Distribution grid planning for a successful energy transition – focus on electromobility

Conclusions of a study commissioned by Agora Verkehrswende, Agora Energiewende and Regulatory Assistance Project (RAP)

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1 Researching distribution network planning for the energy transition

In this paper, Agora Verkehrswende, Agora Energiewende and Regulatory Assistance Project (RAP) summarise the conclusions from a jointly commissioned analysis of distribution grid planning for the energy transition, with a focus on electromobility (full study only available in German, download here), and offer wider considerations on the topic. The research was undertaken by contractors Navigant, Kompetenzzentrum Elektromobilität and RE-xpertise. The key findings from the study are summarised in Figure 1 below. The energy transition is facing two major challenges with regard to power distribution: First, power peaks occur when high levels of solar and wind are fed into the grid on days with favourable weather conditions. Secondly, heat pumps and electrified transport cause increases in peak loads with high coincidence factors and power draw. As a result, the peak network capacity needed to meet demand increases. Viewed through the lens of conventional grid planning, these three drivers - feed-in from renewable energy sources, and the additional demand from heat pumps and from electric vehicles – would indicate that the electricity distribution grid needs to be expanded.

However, so-called "smart charging" of electric vehicles can help to reduce peak loads on the networks and, in turn, delay or obviate the need for network expansion. Therefore, charging processes should be shifted to times that benefit the grid, i.e., ensuring higher utilisation of network capacity.

It is not possible to determine which cost driver requires how much network expansion, because the three drivers (additional renewables, electrified

Figure 1: Main results of the study *Distribution grid planning for a successful energy transition - Focus on electromobility*

1. **The energy transition in the power distribution grids can be successful, even if all passenger vehicles are electrified.** Grid-friendly charging reduces the peak loads created when vehicles and electric heat pumps are charged simultaneously. It can also shift electricity consumption to times with abundant generation from solar photovoltaics and wind turbines.

2. **Combining grid-friendly charging with the broader mobility transition can fund the energy transition in the electricity distribution grids by 2050, supplying 1.5 billion euros of annual investments in power lines and transformers.** Without the mobility transition, annual investments of 2.1 billion euros would be needed to accommodate 45 million, instead of 30 million, electric cars.

3. **Electromobility can finance the expansion of the distribution network until 2050. Electric mobility increases electricity sales, while the overall investment needed for power lines and transformers does not increase.** However, it is important that the participants in the mobility transition pay their fair share of grid fees.

4. **Smart charging can be designed to ensure that users hardly notice any restrictions.** To achieve this, grid-friendly managed charging must become the standard. We need secure information and communications technologies, incentives and, if necessary, obligatory managed charging. Precautionary indirect control, in the form of incentives for grid-friendly charging, should take precedence over direct control by the distribution grid operator.

Agora Verkehrswende, Agora Energiewende and Regulatory Assistance Project (RAP) heating and e-mobility) are intertwined. Although electrification of transport was the focus of the research project, all of the findings about investment requirements apply to all three drivers.

In addition to the potential of managed electric vehicle charging, the study examines the effects of the mobility transition on network expansion requirements. By mobility transition, we mean the broader shift toward public and shared mobility and away from private-car-based transport.

Accordingly, the study included a scenario assuming that passenger kilometres travelled remain the same, while public transport, shared mobility, cycling and walking increase and private car travel decreases.

The research project addressed the following questions:

1. What investments in power lines and transformers on low-voltage and medium-voltage networks are needed to further the energy transition in the areas of electricity, heat and transport?
2. To what extent does grid-friendly charging of electric vehicles reduce the need for network expansion and the associated investments?
3. What effects does the mobility transition have on increasing public transport, cycling, walking and shared mobility options?
4. What regulatory framework is needed for charging electric vehicles?

The researchers first established scenarios for development of the three drivers of network expansion for the years 2030 and 2050. They then developed a model based on these assumptions that calculated the effects of the power, heat and transport sector transitions on the different scenarios. The resulting recommendations for smart charging aim to determine how the potential for reducing investment requirements can be translated from theory into practice.

