Usability of Flexible Demand and Generation in the BDEW Smart Grid Traffic Light Concept

Leonard Hülsmann, Jan-David Schmidt, Eckehard Tröster
Energynautics GmbH
Darmstadt, Germany
l.huelsmann@energynautics.com

Markus Koch, Uwe Ohl
EWR Netz GmbH
Worms, Germany

***Abstract*—High renewable feed-in from photovoltaic (PV) systems and wind power plants as well as new demand from electric vehicle (EV) or heat pumps (HP) pose new challenges for the electric distribution system. Peak demand or peak generation may overload the network only for short periods of the year and can be mitigated by demand side management instead of expensive grid reinforcements. In light of this, the German Association of Energy and Water Industries (BDEW) has developed the "BDEW smart grid traffic light" concept. Its aim is to communicate regional flexibility needs during the amber phase by means of a local flexibility market in order to safely return to the green phase, as opposed to the red phase where a grid congestion prevails. This paper investigates the working principles of this amber phase and the local flexibility market to effectively allocate flexibilities to resolve the congestion issues. For this, a radial medium voltage (MV) feeder in a rural area is analysed, supplying multiple small villages. The feeder is heavily penetrated by PV and wind generation but still only 17 % of suitable rooftop area is occupied by PV. Rooftop PV and wind power production has been further increased and new EV and HP demand was modelled to represent a scenario with a 75 % EV and HP adoption rate in households. Load flow calculations in DIgSILENT PowerFactory show that this leads to voltage violations and overloading outside the specified ranges. Two flexibility options, namely shift in EV and HP demand, are utilized in the traffic light concept and chosen based on their sensitivity to alleviate the grid congestion as well as their costs. The simulation results show that the concept can effectively allocate the most cost-effective flexibility options and reduce grid congestion due to peak demand to almost zero and lower curtailment due to peak generation by 75 %. The cost benefits of such a concept need however be weighed against the communicational and regulatory challenges that such a flexibility market poses.**

Distribution grid - Grid congestion – Overloading - Voltage violation - Flexibility market - Demand side management - Electric vehicles - Heat pumps - Traffic light - BDEW

I. Introduction

With increasing capacities of distributed renewable generation, such as wind power and photovoltaics (PV), being connected to the distribution networks, distribution system operators (DSOs) are facing a number of challenges. In grids that were designed for unidirectional flows from the transmission grid to the end customers, high shares of distributed generation can lead to voltage and overloading problems (grid congestion). Voltages have to be kept within a +/-10 % band of the rated voltage [1], while cables and transformers need to stay within their thermal rating. Congestion in the distribution grids may be aggravated further by increasing numbers of heat pumps (HP) and electric vehicles (EV) that suffer from a high simultaneity during evening times for EVs and cold spells for HPs. New control strategies are thus necessary to alleviate local grid congestion problems. Demand side management (DSM) can be used to shift HP operation and EV charging from times of high demand to times of low demand or excess PV and wind power generation, increasing the hosting capacity of a grid for both renewables and new demand.

Providing this flexibility at the right location and at the right time requires both IT infrastructure, that enables the necessary communication, and a defined regulatory framework governing all market participants to work effectively towards an efficient utilization of flexibility. In this sense, the German Association of Energy and Water Industries (BDEW) has proposed the BDEW traffic light system. It enables DSOs to signal a local flexibility market if a grid congestion problem prevails. For this, the amount of necessary flexibility is determined in a specific grid segment and for a specified period of time. Flexibility providers and aggregators then compete against each other and the most cost-effective providers are chosen.

This paper is building up on analyses already performed in [2], expanding the focus on grid congestion due to peak demand as well as wind power generation. It is part of the DESIGNETZ project [3], one of five showcases under the German funding program "Smart Energy Showcases – Digital Agenda for the Energy Transition" (SINTEG). It seeks to test the BDEW traffic light mechanisms through simulations on a model of a real distribution network with enhanced load and generation capacity, that will be described in Chapter II. The BDEW traffic light system is explained in more detail in Chapter III, followed by a description of the modelled flexibility provision from HPs and EVs in Chapter IV. Finally, simulation results are presented in Chapter V and a conclusion given in Chapter VI.

