BERGISCHE UNIVERSITÄT WUPPERTAL

Automated Optimal Placement of Distribution Substations for Future Supply Tasks

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Abstract

The increasing penetration of distributed energy resources and the electrification of the mobility and heating sectors are increasing the demand of strategic network planning in low-voltage distribution networks. This contribution introduces a novel, automated method for the cost-optimal placement of new distribution substations to systematically address the future challenges in low-voltage network areas. The method first employs public geospatial data to identify all physically and legally feasible positions for new distribution substations. Subsequently, an iterative algorithm performs a detailed cost-benefit analysis for each position. It monetizes technical limit violations and selects the location offering the maximum net economic benefit, defined as the avoided conventional expansion costs deducted by the investment for the new distribution substation. Applied to a real low-voltage network area of a German distribution system operator, the method demonstrates a significant reduction in total expansion costs. Notably, the strategic placement of substations substantially reduces the need for line expansion and therefore civil engineering measures. The method provides a scalable and systematic tool for efficient strategic low-voltage network planning.

Keywords

Active Distribution Systems, Distribution Substation, Low-Voltage Networks, Substation Planning, Strategic Network Planning

1 Introduction

The global energy transition, accelerated by the imperative to meet climate targets such as those defined in the Paris Agreement [1], is fundamentally reshaping electricity distribution systems. A marked increase in distributed energy resources (DER) along with the electrification of the mobility and heating sectors is intensifying the demand on distribution networks, especially low-voltage (LV) networks [2]. As a result, LV networks are increasingly affected by technical limit violations (TLV), including transformer and line overloads as well as voltage band violations. These challenges increase the planning demand for LV networks, making innovative and scalable planning solutions essential to reliably fulfil future supply tasks in a secure, sustainable, and cost-efficient manner.

An effective measure to mitigate severe TLV in LV networks is separating given networks by integrating a new distribution substation (DSS) [2]. A new DSS can resolve TLV across multiple feeders or adjacent networks simultaneously and addresses transformer as well as line overloads and voltage band violations. However, the planning complexity is significantly higher compared to conventional expansion measures, such as the replacement of existing lines or transformers [2]. Integrating a new DSS involves numerous degrees of freedom but also restrictions in terms of their exact placement and the emerging topology.

A review of the literature reveals that existing approaches for the optimal placement of new DSS can be distinguished based on their planning scope and level of detail. The first category comprises approaches for planning new DSS in large-scale areas. In these top-down approaches, the primary criterion for optimal positioning is often the geographical load density [3-7]. Geospatial analysis and clustering techniques, such as K-means, are used to identify load centres that serve as candidate locations for new DSS [3]. The existing network infrastructure, if considered at all, is typically limited to the medium-voltage (MV) network [4]. Consequently, if TLV from load flow analyses are used as an input, these are generally derived from the MV network rather than from specific TLV in the underlying LV networks [5]. A second category consists of holistic planning approaches. These approaches often address Greenfield planning, where entire distribution networks are designed with no existing network infrastructure [8] or existing networks are expanded [9]. In this context, the optimal placement of new DSS is not an isolated task but rather one of several interdependent measures within a comprehensive optimization problem. The third category includes a preceding contribution that introduced a method for the optimal integration of a single new DSS into an existing small LV network area [10]. This method, however, had two notable limitations: First, the potential positions for the new DSS were restricted to existing nodes within the LV network area. Second, its application to large-scale areas required a preliminary, separate step to identify smaller, suitable sub-areas, which was again based on an analysis of load density.

This contribution addresses these limitations by introducing an automated method for the optimal placement of new DSS within large-scale LV network areas. The proposed method initially uses spatial data to identify suitable positions for new DSS. In a second step, the positions that minimise approximated costs for expansion in the LV network area are chosen. This is done by iteratively evaluating potential DSS placements based on their net economic benefit. To prove effectiveness in reducing overall expansion costs of the LV network area and especially in reducing line measures, the whole LV network area is subsequently fed into an automated network planning tool [11, 12], comparing necessary expansion costs with and without integration of new DSS.

This contribution is structured as follows: In Section 2 the method for the placement of new DSS is presented. Section 3 shows results for an exemplary LV network area of a German distribution system operator (DSO). Section 4 summarizes the findings, implications, and potential future developments.