2 Scenarios and assumptions for modelling future investment needs

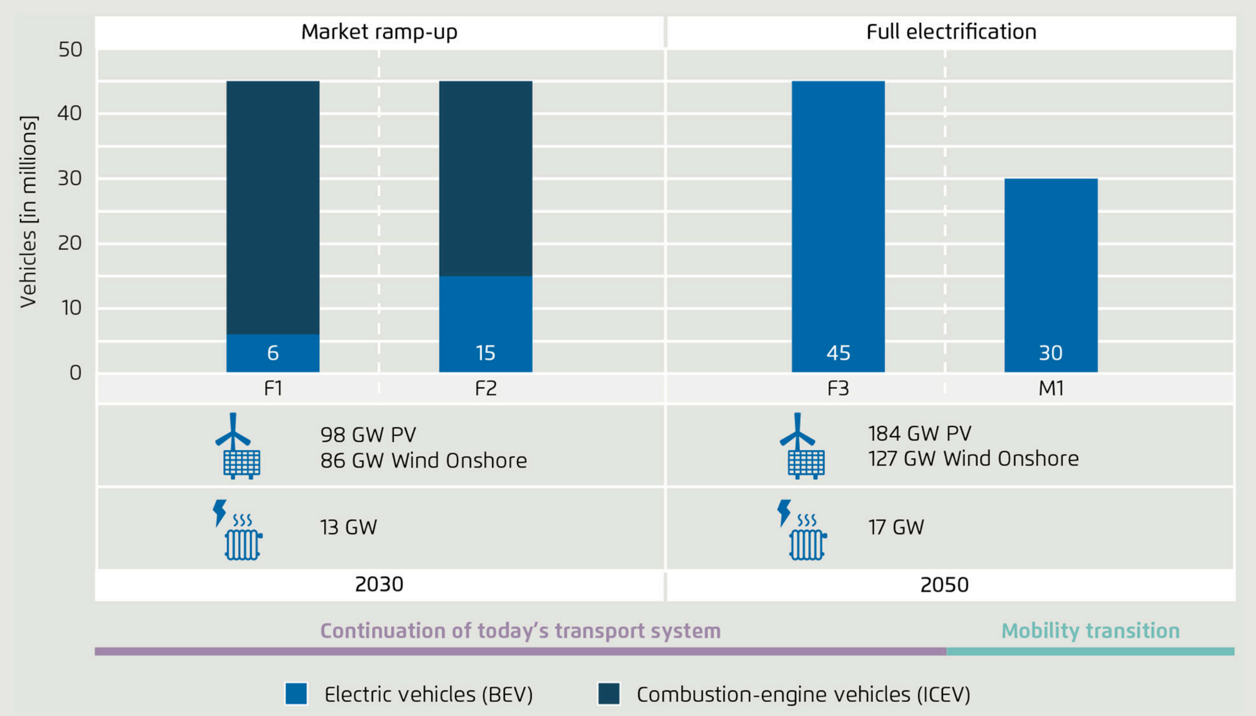
The researchers considered two fundamentally different scenarios for the transport system when modelling the future development of the energy transition in the distribution networks.

In the scenario "Continuation of today's transport system," the shares of different transportation modes that make up Germany's transport capacity do not change. The result is a progressive electrification of the current passenger car fleet of around 45 million vehicles in Germany. For the year 2030, between six and 15 million electric cars were assumed as "market ramp-up." For the year 2050, 45 million battery electric cars are assumed in the "full electrification" scenario. Of the 80,000 buses registered in Germany today, 60,000 will be operated exclusively as battery electric vehicles in 2050, according to the fully electrified scenario. The assumed rate of electrification in 2030 is equivalent to the share of electric vehicles in the passenger car fleet.

In the second scenario, "mobility transition," 30 million electric cars and 60,000 fully electric battery-powered buses are assumed to constitute "full electrification."

We further assumed that 65 percent of electricity consumption in 2030 is supplied by renewable energy, as set out in the German government's targets, aiming at 100 percent by 2050. For the 2030 renewables share, we assume 88 percent will come from wind, solar, biomass and hydropower. The remaining 12 percent is provided by synthetic green gases generated in gas-fired power plants. Figure 2 shows the installed capacity for photovoltaics and onshore wind power. Heat pumps have a total installed capacity of 13 gigawatts (GW) in 2030 and 17 GW in 2050. The network levels considered in our model are the low-voltage and medium-voltage levels.

Figure 2: Overview of scenarios



Navigant, Kompetenzzentrum Elektromobilität, RE-xpertise (2019)

In addition to the number of vehicles, assumptions about the number and performance of charging points are important for the modelling. Moreover, the coincident peak of this additional load determines the results: High coincidence factors lead to (new) load peaks and higher requirements for expansion of the distribution networks. Most of the charging points modelled in our study are connected to the low-voltage networks and have a rather low coincident peak; for example, at home and at work. The coincident peak for private cars is determined using a Monte Carlo method, which maps the typical use cases for private cars. For more detailed descriptions of the assumptions used for coincidence factors, please refer to the full study.

As demonstrated, grid-friendly charging lowers the coincidence factor, and with it peak load, thus lowering the need for grid expansion.

For the modelling, charging behaviour and standards were defined using the following three scenarios:

