The Power Grid is the Backbone for E-Mobility

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***Abstract* — The German power grid is a highly reliable infrastructure that will serve as the backbone for the integration of e-mobility. By 2030, as reported by the Federal Network Agency, 6 million electrical vehicles (EV) could be driving on German roads [1]. This will add a significant load to the system that could lead to increased congestion in the network. A well planned integration can avoid additional grid expansions as well as allow for a higher penetration of renewable energy (RE) through flexibility services. If the integration of e-mobility is thoroughly planned from the start, it can generate added value for all parties in the power grid and contribute to the energy transition ("Energiewende"). This paper summarizes current network conditions in Germany, explains effects on the power grid and outlines the necessary next steps to facilitate e-mobility integration. Key findings from the meta-study commissioned by VDE|FNN and BDEW also provide a description of the key factors for the integration of e-mobility and offer suggestions for future research.**

Keywords- grid integration; e-mobility; power grid; flexibility; charging infrastructure

I. INTRODUCTION

The conditions for a broad use of e-mobility are examined by VDE|FNN as the technical regulator for the power grid in collaboration with stakeholders, in order to ensure an efficient integration into the electrical system. To that end, early and forward-looking requirements must be defined to develop further the power grid as the backbone for e-mobility. The development of e-mobility is linked with the energy transition. It relies on renewables to support its integration and at the same time provides flexibility to allow a reliable operation of the grid infrastructure with a high share of variable renewable energy (VRE); in Germany it already reached 23.2% in 2017 [2], one of the highest shares in the European Union [3]. A flexible and reliable grid infrastructure is the backbone to increase the share of RE and support the integration of e-mobility towards the mass-market.

The following questions should be tackled to ensure a successful integration of e-mobility:

a) What must be considered in the design and planning of the power grid to integrate e-mobility in a cost-effective way?

b) What capabilities must electric charging stations (ECS) have to support the power grid and the overall system, for example, in the event of a fault or voltage instability?

c) What services can be provided by e-mobility to increase flexibility and enable a higher RE share?

d) Which parameters must be taken into account when synchronizing with the network via a smart metering system, so that e-mobility can provide additional services?

E-MOBILITY MAKES AN IMPORTANT CONTRIBUTION TO A FLEXIBLE POWER GRID

A. Impact of e-mobility on the power grid

A major advantage for e-mobility in Germany is that the backbone for a charging infrastructure is already available. The power grid offers a very reliable infrastructure that is available to every household; the reported System Average Interruption Duration Index (SAIDI) has been consistently under 20 minutes per year in the last 10 years [4], situating Germany among the best in Europe for security supply [5]. E-mobility should contribute to the backbone by providing required additional flexibility for the power grid to support the energy transition, for example by acting as mobile storage units and in the long term serving as bidirectional buffer storage through vehicle-to-grid (V2G) technology. ECS can help to reduce load peaks through load shifting for example through the synchronization of market signals with network signals, especially in case of network constraints. The integration of e-mobility depends upon advances in battery technology as well as smart communication interfaces that allow an efficient integration into the market and the power grid. The flexibility offered by e-mobility has to support further integration of RE and future grid operation requirements.

E-mobility introduces new variable loads and feeds to the electrical system which could place an additional strain on the grid, causing further need for grid expansions and requiring additional generation capacity. A greater use of EVs increases the likelihood of new network constraints, for example at the end of the working day or due to ECS control being triggered by market signals. Network congestion could occur if the charging processes are not responsive to system needs. Therefore, the integration of e-mobility must be thoroughly planned to avoid becoming an additional strain to the power grid and support network operation in critical situations [6].

