Scenario-based assessment of the Smart Grid Traffic Light Concept including the Flexibility from Electric Vehicles

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Abstract – **In the course of the German energy transition, the share of distributed energy resources is increasing significantly. This transformation poses major challenges for the planning and operation of power systems since new generation, load and flexibility patterns might induce additional grid congestions. Exploiting distributed flexibility for grid-oriented purposes has been widely discussed as an alternative to conventional grid expansion measures for congestion management purposes. Against this background the smart grid traffic light concept has been proposed as an unbundling compliant concept to procure and retrieve grid-orientated flexibility in a timely manner. This may provide a cost-efficient grid integration strategy for the assets, while also supporting their market integration. However, the existing conceptual approach provides a high-level framework definition, rather than a concrete implementation proposal. Therefore, this paper focuses first on the specification and then on the simulative assessment of the concept. As a result, the paper aims at substantiating ongoing discussions with regard to the traffic light concept with particular focus on the role of electric mobility for flexibility provision.**

Keywords— smart grid traffic light concept, grid orientated flexibility, virtual power plants

I. Introduction

Due to the rising share of renewable energy sources (RES), accompanied by the decommissioning of large fossil power plants, the majority of generation capacities in Germany is shifting to the medium and low-voltage levels [1]. This decentralization process is intensified by the electrification of the transport and heating sector [2].
The increasing number of distributed energy resources (DER), such as photovoltaic systems (PV), battery storage systems (BSS), heat pumps (HP) and battery-powered electric vehicles (BEVs), invokes many challenges with respect to a cost-efficient market and grid-oriented integration strategy. Particular emphasis is laid on the holistic integration of BEVs, since high power charging demands and the expected simultaneity of charging processes give rise to the expectation that especially distribution grids will be pushed to their operational limits inducing bottlenecks [3].

At present, distribution system operators (DSOs) rely on very limited operational measures for congestion management. Besides curtailment measures requiring financial compensation for DER operators, DSOs fall back to grid expansion measures. The latter are not only time-consuming but also induce questions relating to the efficiency of expanding the grid to accommodate each worst case grid utilization scenario, since the relevant grid stresses only occur temporarily. Therefore, the use of DERs flexibility for grid purposes, as a way of mitigating congestion and thus reducing the need for grid expansion, is considered a viable alternative [4] [5].

In this context, the smart grid traffic light concept, as an unbundling compliant framework for the allocation of grid-oriented flexibility, has been widely discussed by several institutions in Germany [6]-[9]. This concept envisages a rule-based attribution of responsibilities. In stable grid conditions, market mechanisms have priority (green traffic light phase). In the event of bottlenecks the grid operator can carry out curative ultima-ratio interventions, such as curtailment of RES, irrespective of market schedules (red traffic light phase). The green and red traffic light signals reflect the present operating regime. In addition, the concept envisages an interactive/ hybrid phase (amber) in which the grid operator tries to prevent the fallback to ultima-ratio measures and thus the transition to the red traffic light phase by procuring and retrieving local grid-oriented flexibility of DERs in a timely manner.

II. Goal and Scope

The rather general framework set by the traffic light concept requires the specification of several features. Building on the approach presented in [10], this present paper focuses on the assessment of subsequent questions:

- How does the introduction of an amber phase affect the current grid operation paradigm?
- How can optimal threshold values be determined considering cost and effectiveness criteria?
- How suited are electric vehicles as grid-oriented flexibility providers?

For a substantiated analysis of the above mentioned questions, a comprehensive scenario framework for distributed energy systems simulations, comprising market and grid simulations, is set up and analysed.

III. Traffic Light Concept Specification

The proposed configuration in [10] defines a clear role assignment of the involved actors in a demarcated grid segment as well as their interaction schemes (communication and control). This features are shown in Fig. 1 and Fig. 2.