1. Uncontrolled charging
2. Smart charging
3. Smart charging+

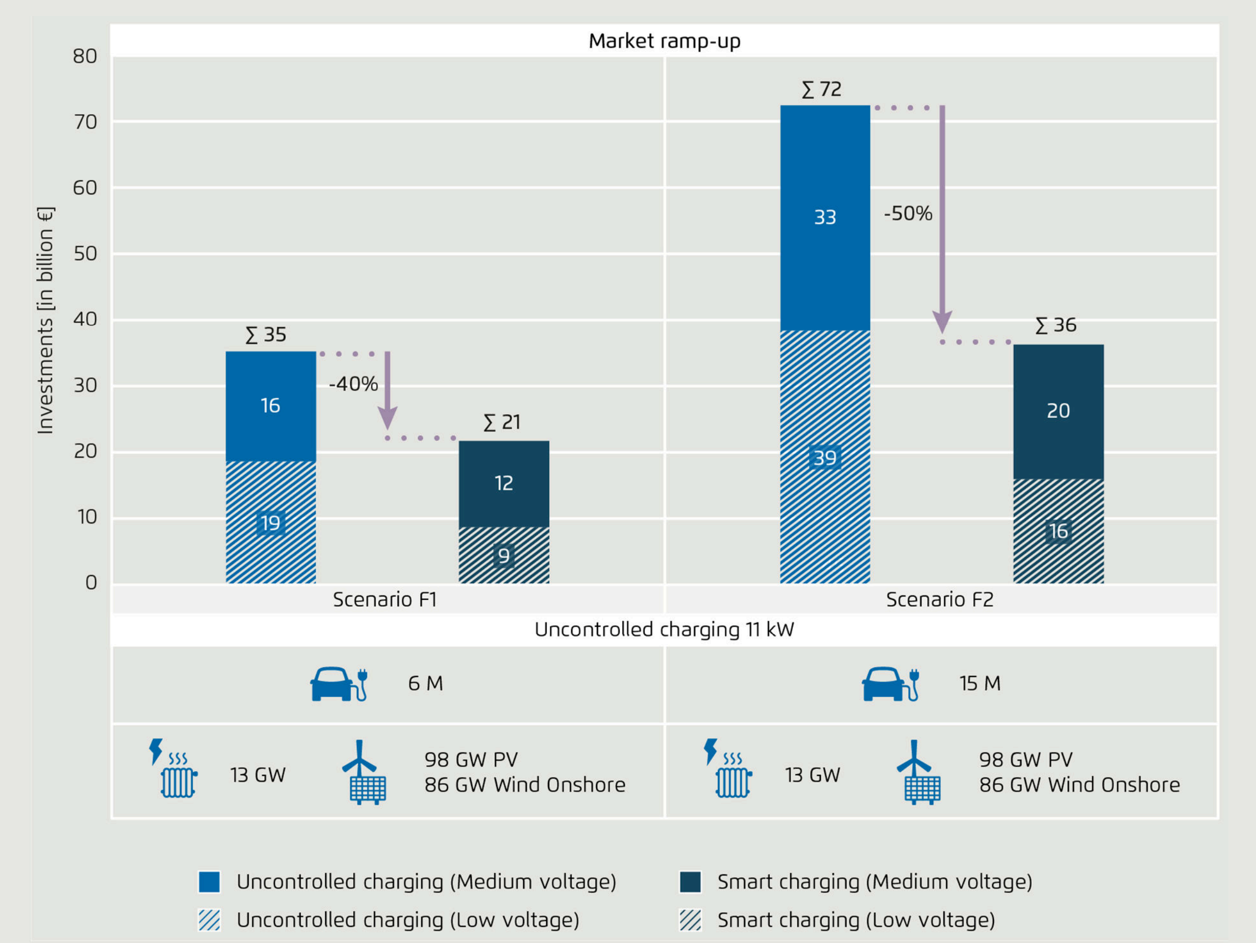
With **uncontrolled charging**, cars are connected directly to the power grid for charging as soon as they arrive at a charging point. The charging process is complete as soon as the amount of energy used for travel has been replenished, or simply when the vehicle leaves again (top-up charging). The arrival and departure times and distances travelled assumed in the model are based on the *Mobility in Germany* study by the Federal Ministry of Transport and Digital Infrastructure (*Bundesverkehrsministerium für Verkehr und digitale Infrastruktur*).

Smart charging also assumes that top-up charging is a customer preference. This differs from the uncontrolled charging scenario in that charging can be shifted within the time frame when the vehicle is parked. This allows the consumer to avoid demand peaks, and network utilisation can be increased during off-peak periods. However, this charging scenario still requires charging to happen while the vehicle is parked – so peak loads will still occur.

Smart charging+ further refines charging behaviour beyond one specific instance when the vehicle is parked to further reduce the remaining load peaks. This scenario assumes that a driver, or an optimisation app (software), has sufficient information to determine whether it would be more cost-effective to charge to the desired level at a later time. This optimises the charging process over several uses and parking periods. The user would thus not be affected by any cap on peak demand and smart charging+ would smooth network load more than smart charging. As a last-resort option, this scenario allows for a cap of up to 3 percent of annual peak demand if circumstances on the network cannot support charging. In this case, for example, the user would have to forgo his or her private charging point and use a (public) fast charging station.

Chapter 4 examines the best regulatory framework to enable this optimised charging without impacting electric vehicle drivers' needs and comfort.

