 1970. In Germany, for example, there were 71 percent more trucks and 31 percent more cars on the road in 2019 than 30 years earlier, and a trend toward larger, heavier, and more powerful vehicles offsets gains in energy efficiency. In fact, 95 percent of new vehicles in 2019 still used gasoline or diesel.[1]

As Europe's largest national economy, Germany can play a significant role in reducing emissions. In accordance with the Paris Agreement, which aims to limit global warming to 1.5 degrees Celsius and achieve climate neutrality by midcentury, Germany has committed to reducing CO_2 emissions by 55 percent by 2030.[2] While the country has made a solid start, current reductions will clearly not be enough. By 2030, emissions from the transport sector in Germany must be reduced by 42 to 44 percent.[3]

Electromobility fueled by green energy is one way to reach these reduction targets. Grid operators (both distribution and transmission) and regulators are engaged in a wide-ranging discussion on how to increase electric capacity to scale electromobility. Successful grid integration is a central component for the future ramp-up of electromobility and sector coupling, which refers to the integration of energy supply and end uses. However, significant risk must be mitigated, primarily for grid balance. For example, the rapid proliferation of fast charging will likely increase the impact of newly occurring loads from unmanaged charging of electric vehicles (EVs).

Supplying adequate electricity for the future fleet of EVs will rely on the collaboration and cooperation of several stakeholders, including utilities, policy makers and regulators, OEMs, and EV-charging companies. Further complicating matters, each of these stakeholders is simultaneously struggling to predict and anticipate the impact of decarbonization trends at a granular level. Thus, it is crucial to understand how increased electromobility will affect average and peak loads in the coming years. Grid operators will need to upgrade infrastructure, including distribution lines, residential substations and transformers, and switchgear. Managed charging programs and accurate planning, for example, can smooth loads over time, saving billions in investment needs for infrastructure extensions.

In this article, we apply a structured methodology (see sidebar, "About the research") to forecast the impact of EVs on power grids, using Germany as an example. Our proposed guidelines can provide a road map for other countries to navigate their own electric-grid upgrades.

Electric-vehicle penetration in Germany

Germany has a strong tradition of both an automotive culture and an ecological mindset. Unsurprisingly, the country is forecast to have relatively high penetration of EVs.[4] As previously stated, the country also aims to reduce CO_2 emissions (which make up a vast majority of GHG emissions) by 55 percent by 2030. Compared with 1990, GHG emissions for 2020 are estimated to be around 41 percent less, exceeding the set target value of 40 percent. However, COVID-19 restrictions were responsible for around one-third of the total reduction from 2019 to 2020. Thus, it stands to reason that without COVID-19, Germany would likely not have reached its emissions target.

As a result, the pressure to act has intensified. To this end, Germany's federal government has promoted the development of alternative modes of transportation as well as the establishment

[1] "Bis 2030 die Treibhausgase halbieren," German Federal Government, September 13, 2019, bundesregierung.de.
[2] For more, see "The Paris Agreement," United Nations Framework Convention on Climate Change, unfccc.int.
[3] *Klimaschutz in Zahlen: Fakten, Trends und Impulse deutscher Klimapolitik*, Germany's Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, 2018, bmu.de.
[4] For more, see Timo Möller, Asutosh Padhi, Dickon Pinner, and Andreas Tschiesner, "The future of mobility is at our doorstep," December 19, 2019, McKinsey.com.

About the research

Measuring and forecasting the impact of new technologies on the electric grid—including electric vehicles (EVs), storage, heating electrification, distributed solar photovoltaics, and the impact of new energy efficiency and management—is a complex undertaking. Our forecasts for the next 20 years focus primarily on the following factors for widespread EV adoption:

- the number of EVs, including passenger cars, taxis, trucks, and buses
- demand for energy charging
- charging patterns (when, where, and how vehicles are charged)
- the implications and cost for the electric grid

By modeling medium-voltage nodes, EV allocation against the collective number of EVs, segmented customer behaviors, and distribution-level loads and congestion levels, this forecast provides the required level of granularity on a medium-voltage level to support strategic and tactical decision making for a number of stakeholders.

of charging infrastructure. Through the Climate Action Programme 2030, the government is investing billions of euros in the electrification of transport through direct subsidies and tax incentives.[5] In addition, it also responded to the COVID-19 crisis by creating an economic stimulus package that includes several measures to promote electromobility through a wide range of grants, tax incentives, and other benefits when purchasing an EV or charger. For example, the state doubled its share of the environmental bonus in the form of a new "innovation premium" of up to €9,000 per vehicle and lowered tax rates for company cars.