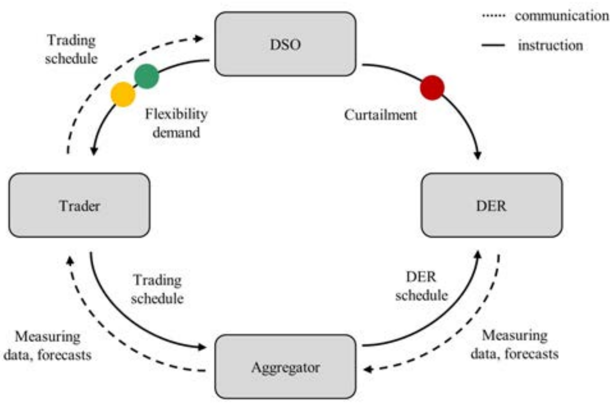

Fig. 1. Refined traffic light communication and control scheme [10]

The daily operational scheduling process (OSP) begins with the trader procuring load and feed-in forecasts of the subordinate aggregate units (bundling of the DERs via the aggregators, e.g. Virtual Power Plants). In addition, he obtains information on the flexibility available from the aggregation units. Based on this, the trader prepares an economically optimal, market-oriented, schedule for the DER- network and reports it to the DSO in compliance with contractual arrangements (e.g. a flexibility agreement according to the BDEW concept [6]).

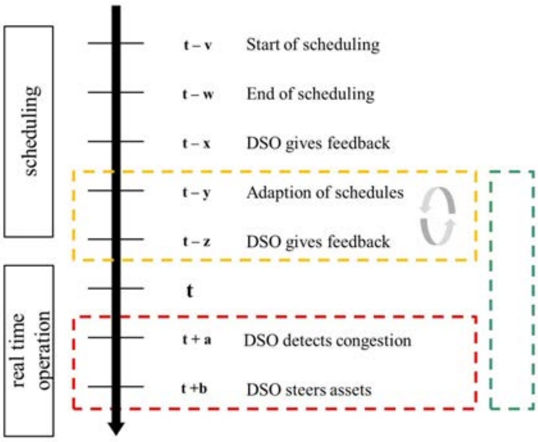

Fig. 2. Process scheme of the refined traffic light concept

The DSO subsequently carries out a state estimation taking into account the DER schedules and examines whether critical grid conditions can be expected in the relevant grid area. If no critical grid situation is anticipated, a green traffic light signal is activated and no intervention in the market activities is undertaken upfront. However, if a bottleneck is anticipated, the DSO informs the trader about the temporally and spatially specific flexibility demand within the scope of the amber phase signaling. According to the contractual agreement, the trader takes these requirements into account while adapting the market-oriented schedules. The grid-oriented flexibilities usage and the resulting adjustment of the market-oriented schedules might lead to a shift instead of a definitive prevention of the bottleneck. Therefore, the schedules' verification and grid-oriented flexibilities allocation might be an iterative process in the amber phase.

In real-time operation, the DSO can only distinguish between the green and red phases due to the short lead time to procure and retrieve grid-oriented flexibilities from DER. Potentially remaining bottlenecks in this phase are either caused by forecasting uncertainties that lead to incorrect grid state predictions at the time of the grid-oriented flexibility solicitation or by a limited flexibility provision of generators and loads.

IV. Scenario And Simulation Framework

A key feature needing specification in the context of the traffic light concept is the definition of the thresholds triggering the transition between the green and amber phases. Among the threshold parameters considered, both permissible voltage boundaries and the assets' utilization can be taken into account. The DSO could consider using the permitted boundaries prescribed by the technical regulations both for the switch to the amber and to the red phase. By setting stricter threshold values and thereby increasing his flexibility costs in the planning phase, the DSO could in turn increase the robustness of his operational planning. The key challenge hereby is thus finding a reasonable threshold parametrization compromise between low remuneration costs and the effectiveness of the congestion management approach.
In order to investigate these causalities, a comprehensive scenario framework containing a large variation of topology use cases is developed. The multitude of scenarios considered differ in terms of the grid topologies, the load and generation capacities in the respective grid area, as well as of the threshold parameterization of the amber phase.

A. Scenarios

As a basis for the investigations we refer to three model grids taken from the study in [11]. These represent typical low-voltage (LV) grids in various densely populated areas (rural, suburban, and urban) in Germany. Their characteristics are depicted in Table 1 and they differ in terms of static energy demand per year, and their topology.