B. Research status quo: e-mobility meta-study

The e-mobility meta-study to be published in October 2018 [7], was commissioned by the technical regulator for the power grid in Germany (VDE|FNN) and the Federal Association of the Energy and Water Industry (BDEW). The meta-study identified and analyzed the 60 most relevant research projects, scientific publications and dissertations (national and international). The papers were evaluated according to several areas: future development of e-mobility and RE; technical limitations; network aspects; system and network services; charging processes and sector coupling. A total of 157 scenarios covering a wide range of possible developments were evaluated according to a chosen set of parameters to provide insights into technical regulation and network operation.

The meta-study provides:

- an overview of relevant research projects
- an analysis of procedures and assumptions for the technical design of e-mobility
- an evaluation of EV integration influence on network load
- requirements for successful network integration
- recommendations for further research

C. General requirements

The design of e-mobility must consider the requirements not only for a safe integration into the existing grid, but also for the development of the future power grid:

- Support measures must be geared towards a secure and economic integration into the system.
- EV must follow the same technical requirements for grid integration as generating plants and consumers.
- Ramp-up processes must comply with technical requirements. Flexibility in the power grid is necessary and should be supported by e-mobility, especially to avoid regional network congestion.
- Contribution to system services (e.g. balancing power, frequency control and reactive power supply) must be considered in the design of e-mobility.
- Defined market rules must be established for the interaction of controllable generators, demand facilities and energy storage facilities.

II. GRID AS THE BACKBONE IN GERMANY

Power grids are a long-lasting infrastructure whose planning must consider future challenges. The traditional operation delivered electricity from central large-scale power plants to consumers unidirectionally. A bidirectional operation of the power grid is however necessary with increasing decentralized generation. The federal government has set the goal of increasing the percentage of electricity generated from RE in gross electricity consumption in Germany to at least 80% by 2050 [8]. As a result, the dynamics and diversity of power grid operation modes will increase due to the higher percentage of fluctuating generators and active consumers.

The faster integration of renewables in Germany has led to a VRE share in the electricity system among the highest in Europe [3]. This triggered the need to develop forward-looking requirements to enable higher RE penetration rates without compromising the operation of the power grid. A clear example is the mass integration of photovoltaics (PV) into the German power grid. A large amount of PV could switch off synchronously at 50.2 Hz, posing the risk of the system falling short of 3GW, the primary regulation considered for the Regional Group Continental Europe. A directive was enacted in 2011 to retrofit existing distributed generation to ensure they remained online long enough to avoid a mass disconnection that would threaten system stability [9]. This shows the importance of forward-looking requirements; as illustrated by Figure 1. the existing grid-connected VRE systems will not contribute to the future electrical system needs and can remain in the system for 20 or more years. Only new installations will actively contribute to system stability (e.g. frequency behavior). The roll-out of e-mobility should take into account the effect of its integration and develop standards to ensure a safe operation of the future grid.

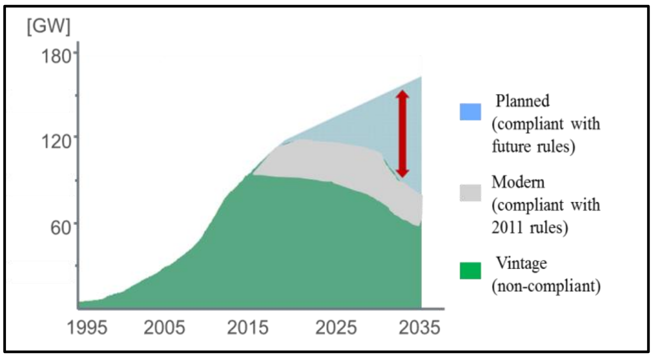

Figure 1. Integration of total VRE systems into the german power grid – approximated figures, adapted from [9]

A. Roles in the power grid and existing requirements

Decentralized production structures combining different types of systems (i.e. energy storage, RE systems) increase the complexity of the grid, leading to a shift in responsibilities between DSOs and TSOs. A closer cooperation between the different grid users and operators is hence increasingly important, at national as well as regional level.

