Fundamentals for Planning and Operation of Urban Distribution Power Systems with Integration of Electromobility and Heating Sector

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***Abstract*— This contribution presents preliminary results of a research project that tackles the issue of electrifying the heating and transport sectors in urban distribution power systems. The paper starts with presenting the concept of a load forecast demand model that considers the different trends and developments affecting cities, in particular the integration of electrified transportation sector (eMobility) and the heating sector (called as new loads). The paper then continues with an explanation of the work to be done within the scope of the project. Germany-wide scenarios for new loads are forecasted in the years 2030, 2040 and 2050 and afterwards regionalised up-to street level. In parallel, a selection of representative power networks is reached after performing a clustering analysis for the collected Low Voltage (LV) and Medium Voltage (MV) networks. After that within the scope of the project, several remedy measures are considered including conventional and innovative technologies. These remedy measures are then compared to each other on an economic basis. Finally, the project concludes new guidelines for the planning and operation of urban distribution power systems in order to prepare it for the future transformation of loads in cities.**

Keywords—electrification of heating sector, integration of electromobility, load demand model, power demand model, urban distribution power systems

I. Introduction

The transition of the electrical power systems represents an unprecedented change of the energy landscape. The increase of Decentralized Generation (DG) units in the distribution network on one hand and the integration of new electrical loads like Electric Vehicles (EVs) and Heat Pumps (HPs) on the other hand pose enormous challenges for Distribution System Operators (DSOs). Whereas renewable energies based on solar radiation and wind power are a fluctuating energy source and need high installed capacities to enable a significant contribution to the electrical power supply, the new electrical loads are flexible demand units with new consumption behaviour. While DG and their infeed in general poses a challenge for rural distribution networks, the power supply of new loads drives the network expansion in urban areas.

The integration of eMobility and HPs requires the adaptation of planning and operating principles for urban distribution power systems, in order to incorporate network optimisation and expansion measures. Load increase, the characteristics of the new load patterns and the current main drivers in the power system - decarbonisation, electrification, decentralization and digitalization- need to be taken into account while adapting the planning and operating principles.

The following study is part of the research project “New Planning and Operation Principles for urban distribution power systems in the context of the energy transition” (POP) funded by the Federal Ministry for Economic Affairs and Energy. The project aims at defining new planning principles with consideration of innovative planning methods as well as innovative network equipment for urban distribution power systems from low voltage up to the high voltage level. With the new principles an economical comprehensive optimum of different intelligent and conventional measures and components shall be derived. The project is the follow-up of a project conducted between 2013-2016 which focused on rural distribution networks and resulted in the publication of guidelines for planning principles for rural distribution networks.

The POP project started in October 2018 and has a duration of 3 years. The steps for deriving the planning principles for urban distribution power systems under consideration of innovative applications are shown in Fig. 1.

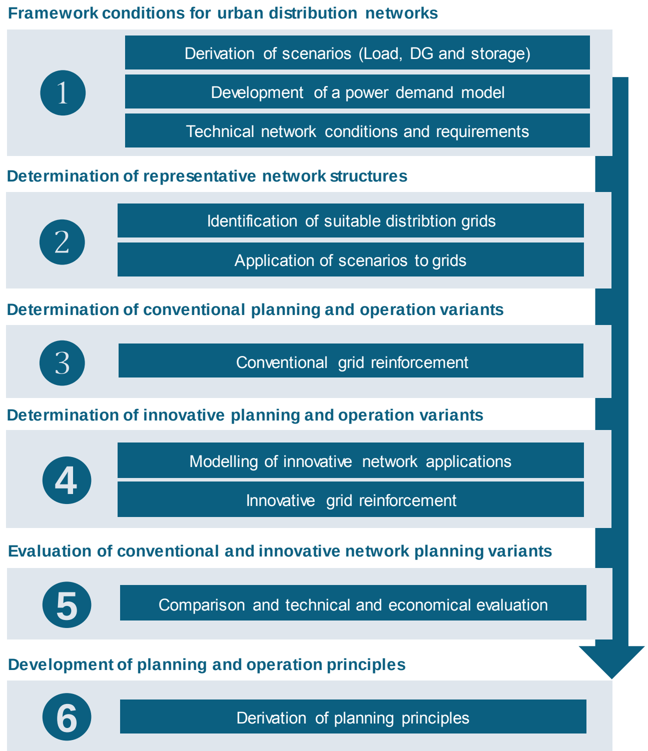

Fig. 1. Project steps for deriving planning principles for urban distribution power systems.