Figure 3: Reduction of cumulative distribution network investment needs through smart charging



Navigant, Kompetenzzentrum Elektromobilität, RE-xpertise (2019)

3 Modelling results and context

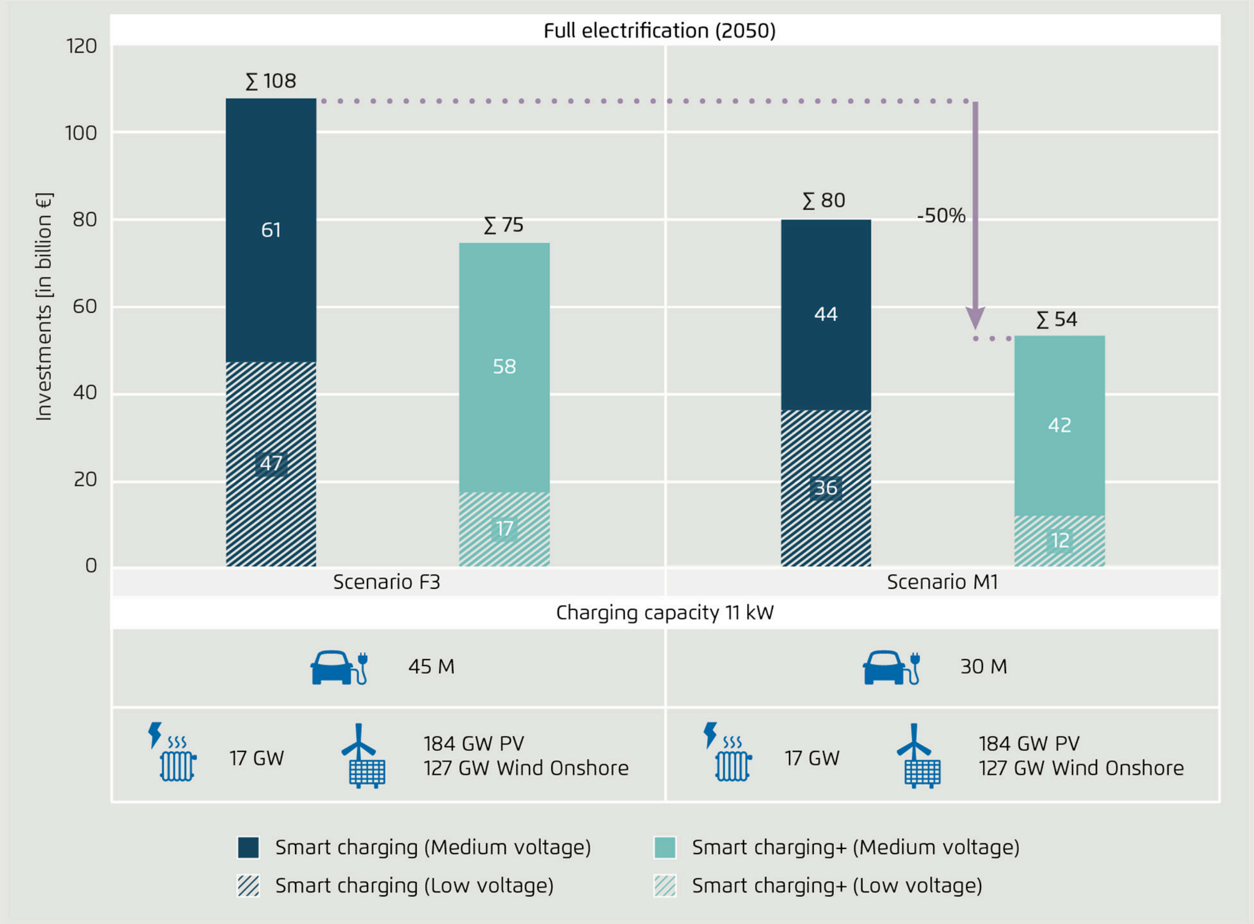
Smart charging can reduce investment in distribution networks by up to 50 percent by 2030.

A very ambitious scenario, with 15 million electric cars by 2030, would require 36 billion euros in investments in the distribution networks (for electricity, heat and transport transitions), or 2.4 billion euros annually (2015-2030). In the less ambitious scenario with six million electric cars, investments in distribution networks amounting to 21 billion euros or 1.4 billion euros per year are necessary for the same period (see Figure 3). A large part of these investments would have already been necessary in any case to replace aged equipment.

The mobility transition and smart charging+ can halve investments in distribution networks by 2050.

Figure 4 shows that investment in distribution networks can be reduced by an additional 50 percent by 2050 if the smart charging+ scenario is applied and the mobility transition is implemented. The transition for mobility alone will reduce investment requirements by up to 28 percent compared with continuing the current transport system. Smart charging+ alone reduces investment requirements by up to 33 percent compared to smart charging. With

Figure 4: Reduction of the cumulative distribution network investment needs through smart charging+ and the mobility transition



