Determination of the integration and influencing potential of rapid-charging systems for electric vehicles in distribution grids

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Abstract — **An increasing share of electric vehicles needs an adequate charging infrastructure to enable sufficient range, which is one of the most important issues to gain users' acceptance. Therefore, a multi-objective assessment model is developed to identify suitable and sustainable locations for rapid-charging infrastructure. The model assesses sites by different evaluation criteria. This paper treats the evaluation of sites by the ability to connect rapid charging stations to the local electric distribution grid. It gives information about the integration potential for rapid-charging stations at every single grid connection point in a distribution grid and about the influence of one rapid-charging station onto the integration potential at other grid nodes. This method is applied to distribution grids of the German cities of Düsseldorf and Stuttgart.**

rapid-charging stations; integration potential; influencing potential; electric vehicles; distribution grid analysis; hosting capacity

I. INTRODUCTION

To achieve climate goals not only an increasing share of renewable energy resources but also a decarbonisation of all sectors are necessary in the long term. Thus, also the private vehicle sector must be decarbonised either with the help of synthetic fuel or electrification. While at the end of the year 2016 about 77.000 electric vehicles (EV), thereof about 44,500 battery EVs, were registered, the national goal of Germany is 1 million EVs until 2020 [1]. This increasing share of electric vehicles needs an adequate charging infrastructure. As sufficient range is one of the most important issues to gain users' acceptance to buy an EV [2], the project „SLAM - Schnellladenetz für Achsen und Metropolen" (rapid-charging network for traffic axes and metropolitan areas) aims to roll out a country-wide rapid-charging network [3]. To identify suitable and sustainable sites for rapid-charging infrastructure a multi-objective assessment model is developed. This model takes into account three essential influence layers:

- user layer: user's demand as well as todays and future predicted density of EVs
- traffic layer: traffic grid and traffic
- infrastructure layer: settlement structures, existing charging infrastructure and points of interest

As an output, countrywide clustered potential maps are provided considering all three described layers with clustered square areas, each having a certain quantified potential [4–7].

From a grid point of view, rapid-charging systems are large loads that might lead to congestions in distribution grids. In context of the project, charging points are often provided with one or two Combined Charging Systems (CCS) DC 50 kW charging stations [3]. Line or transformer overloading or inadmissible low voltages can be the result. Therefore, it is necessary to identify locations in the distribution grid with sufficient integration potential to avoid grid expansion costs.

In this paper, an electric layer is added to the multi-objective assessment siting model as a fourth layer. This layer gives information about suitable sites for rapid-charging stations from the point of view of distribution grid operators (DSO). This is the focus of this paper.

Unlike the introduced multi-objective assessment model, a countrywide modelling of the electric layer is impossible, as detailed data to model distribution grids for power flow calculation and further analysis are not publicly available. In cooperation with the DSOs Netzgesellschaft Düsseldorf mbH and Netze BW GmbH, it is possible to examine medium voltage (MV) and low voltage (LV) distribution grids of Düsseldorf and Stuttgart.

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II. Methodology

Integration potential is defined as the maximum load or generation power up to which the validity of the grid state is maintained. In this context, different assessment criteria can be applied [8], as voltage quality (e.g. rms value, flicker, harmonics) or asset loading. Instead of integration potential the term "hosting capacity" is also used [9, 10]. In this paper, rms voltage value violation and nominal apparent power (i.e. long term thermal limiting current) are the assessment criteria focused on.

The developed model for the electric layer aims at answering the following questions:

- What is the individual integration potential at all grid connection points?
- How does one rapid-charging station influence the integration potential of other sites?
- Where in the grid are sites with sufficient integration potentials (e.g. 100 kW), which at the same time have a low influence on the integration potential of neighboured grid connection nodes?