II. Model Setup

A. Distribution Feeder Model

To study the effects of demand and generation flexibility embedded in a flexibility market framework, steady-state load flow calculations are performed with DIgSILENT PowerFactory on a real 20 kV distribution feeder located in a rural area close to Worms, Germany. Only the MV network is modelled, no LV grids are considered. Loads are predominantly households, modelled with standard load profiles, and aggregated through a total of 32 MV/LV substations. Line types consist mainly of NA2XS2Y 3x1x150 cables. The feeder has a length of approximately 20 km, with a large 6.4 MW wind power plant located at the end of the feeder. Together with an installed rooftop PV capacity of 2.3 MWp in the LV grids, this is already leading today to large voltage deviations of close to 0.05 p.u. along the MV feeder, hence allowing only a small voltage band for the LV grids in order not to violate the EN50160 threshold of 1.10 p.u.

The current MV feeder has been adapted towards a scenario with increased wind power capacity, additional rooftop PV generation as well as new heat pump and electric vehicle demand, to represent a case study in which grid congestions regularly occur and therefore demand side management can be an alternative to overcome the congestion issue.

B. Distributed Generation Development

The already existing wind power plant has been expanded from an installed capacity of 6.4 MW to 10.6 MW.

Rooftop PV capacity has been increased based on a rooftop PV potential analysis. The suitable rooftop area facing south has been estimated at 13.6 MWp using OpenStreetMap building and residential area data [4]. A more detailed methodology for the estimation can be found in [2]. Currently, 17 % of the potential rooftop area is utilized. This amount has been tripled to 50 % to reflect a high DG scenario. This results in an installed PV capacity of 6.8 MWp.

C. Heat Pump Model

For this case study, a very high HP and EV penetration rate of both 75 % is assumed. Due to being located in a rural area but with high DG penetration, the MV network is considered as relatively strong. Hence, high penetration rates of HPs and EVs are necessary to have a significant impact on the grid operation. The penetration rates have been chosen deliberately to result in grid congestion both during peak demand as well as peak generation.

Heat pumps were modelled with an aggregated profile of 40 HPs. Measured solar irradiation and outside temperature values for the entire year 2015 in hourly resolution, obtained from PVGIS [5], were used as inputs for heating demand. Heating demand was disabled if daily average outside temperatures exceeded 15 °C. To determine hot water energy demand, the CREST demand model [6], a high-resolution stochastic model of domestic thermal and electricity demand, was used. The combined heating and hot water energy demand, in a 15-minute resolution for a whole year, was then scaled to the number of HPs per substation.

Normalizing the aggregated profile to a single heat pump results in the profile shown in Figure 1. It can be observed, that due to the aggregation, the maximum value of the

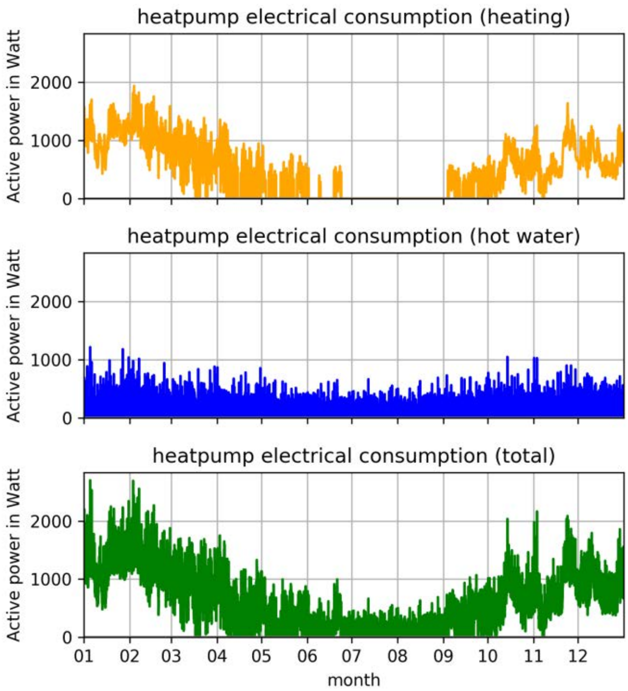

Figure 1. Electrical demand of the heat pump for heating, hot water and in total

averaged electrical consumption of the single heat pump is lower compared to the maximum capability of typical heat pumps (e.g. 3 kWel). Further, a seasonal trend can be observed in the total consumption, which results from the significantly lowered electrical demand for heating during summer as well as higher outside temperatures that improve the coefficient of performance (COP) of the heat pump. The electrical demand for providing hot water is also slightly lower in summer, mainly caused by higher outside temperatures.