2 Method

2.1 Filtering for suitable DSS positions

The first step of the proposed method involves identifying all sites within the study area where the construction of new DSS is generally feasible. The siting process accounts for the different types of DSS typically used in LV networks. These include (in cable networks): (1) masonry stations housed in dedicated small structures, which are no longer standard for new installations; (2) compact stations in prefabricated enclosures, suitable for open-space installation; and (3) basement stations integrated into public or industrial buildings, which typically incur higher costs due to regulatory compliance requirements for interior rooms. [13]

To define the spatial extent for potential sites, polygon geometries around all considered individual LV networks within the LV network area are created. The outer boundary of the merged set of these polygons defines the overall study area. Within this area, publicly available geospatial datasets from the ALKIS land information system provided by the state platform of North Rhine-Westphalia (ALKIS NRW) are utilized [14]. Comparable platforms are available in all other German federal states. These datasets include parcel boundaries, land use classifications, and building footprints. The datasets are spatially intersected to form a basis for identifying viable siting options. An example for a 1 × 1 kilometre study area in Wuppertal is provided in Figure 1.

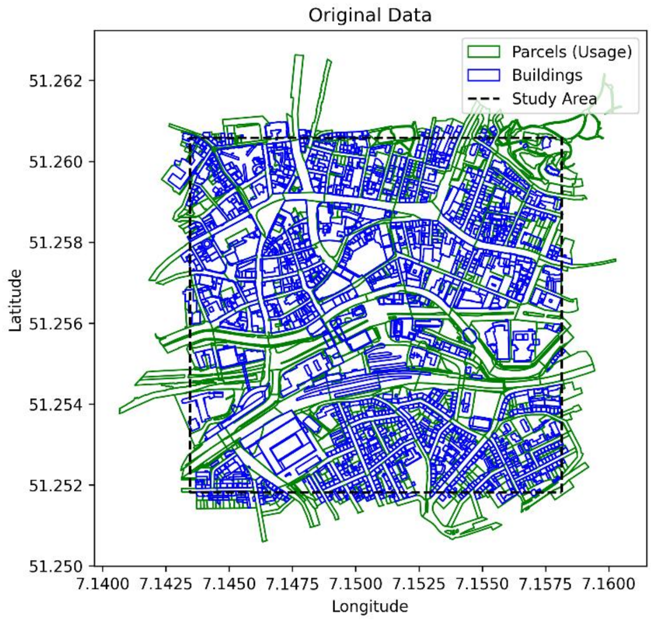


Figure 1 ALKIS data ("NutzungFlurstueck", "GebaeudeBauwerk" layers) for an example 1 × 1 kilometer area in Wuppertal

Preselection of Generally Suitable Areas and Buildings: For compact substations, suitable sites include public spaces, greenspaces, pedestrian zones, and publicly accessible land parcels. Private residential properties, industrial zones, and transportation infrastructure such as roads and railways are excluded. For basement substations, suitable sites are buildings designated for public or industrial use, such as schools or municipal facilities, located on appropriate parcels. Preselection results for the example study area are provided in Figure 2.

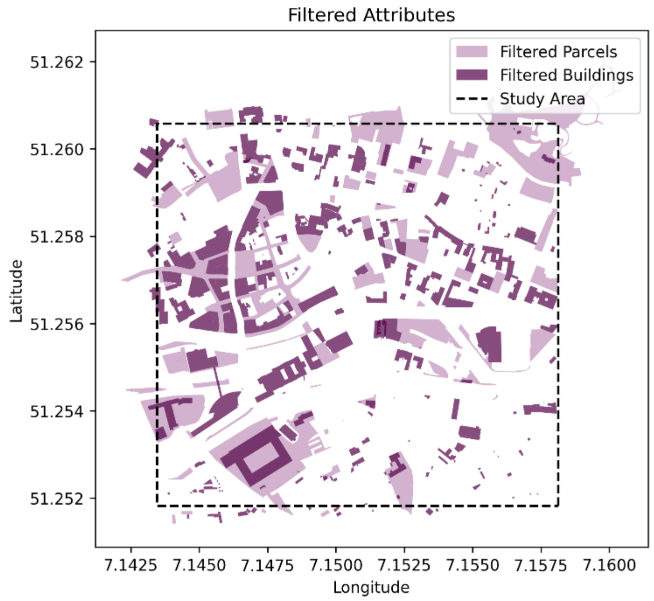


Figure 2 Example ALKIS data filtered by parcel usage and building function for the example study area

Filtering Based on Minimum Required Space: Spatial requirements are evaluated for each possible site to ensure a sufficient area is available for installation and maintenance. Compact substations typically require an area of approximately 4 × 2 metres [13]. In addition, open-space installations demand clearance zones to allow access for maintenance and to preserve public accessibility. Basement substations similarly require technical access areas, albeit with reduced clearance needs. For open-space clearance zones, 1.5 metres around the DSS footprints were chosen, 0.75 metres for basement DSS. Again, the results for the example study area are shown in Figure 3.