TABLE I. Characteristics of the considered LV grids

grid typology	**model grid 1**	**model grid 2**	**model grid 3**
Area Classification	Rural	Sub-Urban	Urban
Energy demand of loads/ a	332,8 MWh	595,8 MWh	750,4 MWh
Sum of branch length	2,85 km	3,36 km	4,41 km
Num. of connected buildings	55	154	155

Model grid 1 (rural grid) is a grid with a supply structure dominated by private households. A quarter of the annual energy turnover is attributed to agricultural loads. In contrast, the supply task of model grids 2 and 3 is dominated by residential loads (94%/ 97%) and commerce, trade and services (CTS). Common to all is that they are arranged radially (partially open-looped). Model grid 1 consists of 150 mm² aluminum cables (NAYY 4x 150 SE) and three feeders. Model grid 2, on the other hand, is an overhead line grid with lines of type 4 x 95 AL and has 5 feeders. Model grid 3 is equipped similarly to model grid number 1 with NAYY 4x 150 SE cables and has 5 feeders.

For the installed DERs (e.g. PV, BSS, BEV), a large number of scenarios, as shown in Table 2, comprise various shares of the respective technologies in the grid. Thereby, those scenarios reflect possible development pathways of the generation and load structure in the regarded low voltage grid segments. The DERs are assigned to the buildings according to their holding capacity.

TABLE II. Relative shares of DERs in the considered scenarios

	relative diffusions		
	PV	stationary domestic BSS	BEV & charging station
reference	10%	0 %	0 %
scenario 1	50%	50%	0 %
scenario 2	100 %	100 %	0 %
scenario 3	10%	0 %	50 %
scenario 4	10%	0 %	100 %
scenario 5	50%	50%	50 %
scenario 6	100 %	100 %	100 %
power:	probability distribution	each 3,5 kW	each 11 kW
capacity:		each 12 kWh	each 60 kWh

In the reference scenario, the focus lays on examining the status quo considering only PV systems. Scenarios 1 to 6 allow evaluating the impact of the considered DER deployment pathways ceteris paribus on both the amount of gird congestions and the grid-oriented flexibility potential.

The selected two-dimensional combination possibilities for the threshold values (maximum asset utilization and permissible voltage band) of the amber traffic light phase are analysed in order to quantify the trade-off results between the costs and the effectiveness of the congestion management approach. To ensure the comparability of the calculated results, the per-unit system is used. The simulations envisage a reduction of the permissible voltage band from 0.95 - 1.05 pu in 0.005 steps to 0.97 -1.03 pu. Furthermore, the maximum component utilization of 1 pu is reduced in 0.05 steps to 0.7 pu. These variations yield a total of 35 possible combinations, which are investigated in separate annual simulations for the DER scenario and model grid. In total, 735 sensitivity calculations are carried out.

B. *Simulations*

For the simulations, we apply the tool described in [10]. This simulation framework structure is shown in detail in Fig. 3. It allows for market, network and flexibility mechanisms to be simulated, implicitly considering the defined actor roles and processes.

1) *Input*

Besides the described scenario specifications, the relevant generation and load profiles as well as the DERs technical parameters are provided as input. For BEV, the data consists of driving and charging profiles, as well as a daily timeline for the vehicles' targeted states of charge (SOC). These synthetic profiles are obtained using a BEV driving simulation model, which is based on statistical mobility data from the studies [11] and [12]. For the electrical demand of residential, agriculture and CTS loads, standard load profiles are used. PV profiles (forecasts and feed-in time series) are based on standardized feed-in time series available from the German National Meteorological Service (Deutscher Wetter Dienst – DWD) website.

2) *Simulation model*

The simulation model is divided into two major submodels that are iteratively applied for a one year period. In the first submodel, the day-ahead market-oriented operational scheduling process (OSP) is first carried out using a forecasted weather and market price scenario for the upcoming day as input. The OSP aims at maximizing the contribution margin of the local aggregation of installed DERs on the day-ahead spot market in Germany and is formulated as a mixed-integer linear problem (MILP), which incorporates technical restrictions of the DER and market constraints. Subsequently, taking into account the calculated market schedules and the predetermined threshold values for the traffic light phases, power flow calculations are executed within the grid simulation submodel. These results provide information about grid utilization, possible grid congestions and the need for grid-orientated flexibility. The latter is determined by means of optimal power flow calculations, which deliver the cost-minimal grid-oriented flexibility needs for each time step and grid node. Depending on the cause of the bottleneck, either positive or negative flexibility may be required. This information is fed into the market simulation submodel, which adjusts the market-oriented operational schedules of the DERs accordingly and forwards the updated schedules to the grid simulation submodel. This internal iteration procedure is terminated as soon as there are no more grid congestions or when the flexibility potential is depleted.