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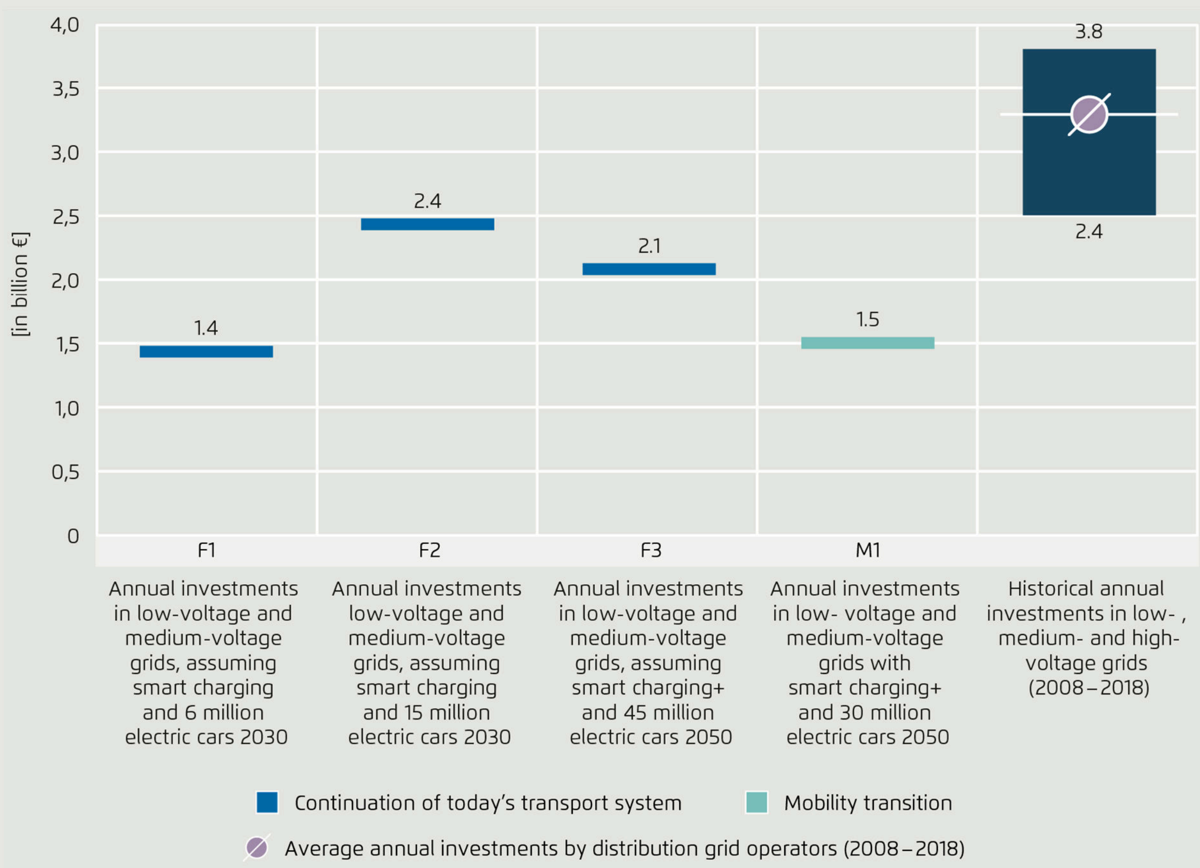
the mobility transition and smart charging+, the energy transition for the distribution networks will require investments totalling 54 billion euros, or 1.5 billion euros per year (2015-2050), by 2050.

Without the mobility transition to reduce the number of passenger cars, the energy transition for the distribution grids will require 75 billion euros in investment, or 2.1 billion euros annually by 2050.

On average, future EV grid integration does not require more investment in cables and transformers than in the past.

The necessary distribution grid investment levels differ considerably in the various scenarios. They can be divided over the periods from 2015 to 2030 and 2015 to 2050. The reference year for the network data used in the model is 2015. Compared with past investments, the scenarios deliver results that are comparable in size. Figure 5 compares the scenario results with past investments in distribution networks. The historical comparison is based on data published by the Federal Network Agency (*Bundesnetzagentur*) in its annual monitoring report. The figures show the investments made between 2008 to 2018. It should be noted that the Federal Network Agency's figures also include the high-voltage level, which is not the case in our study. The lead study of the German Energy Agency (Deutsche Energie-Agentur (dena)), *Integrierte Energiewende 2017*, provides estimates of the level of future annual

Figure 5: Annual distribution grid investment requirements for the 2015-2030 and 2015-2050 scenarios, compared to historical investments by distribution grid operators