Today, 48.2 million passenger cars and 3.4 million trucks are on German roads.[6] In our base-case scenario, about eight million EVs will be in circulation in Germany by 2030, including passenger cars, commercial vehicles, trucks, and buses (Exhibit 1). According to the Climate Action Programme 2030, which was adopted in October 2019 as a supplement to the country's Climate Action Law, the country needs to have seven million to ten million EVs by 2030 to reach its climate targets.[7] By comparison, Germany had 194,000 EVs registered in January 2021 (395,000 when plug-in hybrid cars are included). Our research shows that seven million to ten million EVs represent approximately 15 percent of all cars expected to be in circulation in Germany and around 40 to 60 percent of new sales by that date.[8] Among other things, the Climate Action Programme 2030 aims for one million publicly accessible charging points by 2030 with corresponding subsidy programs by 2025, as well as the subsidization of shared private and commercial charging infrastructure.

Grid capacity will rise dramatically, driven primarily by the adoption of passenger-car EVs

In 2019, electricity consumption in Germany was 568 terawatt-hours (TWh), a year-over-year decrease of 0.4 percent over the past decade (594 TWh in 2010, with a historical peak of 596 TWh in 2007). Although this downward trend may reverse due to decarbonization efforts, transportation remains one of the two main areas in which Germany lags in its energy transition (with heating).

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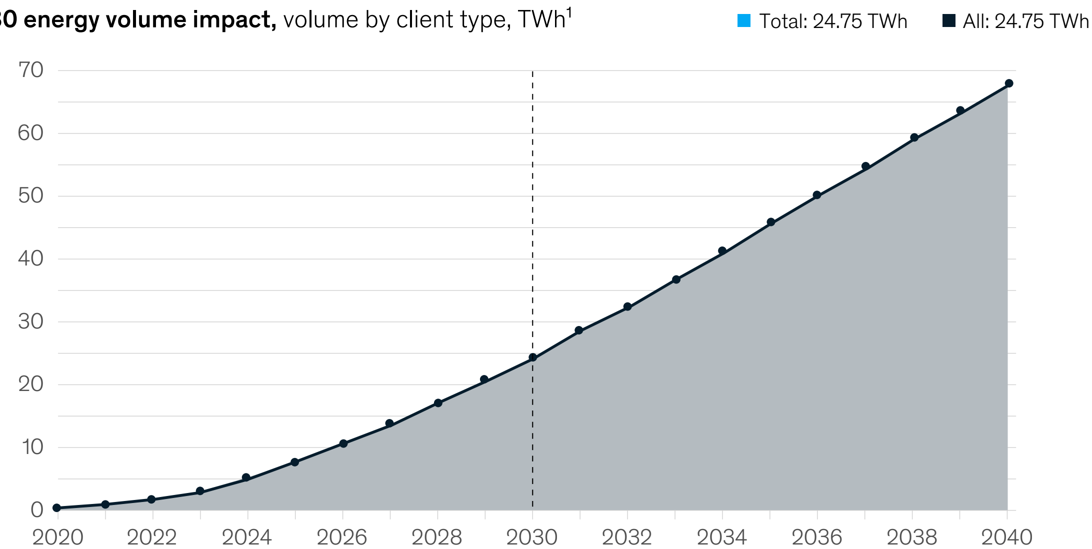
5 *Klimaschutzprogramm 2030 der Bundesregierung zur Umsetzung des Klimaschutzplans 2050*, Bundesregierung, 2019, bundesregierung.de.
6 "Bestandsüberblick am 1. Januar 2021," Kraftfahrt-Bundesamt, 2021, kba.de.
7 "National energy and climate plans (NECPs)," European Commission, 2020, ec.europa.eu.
8 This means that the share of new registrations must increase to 40 to 45 percent from 2025 to arrive at around seven million electrified cars in 2030. The achievement of ten million electrified vehicles requires new registration rates of 55 to 60 percent from 2025.