Finally, in the second submodel, the real-time grid operation is simulated using the synthetic real-time generation and load profiles as well as the DSO's grid-oriented flexibility retrieval. Thereby, it can be determined whether despite the flexibility retrieval congestions still occur in the regarded grid and the DSO has to resort to curtailment.

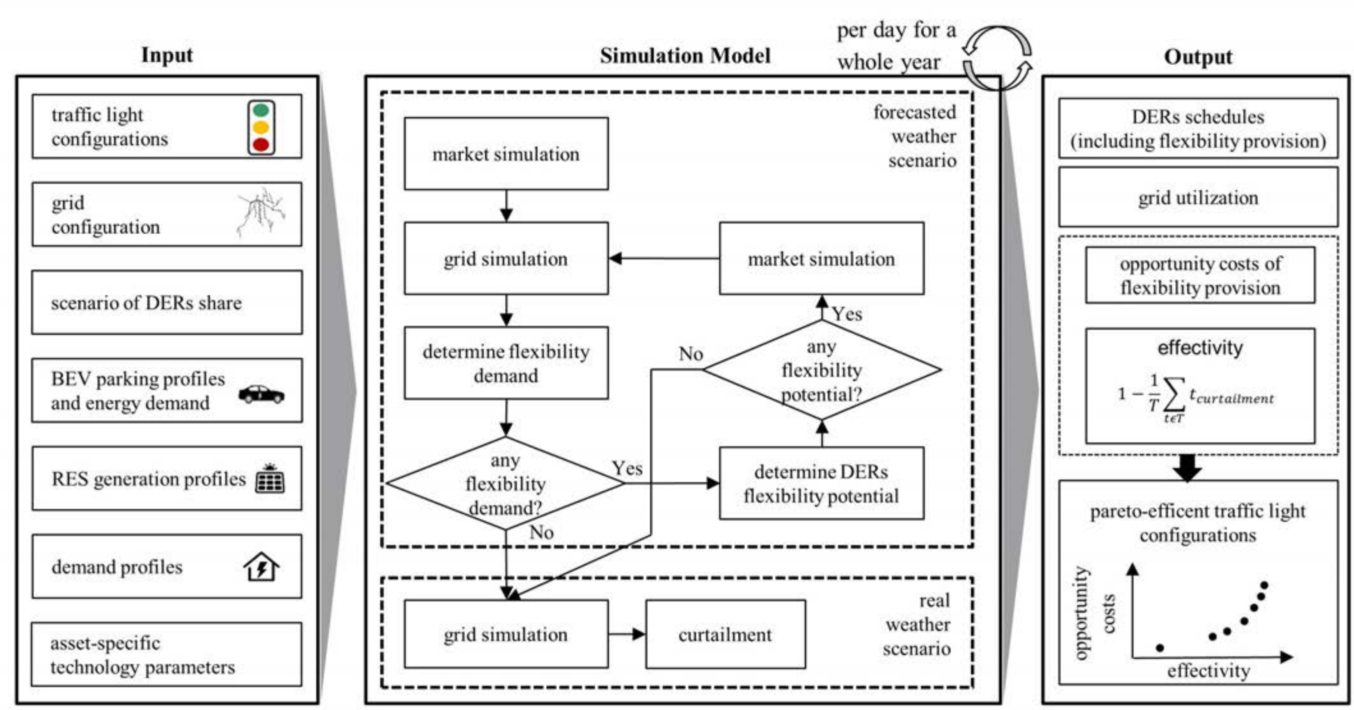

Fig. 3. Simulation Framework for the assessment of the smart grid traffic light concept under different scenario settings

3) Output

In addition to the results from the individual submodels, further evaluation parameters are calculated. The opportunity costs of DER operators resulting from the provision of grid-oriented flexibility correspond to the difference between the contribution margin of the initial and last market simulation within the one year period. Furthermore, the effectivity of the traffic light concept is calculated according to the formula shown in Fig. 3.

On this basis, the pareto-efficient traffic light threshold parametrizations considering these two efficiency benchmarks can be determined. In this context, a pareto-efficient configuration is characterized by the fact that neither measure can be improved (increase of efficiency, decrease in opportunity costs) by another threshold parametrization, without simultaneously worsening the other measure.

V. Simulation Results

A. *Effectivity and opportunity costs*

Fig. 4-6 show the relative effectivity and total opportunity cost results of the 735 simulation calculations, distinguished by grid topology and scenario. Each of the depicted markers reflects a simulation result over a period of one year.