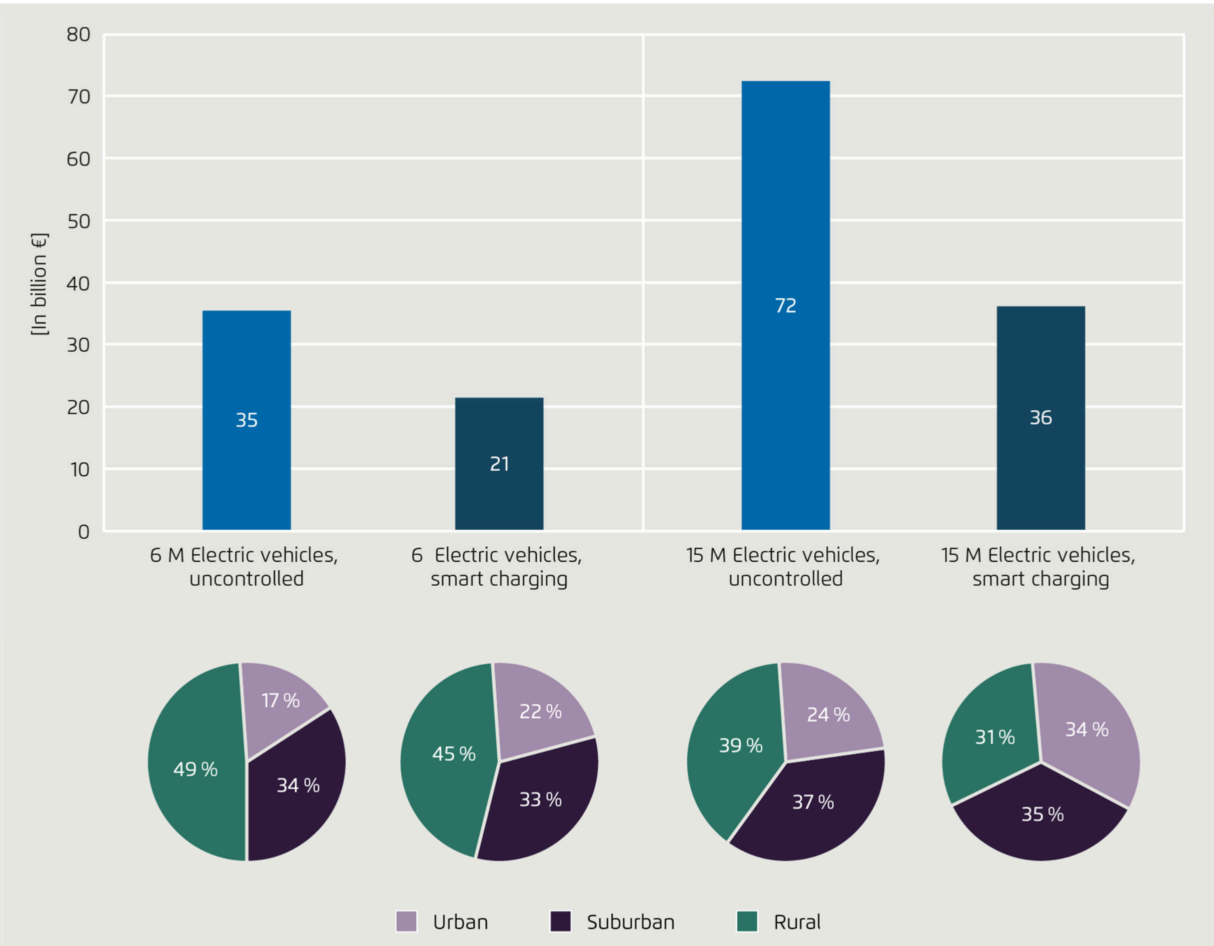


Navigant, Kompetenzzentrum Elektromobilität, RE-xpertise (2019)

investments needed for the high-voltage distribution grids. The level of investments required by 2050 according to the dena study — 67 billion euros, or 1.9 billion euros per year, for the period from 2015 to 2050 — was not determined through modelling, but by extrapolating past investments and considering the anticipated future expansion of renewable energy sources. Dena's 2050 figures are based on onshore wind electricity generation that is one-quarter higher and photovoltaic electricity generation that is one-seventh lower than in our study. The investment requirement for 2050 calculated in our Agora-RAP project, plus the dena figures for the high-voltage level, total at most four billion euros per year. The historical investments from 2008 to 2018 amounted to a maximum of 3.8 billion euros annually. Due to the higher installed generation capacity of wind turbines assumed by dena in 2050 and the corresponding higher investments in the high-voltage level, it can be argued that in future, on average, we will not need to invest more in distribution grid lines and transformers than in the past.

Of course, this comparison bears a certain degree of uncertainty as to whether these statements about the future will prove to be accurate. It is possible that the underlying conditions will change. It is also

Figure 6: Annual distribution grid investment requirements for the 2015-2030 and 2015-2050 scenarios, compared to historical investments by distribution grid operators



Navigant, Kompetenzzentrum Elektromobilität, RE-xpertise (2019)

conceivable that the average investments will not be higher than those in the past, but that individual years will be significantly higher or lower.

Smart charging can reduce the per capita investment in network expansion for rural citizens.

In the broader context of the energy transition, not only the level of annual investment in distribution network expansion is relevant, but also where the investments are made on the infrastructure and who, as a result, pays for them.

Figure 6 illustrates the level of investment in distribution networks with six and 15 million electric cars in both the uncontrolled and smart charging cases, as well as the distribution of investments between urban, suburban and rural communities in Germany. The graphic illustrates that the share of investments borne by rural areas will decrease in the event of nationwide smart charging and increasing numbers of electric cars. In the case of six million EVs and uncontrolled charging, rural areas will be responsible for 49 percent of the investments and urban areas only 17 percent. With 15 million EVs and smart charging, the distribution of costs changes to only 31 percent in rural areas and 34 percent in urban areas.

This shift can be explained by the fact that home charging points in rural communities play a greater role due to the higher proportion of detached and semi-detached houses. When charging at home (and at work), the potential for shifting the timing of charging is highest, which means that smart charging has a disproportionately positive effect in rural areas. In addition, shifting charging processes with the aim of smoothing residual loads can reduce feed-in peaks. Consequently, particularly in rural areas with a higher share of renewable energy sources on the distribution grid, we can reduce the amount of backfeed of higher voltage levels.

