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Top-Down modelling of distributed flexibility for usage at higher voltage levels

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Abstract: The number of units on both the generation and consumption sides of the electric sector continue to increase over the course of the energy transition, especially at lower voltage levels. Many of these systems (e.g. heat pumps or battery storage systems) offer the potential to provide flexibility, although the low power level of single units limits their network effect when operated individually. By modelling aggregations of the respective flexibility type, a remarkable flexibility potential can be made available for the grid operator to use for e.g. congestion management at a point upstream.

Keywords: flexibility, energy system, modelling, distribution grid

1. INTRODUCTION AND MOTIVATION

The discrepancy in the construction speed of renewable energy plants compared to the necessary expansion of the grid has increased significantly in recent years. For this reason, power grids frequently cannot implement the market result without subsequent intervention due to the current design: The volume of congestion management measures are increasing rapidly. After the record year 2017 (more than 18 TWh), the energetic quantity of redispatch in the following year is estimated to be approx. 16 TWh (Bundesnetzagentur, 2019b). One of the last measures available to grid operators is the curtailment of renewable energy plants. The scope of this measure has increased in recent years along with the use of redispatch. The amount of curtailed energy has fluctuated between approx. 4 and 6 TWh in the last four years (Bundesnetzagentur, 2019b). The associated costs of redispatch and feed-in management have increased with the increasing amounts of energy subject to congestion management (see Fig. 1).

Due to the current feed-in priority for renewable energies, power plants with an output of 50 MW or more are currently being used to carry out redispatch measures. Due to a decreasing conventional power plant portfolio in the coming decades (see Fig. 2) as well as the necessary assumption of system responsibility by renewable energies, the NABEG 2.0 legal environment envisages reducing the feed-in priority of renewable energy plants and including them in the redispatch process (Bundesministerium für Wirtschaft und Energie, 2019). However, smaller decentralised generators, and in particular controllable low and medium voltage loads, can also contribute to the integration of larger amounts of renewable energy by providing system and network services. The electrification of the consumer side, especially at the low and medium voltage levels introduces additional electrical assets, like heat pumps (2015: approx. 0.5 million units; 2050: 6.5 - 16.7 million units) and electric vehicles (2015: 0.1 million units; 2050: 12.1 - 30.2 million units) (Bründlinger et al., 2018). The numbers vary with the scenario considered.

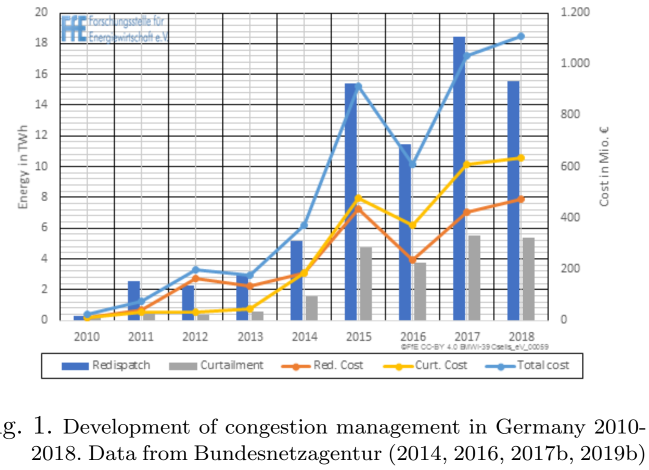

Fig. 1. Development of congestion management in Germany 2010-2018. Data from Bundesnetzagentur (2014, 2016, 2017b, 2019b)

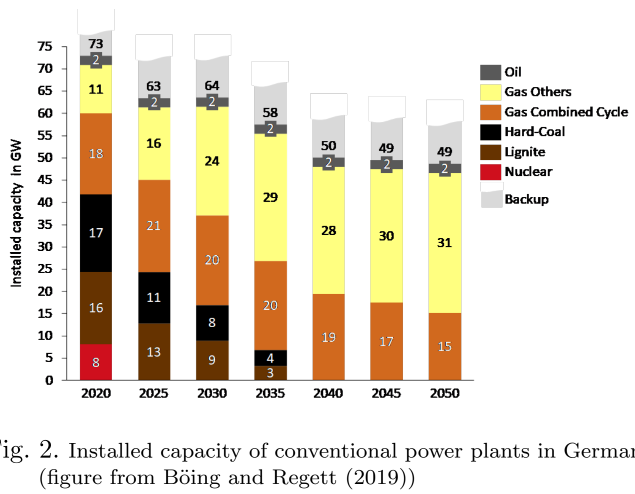

Fig. 2. Installed capacity of conventional power plants in Germany (figure from Böing and Regett (2019))

At present, the technical and information processes and the regulatory approval to use such systems for network and system services are still missing in some places.