For this purpose, two parameters are determined for each grid connection node in a distribution grid: the integration potential ($IntP_i^0$) describes the maximum additional installable power to one node i considering the technical constrains (maximum cable and transformer loading as well as voltage threshold values). However, a rapid-charging station installed at a particular node i has an influence on neighbouring nodes. It can cause both higher loading of the feeders it is connected to and higher voltage drops. Thus, it decreases the maximum installable load at neighbouring nodes and influences its integration potential. This cannibalisation effect is called influencing potential. The influencing potential at node i equals the sum of the integration potential reductions of all other $(n-1)$ nodes.

$$InfP_i = \sum_j IntP_j^0 - IntP_j^{new}, \quad j\epsilon N\backslash i, N = [1 \dots n] \tag{1}$$

The influencing potential depends on the specific active power, which is connected to one node. In this paper, all influencing potentials are determined for a 100 kW load, representing two CCS 50 kW rapid-charging stations.

Rapid-charging stations are connected to the LV. In this paper for investigations of MV grids, rapid-charging stations are installed at the existing DTs' busbars. Consequently, the difference between the DTs' apparent power $S_{i,DT}$ and an assumed aggregated LV grid load $S_{i,load}$ is the theoretical upper limit for the integration potential ($IntP_{i,max}$) at node i. The DTs' impedances are neglected for the calculations of MV grids. In LV grids however, the theoretical maximum integration potential is given by the thermal limiting current of the house connection line.

As rapid charging shall be possible at any time, integration und influencing potentials are calculated considering a worst-case situation for each grid. Thus, each grid connection node has an initial worst-case apparent power $S_{i,load}$. Other time-series based load-modelling approaches as probabilistic load flow calculation are not applied. It determines different risk degrees of grid loading, where the worst-case is by definition rare [11, 12]. However, a probabilistic approach based on Monte Carlo Simulation takes more simulation time and is rather an academic approach than used in practice. Thus, the worst-case approach is chosen for the assessment of suitable sites for rapid-charging stations.

With an initial power flow calculation grid areas with bottlenecks and inadmissible low voltage values can be identified. Nodes in these areas are excluded from further investigations. The respective integration potentials of all other nodes are determined with a golden section search algorithm. The upper border is set equal to $IntP_{i,max}$.

As the first three layers of the multi-objective assessment siting model provide maps with integration potentials clustered in squares [4], potential maps of the same square resolution are created for the electric layer, as depicted in Figure 1. The square area values of clustered integration potential maps equal the maximum integration potential value of all nodes inside the respective square area. Thus, after applying the first three model layers and identification of a square area with potential for a suitable site, the fourth electric layer is applied. It gives information, about the maximum integration potential within this area.

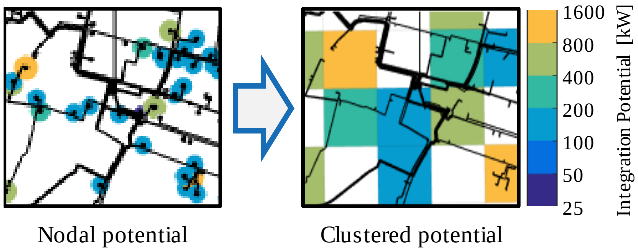

Figure 1 Clustering of nodal potentials

If the power of the charging station that shall be installed is specified (e.g. 100 kW), it is necessary to choose a site with adequate integration potential and at the same time an influencing potential as small as possible. For each node that has an integration potential equal or superior to the specified power, the nodal influencing potential is calculated. A clustered square area of an influencing potential map equals the minimum of the influencing potentials.

III. Investigation Scope and Assumptions

A. MV grid of the south of Düsseldorf

Netzgesellschaft Düsseldorf mbH provided grid data of an MV grid in the south of Düsseldorf. The grid depicted in Figure 2 consists of 18 km HV cable grid, 2 HV/MV substations with 2 transformers each, about 234 km 10 kV and 25 kV MV cable grid and 463 DTs.

The combined maximum loading of all MV feeders is 100.4 MW and 55 MVAr and is divided homogeneously across the DTs as a worst-case load parametrisation.