There are several studies focusing on quantifying the need of expansion of distribution networks and assessing the impact of applying innovative components and concepts in the distribution planning, but there is no uniform strategy for planning the reinforcements of urban distribution power systems with regards to the rising requirements and innovative technologies.

Therefore, this paper outlines a methodology that allows the definition of planning principles that consider innovative technologies based on existing distribution networks.

The focus of this paper is the boundary condition assessment of urban distribution power systems and the development of a power demand model, considering eMobility as one of the main drivers. Furthermore, an outlook to future research points and POP project work packages is presented.

II. Development of Urban Distribution Power Systems

A. *Trends and Impact Factors*

As a first step and as a basis for all subsequent tasks, the characteristics of urban distribution power systems are identified. In this context, the current trends and impact factors on the development and – directly or indirectly – on the energy supply system in urban areas are defined based on an extensive literature research. Fig. 3 shows an overview of the identified trends in urban areas. One focus topic for example is the influence of new mobility concepts (e.g. intermodal mobility) with simultaneous electrification of the transport sector on the electricity consumption in cities.

In order to develop a load forecast model, the trends were linked to the development of the urban energy consumption by specific impact factors displayed in Fig. 2. In the first step, the trends are assessed qualitatively, whereas later on a quantitative evaluation is carried out within the load forecast model. The considered electric loads are divided in five main categories: residential, commercial, industrial, EVs and heating sector. While the first three are considered as conventional loads, EVs and heating sector are treated separately. In addition, the industrial loads are excluded from the demand model and handled separately since they serve as single isolated cases.

B. *Evolution of Load Types in Distribution Power Systems*

To determine the future network requirements, long-term planning for urban areas will be conducted in the scope of POP project. The planning is based on the definition of scenarios for future loads and generation units, where the three target years 2030, 2040 and 2050 will be evaluated. 2020 is the planning reference year. The scenario definition is based on the development of conventional loads and relevant boundary conditions, on the defined impact factors, as well as on an upper and lower bound scenario for the development of the EVs and HPs.

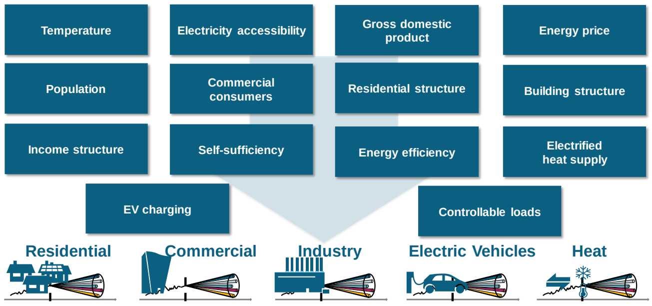

Fig. 2. Identification of essential impact factors on electric loads.

Both, the development of conventional loads based on determined input parameters for the load forecast model (see section III) and the scenario definition are derived from the results of multiple studies that take current technical, socio-economic and political conditions into account. For the respective impact factors for the conventional load development, a qualitative assessment of the trends to be applied is carried out according to the literature researched [1] [2] [3] [4]. As input for the EV development, one conservative and one optimistic scenario are used for the market ramp-up from 25 different scenarios from a total of multiple analysed studies, which shows the greatest similarities with the identified trends and impact factors. As for power-to-heat systems, HPs for domestic use are considered as (new) electrical loads. In analogy to electrified individual mobility, a conservative and an optimistic scenario are used for the market ramp-up. Fig. 4 outlines the results for the scenario definition of EVs and HPs in Germany from today until target year 2050, the data comes from [5] [6].