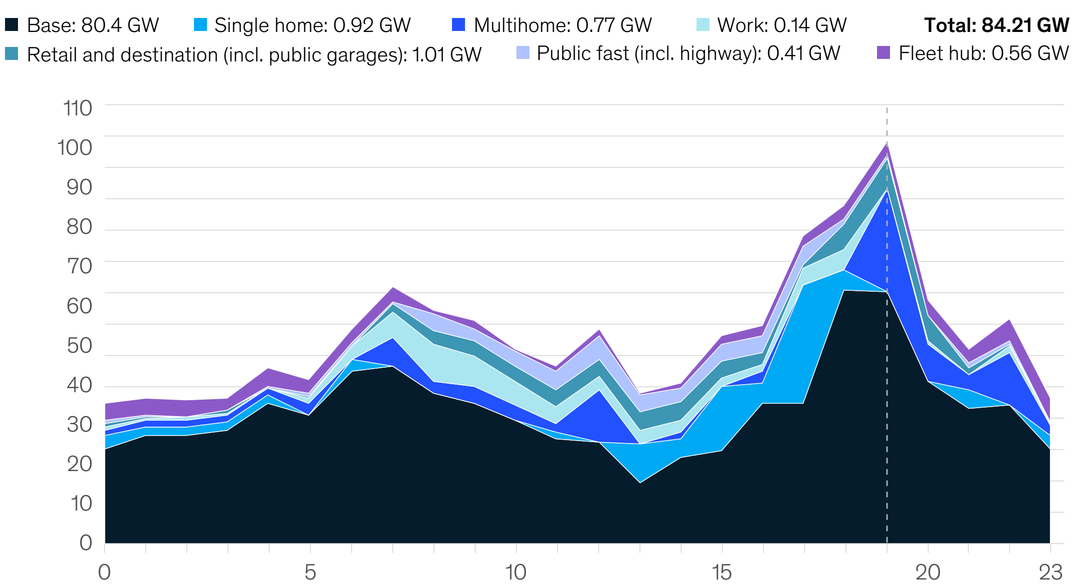
Exhibit 1

The deployment of eight million electric vehicles by 2030 will entail an increase in energy volume of approximately 4 percent.

2030 energy volume impact, volume by client type, TWh[1]



2030 winter peak day hourly impact (unmanaged charging), peak impact, GW[2]



[1] Terawatt hours.
[2] Gigawatts.
Source: McKinsey EV Grid tool, McKinsey Center of Future Mobility, Global Energy Perspective

We consider several alternative scenarios of EV adoption in our projections. Our base-case scenario of eight million EVs by 2030 reflects the target of the Climate Action Programme 2030. The most aggressive scenario of 16 million EVs by 2030 reflects EU-commissioned studies and an early implementation of the proposed EU ban on vehicles with internal combustion engines (ICE), which would anticipate the switch to electric engines by both consumers and manufacturers.

In a base-case scenario, EV-charging demand could reach 23 TWh per year in Germany by 2030 or up to 43 TWh in an accelerated-adoption scenario, an 8 percent increase over current energy demand. This accelerated scenario corresponds to 16 million EVs in Germany by 2030, an increase in line with studies commissioned by the European Union and spurred by its proposed ICE vehicle ban as well as improving engine-efficiency rates.[9]

An increasing amount of charging-energy demand will come from light commercial vehicles (LCVs) and trucks, growing from around 28 percent of the charging energy in 2020 to around 42 percent in 2030. Passenger cars will remain the largest segment, decreasing from its current 67 percent share to approximately 55 percent by 2030. The share of buses will grow from 3 to 5 percent.