Decentralised and controllable generators, consumers and storage facilities (hereinafter referred to as flexibility options or *flex options*) also have an electrical effect. By aggregating the individual types, the combined effect on higher network nodes can also be determined. This is a possible use-case, particularly as a countermeasure to feed-in management, since 89 % of the regulated energy was curtailed due to bottlenecks in the transmission grid (Bundesnetzagentur, 2019a).

Each type of flex option mentioned above has an individual operating baseline, which depends, for example, on parameters such as ambient temperature. Therefore, it is necessary to model the respective behaviour in order to be able to identify a potential for flexibility (*flex potential*). Subsequently, the individual flexibility load curves can be aggregated to determine their effect on nodes in the upstream, higher voltage, networks of the municipality or region.

2. METHODOLOGICAL APPROACH

For the later categorization and description of flex potential, the first step is a definition of flexibility. In general, this refers to the adaptability of the generation or consumption capacity and is defined in Müller et al. (2018) as follows in accordance with Bundesnetzagentur (2017a):

> "Flexibility describes the technical ability of a plant to change the current and/or predicted performance [P, Q]. To describe this capability, characteristic values such as the maximum possible ramp (maximum power change per time unit) [P/t] or the minimum/maximum possible power are required. Furthermore, the maximum shift-able energy quantity [E] as well as a time specification [t1], how long the power changes and - if necessary - until when the differential energy must be compensated, must be taken into account. The location (both geographically and the connection point in the grid area) and the associated effective radius are important for the targeted use of flexibility."

Generally, flexibility can be provided actively (based an an external signal) or passively (autonomously based on characteristic curves). This paper focuses in the following sections on the active provision of flexibility for usage in congestion management measures. Müller et al. (2018) introduces various relevant terms for the description of flexibility, which will be used in this paper:

- Flexibility types (*flex types*): can be described with the same selection characteristic values
  - · Groupings of flex options
  - · Similar in behaviour, primary purpose, and restrictions
- Flex options: capable of actively providing flexibility
  - · One or multiple units of one flex type
  - · Included control unit and a single connection point to the grid

Many different Flex types can be distinguished. However, only those that can be connected to the Smart Market Platform via Smart Meters in a field test will be investigated in this paper. Estermann (2019)

Fig. 3 contains the main structure of the paper. Initially, the various flex types are regionalized on the basis of various regulations and specific characteristics at the municipal level, whereby the number or output of plants per municipality can be determined. Based upon baseline load curves, a load curve depicting the potential flexibility can be created for each flex type and for each municipality, subject to certain restrictions.

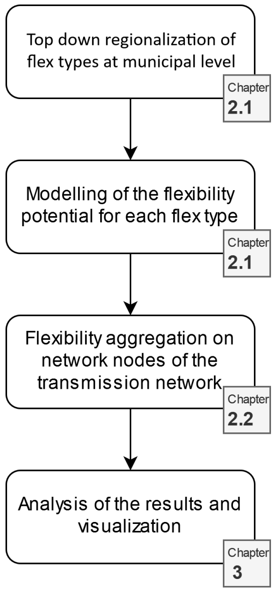

Fig. 3. Schematic structure of the paper

In order to be able to demonstrate the potential effect on the transmission network, the municipalities are assigned to the nearest transmission network node using the Voronoi approach.

Therefore the methodology in this paper describes the modelling of the technically feasible potential of flex options, which is analysed using a top down approach. The use of flexibility is possible for different actors, whereas the following content refer to network related applications.