Requirements particular to the operation of ECS in Germany are outlined in the Network Connection Rules (NCR) for low-voltage (LV) networks [10] and for power generation plants in the LV networks [11]. Systems must have the capabilities to ensure operation within the allowable limits and the network operators must have access to certain control measures to ensure the safe operation of the network. In the future, market mechanisms will be capable of managing grid users connected to the LV network. The roles of grid users must be clear and comprehensive to support a safe and efficient operation. It is also essential that electrical system needs are prioritized in case of network constraints.

TABLE I. LIST OF REQUIREMENTS FOR CONNECTION OF ECS TO GERMAN LV NETWORKS [10]

Capability	*Description and Roles*
Load management	ECS operator can participate in load management with network operators, if required
Reactive power	ECS must ensure a minimum cosφ = 0.95 at rated power. The network operator may specify regulations for reactive power or cosφ for DC or inductive ECS >12kVA
Active power control	When necessary, either through a sensor for value-based control or a fixed system. Control and disconnection devices are required for ECS >12kVA. Control during charging/discharging cycles can be regulated in function to the voltage to avoid tripping of overvoltage protection.
Active power control during over- or underfrequency	ECS must regulate their power to support deviations of +/- 0.2Hz from 50Hz nominal frequency and be able to reinstate operation within stipulated times.
Dynamic network support	ECS which disconnect a customer's system from the grid in the event of grid disturbances must participate in dynamic grid support until the customer's system is disconnected from the grid (with certain exclusions). Network operators can enforce an earlier disconnection from the grid under certain grid conditions.
Compliance	ECS that charge and discharge electricity from and into the public grid must be certified through a declaration of compliance.

B. Plans for e-mobility infrastructure

E-mobility is still considered a niche market in Germany; its implementation in terms of market reach, charging infrastructure and supporting policies are under development. About 103,500 EVs were registered in Germany since 2009, with 10,700 public charging points as of September 2017 (4,730 standard and 530 fast charging points), according to the German National Platform for Electric Mobility (NPE), the advisory body to the German government for electric mobility [12]. The charging infrastructure required will include 70,000 public charging points and 7,100 fast charging stations for long journeys by 2020, as reported in their website [12]. The integration of renewables and the creation of sustainable business models are the basis for these developments to take place [12].

A moderate scenario for e-mobility developed by the Federal Network Agency, aims at having 6 million EVs by 2030 [1], updating the NPE ambitious 2020 goal.

C. Integration of e-mobility into the power grid

An action plan for the development of the network to support the energy transition in Germany was presented by the Federal Ministry for Economic Affairs and Energy in August 2018 [13]. This strategy is geared towards the optimization of the existing infrastructure and the acceleration of grid expansion at regional and national level. The advance of e-mobility and its integration into the power grid should work within the national framework for network development. The investment will be focused on the LV and medium-voltage (MV) distribution networks, where most ECS are expected to be installed [12].

The charging infrastructure will need to have the ability to answer customer needs for EV charging. The charging processes from EV batteries are characterized by relatively high charging capacities in comparison to typical household appliances on the LV network as well as a variable load that greatly depends on the EV´s usage profile and battery capacity [14]. Regular or standard charging are meant to be for long periods, i.e. overnight, while fast charging is required for short stays and allow to cover long distances. This type of charging requires large amounts of power which can lead to constraints on the power grid. In the future, outputs of 150 kW and above for fast charging will require investment also in MV networks [15]. It would be strongly recommended that high power charging (HPC) stations with capacities of 350 kW and above are connected directly to the MV network. A connection to the LV network could be considered in this case as long as it is with a grid compatible connection concept, for example in combination with energy storage devices [14]. Regardless of whether the fast-charger is connected to the LV or MV networks, it must be possible to control the system in accordance with the NCRs in Germany. With an increasing penetration of e-mobility, it will be important to develop the ability to coordinate network control signals especially during critical power grid situations [7].