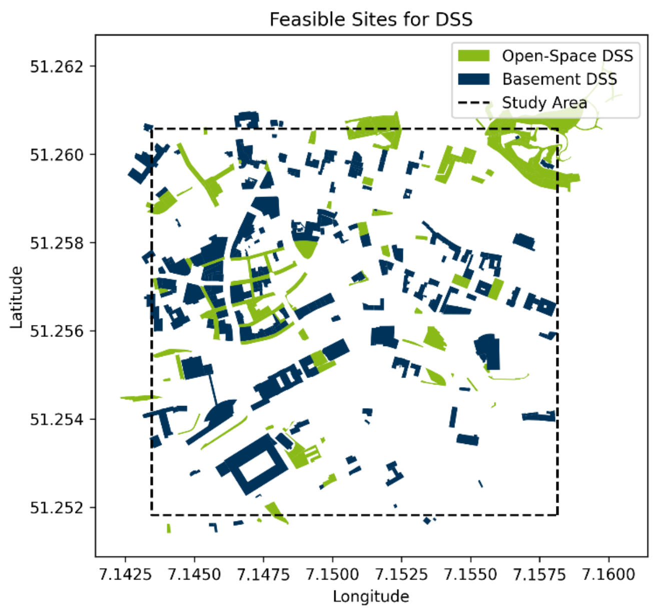


Figure 3 Feasible sites for DSS after considering footprint and clearance zones in example study area

Only sites that meet both the land-use criteria and the spatial requirements are retained for the subsequent analysis steps. This pre-filtering ensures that all further optimizations are based solely on technically and spatially feasible DSS locations.

2.2 Economic Evaluation and Optimal Placement

Following the identification of feasible sites in section 2.1, the second step of the method involves a systematic, economic-driven search to determine the optimal position for a new DSS. The objective is to identify the position that maximizes the net economic benefit, defined as the difference between the prevented expansion costs in the existing LV networks by the new DSS and the costs for the new DSS and its network integration. The process is executed in an iterative sequence of evaluation, placement, and network state updates.

A high-resolution point matrix (e.g., a 2-metre raster) across the entire study area is created. This matrix is then filtered, retaining only those points that lie within the suitable sites identified in 2.1. Each remaining point is considered as a candidate position (CP) for a new DSS and is subjected to the following evaluation.

2.2.1 Monetization of TLV

To quantify the net economic benefit of a new DSS, it is first necessary to translate all existing TLV within the existing LV networks into an estimated monetary value. This score represents the conventional expansion costs that would be incurred to resolve these issues without building a new DSS. This scoring is performed separately for each feeder and transformer.

Assessment of Feeder-Specific Expansion Costs

For each LV network, every individual feeder is analysed to determine its specific score, representing the estimated costs for necessary expansion measures within that feeder. Therefore, the network first is virtually dissected into its individual feeders. For each feeder, a distinct submodel is created. Load flow simulations are then conducted for two critical operating points: a peak load operating point (risk of line overloads and undervoltages) and a peak in-feed operating point from DER (risk of line overloads and overvoltages).

Thermal Overloads: Based on the load flow results, all line segments with a loading above 100% are identified for both operating points. The one resulting in the greater total length of overloaded lines is deemed the dimensioning case for thermal expansion. The initial part of the feeder score is calculated by multiplying this cumulative length of overloaded cables by the standardized costs per kilometre for a new line segment.

Voltage Violations: To prevent double-counting costs, an additional analysis is performed to monetize remaining voltage violations. First, the maximum voltage deviation (either under- or overvoltage) across both scenarios is identified. The electrical path from the substation to this critical node is traced. The algorithm then quantifies the voltage improvement attributable to the line replacements already accounted for in the thermal overload calculation. This is done by approximating the difference in voltage drop over the respective line segments using the current and original voltage drop from the load flow results and the new impedance values for the new line type. If a residual voltage violation persists, the algorithm virtually replaces additional lines along this critical path, prioritizing those that offer the greatest voltage improvement per monetary unit of investment. The associated costs are added to the feeder's score until the voltage band is respected. If the issue cannot be resolved by replacing all lines on the path, an additional penalty score is added to approximate further needed line measures (f. e. splitting the feeder).