Considering charging behavior and charging time and location patterns, most charging (approximately 40 percent of energy) will take place at single- or multiunit homes, around 14 percent at places of work, around 11 percent on highways and at public stations, and around 5 percent at retail and other destinations (such as shopping malls). The remaining 30 percent, give or take, will be charged at van or truck fleet hubs. These locations, together with public charging, will experience the greatest growth rates (subsequently decreasing the share of home charging), as eTrucks and LCVs become increasingly common. Thus, additional stress will be added to the grid: compared with home charging, fleet and public charging is more difficult to manage due to the nature of use of heavy vehicles, the concentrated simultaneous demand, and the need for fast charging.

By 2030, 55–60 percent of energy will still rely on AC chargers (approximately 23 percent from slow chargers and approximately 35 percent from fast chargers). This represents a ten-percentage-point decrease of AC slow charging (4–15 kilowatts [kWs]) from the current levels of around 33 percent, and a five-percentage-point decrease for AC fast charging (15–22 kWs) from the current levels of 39 percent, in favor of DC fast charging (DCFC), mainly at rates of 50 kW DC (22–27 percent) and 150 kW DC (10 percent).

The move to faster charging increases the challenge of managing EV loads, which increases the need for grid operators to understand average and peak loads.

Managing customers’ charging times

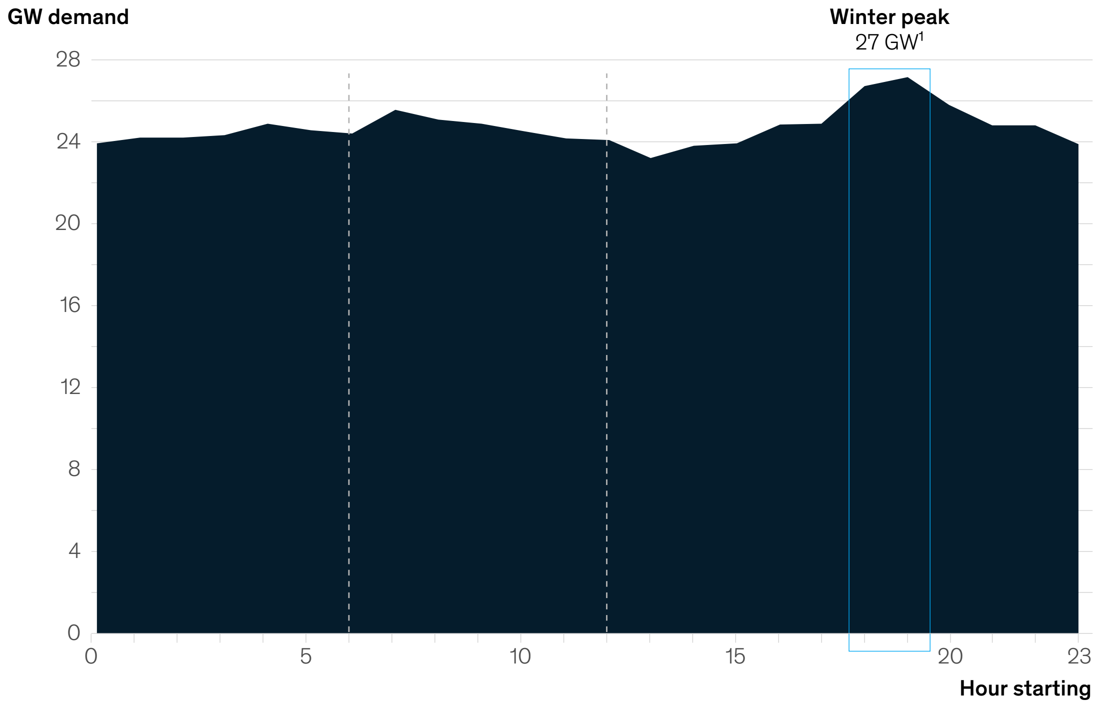
Electric load shapes, which represent load as a function of time, can provide granular insights into the charging habits of customers. For example, across Germany the typical electric load shape during the winter months sees a sharp increase between 6:00 and 8:00 p.m., typically reaching its peak of more than 27 gigawatts (GW) around 7:00 p.m. (Exhibit 2). This time coincides with when a typical homeowner plugs in an EV after returning from work.