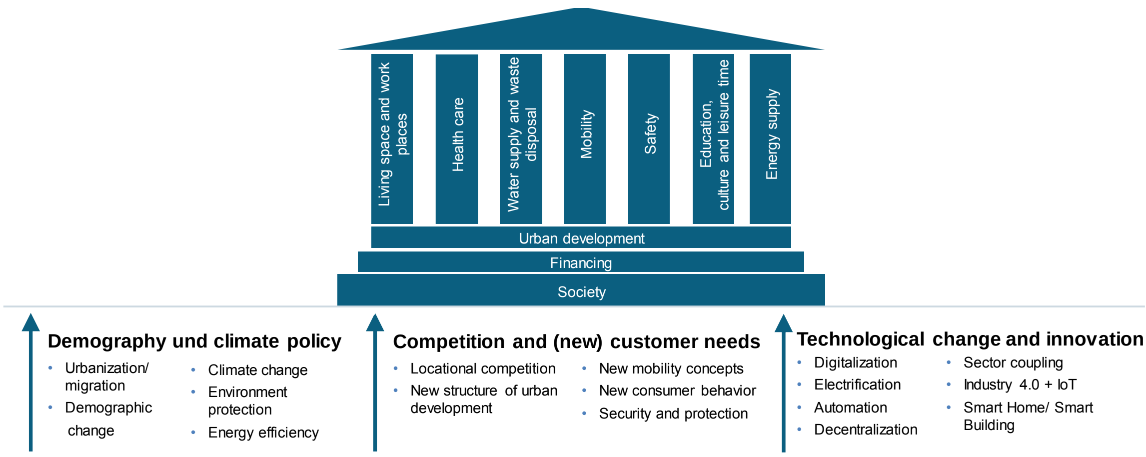

Fig. 3. Urban development and their trends.

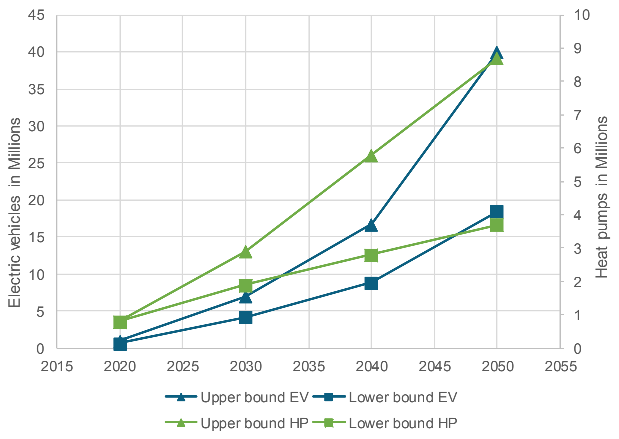

Fig. 4. Development of EV and HP for the scenario definiton in Germany.

In order to provide expansion scenarios for all examined networks, the Germany-wide scenarios both for EVs and HPs are regionalized by using market data like income and building structure [7]. The regionalization of Germany-wide scenarios on a local distribution level is essential to determine the new loads to be connected in the respective LV networks. For instance, a parameter taken into consideration in regionalization methodology is that the integration of private charging infrastructure happens predominantly in detached and semi-detached houses. The EVs are distributed on a street level by applying an iterative Sainte-Laguë method based on the household net income and the building structure.

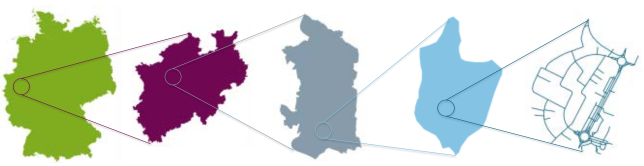

Fig. 5. Methodology of regionalization of EV and HP scenarios.

The private EV scenarios are accompanied by scenarios for the electrified Public Transport (e-PT) in urban areas. It can be foreseen that the scale of the e-PT will continue to grow in the future. In contrast to the private EVs, which are normally connected to the LV level, the charging structure of e-PT - due to the high connection power - is connected to the MV or even to the High Voltage (HV) level. Within the POB project e-PT are fed with depot and "on the way" charging systems based on a stationary wired technology. Two ramp-up scenarios are considered. A scenario with 100 % battery-operated e-PT in 2040 is defined, and a second scenario with 50 % battery-operated and 50 % fuel cell-operated e-PT in 2040 is determined. In both scenarios it is assumed that there will be a significant increase in local public transport, which will result in an increasing number of electrified buses and the corresponding number of bus depots, or in increasing depot sizes.

III. Power Demand Model

In order to investigate network scenarios and consider the load development, a demand model for the long-term forecast of residential and commercial loads is developed.

A. *Methodology of the Demand Model*

The flowchart of the demand model is shown in Fig. 6. The model is a 3-phase process and is based on a combination of a statistical and a deterministic model. This model structure originates from the available database used for forecasting future load development.