In one color group (reflecting the DER share scenarios) for each grid typology considered, a total of 35 markers exist representing the different threshold parametrizations of the traffic light concept. In such a tuple, the markers located in the bottom right corner are deemed pareto-efficient. Accordingly, the pareto front per scenario is defined by the markers at the lower-right corner of the tuple.

In general, the results confirm that the less strict thresholds lead to lower opportunity costs but at the same time lower effectiveness as well. The combination of permissible voltage band and asset utilization yields no clear functional relation.

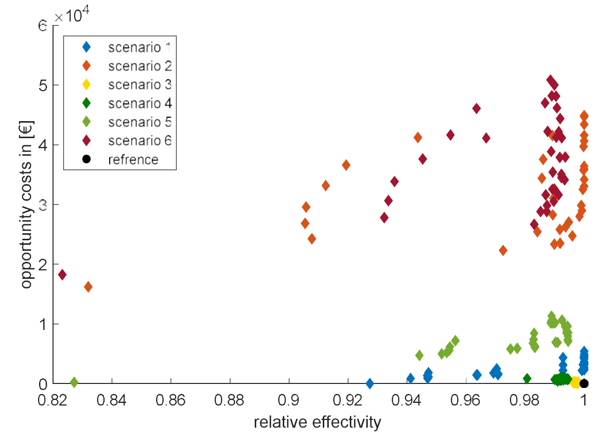

Figure 4: Results for the model grid 1: rural area

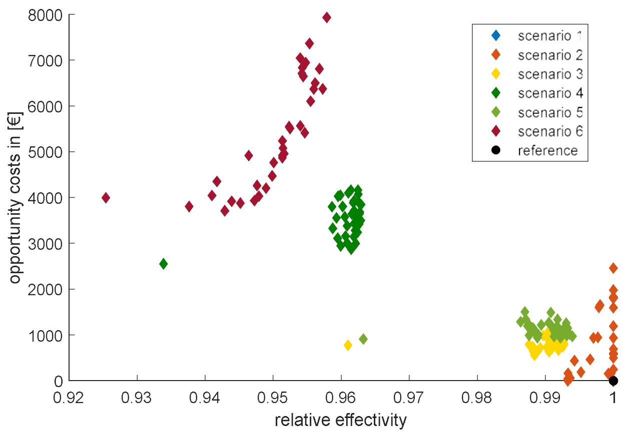

Figure 5: Results for the model grid 2: sub-urban area

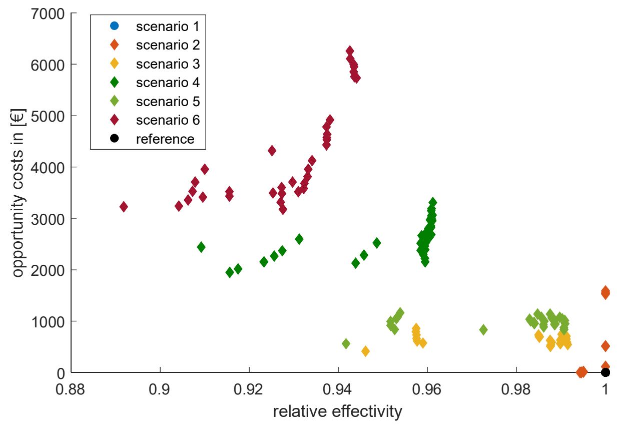

Figure 6: Results for the model grid 3: urban area

In view of the distributions of the colored marker groups for the different grid types, no conclusive pattern can be identified, thus not allowing to derive general conclusions with regard to the effects of the DER share scenarios and the traffic light threshold parametrizations. Each grid area thus requires an individual evaluation of suitable traffic light threshold values.

B. *Grid-Orientated flexiblity potential of BEV*

BEVs provide grid-oriented flexibility by either peak shaving or shifting the charging process. This flexibility is generally used to increase the grid nodes voltages and to reduce asset utilization by obtaining a more even grid utilization. The use of flexibility presupposes that the periods in which the vehicle is parked at the charging station are known one day in advance. Fig. 7 depicts the grid-orientated flexibility provision of all BEVs in scenario 6 for the different model grids.