2.1 Top-Down flexibility modelling: Case study heat pump

Regionalization Before the flex potential of individual flex types can be assessed, regionalization must be carried out at municipal level. The underlying framework numbers for the individual flex types are listed in Table 1. The status as of 2016 and forecasts for the year 2030 are presented, based upon data from Schmid (2010), Schmid et al. (2012), Figgener et al. (2017), and Bundesverband Wärmepumpen e.V. (2017). The specifications for the implementation of the regionalization have already been published in Müller et al. (2019). For the regional distribution of heating systems, different parameters such as building type and age are taken into account.

Table 1. Installed electrical power and unit counts of each flex type in 2016 and 2030

Flex type	2016	2030
Heat pump	2.1 GW (0.8m)	4.1 GW (1.6m)
Battery storage	0.2 GW (0.02m)	3.1 GW (0.4m)
El. storage heater	25.4 GW (1.8m)	16.4 GW (1.2m)
Total	27.7 GW (1.62m)	23.6 GW (3.2m)

Table 1 shows that the installed capacity of heat pumps will double in 2030 compared to 2016. In the same period, a tenfold increase in capacity is anticipated for battery storage systems. Electric storage heating systems will see a very different trend compared to these two flex types: Here the installed capacity drops by approx. 35 percent. Due to the current dominant share of electric storage heaters, the future total installed capacity is reduced by almost 15 percent to 23.6 GW as their numbers decline.

Modelling of baseline load curve After the regionalization and determination of relevant parameters (e.g. installed capacity of heat pumps for different building types (see Schmid et al. (2012)), the next step is to model the electrical baseline for each municipality. The baseline represents the behavior of the flex types without a flex call-off.

The heat demand curve (input data and modelling described in Köppl et al. (2017) and Müller et al. (2018)) is an essential input to calculate the baseline of heat pumps. Assuming that the baseline of several heat pumps of one building type in a municipality correlates strongly with its thermal demand curve, the electrical baseline for one building type is calculated according to equation 1.

$$P_{ref}(i) = \frac{q_{th}(i)}{COP} \tag{1}$$

i	time step
$P_{ref}(i)$	electrical baseline in kW
$q_{th}(i)$	thermal demand of the municipality in kW
COP	coefficient of performance (typ. value 3.15)

The COP is constant over all operation points of the heat pumps.

Modelling of flex potential The flex potential for a power change compared to the baseline in a certain direction is designated as follows:

- positive potential (+): shift of the operating point towards higher supply or lower load (power can be switched off)
- negative potential (-): shift of the operating point towards lower supply or higher load (switchable power)

The available flex potential (negative and positive) is determined by the minimum of three different restrictions in equation 2.

$$P_{\pm,t_s}(i) = min(P_{\pm P,t_s}(i), P_{\pm SoC,t_s}(i), P_{\pm E,t_s}(i)) \tag{2}$$

$P_{\pm P,t_s}$	pos/neg power restriction in kW
$P_{\pm SoC,t_s}$	pos/neg State-of-Charge restriction in kW
$P_{\pm E,t_s}$	pos/neg restriction of energy demand in kW

Hereafter, the restrictions are described in detail:

- power restriction: limited by the maximum charging power of a typical heat pump
- lower Stage-of-Charge (SoC) restriction: the highest permissible flexibility call off encompass the maximum energy demand in a time period of two hours
- upper restriction of energy demand: flexibility call off does not extend the energy demand of the whole day

The positive flex potential in general is additionally limited by a modified SoC restriction. The restriction is based on § 14a EnWG, according to which heat pumps may be switched off when required by the grid operator. Usually, the interruption period for this is two hours, which is why the switch-off period in the simulation is also two hours. This shows that a heat pump cannot be switched off too long. The potential in equation 3 is calculated from the maximum energy demand within all two-hour time windows of the simulation. It is a constant limit over all time steps and is therefore a scalar and not a vector as with the remaining restrictions.

$$\begin{aligned} P_{+E,t_S}(i) &= \max_z(\frac{1}{t_S} * E_{el,dem}(i)) = \\ &= \max_z(\frac{t_s t}{t_S} * \sum_{i}^{i+i_{ab}-1} P_{ref}(i) \end{aligned} \tag{3}$$

t_S	duration of a flexibility call off
$E_{el,dem}(i)$	Max. energy demand in permitted call time
$t_s t$	duration of a time step

With the equations 2 and the described restrictions the flex potential can be determined for every municipality with different duration of the the flexibility call off. Furthermore the methodology can be adopted for analyzing the potential of other flex types, such as electric storage heaters or battery systems (see Müller et al. (2019) for more details).