As the aging of asset increases with higher asset loading and temperature, overloading shall be avoided. Thus, the individual rated apparent power and thermal current limits, respectively, of the transformers and cables are used as technical constrains for the calculation of the integration potential. For grid planning, Netzgesellschaft Düsseldorf mbH uses a maximum allowed cable loading of 80% of the rated thermal current limit.

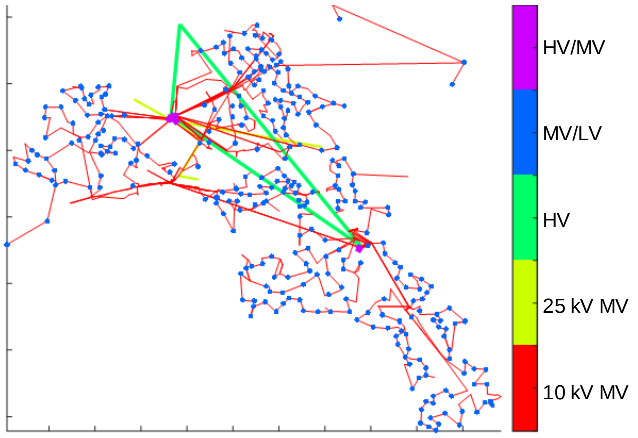

Figure 2 Distribution grid in the south of Düsseldorf

DIN EN 50160 requires that 95% of the 10-minutes average value of the voltage rms value at all grid connection points in MV and LV grids must be within the tolerance of ± 0.1 p.u. related to the nominal voltage U_n. As tap changers of HV/MV and MV/LV transformers are considered to have nominal ration, it must be taken into account that underlying LV grids need sufficient voltage buffer to meet the allowed voltage borders. Thus, higher values than 0.9 p.u. must be considered for grid planning purposes. Table 1 shows the allowed minimum voltage limits that are applied for the potential calculations.

Table 1 Minimum voltage limits for different voltage levels in the distribution grid of the south of Düsseldorf

Voltage level	U_{min}
110 kV	1.00 p.u.
25 kV	0.96 p.u.
10 kV	0.97 p.u.

B. MV grid of Stuttgart

The examined MV grid of Stuttgart consists of 23 public HV/MV transformer stations with a total nominal apparent power of 2150 MVA, 2522 km 10 kV MV cable grid and 2,239 DTs. Netze BW GmbH provides georeferenced GIS data including among other things DT drag indicator values, DT apparent power and cable types.

As a worst-case assumption, the DTs' residual loads are set to their drag indicator values in order to meet possible DT loading restrictions. As there are no drag indicator values of customer transformers available, their load is assumed to be 70% of their nominal apparent power. With this worst-case assumption the initial load of the whole MV grid of Stuttgart is 974 MW which is the sum of the DTs' drag indicators.

The MV grid is operated as an open circuit structure and radial networks, respectively. As there is no information available regarding the switching state of disconnectors, the grid is initially intermeshed. A heuristic is developed and applied to find suitable switching states for all disconnectors to guarantee a radial network and no initially overloaded HV/MV transformers. Figure 3 shows the MV grid of Stuttgart. The MV grid is divided in terms of colour into grid areas, one for each HV/MV transformer station.

The lowest allowed rms voltage value in the MV grid is set to 0.96 p.u. while the HV slack node reference voltage equals 1.0. For grid planning, Netze BW GmbH uses the maximum allowed cable loading of the rated thermal current limit.