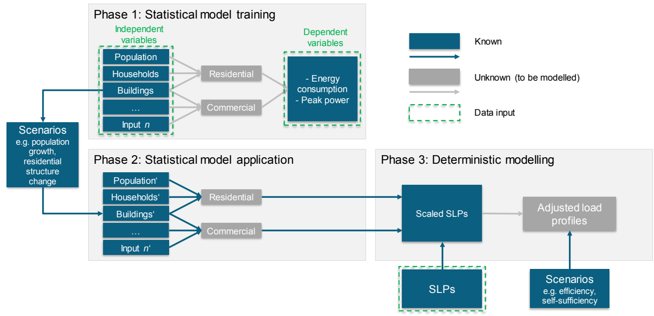

Fig. 6. Process steps of profile-based long-term load forecast.

The statistical model is used where available historical data can be used to determine the influence on the electrical load (e.g. population, buildings and income structure) and to decompose the energy consumption into residential and commercial sectors. For new applications like EV, HP and degree of self-sufficiency whose influence cannot be identified based on historical data, the load development is conducted by a subsequent deterministic model phase.

Using the demand model, specific load profiles for residential and commercial loads for given scenario conditions can be determined. These profiles are modelled based on the historical and the emerging trends. The process steps for this profile-based long-term load forecast are as follows:

Phase 1: Statistical model training

The model uses a linear regression approach with a constrained elastic net algorithm. Based on available network data, energy load data and collected socio-economic data such as the number of households and the income structure (data from market research institute or OpenStreetMap) the model coefficients are determined within the model training. This is done by minimizing the loss function of the model defined as penalized sum of the squared errors. It takes into consideration the error between the modelled and the measured energy consumption, the error between the modelled and measured peak power, as well as penalties for over-fitting. The available data comprises load profiles from distribution substation level (MV/LV substations), measured values at house connection level and Standard Load Profiles (SLP).

Phase 2: Statistical model application

After the model determination the defined scenarios are applied to the model in the second phase. As a result, energy consumption for the specific scenario use case for residential and commercial loads are generated.

Phase 3: Deterministic modelling

The subsequent deterministic modelling part as phase 3 uses the decomposed energy consumption to scale the SLPs and adjusts the profiles based on scenarios for the new energy technologies, such as EV and HP.

IV. Further Research Points

A. *Clustering of Low and Medium Voltage Power Systems*

Within the framework of the POP project, the planning principles for urban distribution power systems from HV to LV level are determined based on real networks provided by six German Distribution System Operators (DSO). The methodology aims to generate general planning principles on basis of a limited number of real distribution networks.

In order to determine reference networks, that are representative to derive the guidelines, it is necessary to select a network which shows common characteristics from a set of networks. For that reason, the chosen networks should cover an extensive range regarding its technical and physical characteristics. In this case, this is accomplished by clustering the available LV and MV grids according to network structure parameters (HV networks are not clustered as all provided grids are investigated). Parameters used for the clustering in LV level are the number of building connections per kilometre LV line length (connection density) and number of metering points per building connection (load density). Whereas the clustering parameters in MV Level are the number of distribution substation per kilometre MV line length and number of metering points per distribution substations. Exemplary results of the LV network clustering are shown in Fig. 7.

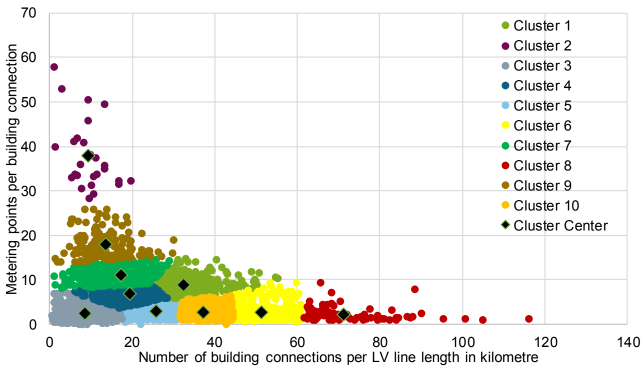

Fig. 7. Clustering of LV networks into 10 Clusters.

The network clustering and load forecast including EVs and HPs represent the input data for the subsequent scenario implementation and the network planning. The overall methodical procedure describing the work steps, causal direction and data sources are shown in Fig. 8.