Single-phase and two-phase loads can cause phase unbalances in the network, which can have negative effects like increased losses on electrical lines and transformers [16]. Charging on a single-phase, for example at the household socket, also results in longer charging times [6]. Three-phase charging is not only better for the network, but also more convenient for residential consumers in Germany, where three-phase supply is standard for household connection. The NCRs in Germany specify conditions for all grid users at every voltage level and as such, ECS must also comply with these requirements, especially in relation to network disturbances. Market incentives or support programs should also contribute by establishing three-phase charging as standard.

The integration of e-mobility is expected to increase the demand on the network especially during evening hours, a so-called “after-work” effect. Mechanisms will be required to control charging and distribute the demand throughout the day. A scenario where charging is controlled can halve the demand peak, depending on the type of system (see Figure 2.) [15]. The EU directive 2014/94/EU on the deployment of alternative fuels infrastructure already promotes the use of intelligent metering systems to allow adapting charging processes to support the power grid. The technical specifications have already been developed and can support the development of technology for EV and ECS [15].

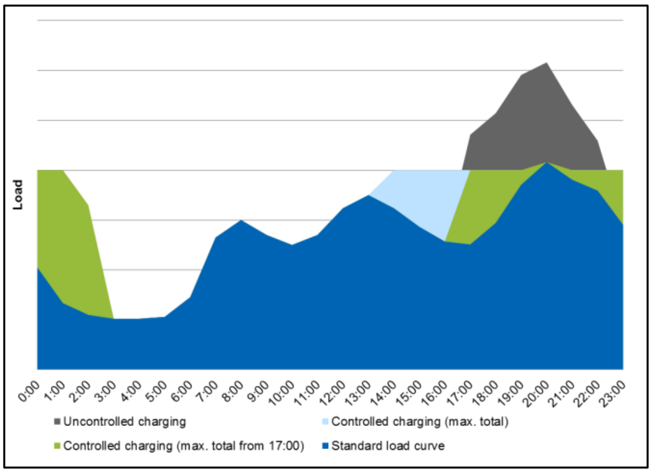

Figure 2. EV load profile example for single household [7]

The promotional programme launched by the German government, "Electric Mobility Showcase", finds that a smart charging system is necessary to balance the fluctuations from VRE generation. Projects were showcased under this premise aimed at creating a network that would connect generators, consumers and energy storage systems in an intelligent manner, including local virtual power stations all the way to a transregional smart grid [17]. Smart charging was found through the PlangridEV project, included in the meta-study, to be the most critical aspect to allow for a mass roll-out of e-mobility without the need to reinforce the network infrastructure [7]. The project "Controlled Charging V3.0" funded by the Federal Ministry of the Environment, Nature Conservation and Nuclear Safety established that a significant increase of e-mobility integration can already be achieved through temporarily switching off charging processes [7].

A simplified charging control based on time-of-use tariffs can lead to mass effects and thus to an increase in network load. A controller that also takes into account network aspects can reduce the network load and, for example, reduce the charging capacity in critical situations [7]. As found by the meta-study, grid-focused charging control is more efficient than market-led charging. Market signals must therefore be coupled with network-relevant parameters to find the most cost-efficient solution.

D. *Additional e-mobility services*

Services can be provided by charging and discharging strategies through V2G and further ancillary services such as frequency and voltage control [14]. V2G technology supports the safe operation of the grid by recovering the energy stored in the batteries of EVs and feeding it back into the grid. This technology could help network operators in keeping grid stability during critical grid situations, such as a major mismatch between generation and consumption. These flexibility options are an important building block for network operators in mastering the challenges of the energy transition while keeping grid expansion as low as possible [6].