The final feeder score is the sum of the costs calculated for thermal overload and voltage violation mitigation.

Assessment of Transformer Expansion Costs

Concurrently, the main transformer of each existing DSS is evaluated. The maximum load across both simulated operation points is determined and compared against the transformer's rated power. If the transformer is overloaded, a score is assigned based on a staggered cost function. This score represents the costs of an upgrade to the necessary standard transformer size. If the maximum power exceeds the highest available standard transformer size (e. g. rated power of 1000 kVA), the score corresponding to the costs of a new DSS enclosure and switchgear and the additional required standard transformer size is added.

2.2.2 Cost-Benefit Analysis for each Candidate Position

For each CP, the net economic benefit of establishing a new DSS at that location is evaluated. This involves calculating the total investment costs for the new DSS and the total savings, which are the equivalent to total prevented expansion costs.

Investment Costs: The costs side comprises fixed base costs for the DSS enclosure and switchgear, the costs of the transformer and variable connection costs. The base costs are adjusted to the DSS type (basement or open-space). To account for inaccuracies of the given assumptions and costs for integration on MV level an additional buffer is added to the base costs. The connection costs are calculated for each feeder that would be connected to the new DSS. Connection costs of each feeder is based on the linear distance from CP to the existing line route, corrected by a detour factor of 1.5 to account for the difference to actual line routing compared to linear distance. The required transformer standard size is estimated by the sum of the maximum load of all connected feeders.

Avoided Feeder-Specific Expansion Costs: The savings side is determined by analysing which feeders from nearby, overloaded LV networks can be economically connected to the new DSS at CP. A feeder is only considered for connection if the expected saving exceeds its specific connection costs. The connection point along the feeder is determined by projecting the CP along its geometry. Depending on the selected connection point, either the full pre-calculated score or only a fraction of it is considered (see 2.2.1). The farther the connection point is located from the existing DSS, the more evenly the feeder and therefore the load can be split between the existing and new DSS, leading to higher realizable savings.

A secondary, transformer-driven logic is applied in cases where an existing DSS transformer is either moderately overloaded and no associated feeder was deemed worth connecting or severely overloaded and only a single associated feeder was deemed worth connecting. Under these conditions, an additional feeder may be connected, even if its individual savings-to-costs ratio is unfavourable, if the sum of feeder and transformer savings remains worthwhile.

Avoided Transformer Expansion Costs: After determining the final set of feeders to be transferred to the new DSS from a given existing LV network the resulting savings for their transformers are calculated. Transferring one or more feeders significantly reduces the load on the existing transformers. These reliefs are monetized as avoided costs, corresponding to the magnitude of the overloads and the amount of feeders connected.

The final evaluation for the CP aggregates the costs and savings from all surrounding existing networks. The result is a net economic benefit for the examined CP.

2.2.3 Iterative Placement and Score Updating

This evaluation is performed for all CP within the study area. The CP yielding the highest positive net economic benefit is selected as the optimal location for the new DSS.

Following this virtual placement, the scores of all network elements (feeders and transformers) that are now supplied by the new DSS are updated to reflect their resolved TLV. With this updated network state, the entire evaluation process is repeated. The system searches for the next best DSS position, considering the remaining, unaddressed TLV. This iterative procedure continues until no CP in the LV network area offers a positive net economic benefit, ensuring a systematic and economically optimized expansion of the entire LV network area.

2.3 Integration of DSS

Once the optimal location and the corresponding feeders to be connected have been determined by the economic evaluation in section 2.2, the final step is the integration of the new DSS into the existing LV network area topology. This process ensures that the structural changes result in a technically valid and radially operated network. It comprises two main actions: routing new connection lines and performing the sectionalisation of corresponding feeders to split them between the existing and the new LV networks. This procedure is based on a method from a previous contribution [10] for optimal integration of a single DSS into a small LV network area. Appropriate adjustments are made to fit in with the previous steps and all deviating conditions.

First, new line routes are created to connect the new DSS to each of the corresponding feeders. Leveraging underlying terrain and the road network model from public geospatial data [15], the most cost-efficient routes are determined and installed.