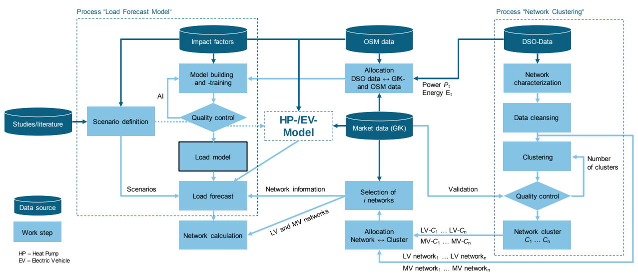

Fig. 8. Overall flow chart for the systematic appraoch of load forecast, network clustering and network selection.

B. Planning Power Systems Using Convetional and Innovative Technologies

In order to evaluate the impact of eMobility and the electrification of the heat sector and derive planning principles for urban distribution power systems the selected representative LV, MV and HV networks are planned considering the applied scenarios to reveal the necessary network reinforcements. By means of a load flow calculation as well as the use of applicable standards and directives (e.g. [8] [9] [10] [11]) technical limitations are analysed and the steady state of the network is evaluated by assessing possible overloading of equipment and voltage deviations which result from new loads in network e.g. caused by fast charging or electric heating.

The networks are planned considering conventional reinforcements including the replacement or additional installation of network components such as transformers and cables as well as the optimisation of the topology. It will be evaluated to which extent these conventional planning and operating variants can be used to meet given network requirements, taking into account the increasing number of EVs and HPs. The planning of the networks is then complemented by the application of intelligent network components, e.g. network automation systems on the LV and MV level, use of load flexibilities and network control equipment. The planning process for both the conventional and innovative approach results in:

- list of measures that can be performed to overcome the identified challenges and
- bill of quantity of network components for each assessed network variant.

To define a set of key technologies to be considered in the adapted grid planning guidelines, the following steps need to be conducted: A technical analysis categorizes the technologies by their functionalities. Subsequently, cost scenarios for distinct products are used to define general cost scenarios for the application of innovative technologies and functionalities that represent the basis for a comparison of different planning variants. A preliminary selection of innovative technologies and their functionality is displayed in Table I.

To compare different variants typically the conventional planned target networks, represent the reference case for the evaluation of innovative planning and operation variants as they reflect today's fundamentals of network planning and development.

C. Economic assessment of the reviewed Technologies

Based on the bill of quantity an economic assessment of each scenario variant can be conducted considering both, Capital and Operational Expenditures (CapEx, OpEx). In consequence financial key performance indicators can be derived to evaluate the related costs of one variant and compare between different scenarios and variants. By doing so mandatory and optional network optimisation and expansion measures are identified and lead towards an efficient, reliable and sustainable integration of eMobility and HPs over the next decades.

TABLE I: EXTRACT OF THE CONSIDERED FUNCTIONALITIES AND TECHNOLOGY EXAMPLES:

Technology	**Impact**		**Network level**			
	Voltage	***Loading***	***HV***	***MV***	***LV***	***Across network levels/ repercussion***
Reactive power management	X		X	X	X	X
Voltage control at primary substation	X			X	X	X
On-load voltage controlled transformer	X			X	X	X
Voltage regulator	X			X	X	(X)
Static demand side management	X	X	(X)	(X)	X	X
Dynamic demand side management	X	X	X	X	X	X
Controlled operation of energy storage	X	X	(X)	(X)	(X)	X
Power flow control applications	X	X	X			
Decentralized grid automation systems	Requirement for different applications			X	X	X

V. CONCLUSION

While increasing installed capacity of DG presents a challenge to rural distribution networks, urban distribution power systems are facing network expansions due to the integration of new loads like EVs and HPs.

From this perspective the development of new planning principles for urban distribution power systems considering all kind of network extension measures including conventional and innovative applications can provide a helpful guideline for DSOs, who face the challenge to integrate EVs and HPs into their networks. Therefore, this paper presents the fundamentals and an abstract methodology as part of the research project “New planning principles for urban distribution power systems in the context of the energy transition” funded by the Federal Ministry for Economic Affairs and Energy, on how new planning principles are developed. The concept for a profile-based long-term load forecast model is presented and the method to clustering real MV and LV networks to select representative networks from a set of networks is described. Subsequently the procedure of performing conventional and innovative network planning variants and their techno-economical assessment is introduced.

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