[9] “European vehicle emissions standards – Euro 7 for cars, vans, lorries and buses,” European Commission, ec.europa.eu; Leonore Gewessler et al. to Frans Timmermans and Adina Vălean, “Transition to zero-emission light-duty vehicles,” March 10, 2021, klimaat.be.

Exhibit 2

The average peak load time for electric vehicles in Germany is 7:00 p.m., when most vehicle owners are home from work.

Winter load shape and peak in Germany, transmission territory example, 2019



[1]In 2019, the peak load for Germany was 80.4 GW.
Source: Publicly available TenneT hourly load data 2019

Attempting to influence the timing of vehicle charging—most important, to reduce charging during peak loads—is known as "managed charging" (Exhibit 3). This practice enables flexibility around when and how long end users charge their cars and can rely on a combination of "passive" time-of-use pricing plans to modify user behavior, and "active" remote-control management of charging by the utility or a third-party aggregator.

The success of regulators and utilities in engaging vehicle owners in managed-charging programs will ultimately determine the programs' impact on the system's peak load and the required grid infrastructure upgrades. Under a fully unmanaged charging scenario, up to 7 additional GW of energy could be added to peak demand by 2030, an 8 percent increase over the current German peak.

With the appropriate managed-charging devices in place as well as incentives to charge during nonpeak hours (including delayed charging and differentiated electricity pricing), a substantial portion of single- and multiunit home charging can be shifted from 10:00 p.m. to 4:00 a.m. This scenario mitigates much of the customer impact on the electric grid while leaving commercial and fleet-charging hubs, public spaces, and unmanaged highway fast charging. As a result, the peak load curve flattens by approximately 80 percent in other managed scenarios, but the specifics can be adjusted on a grid-by-grid basis.

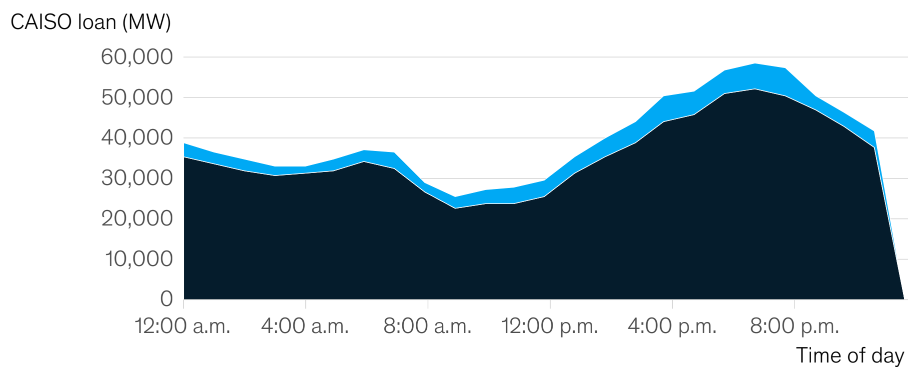
Exhibit 3

By controlling charging time, duration, and intensity, managed charging can optimize power consumption.

Energy management solutions provide monetizable site and grid services
CAISO[1] illustrative 2031 grid profile with and without managed charging