D. EV Model

The EV modelling is based on a large-scale German mobility study [7]. In this study, data has been collected on trip numbers depending on weekday, time and activity as well as driving duration. Based on a model by [8], probability distributions are set up and a one-year driving profile is randomly created for each EV, specifying departure and arrival times as well as driving distance.

The driving profiles are then translated into a charging pattern with the assumptions as seen in Table 1. It is assumed that the EV is recharged only if the SOC at EV arrival has fallen below 50 % or if one of the next two trips will fully deplete the battery, assuming perfect foresight of the EV user's upcoming travels. Once the battery is charging, the charging process is not interrupted until the EV reaches full capacity or is departing again. If the EV would be charged as

Table 1. Assumptions on the electric vehicle parameters

Indicator	Assumption
Battery capacity	60 kWh
Fuel economy	20 kWh/100 km
Driving range	300 km
Charging power at home	11 kVA
Charging efficiency	93 %
Power factor	0.98 under-excited
EV share of total cars	75 %
Number of EVs	2292

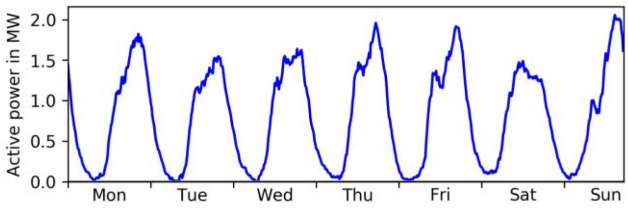

Figure 2. Aggregated electric vehicle charging profile of one week

soon as it returns, it would keep the average SOC high, which has detrimental effects on battery lifetime [8], [9]. Additionally, the proposed charging strategy has only negligible impacts on user comfort, as the number of times with full battery depletion during the trip increases only from 0.91 % to 0.94 %. However, it enables the EV to be charged also during times when grid congestion due to excess generation exists and may therefore offer an additional income source for the EV user. Figure 2 shows the aggregated charging profile for all 2292 EVs during one example week.

III. Description of BDEW Traffic Light Concept

A. *Definition of green, amber and red phase*

In two papers [9], [10] from 2015 and 2017, the German Association for Energy and Water Industries (BDEW) has proposed the BDEW traffic light concept. The idea behind this concept is that a three-step system indicating the state of grid congestion is established for distribution grids. In this regard, the green phase signalizes that no grid congestion exists and the DSO is able to keep voltage and loading limits within safe boundaries by his own means, such as voltage control at the primary substation or reactive power control. During the red phase, on the contrary, the DSO must intervene by curtailing load or generation, depending on the nature of the problem, to stay within the defined limits. Hence, unrestricted electricity trading is interrupted. In between the two phases an amber phase is defined, where a potential bottleneck is predicted in a defined network segment. In this phase, the DSO calls upon flexibility that is offered by market participants. If the requested flexibility can be met, the grid is returned to the green phase, if not, the DSO has to directly intervene according to the red phase. Hence, the amber phase allows for a more economical allocation of flexibilities. A schematic is shown in Figure 3.

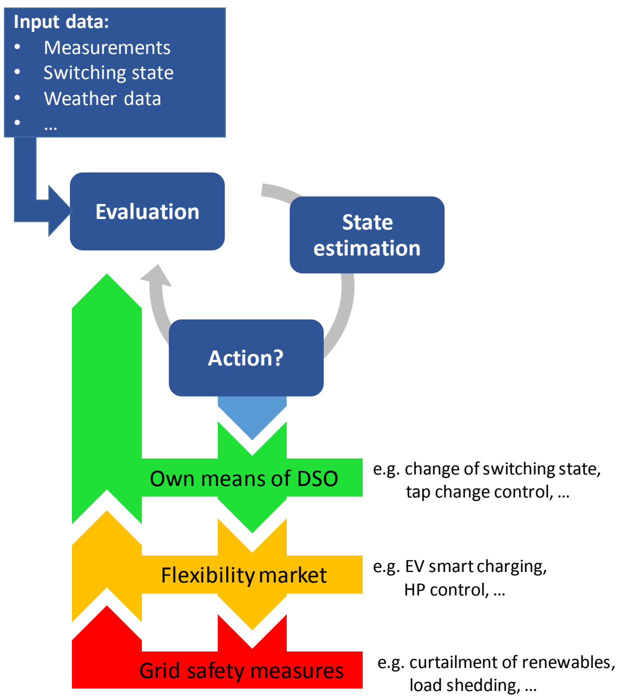

Figure 3. Flow chart of the traffic light concept

In this project, the traffic light concept has been put into practice on the distribution feeder described in section II.A to quantify its effect and test its ease of use. During the DESIGNETZ project, a real-life example of this traffic light concept is planned to be set up.