Second, the corresponding feeders must be restructured by establishing new sectionalization points. This is essential to maintain a radial network topology for both the LV network belonging to the newly installed DSS and the already existing LV networks. For each corresponding feeder, the optimal sectionalization point must be identified, which defines the new electrical boundary between the two DSS that are connected to the feeder. In the previous contribution [10], the evaluation of possible combinations was based on minimising overall expansion costs. In the present method, this step serves to implement the optimal configuration of feeders with minimal remaining TLV, as an economic evaluation was already done in the previous step.

The process for each feeder is as follows: Potential sectionalization points are identified, which can be existing switches or viable physical locations for a new disconnection point along a line segment. A load flow analysis is performed for each configuration to identify the optimal sectionalization points. To minimize operational effort and costs, opening existing switches is prioritized over physically cutting a line while TLV, or lack thereof, are identical.

Upon completion of the integration for all feeders connected to the new DSS, the LV network area topology is updated. The result is a new topology that contains the existing and new individual LV networks and is ready for subsequent strategic network planning.

3 Results

To show the effectiveness of the proposed method, it is applied to an exemplary LV network area of a German DSO. The LV network area, shown in Figure 4, comprises 63 individual LV networks and encompasses all DSS supplied by an overlying MV network. A projected future load and generation scenario is applied to the LV network area to simulate a future supply task (Exact numbers for different technologies are based on [16]). All cost parameters (e.g. line material, trench, different rated power transformers, DSS enclosure and switchgear etc.) are generic but derived from German DSO experience.

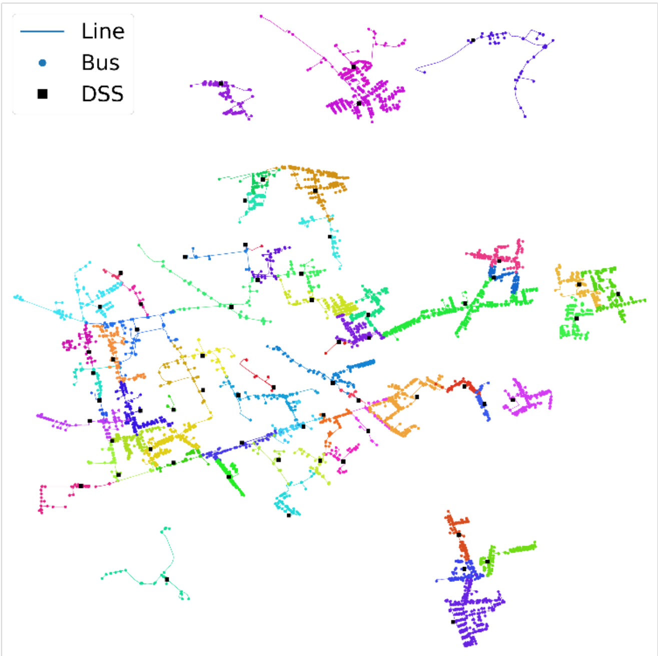


Figure 4 LV network study area base topology

Figure 5 displays the resulting point matrix generated for the study area. The centre of the area is characterized by an urban and commercial landscape, whereas the peripheral regions include, among other features, green spaces. This characteristic is reflected in the presented results: in the central subareas, building DSS are permissible in many positions, while open-space DSS are rarely allowed. Conversely, the peripheral regions show large subareas where open-space DSS are permitted.