2.2 Voronoi approach for grid node aggregation

In order to aggregate flex potential, one could consider summing the potential of municipalities by their corresponding county or even state. This approach would neglect the network topology of the transmission and distribution network. In an effort to account for this problem, but without having to consider the full complexity of network transmission capacity, flex potential is aggregated by "Voronoi high-voltage grid regions" following the methodology (adapted from the approach in Fattler et al. (2019)). Fig. 4 shows the schematic aggregation procedure.

First, locations of extra high-voltage network nodes in Germany are examined - 448 in total - by using OSM Tool kits SciGRID (SciGrid (2015)), Gridkit (Wiegmans (2016) and "FLOSM power grid map"(flosm (2019)). To obtain more uniform areas, nodes that are closer to each other than the mean distance are combined to form a new fictitious extra high-voltage node. By this the number is reduced to 250. This prevents areas with many extra high-voltage nodes, mainly densely populated areas, from being represented by a multitude of Voronoi regions of significantly smaller size which could skew average values. Afterwards the flex potential is multiplied by the area share of the municipality in the corresponding Voronoi region and summed up.

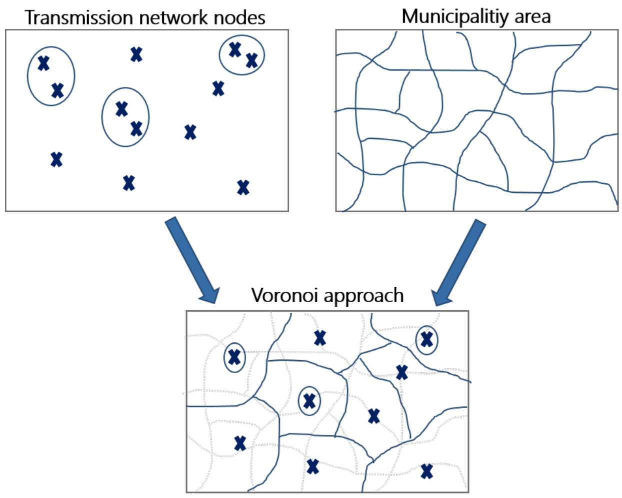

Fig. 4. Schematic Voronoi approach

3. RESULTS

By employing the modelling method presented here, the annual duration curves shown in Fig. 5 were obtained, depicting the share of the year for which different amounts of potential flexibility are available. The curves for heat pumps as well as a summed consideration of all three flex types are shown. A shift time of at least 30 minutes was assumed for the positive (switch off power) and negative (switch on power) flex potential.

This shift time represents a typical duration of a feed-in management measure according to Rios (2019). The duration of a feed-in management measure does not necessary represent the duration of the grid congestion. Therefore, for further research, four different shift durations (15 minutes, 30 minutes, 1 hour, 4 hours) have been modelled. In principle, the following applies: If the required minimum shift duration increases, the available flex potential is reduced and vice versa.

As already shown in Table 1, the installed capacity of the electric storage heaters is the dominant aspect despite the reduction by almost 9 GW (from 2016 to 2030). The peak of the positive flex potential occurs only for very few hours. This is the case when forward and backward controlled electric storage heaters overlap in load behaviour. The plateau up to approx. 10 percent of the year (about 900 hours) results from the switching off of electric storage heaters. In comparison, the shift potential of heat pumps is available much more continuously throughout the year. This is mainly due to the fact that heat pumps are usually used to heat water for both domestic use and heating purposes. In addition, heat pumps are not restricted to only being operated at night (10 p.m. - 6 a.m.).
Compared to the positive flex potential, negative flex potential is available more frequently and in larger amounts. Here, too, the influence of the electric storage heaters is the decisive factor, since they can be switched on - at least for the shift duration shown here.