To allow for a voltage deviation of up to 5 % in the LV grid, a currently applied design criterion of the local DSO, a maximum voltage band of +/-5 % has to be kept within the MV feeder. Furthermore, according to the DSO's planning and operating principles, MV line loadings need to be kept below 60 % during peak load situations to allow for a maximum loading of 120 % during n-1 situations. During times of peak generation, however, line loadings are allowed to increase up to 100 %. The red phase is evoked if any of the permissible thresholds are exceeded.

Table 2. Applicable voltage and loading limits to stay in the green phase

	Current I_{max}	Voltage deviation ΔU
Load situations	≤ 60 %	± 5 %
Generation situations	≤ 100 %	± 5 %

With a better knowledge of voltages in the MV and LV networks, e.g. by means of a wide area voltage control, these limits can be expanded, reducing the need for flexibility.

Figure 5 shows the times of the year where a voltage or overloading violation occurs. The following observations can be made:

- On the demand side, frequent overloading occurs for winter evenings due to high HP demand (see Figure 1) combined with high EV demand in the evening (see Figure 2).
- On the generation side, the predominant impacts are overvoltage problems during days with high wind speeds and, either blue sky conditions during day with high PV generation or during night with low consumption.

Both situations would initiate the red traffic light phase and the DSO would have to intervene. The purpose of this paper is now to define the amber phase in which the grid congestion situations are forecasted (assuming perfect foresight) and flexibility is called upon to mitigate the grid congestion and bring the system back into the green phase.

B. *Flexibility List*

There are two mechanisms described in [10] to put a flexibility market into practice: A quota-based system and the flexibility list. In this paper, the working principles of the flexibility list are applied and will be introduced next.

The flexibility list describes within which boundaries, or flexibility bands, the active power output of all flexible users (here HPs and EVs) has to operate. Hereby, it specifies the maximum feed-in (Pmin) and demand (Pmax) that limits the combined output power of all flexibility providers, adjusted by their respective sensitivity, to stay within the allowed

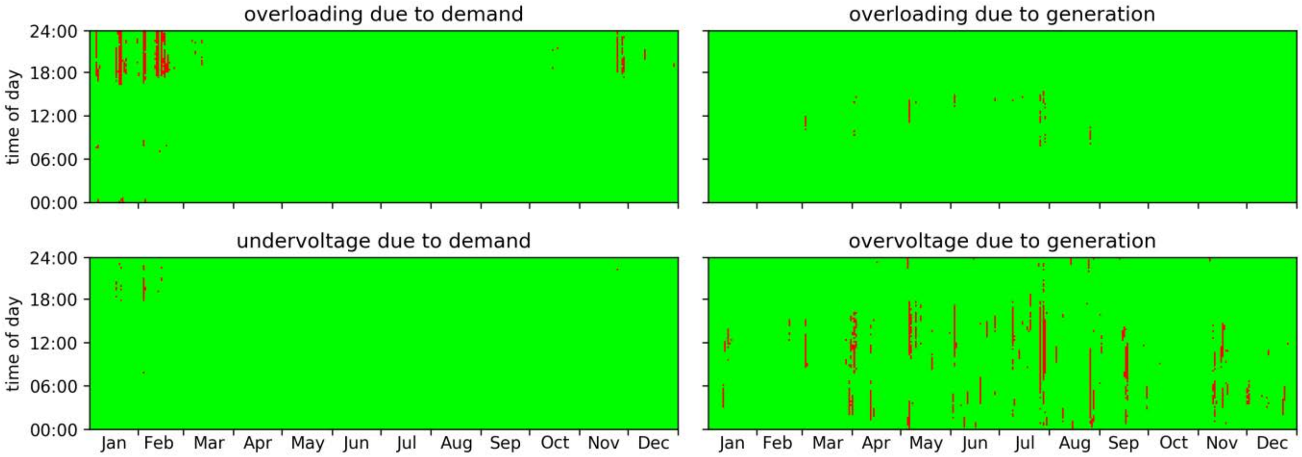

Figure 5. Grid congestions without flexibility use throughout one year, indicated by the red phase

voltage and overloading (current) limits. An example is shown in Table 3.