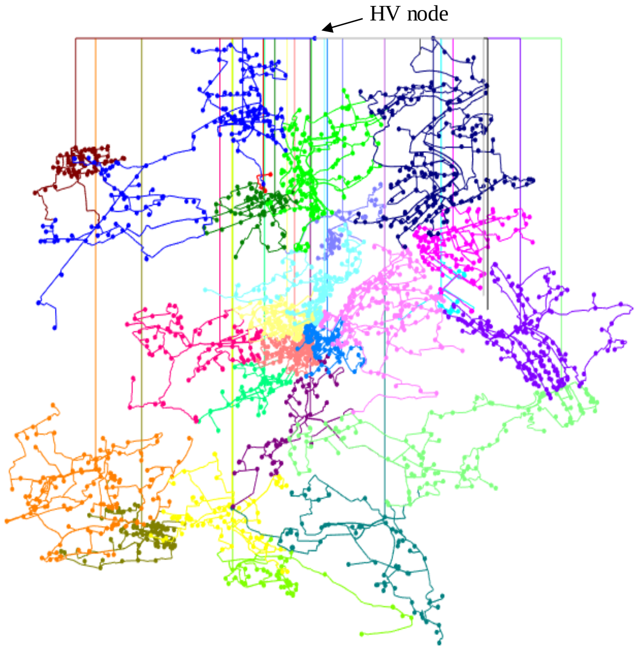

Figure 3 MV grid of Stuttgart

C. LV grid of Stuttgart-Hausen

In addition to the calculations for the MV grid, further integration and influencing potential calculations are performed for an LV grid in the district Stuttgart-Hausen. It consists of three separate LV grids, two DT with an apparent power of 800 kVA and one with 630 kVA. 328 loads, mainly households, are supplied. Table 2 shows the cable types and maximum apparent power loading of the grid.

Table 2 Cable types in the LV grid of Stuttgart-Hausen

material	Cross section area $[mm^2]$	S_{max} $[kVA]$
Al	35	86
Al	50	97
Al	95	146
Al	150	186

For load parametrisation, the maximum values of nominated standard load profiles $p_{SLP,max,i}$ weighted with the individual annual energy consumption $W_{annual,i}$ and multiplied with a coincidence factor CF are calculated for each node i.

$$P_{load,i} = p_{SLP,max,i} \left[\frac{W}{Wh}\right] \cdot W_{annual,i}[kWh] \cdot CF \qquad (2)$$

The concurrency factor, which is calculated for all loads equally, is chosen to be 74%. It is calculated as the quotient of the sum of all drag indicator values $S_{DT,max}$ divided by the sum of the LV loads of the whole distribution grid of Stuttgart.

$$CF = \frac{\sum S_{DT,max}}{\sum p_{SLP,max,i} \cdot W_{annual,i}} \approx 74\% \quad (3)$$

The maximum load of all 328 loads is 24 kW, while the mean value is equal to 2.8 kW. The sum of all loads equals 903 kW.

The lower voltage limit is according to DIN EN 50160 set to 0.9 p.u. The reference voltage at the common MV slack node is set to 1.0 p.u. The maximum allowed cable and transformer loading is 100%.

IV. Results

A. MV grid of the south of Düsseldorf

The integration potential map of the south of Düsseldorf is shown in Figure 4. The size of one square area is 400 m x 400 m. The integration potential is mainly limited by the DTs' apparent power and is between 0 and 560 kW. In the dark blue regions, there is hardly any potential for the integration of rapid-charging columns, compared to the green and yellow areas. The map shows that the square areas with integration potentials are homogeneously distributed over the entire grid. Main limiting factor are the apparent power values of the DTs.