Fig. 6 shows the positive and negative flex potential of heat pumps for 2016 and 2030. Due to the increase in installed capacity from 2.1 to 4.1 GW (table 1) in this period, there

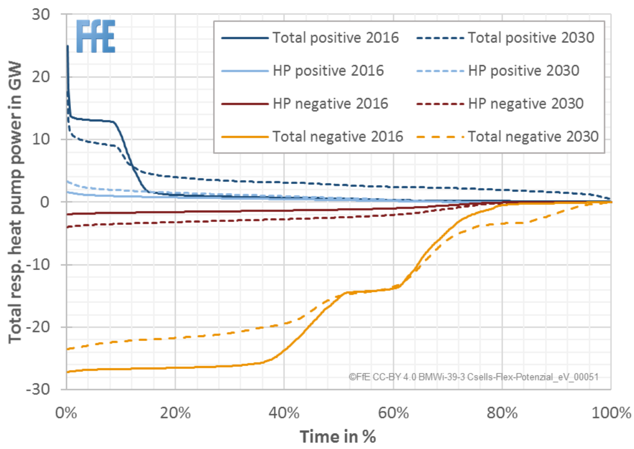

Fig. 5. Duration line of positive and negative flex potential in 2016 and 2030 (call off period 30 minutes)

is a higher potential for the respective transmission nodes across the board (allocation method according to Fig. 4).

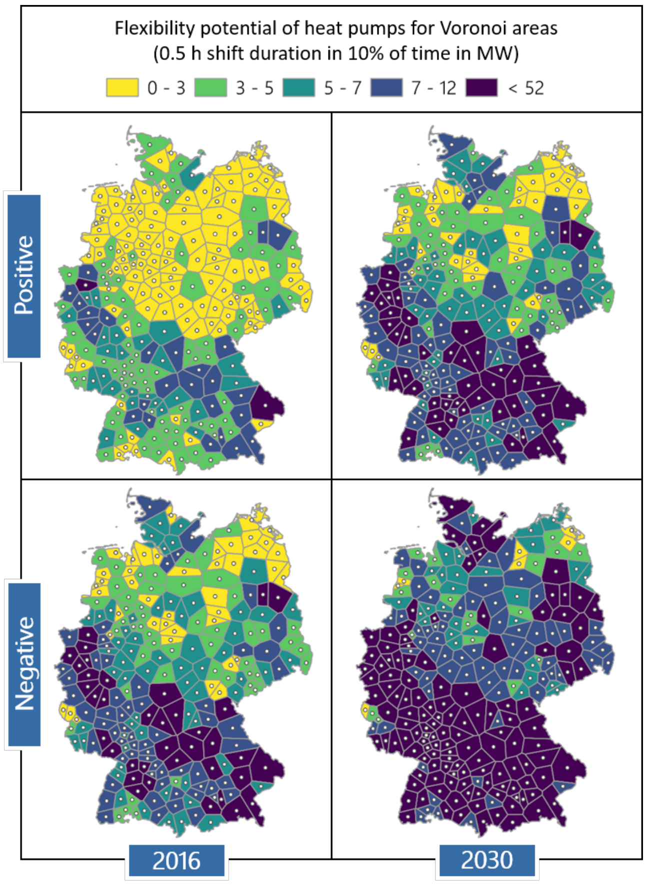

Fig. 6. Flex potential of heat pumps for Voronoi areas

The average switchable output of heat pumps (positive flex potential) per transmission grid node increases from 3.7 MW in 2016, with nearly 200 Voronoi regions having a switchable heat pump output of less than 5 MW, to 7.5 MW in 2030. With regard to the associated negative flex potential, there is an increase in 2030 to an average of 14.3 MW compared to 7.0 MW in 2016. In 2030, more than 125 Voronoi regions have a negative flex potential of at least 12 MW.