III. KEY FINDINGS FROM THE META-STUDY

A. *Central parameters for future network planning: simultaneity and local network situation*

The increase in network load is the key parameter for evaluating the effects of e-mobility integration on the network. The network load resulting from the integration of e-mobility is dependent on two main factors:

1. the number of EV, their charging curve and charging "simultaneity"
2. the situation in the respective local distribution network

The load on the network was studied through an analysis of penetration and a simultaneity factor (SF), which represents the probability of a group of consumers drawing power from the grid simultaneously. Figure 3. shows the increase of network load with respect to the reported penetration rate.

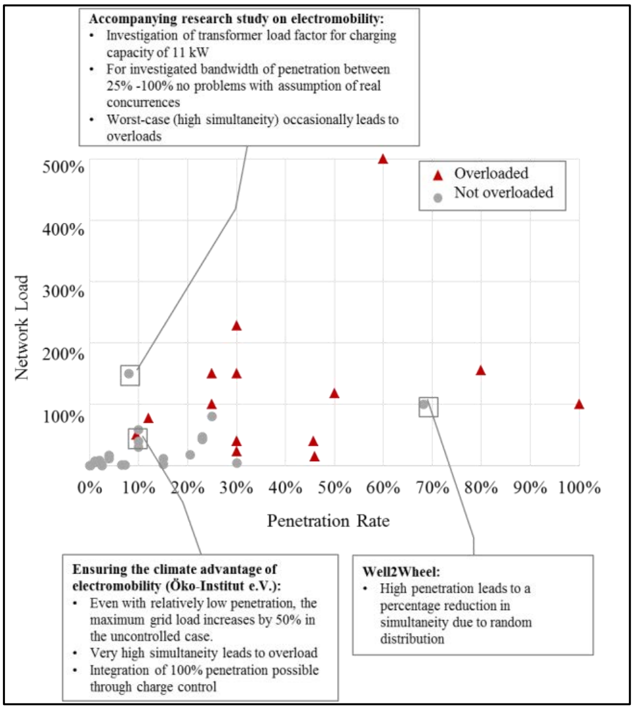

Figure 3. Network load in reference to penetration rate of e-mobility in Germany [7]

Although 44 scenarios show an increased probability of overloading due to an increasing network load, there is no direct correlation between these parameters. In addition, the SF was compared with these two parameters. Scenarios with high penetration but a low SF, show similarly high relative increases in network load as scenarios with a relatively small proportion of e-mobility and high SF.

The network load depends in particular on the network topology investigated, the network planning (before e-mobility integration) and the location of ECS in the network as well as their usage.

B. *Path for e-mobility development still unclear*

There is a high degree of uncertainty about the future design of e-mobility and its effects on the power grid which presents a high risk for network operators. Tools are necessary for network operators to deal with this uncertainty and respond to the local changes in network load.

Currently network operators are not able to fully monitor the load status for distribution networks at MV and LV levels. In the long term, a targeted and maximum utilization of the existing network capacity would become possible with increased monitoring and better control at these levels.

The development of e-mobility does not depend solely on technical factors. Political decisions also play a major role, particularly in promoting the purchase of EVs and driving the expansion of charging infrastructure forward.

C. *ECSs must be responsive to network signals*

An analysis of the scenarios with controlled and uncontrolled charging show that intelligent control concepts can significantly reduce the simultaneity of ECS and the network load. As it could be expected, the majority of scenarios with network-based control show a comparatively lower increase in network load. These control systems allow to shift charging sessions to periods of lower network utilization as well as to limit charging simultaneity.

Although the introduction of network-based control has often led to a strong reduction in network load, this is not sufficient to avoid overloads in the case of larger e-mobility penetration rates. Further measures in grid operation or in the form of grid expansion would be necessary to counteract this effect. Other study results postulate that network control reduces the network load to such an extent that operating resource overloads occur often in areas with high concentrations of e-mobility and therefore no large-scale network expansion is necessary.

Network-based control is recommended as a safety measure for the power grid and for optimising network expansion through increased forecasting reliability - similar to “peak shaving” of wind and PV plants to avoid additional investment on the network [18]. This control mechanism, which can be deployed at short notice by the network operator, is decisive for a successful network integration of e-mobility.