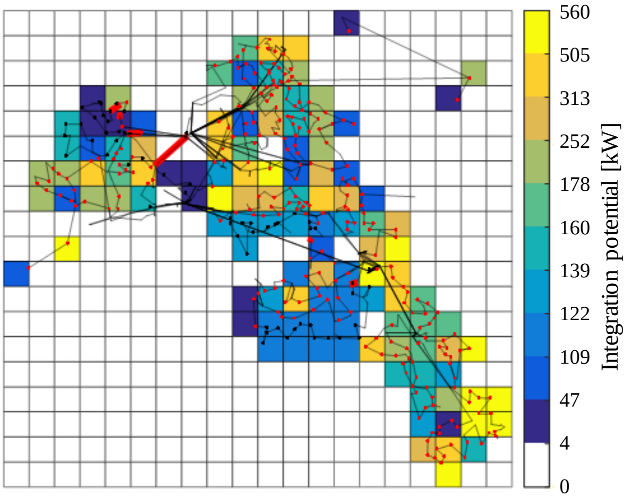

Figure 4 Integration potential map of the MV grid of the south of Düsseldorf

The influencing potential of a charging point on other grid connection points is examined by means of an additive load of 100 kW. The potential map is depicted in Figure 5. The influencing potentials are negligibly small in the majority of the grid since most of the integration potentials are limited by the DTs' nominal apparent power and therefore have no influence on other sites. Only in 4 circuits of the MV grid there are high influencing potentials: in the yellow-marked area there is a very high influencing potential, since the line supplying the circuit represents the common bottleneck. An additional charging station in this area reduces the integration potential of the entire circuit. This case also occurs in the areas marked green and blue, but to a smaller degree.

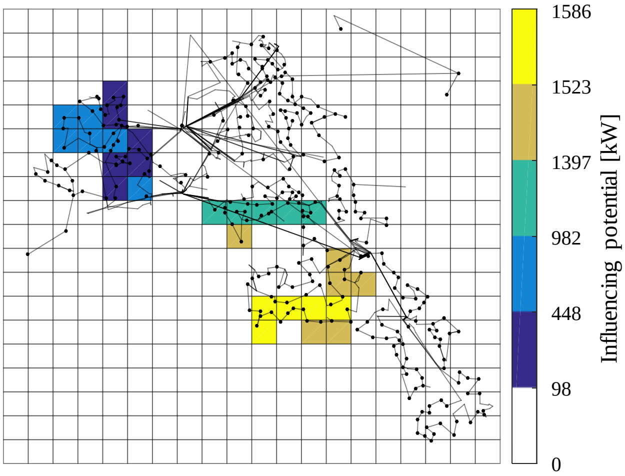

Figure 5 Influencing potential map of the MV grid of the south of Düsseldorf

B. MV grid of Stuttgart

Figure 6 shows the integration potential map of the MV grid of Stuttgart for a square size of 250 m x 250 m. In addition, the integration potentials at all 2,239 DTs (load nodes) as well as the individual restriction reasons are clustered in Table 3. It shows that due to the worst-case load assumption 7.9% of the load nodes have no integration potential. For approximately half of these cases, inadmissible low voltage values (U < 0.96 p.u.) are the reason. These nodes are located north east and south east of the city. Other reasons are initial DT overloadings and MV line overloadings in the local grid area. 63.9% of the grid nodes have integration potentials larger than 100 kW. These integration potentials are almost exclusively limited by the nominal apparent power of the DTs. Consequently, the integration potential can be further increased if rapid-charging stations are not connected to existing DTs but instead connected to the grid via their own MV/LV transformer.

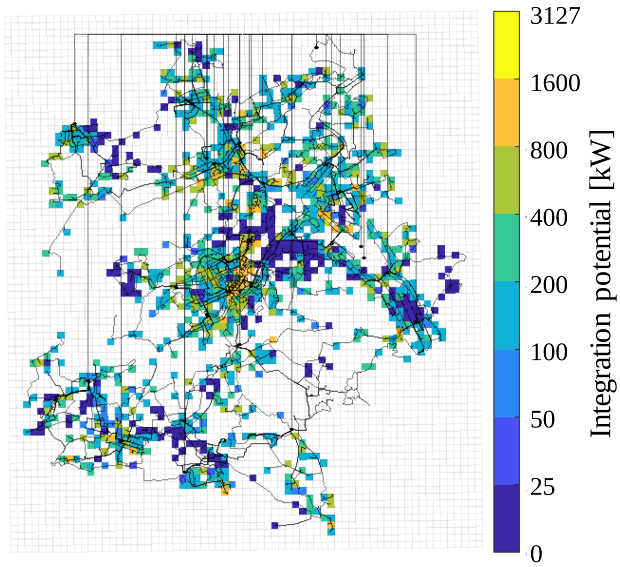

Figure 6 Integration potential map of the MV grid of Stuttgart

Table 3 Clustered results of the integration potentials and reasons for integration potential restriction of the MV grid of Stuttgart