The voltage and current sensitivity, shown in the network diagram in Figure 4, indicate the physical impact any change in power output of the flexibility has on the applicable grid congestion. The voltage sensitivity is based on the resistance between the HV/MV substation and every MV/LV substation. In the analysed distribution feeder, voltage violations typically occur at the end of the feeder. Hence, also flexibilities at the end of the feeder have a higher impact on the voltage than those at the start of the feeder. Conversely, overloading problems typically occur at the start of the feeder. In the analysed network, this is the cable section between substation 01 and 02. The cable between the substation 01 and the HV/MV substation has a larger cross section, thus a higher thermal rating. Also here the current sensitivity increases towards the end of the feeder, as additional line losses lead to a greater impact of any change in power output. Hence, to have the same impact on grid congestion, twice as much flexibility with a sensitivity of 0.5 has to be activated compared to one with a sensitivity of 1.

In electricity networks with a higher complexity, e.g. with a meshed topology, grid congestion may occur at different locations based on the load and generation situation. Here, additional flexibility sublists may have to be defined with their own flexibility bands that govern the power output of all flexibility providers.

Table 3. Example of a flexibility list that lists the current flexibility need for a specific grid segment as well as all flexibility providers with their respective sensitivities

Flexibility list		
Grid operator	**Grid segment**	**Time**
EWR Netz GmbH	MV grid ID 1234567	06.07.2018 12:00 – 12:15
Flexibility band	**Voltage violations**	**Current violations**
	Pmin = -4.80 MW Pmax = 5.75 MW	Pmin = -8.04 MW Pmax = 9.04 MW
ID	**Voltage sensitivity**	**Current sensitivity**
HPs @ substation 01	0.112	0
EVs @ substation 01	0.112	0
HPs @ substation 02	0.127	1
EVs @ substation 02	0.127	1
HPs @ substation 03	0.148	1.005
EVs @ substation 03	0.148	1.005
…	…	…
HPs @ substation 30	0.917	1.086
EVs @ substation 30	0.917	1.086
HPs @ substation 31	0.917	1.086
EVs @ substation 31	0.917	1.086
HPs @ substation 32	1	1.086
EVs @ substation 32	1	1.086

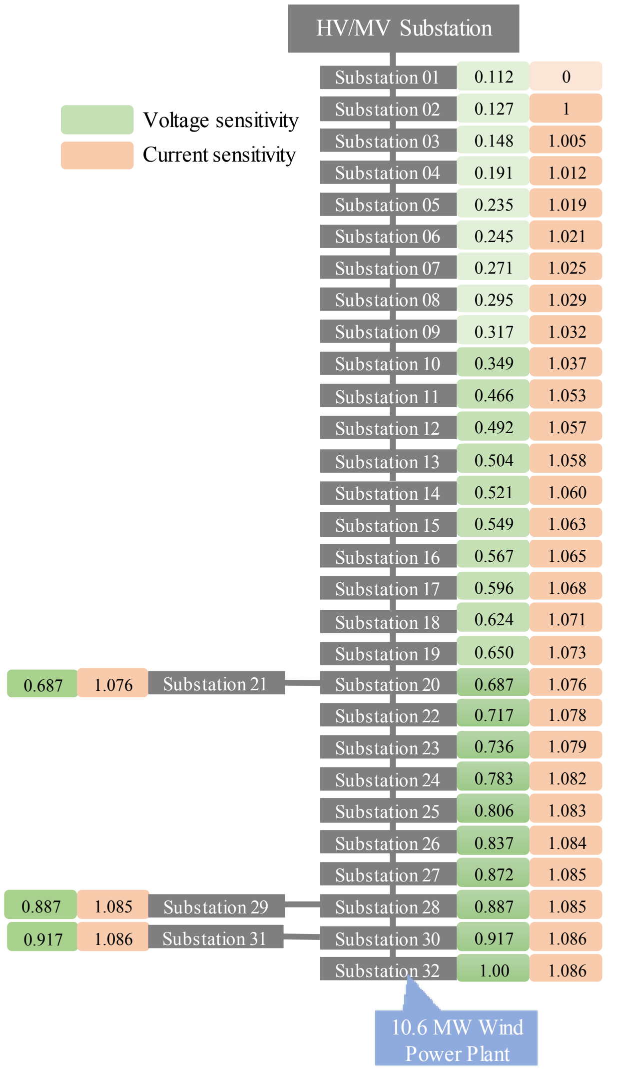

Figure 4. Determination of sensitivities in case of voltage violations and overloading

To give an example: 1 MW of load at the end of the feeder (substation 32) reduces the voltage flexibility band by 1 MW (sensitivity = 1), while it reduces the current flexibility band by 1.086 MW as line losses between substation 02 and 32 have to be taken into account. Likewise, 1 MW of load at substation 02 would result in a reduction of only 0.127 MW for the voltage flexibility band but 1 MW for the current flexibility band.