D. *Flexibility through e-mobility*

Local synergies between e-mobility and RE generation are possible. The prerequisites for a contribution of e-mobility to the system integration of RE are both controllability and network expansion in the medium term.

The integration of e-mobility could have positive effects on networks with high RE penetration. The meta-study identified the following two positive factors:

1. Network-based charging control at local energy management level allows a higher RE penetration. This is however limited by network conditions, particularly at LV level.
2. Market-based control dependent on stock exchange prices can support e-mobility integration while taking into account the availability of generation capacity. This could lead however to a higher simultaneity and thus to a demand increase.

The deployment of e-mobility charging infrastructure will present opportunities to increase the flexibility of the network and thus facilitate a higher penetration of RE. However, a compromise is necessary between a network-based control desired to avoid local network expansion and the market-oriented control which leads to higher simultaneity.

E. *Changes in regulatory framework are needed*

The current regulatory framework does not favor the use of smart grid solutions over an exclusively network expansion. Innovative solutions, such as smart charging represent a comparatively cost-effective, efficient and quick solution to be implemented.

The V2G concept can allow, via a bidirectional interface at the charging units, to employ batteries on EV for network and system services. However, these additional services are not always economically viable. In addition to the high cycle costs of batteries, current regulatory framework for network charges as well as the design of the balancing energy market have an effect on the cost. The regulatory framework should therefore be adapted to promote innovative technical solutions such as smart charging and V2G technology. These in combination with conventional network expansion could present the most cost-effective strategy for the integration of e-mobility and likely the optimal option for network operators.

IV. CONCLUSION AND NEXT STEPS

In addition to the challenges posed by integrating additional loads into the network, e-mobility will also offer opportunities to achieve a higher share of RE and to contribute to the development of the “Energiewende”. A well planned roll-out of e-mobility can help achieve a greater utilization of RE and prevent local network congestion, thereby limiting additional investment on network infrastructure [14]. As well as charging control, e-mobility could provide network supporting services in the future, such as V2G technology and frequency control.

Although the effects on the power grid have been thoroughly analyzed, there is high uncertainty regarding the development of a planning corridor necessary to reach 6 million EVs by 2030. In order to compensate for this risk, tools should be developed for network operators to better monitor local networks and to respond to the increased network load. Nevertheless, the evaluations from the meta-study confirm that no area-wide network expansion demand is to be expected at low penetrations. Measurements from ECS behavior will help to develop grid models through which lessons can be learnt about the effects from e-mobility on the network. It is however critical to work already on developing technical and regulatory mechanisms that consider future grid requirements.

A. *Further research and requirements*

The following points were identified through the meta-study as areas that require future research:

a) Assumptions regarding simultaneity are rarely shown in previous studies. In future studies, simultaneity should always be taken into consideration and reported for better comparability.

b) Current technologies and developments must be taken into account. Future research projects should use comprehensive, forward-looking models of mobility concepts and present analysis of the impact at different voltage levels.

c) Most studies focus on suburban networks. Future studies should examine rural networks, in particular with regard to the challenges of voltage stability and the possibility of reactive power supply by ECS.

d) Apart from current and voltage limits, voltage quality aspects (also to be considered in distribution networks) are rarely addressed. Future studies should also consider the influence on voltage quality, especially load unbalances in single-phase charging as well as harmonics.

e) Only a few of the studies investigated quantify the need for network expansion. Even when this is considered, the statement is limited to selected model networks. There is a need for research to determine grid expansion requirements based on the network distribution (i.e. urban, rural).

The power grid provides the backbone to support the development of e-mobility. Many necessary requirements for EVs as new grid users have been identified. It is now critical that these are implemented to support the aim of achieving 6 million EVs by 2030. The continuous development of technical rules will provide the framework for their grid integration and ensure a safe and efficient operation of the future power grid.

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