Total number of DT: 2239		$IntP = 0\ kW$		$IntP > 0\ kW$		$IntP \geq 100\ kW$	
Number / share of nodes		176	7.9%	2063	92.1%	1431	63.9%
restrictions	$S_{DT,rel.} > 1$	47	26.7%	1479	71.7%	1394	97.4%
	$S_{line,rel.} > 1$	37	21.0%	584	28.3%	37	2.6%
	U < 0.96 p.u.	92	52.3%	0	0.0%	0	0.0%

Figure 7 shows the influencing potentials map in case of applying 100 kW rapid-charging stations. Table 4 shows the influencing potential of all nodes clustered in four categories. Nodes with an integration potential smaller than 100 kW (36.1%) cannot be used to calculate an influencing potential for a 100 kW load. An additional 100 kW loads at nodes in grid areas with all nodes having DT overloading restriction cannot have any influence on other nodes. This is the reason for the high share of nodes without influencing potential. These DTs are especially suitable for charging points up to 100 kW charging capacity. Only a few nodes in the north and east of the grid have influencing potentials ≥ 100 kW (4.5%). The largest influencing potential is 806 kW.

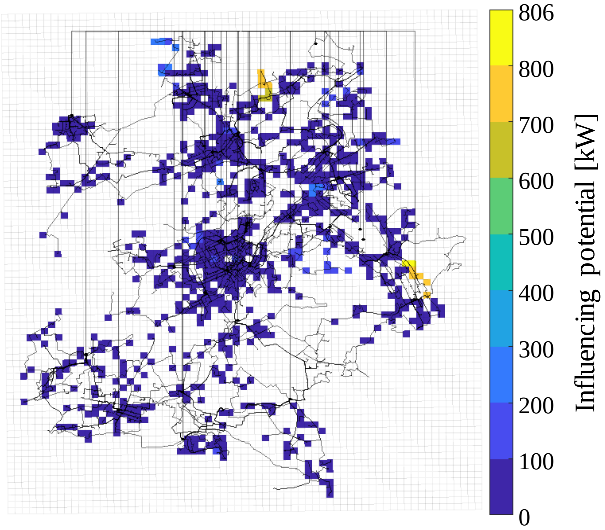

Figure 7 Influencing potential map of the MV grid of Stuttgart

Table 4 Clustered results of the influencing potentials of the MV grid of Stuttgart

$IntP < 100\ kW$	$IntP \geq 100\ kW$		
$InfP = 0\ kW$	$InfP = 0\ kW$	$0\ kW < InfP < 100\ kW$	$InfP \geq 100\ kW$
808 (36.1%)	1277 (57.0%)	53 (2.4%)	101 (4.5%)

C. LV grid of Stuttgart-Hausen

Figure 8 shows the integration potentials in the LV grid of Stuttgart-Hausen. The square area size is 25 m x 25 m. Table 5 shows the integration potentials at all 328 households as well as their individual limiting reasons. 39% of all nodes have integration potentials of more than 100 kW. The maximum value is 183 kW. 73.5% of the integration potentials are limited by the rated apparent power of the connection cables ($s_{cc} > 100\%$). Most of the connection cable have cross-sectional areas of 35 mm² to 50 mm², limiting the maximum integration potential to less than 100 kW (see Table 2). The other calculations show that the feeder cable is overloaded ($s_{fc} > 100\%$). Voltage violations are no problem in this specific exemplary case. There are higher integration potentials in the western part of the grid than in the eastern part.