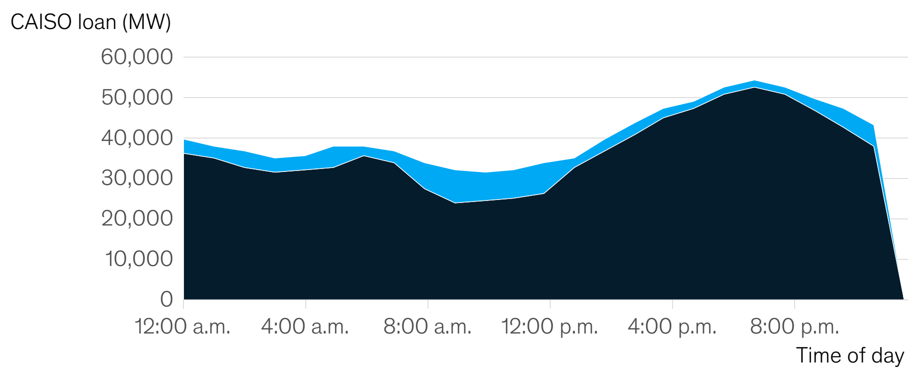
Without managed charging

EV demand   Non-EV demand



With managed charging

Smart EV demand   Non-EV demand



[1]California Independent System Operator.
Source: Rocky Mountain Institute

Fast-charging stations and managed charging are key to upgrading infrastructure

An analysis of grid topology and transformer congestion at the distribution level illustrates the effect of EVs on grid infrastructure. Our forecasts allocated the various segments of vehicles in operation to individual medium-voltage nodes. We then combined the different behaviors, charging times, and patterns in the various nodes (such as urban areas with multiunit homes and increased work-hour charging versus suburban single-home or farmland areas) with specific utility-grid information (node load shapes and transformer load levels) to identify bottlenecks.

The main infrastructure components requiring investment are residential transformers in areas with high penetration of EVs and, to a lesser extent, circuits and switchgear. As EVs gain traction and charging rates evolve from the current AC slow rate (less than 4 kW) to improved rates (four to 15 kW) and finally AC fast rates (15 to 22 kW), the number of overloaded residential transformers increases exponentially. Our estimates show a spike in transformer upgrades once approximately three million EVs are in operation, which could happen as soon as 2025.

At the same time, DCFC charging stations (with rates of 350 kW DC for cars and up to 600 kW DC for heavy commercial vehicles) may challenge the stability of the network, requiring dedicated substations (in most cases) or major overhauls of transformers and cables. Some projects even aim for three-megawatt (MW) DC chargers for trucks—for example, CharIN's high-power commercial vehicle charging (HPCVC) medium-voltage project, which charges at 1,500 volts and can provide significant truck autonomy after a mere 20-minute stop.[10] To put this in perspective, a ten-lane station with three HPCVC chargers and seven 350-kW DC chargers requires a substation capable of providing more than ten megavolt amperes, which would cost several million euros to build from scratch.

Navigating electric-grid upgrades: A road map

EVs are forecasted to account for approximately 15 percent of German parking spaces by 2030, resulting in an increase in energy demand and peak load of 4 to 6 percent. Such profound changes in power consumption demand a targeted upgrade of the grid to ensure stability of supply.

Advanced analytics tools can help players to anticipate these changes and address them proactively. The simulations highlighted the risk of bottlenecks in specific nodes of the distribution network and a high impact of EV charging in the overall system peak. Specifically, in an unmanaged-charging scenario, the overall cost to upgrade residential transformers could total more than €5 billion by 2030 in Germany alone (factoring in the risk of overload due to increased peak demand and the need to install new dedicated infrastructure for public, retail, and destination charging). However, the simulations also show how managed-charging approaches can substantially relieve such cost pressure by reducing the cost of upgrading transformers. Furthermore, tapping into vehicle-

[10] "Charging infrastructure for vehicles using battery storage," CharIN, February 18, 2020, itf-oecd.org.

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to-grid to dispatch stored energy from EVs during peak times can turn a potential problem into an opportunity to balance the grid demand. Vehicle-to-grid technology, which has been an unfulfilled promise since the early days of electric vehicles, was commercially established in Denmark four years ago and has provided frequency regulation in Copenhagen ever since.

These insights have formed the foundation of an alignment process between stakeholders and regulators on mitigating measures such as price schemes for specific time-of-use charging, vehicle-to-grid discharging, approval and planning processes for new fast-charging DC stations, and required capital investments. Going forward, such close collaboration of stakeholders—including utilities, policy makers and regulators, OEMs, and EV-charging companies—is of central importance for Germany to achieve its green-electrification goals and future emission targets.

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