IV. Flexibility Control and Activation

In the considered network, grid congestions occur in situations of both peak demand as well as peak generation. The flexibilities are activated based on their availability, their cost as well as their sensitivity to reduce the grid congestion problem. The costs have been chosen according to Table 4. Costs for the curtailment of the wind power plant have been estimated based on its feed-in tariff. No PV curtailment would occur as the costs would be higher, due to a higher feed-in tariff. For heat pumps and electric vehicles no such data is available and have been chosen arbitrarily to show the principles of operation with a flexibility list. With the assumed flexibility costs, an electric vehicle with a sensitivity of 1 will be activated before a heat pump with sensitivity of 0.3. Furthermore, a heat pump or electric vehicle with an effective flexibility cost higher than the wind power curtailment cost will not be activated. Hence, in the case of grid congestions caused by feed-in, the curtailment costs represent the natural price ceiling for which flexibilities would be contracted.

For each 15-minute time step, flexibility measures are activated as long as the flexibility band (see section III.B) is violated, starting with the cheapest flexibility measure.

Table 4. Costs for flexibility provision

Flexibility option	Cost for providing flexibility
Heat pumps	0.025 €/kWh
Electric vehicles	0.050 €/kWh
Wind power curtailment	0.090 €/kWh

A. Heat Pump Flexibility

Heat pump flexibility is provided by temperature regulation in the individual households. It is assumed that during normal operation the inside temperature is kept at 21°C. To provide flexibility the heat pump can vary its output between 0 and 3 kW_{el}. Depending on its output the inside temperature of the households decreases or increases but is kept within a temperature range between 20 and 22°C. If the time for flexibility provision has passed, the inside temperature is gradually brought back to 21°C.

B. Electric Vehicle Flexibility

During normal operation EVs at home are only charged if their SOC falls below 50 %. To provide upward flexibility during peak generation, also available EVs with SOCs above 50 % are charged. To provide downward flexibility during peak demand, the charging process of EVs is interrupted except if the SOC is below 50 % or one of the next two trips will fully deplete the battery.

V. Simulation Results

During most of the year, the flexibility provision by EVs and HPs can successfully mitigate any grid congestions. Figure 6 shows two-day simulation results for the most critical situations through the year.