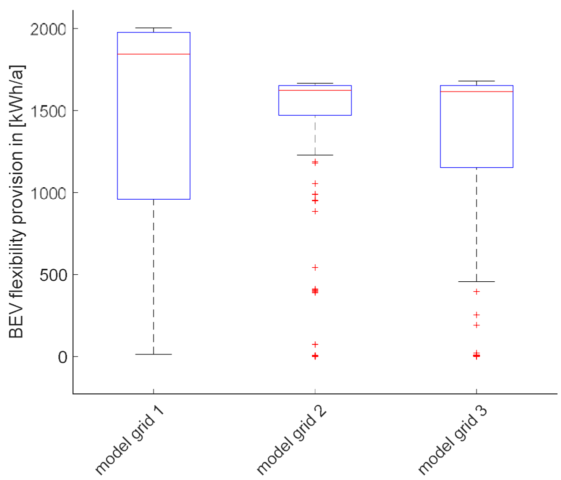

Figure 7: Flexibility-Provision of BEVs in the DERs share scenario 6

Although completely different conditions prevail, the median (red line in Fig. 7) of the provided BEV flexibility amounts to nearly the same value in the model grids in the presented extreme scenario 6. The median nearly equals to ~70% (~1700 kWh/a) of the annual charging demand. Furthermore, the interquartile range (blue box) indicates that in 50 % of all cases between 40 - 75 % of the charging processes are shifted.

In comparison, Fig. 8 depicts the distribution of the domestic BSS flexibility provision in the same scenarios.

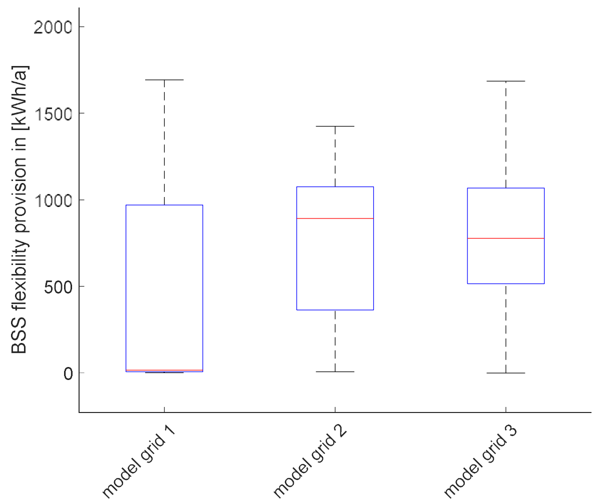

Figure 8: Flexibility-Provision of domestic BSSs in the DERs share scenario 6

In relation to the average storage capacities of BSS and BEV, the flexibility provision of the stationary domestic BSS is in maximum four times as high.

VI. Discussion

The introduction of the smart grid traffic light concept leads to substantial changes in the current grid operation paradigm. Its implementation needs to be accompanied by a change in the DSOs' understanding of their role. The former passive DSO must actively engage in congestion management, applying preventive rather than exclusively curative or expansion-related measures. These preventive measures require the day-ahead grid state estimation as well as the communication with the DER operators. However, in order for the DSOs to implement congestion management measures based on the traffic light concept, they need to have smart grid-ready control infrastructure and the incentive regulation ordinance (Anreizregulierungsverordnung) must create an appropriate legislative framework. An advanced level of automation, enabled by information and communication technologies (ICT), is an essential perquisite to enable the communication and data transfer between the individual players involved.

Quantifying the investment and operation costs of the traffic light concept poses a challenge for two main reasons. First, for determining the flexibility costs, the opportunity costs of DER must be known, which depend on their individual operational objectives. In this paper, it was assumed that DER were exclusively used by aggregators for trading purposes, but this is actually currently rather seldom the case for DER connected at low voltage level, which are rather used for covering self-consumption. Second, the DSO-specific trade-off between costs and effectivity must be known, which can largely vary depending on the risk aversion of the DSO and the specific circumstances in his grid (e.g. share of volatile DER).

Overall, the simulation results confirm the highly case-specific nature of the threshold parametrization. The comparative assessment between the introduction of the traffic light approach and grid expansion measures thus does not necessarily yield definite answers. It must rather take into account current and future framework conditions such as grid topology and DERs shares.

BEVs can make a contribution to congestion management due to the grid-oriented flexibility potential of their charging process. This is however highly dependent on the accuracy of the day ahead forecasts for the driving and charging processes, which is still considered challenging, in particular at the end-user level.

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