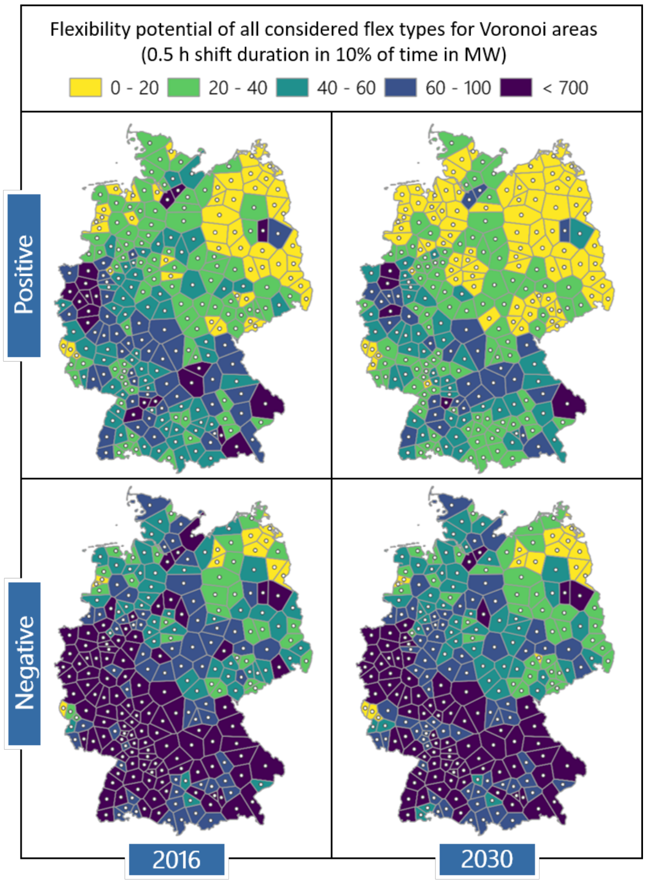

Fig. 7. Flex potential of all considered flex types for Voronoi areas

Figure Fig. 7 shows the added potential of electric storage heaters and batteries in addition to the flex potential of heat pumps. For the total installed capacity in 2030, a reduction of 4.1 GW compared to 2016 can be seen due to the dismantling of electric storage heaters. This also has a corresponding effect on the available positive and negative flex potential.

The average positive flex potential of 34.1 MW per Voronoi region in 2030 is markedly lower than the 2016 average of 46.8 MW. In 2030, only five Voronoi regions have a positive flex potential of more than 100 MW, with a maximum of approx. 220 MW. Due to the dominant share of electric storage heaters in the total flex potential, the negative flex potential is much higher than the positive flex potential. Here, the average value in 2016 of 107 MW is significantly higher than the positive one, but the flex potential in 2030 drops in this case as well, to approx. 90 MW, due to the reduced contribution of electric storage heaters. The shift potential in 81 Voronoi regions is over 100 MW.

4. CRITICAL REVIEW

One weakness of the described top-down analysis is the potential for deviations from reality in isolated cases. In the context of this paper, modeled penetration of flex types, and therefore the flex potential of each flex type, could differ from their real-world values. To guard against such errors, comparisons with real-world data should be made throughout the modelling process. Restrictions on unit penetration specific to a given municipality, whether geographic or regulatory, should be investigated and taken into account.

Furthermore, the modelling of flex potential is based upon simplifications and the typical behaviour of a flex options, meaning complexities and differences in individual's behaviors could cause the usable flex potential to differ from the modelled one.

5. CONCLUSION AND OUTLOOK

The paper explains that smaller-scale flex options show a significant potential flexibility in 2030 (8.5 GW positive and 22.5 GW negative flex potential), especially when the various units connected to each grid node are aggregated into a larger package of flexibility for usage in congestion management processes such as redispatch or feed-in management. Although the focus is on Germany, the used methodology can also be applied to other areas if the needed data is available.

In a next step this technically feasible, but yet mostly unused potential has to be activated by incentive mechanisms and an appropriate market design. In this context so-called smart-market concepts are widely discussed as new tools for congestion management. One such smart-market concept, primarily intended for smaller-scale flex options, is being developed and demonstrated in the SINTEG project C/sells (see Köppl et al. (2019) for further details).

6. DATA AVAILABILITY

The resulting data set for flex potential of heat pumps, electric storage heaters and battery systems is made available at *http://www.flexibilitaetsatlas.de/*

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