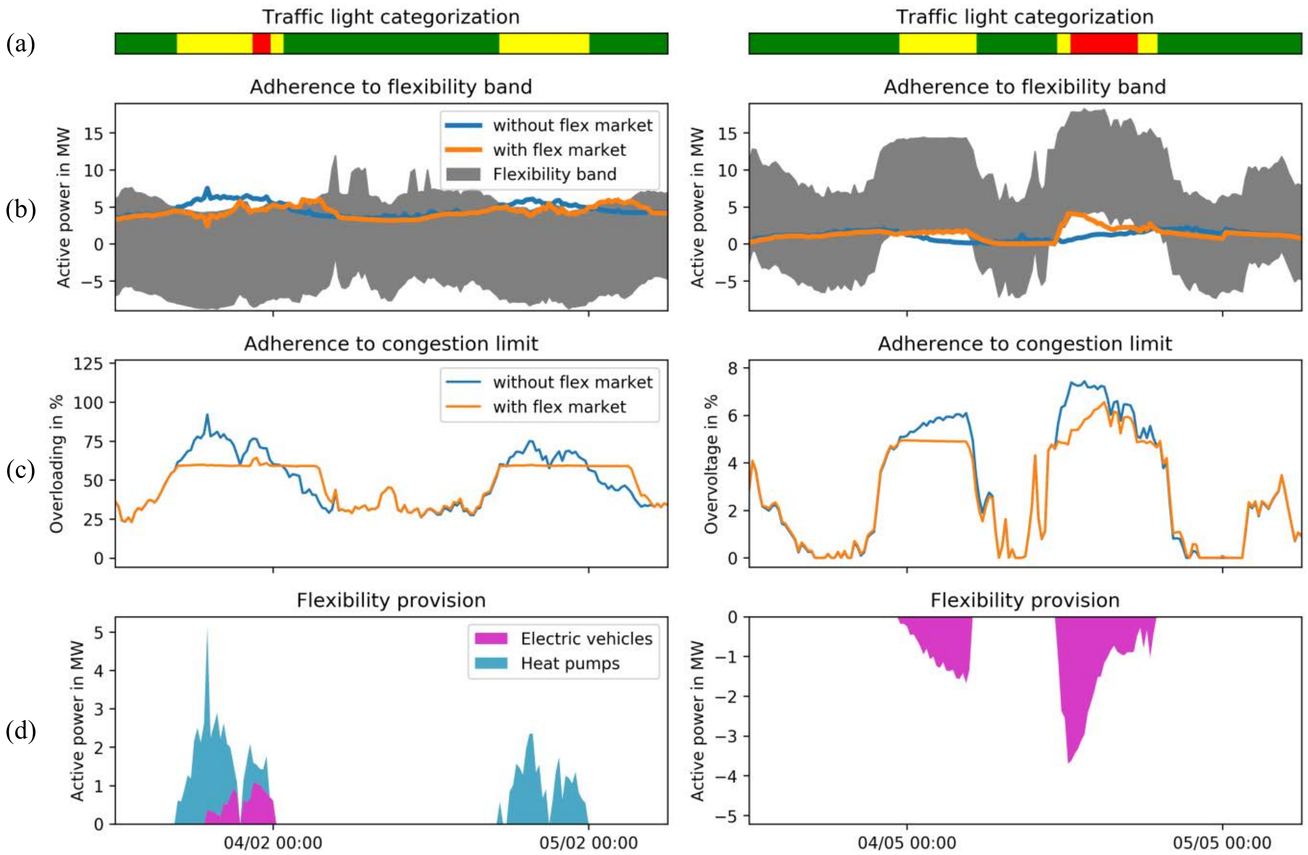

Figure 6. Simulation results with and without flexibility market for two cold winter days (left) and two summer days with high PV and wind energy production (right)

Starting with the cold winter time period (left side), without flexibility provision the flexibility band would be violated (Figure 6 (b)) and therefore the overloading limit of 60 % is surpassed (Figure 6 (c)). To alleviate the grid congestion the flexibility market is activated through the yellow phase (Figure 6 (a)) and the flexibilities activated based on their cost and sensitivity (Figure 6 (d)). Due to lower costs, heat pumps are activated first but due to their limited flexibility, i.e. when the upper inside temperature of 22°C is reached, also EV flexibility is activated. Towards the end, the flexibility is insufficient and the red phase is activated where the DSO must take other measures such as load shedding. The red phase should be avoided as best as possible.

The right side of Figure 6 shows the opposite case where high PV and wind power generation is causing too much feed-in that has to be actively compensated to avoid curtailing. Due to outside temperatures being high and hence heat pumps for heating being switched off, flexibility is only provided by EVs. Also here, the EVs are activated starting with the highest sensitivity, i.e. at the end of the feeder. However, this flexibility is quickly exhausted, hence, the red phase is activated and wind power needs to be curtailed. In this case, the red phase is less critical than in the previous case as no households are directly impacted, e.g. by load shedding.

Figure 7 shows that most of the grid congestions can be successfully alleviated. The majority of the remaining congestions occur in the summer time where only a limited flexibility is available through EV charging.

Table 5 shows the overall contribution of EVs and HPs to the overloading and overvoltage congestions. For overloading, most of the flexibility is provided by the HPs, while for overvoltages EVs are the main contributors. Overloading is almost fully mitigated, with only 0.2 MWh of needed flexibility remaining. Wind power curtailment, on the other hand, cannot be fully prevented but is reduced by about 75 %. The costs represent the expenses the DSO has to make for the flexibilities, considering the cost assumptions introduced in Table 4. However, they also represent the potential revenues the flexibility providers can earn from offering their flexibility. These revenues accumulate to only 9886 € for all flexibilities combined, a mere 2.4 € per flexibility, and are unlikely to provide incentive alone. The low value stems from the rare occurrence of grid congestions and hence, limited energy turnover for flexibility provision.