The potential for easing the investment burden for rural areas in the expansion of distribution networks through grid-friendly smart charging gains new relevance if one also considers geographical population distribution. Rural areas, for example, account for 67 percent of Germany's surface area. However, the share of the population living in rural areas is very low at 23 percent of the total population due to lower population density. By comparison: 35 percent of the population in Germany lives in cities and 42 percent lives in semi-urban areas.

Table 1 shows how the per capita investment needs for 2015-2030 are distributed across the different network classes. This information does not, however, provide any clear indication of how high future

Table 1: Annual distribution per capita of network investments 2015-2030 in urban, suburban and rural areas

Annual per capita investment in € (2015-2030)	6 million electric cars		15 million electric cars	
	uncontrolled	controlled	uncontrolled	controlled
Urban	14	11	40	28
Suburban	23	13	52	24
Rural	61	33	99	39

Navigant, Competence Center Electric Mobility, RE Expertise (2019) network charges might be. This is due to the different network fee calculations and variations in the structural characteristics of individual areas on the network. The above-mentioned balancing effect that smart charging has on the distribution of network expansion investments becomes even clearer when expressed per capita. For example, in a scenario with six million electrical vehicles EVs and uncontrolled charging, consumers in rural areas would pay 61 euros in grid fees annually, or approximately 4.5 times as much as people in the city. With 15 million electric cars and grid-friendly smart charging, rural customers would only pay around 40 percent more for grid expansion than their urban counterparts.

Electric mobility can finance the entire expansion of the distribution network.

We need to ensure that both the transformation of the transport sector and the overall energy transition are just.

One key question is: Who should pay for integrating electric vehicles into the power system distribution networks? The study by Navigant et al. examines the total network expansion required for adding heat pumps, renewable energy and electromobility. Studying each driver of expansion separately would not be a logical methodology because the drivers influence each other. It is therefore not possible to determine how "expensive" the integration of electric mobility alone would be. It is possible, however, to estimate the contribution electromobility can make in financing these investments. Although power supply from renewable energy sources benefits the population as a whole, not all segments of the population have access to private charging infrastructure for electric vehicles. And privately-owned vehicles don't all have the same value. But privately-owned electric vehicles can make a major financial contribution to expanding the distribution network — a fact that will increase the acceptance of electromobility among the general population. As illustrated in numerous studies by Agora Verkehrswende, electric vehicles - including private mobility – are key to achieving climate protection goals in the transport sector.

Assuming that electricity sales in Germany increase by the amount of power used for electromobility, at 18 kilowatt hours (kWh) per 100 km and an average of 14,700 km per year, 45 million electric cars will consume around 120 terawatt hours (TWh) in 2050. For every year leading up to 2050, consumption will increase at pace with the rising number of electric cars. If we also assume that electric vehicle users will pay at least around half of the network charges paid by all residential consumers today — generally around 7 cents per kWh — then the revenue from network charges for electric vehicles will be in the same order of magnitude as the investment requirements for 45 million electric cars, 17 GW of heat pumps, 184 GW of solar photovoltaics and 127 GW onshore wind. This rough calculation shows that there is room to reduce network charges to incentivise consumers to shift charging to off-peak periods — without jeopardising the ability of electric vehicles to provide sufficient funding for necessary investments in distribution networks.

The mobility transition, when coupled with smart charging, has the potential to significantly reduce the need for network upgrades and the associated investments. It is now necessary to create a regulatory framework that makes practical use of this theoretical potential.

4 Setting the right regulatory incentives

Smart, or performance-based, regulation is required to realise these calculated savings in network investments. In the study underlying this paper, Navigant et al. offer four recommendations for the regulatory framework for smart charging.

First, it is important to ensure that the local distribution system operator is aware of the flexibility services of electric vehicle charging points with more than 3.7 kW charging capacity. The operator of the charging point should, therefore, allow the distribution network operator to control charging processes if needed to support grid operation. Distribution network operators currently offer reduced network charges to customers with electric vehicles if they grant the operator consent for controlling charging, i.e., the right to reduce or cut charging at peak times if needed. (This is a situation specific to Germany that evolved from a network tariff for night-storage heaters (EnWG §14a). Electric vehicles were added as a flexible end use.) If the price savings alone do not provide sufficient incentive, policymakers should increase the difference between tariffs that allow and those that do not allow controlled charging. One option is introducing an additional network construction fee for grid connections below the previous limit of 30 kW of grid connection capacity. This network construction fee could be waived for charging point operators who grant network operators the right to control their charging processes. If the incentives are not made sufficiently appealing, however, it's possible that too few customers opt for allowing control. Government requirements for charging equipment should, therefore, at least allow for future control or make the equipment easy to retrofit. In addition to offering financial incentives, it is important to provide clear, comprehensive information about the implications of allowing control.