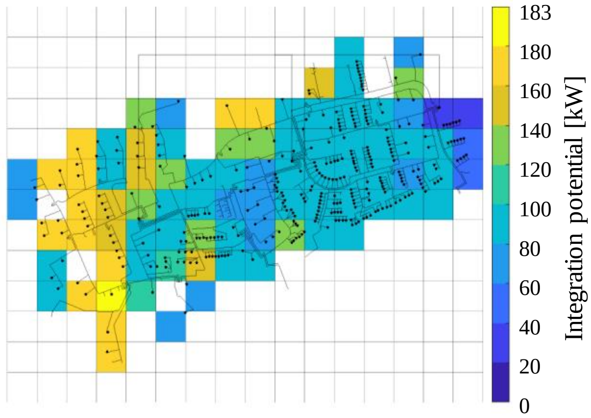

Figure 8 Integration potential map of the LV grid of Stuttgart-Hausen

Table 5 Clustered results of the integration potentials and reasons for integration potential restriction of the LV grid of Stuttgart-Hausen

Total number of DT: 328		$IntP > 0\ kW$		$IntP \geq 100\ kW$	
Number / share of nodes		328	100.0%	128	39.0%
restrictions	$s_{cc} > 100\%$	241	73.5%	192	58.6%
	$s_{fc} > 100\%$	87	26.5%	136	41.4%
	$U < 0.96\ p.u.$	0	0.0%	0	0.0%

Figure 9 shows the influencing potential map for the case of applying 100 kW rapid-charging stations, whereas these calculations are just possible at nodes with integration potentials of larger than 100 kW (39.0%). Table 6 gives the statistical distribution of the influencing potentials. The dark blue marked squares in the figure shows areas where nodes with influencing potentials of less than 100 kW as well as integration potentials larger than 100 kW are located. These nodes are suitable for the integration of 100 kW charging stations. Most of the nodes (95.8%) are unsuitable sites for 100 kW charging stations due to low integration potential or high influencing potentials. The maximum influencing potential is 2,256 kW.

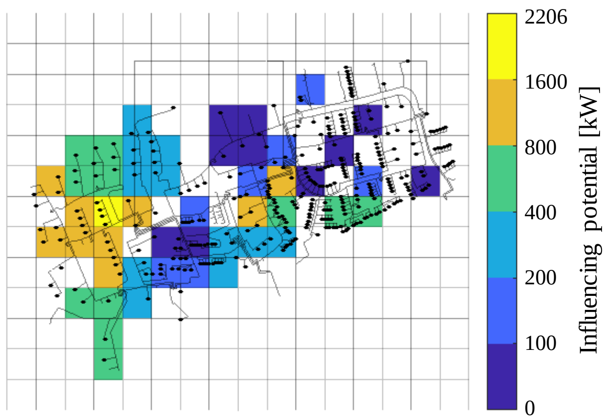

Figure 9 Influencing potential map of the LV grid of Stuttgart-Hausen

Table 6 Clustered results of the influencing potentials of the LV grid of the Stuttgart-Hausen

$IntP < 100\,kW$	$IntP \geq 100\,kW$		
$InfP = 0\,kW$	$InfP = 0\,kW$	$0\,kW < InfP < 100\,kW$	$InfP \geq 100\,kW$
200 (61.0%)	3 (0.9%)	11 (3.4%)	114 (34.8%)

V. Conclusion and Outlook

In summary, a large number of suitable sites for rapid-charging stations can be identified from a grid perspective in a large part of both investigated MV grids, despite a worst-case load modelling assumption. In the MV grid the DTs' apparent power values are the main reason for a limited integration potential.

In the LV grid, the connection cables of most households and buildings are not suitable for 100 kW loads. Beside the influencing potential is very high. Thus, the number of suitable sites are rare in the examined LV grid (4,3%).

As a next step, the electric layer has to be added to the multi-objective assessment model with its user, traffic and infrastructure layers to find suitable sites for rapid-charging stations for a holistic point of view.

In the project SLAM, some rapid-charging stations came with an installation of a new MV/LV transformer. Further investigations on both MV grids can be to calculate integration and influencing potential assuming the installation of an additional MV/LV transformer and neglecting the DTs' nominal apparent power at the examined grid node. This will lead to higher potentials and enable a power system analysis of the MV grid without the DTs' bottlenecks.

As the need for private AC home charging systems will increase with higher share of EVs, further investigations for the integration of home charging systems into the LV girds need to be done.

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