Table 5. Energy flows and costs to provide flexibility against overloading and overvoltages vs. curtailment

		Contribution to flexibility band	Active power needed	Total costs per year
Over-loading	EVs	7.5 MWh	7.0 MWh	348 €
	HPs	48.4 MWh	45.2 MWh	1 131 €
	Missing flex	0.2 MWh		
Overvoltage	EVs	113.2 MWh	148.8 MWh	7 438 €
	HPs	30.2 MWh	38.8 MWh	969 €
	Missing flex	43.1 MWh		
	Only wind power curtailment (no flex)	186.5 MWh		18 645 €

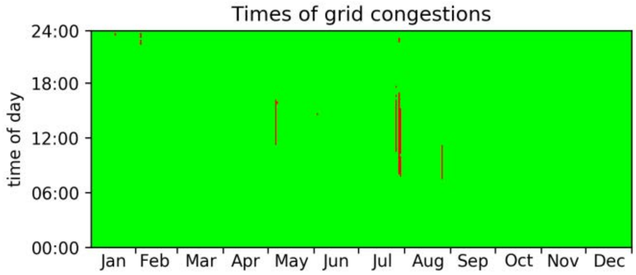

Figure 7. Remaining grid congestions after flexibilities have been activated with the flex market

VI. Conclusion and Discussion

The paper shows how different flexibility options can be integrated into a single framework, in order to select the most cost-effective option to mitigate local grid congestion problems (voltage violations and overloading). The framework is called the BDEW traffic light system, proposed by the German Association of Energy and Water Industries (BDEW). The concept is applied to a medium voltage feeder, where an already high PV and wind power penetration is further increased as well as a 75 % adoption rate of electric vehicles and heat pumps assumed.

Flexibility is provided by delaying or activating EV charging and heat pump operation. The flexibilities are selected based on availability, cost of providing flexibility as well as their respective sensitivity towards solving the grid congestion. Hence, in a cost-efficient manner, overloading problems during peak demand are almost fully mitigated while overvoltage violations during peak generation are reduced by about 75 %.

Based on the cost assumptions, revenue yields for flexibility providers would be low, indicating that a remuneration solely based on energy may not be enough to incentivize flexibility providers. Instead, additional incentives may be necessary, e.g. by receiving a fixed price for the provision of flexibility. Otherwise, the enforcement through regulatory measures that enable the DSO to use flexibility in his grid may be another option.

The proposed concept is generic and other kinds of flexibilities, such as batteries or combined heat and power units, can participate in such flexibility market. If the frequency of grid congestions accumulates due to increasing generation or demand, the DSO's costs for purchasing the necessary flexibility will increase as well, up to the point where grid extension or other options offer cheaper alternatives to the DSO. Hence, such upgrades are effectively delayed or in some cases fully prevented.

To facilitate the BDEW traffic light concept, a high degree of coordination is needed, e.g. by means of smart meters. The flexibility list including the sensitivity matrix can change based on the demand/generation situation and the network topology, which needs to be continuously communicated with the flexibility providers as well as the contracted flexibility.

Furthermore, it should be noted that enough flexibility liquidity needs to be available to ensure operability and competitiveness. Lastly, the activation of flexibility should not result in violations in the lower voltage levels. Hence, it is foreseen that the BDEW traffic light would encompass all voltage levels in the future.

REFERENCES

[1] EN 50160, “Voltage characteristics of public distribution systems,” 2010.

[2] T. Ackermann, E. Tröster, L. Hülsmann, U. Ohl, and M. Koch, “Effectiveness of different flexibility options and innovative network technologies for the use in the BDEW traffic light concept, on the basis of a German distribution grid,” *CIGRE Sess. 2018*, 2018.

[3] “DESIGNETZ.” [Online]. Available: https://www.designetz.de/. [Accessed: 27-Sep-2018].

[4] OpenStreetMap contributors, “Planet dump retrieved from https://planet.osm.org.” 2018.

[5] Joint Research Centre, “Photovoltaic geographical information system,” 2018. [Online]. Available: http://re.jrc.ec.europa.eu/pvgis/. [Accessed: 27-Sep-2018].

[6] E. McKenna and M. Thomson, “High-resolution stochastic integrated thermal-electrical domestic demand model,” *Appl. Energy*, vol. 165, pp. 445–461, 2016.

[7] R. Follmer, B. Lenz, B. Jesske, and S. Quandt, “Mobilität in Deutschland 2008,” *Tempo*, p. 214, 2008.

[8] T. Schlößer, E. Tröster, and T. Kurpat, “Probabilistic Modelling of Charging Profiles in Low Voltage Networks,” *2nd E-Mobility Power Syst. Integr. Symp.*, 2018.

[9] BDEW German Association of Energy and Water Industries, “Smart Grid Traffic Light Concept,” no. March, 2015.

[10] BDEW Bundesverband der Energie- und Wasserwirtschaft e.V., “Diskussionspapier Konkretisierung des Ampelkonzepts im Verteilungsnetz,” 2017.