Second, it is important to provide incentives to electric vehicle users to charge at times when electricity demand and, therefore, load on the grid, is low. Two instruments are available: Time-varying or time-of-use tariffs and critical peak pricing for use of the charging point for time frames stipulated by the distribution network operator. In the case of time-of-use tariffs, charging is cheaper per kilowatt hour during periods of low grid utilisation and more expensive in periods of high grid utilisation. With the critical peak pricing tariff design, the distribution network operator sets capacity limits for specific time periods. If electric vehicle charging draws power in excess of the capacity limit, the customer must pay a penalty to the distribution network operator. Intelligent charging equipment is required for both tariff designs, which is more expensive than non-intelligent charging technology. As a result, the incentives for time-varying tariffs and critical peak pricing must be high enough to justify higher upfront cost for the appropriate technology, and the limitations for the customer need to be acceptable. The particular advantage of time-of-use tariffs is that they are quick and easy to understand, and the potential limitations are easy for most customers to assess.

Third, it is important to develop and distribute software for forecasting network capacity. Such forecasting tools require complex and highly developed information and communication technologies. Granular data on the location and timing of network usage must be collected, communicated and analysed. Once a network model has been developed that can analyse data on grid and load conditions to forecast future congestion, schedules based on those predictions can be communicated to consumers. Time-of-use tariffs can be improved with better time switches, while critical peak pricing requires smart technology that is installed directly in the vehicle or in the charging point to determine the flex window. In the greater context, critical peak pricing schedules based on forecasting tools should help identify available flexibility services or capacity that can then be sold on secondary markets, e.g., through flexibility platforms.

Fourth, distribution system operators should minimise their use of direct control. In case of congestion, they must still always be in a position (either directly or through a third party) to curtail load during the electric vehicle charging process or to interrupt it completely. To make smart charging acceptable more broadly, however, it is important that this intervention is brief in nature or ensures that the car's charge level is sufficient. Network capacities can be used very efficiently if controllable electric vehicles are widely distributed and if distribution network operators encourage charging processes based on the utilisation of their networks. This ensures that charging is managed and only interrupted, if necessary, upon instruction by the network operator.

In summary, for successful electric vehicle grid integration, policymakers should aim to achieve the following distribution grid planning goals in regulating managed charging:

→ Making grid-friendly managed charging of electrical vehicles the standard.
→ Ensuring that grid-friendly charging is normally voluntary and can be adjusted individually by customers with electric cars. Options for this are time-of-use tariffs and critical peak pricing at the charging point for time frames stipulated by the distribution network operator.
→ Enabling precise forecasts of the utilisation rates and possible optimisation of distribution networks. This is best achieved through more secure, high quality hardware and software and can lead to the efficient use of flexibility resources to benefit consumers and accelerate the energy transition.
→ Ensuring that any direct control of charging processes by the distribution system operator is customer-friendly and only occurs when unavoidable.
→ Implementing less complex technical solutions during the ramp-up phase when the relevant information and communication technologies are not yet widely available, and ensuring that equipment can be retrofitted with smart control technology. This will help avoid stranded assets.

Outlook

This study carried out by Navigant, Kompetenzzentrum Elektromobilität and RE-xpertise on behalf of Agora Verkehrswende, Agora Energiewende and RAP, and our conclusions derived from the study, show that the energy transition in the distribution networks can be successful, even if Germany's car fleet is fully electrified. If we harness the potential of smart charging, the investments required for power lines and transformers in the distribution networks need not increase. The mobility transition can generate further savings and, from a distribution network perspective, should be an integral part of the broader transition in the transport sector. We also demonstrated that electric vehicles can help to ensure that investments in electricity distribution networks are distributed more equally between the rural and urban population - and that the necessary investments in distribution networks can be financed in full by transport electrification.

The study did not consider what changes should be made to the regulation of distribution system operators to make it more enticing for them to invest in information and communication technology. The so-called Incentive Regulation Ordinance (*Anreizregulierungsverordnung*) in Germany made it more appealing to invest in physical infrastructure than in smart equipment to tackle impending network congestion. This needs to be reformed. In addition, regulation should give more weight to the fact that excavation work accounts for the largest share of network expansion investments in power line construction, i.e., it would be important to determine whether longer-term planning could ultimately lead to investment savings. One should also consider whether a wind turbine or two might be superfluous from a system perspective because distribution networks with higher capacity mean that the electricity fed in can be more effectively delivered to consumers. Another question that begs an answer is: How can network investments be better aligned with existing maintenance schedules?

In a study also envisaged for 2019, Agora Energiewende, Agora Verkehrswende and RAP plan to address these issues as well as others that look beyond the mechanisms for distributing limited capacity recommended in this summary and the underlying study.

We would like to note, in addition, that our study did not examine other aspects of the charging infrastructure as intensively as those included here. How electric vehicles are charged in the future is key to ensuring effective and cost-efficient distribution network design. Of particular importance, for example, are questions about optimal charging infrastructure in cities. Questions arise for planners, for example: Is it possible (and necessary) to install numerous private charging points and curb-side charging points, while at the same time setting up powerful fast charging infrastructure for cars and high-capacity charging infrastructure in public bus depots? What would the need for investment be if more emphasis were placed on central fast charging concepts and less on curbside charging for cities, where network investments are higher? Are petrol stations, as we know them today, potentially the best site for future fast charging stations? These unanswered questions show that we need long-term strategies and integrated planning, especially in cities, to identify the optimal charging infrastructure for electrifying urban mobility. With these considerations in mind, we can invest confidently and efficiently today to minimise the risk of failed investments.

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