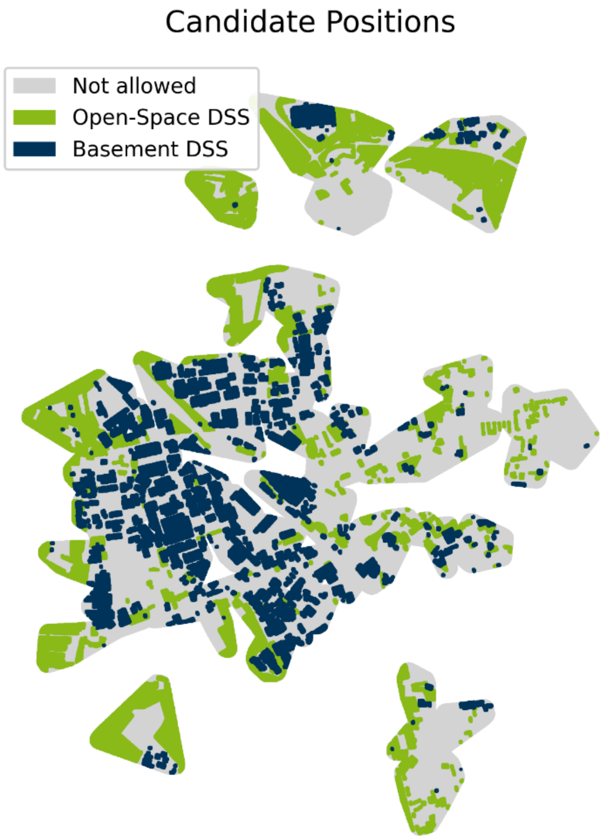
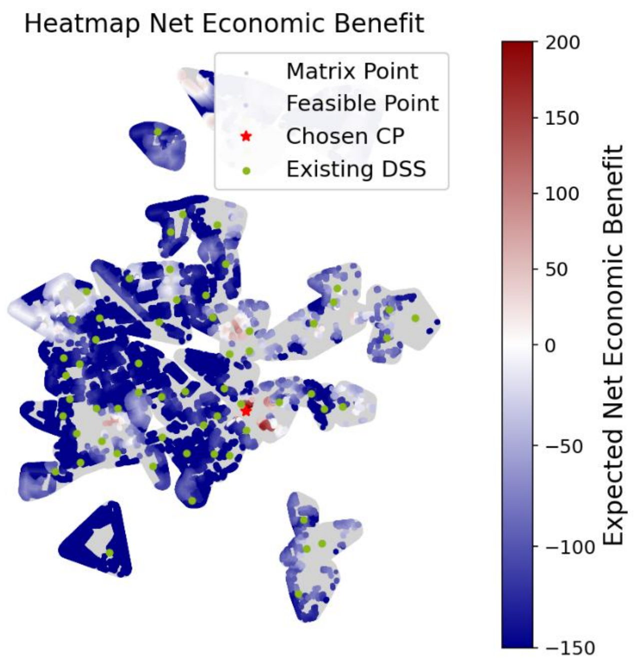
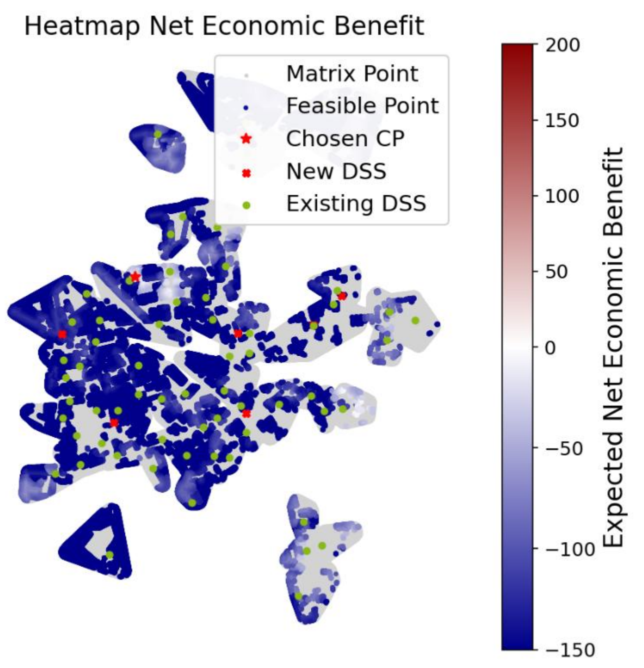


Figure 5 Point matrix, points coloured regarding feasible DSS type

Figure 6 shows the first (Subfigure (a)) and last (Subfigure (b)) iteration of the economic evaluation for all CP in the LV network area. As expected, in the first iteration multiple red-ish areas exist distributed over the LV network area, representing worthwhile CP for new DSS placement. The best CP, which is selected first, is located within a darkred area, translating to more than 200,000 € of estimated net economic benefit. In the last iteration, only blue-ish areas remain, meaning no more worthwhile CP are available, and chosen CP in previous iterations are marked as red crosses. Comparing the Subfigures (a) and (b), it is suitable that red crosses are located in previously red areas.



(a)



(b)

Figure 6 (a) First iteration heatmap of the net economic benefit for study area; (b) Last iteration heatmap of net economic benefit for study area with all new DSS positions marked

Figure 7 shows the result of the integration of the new DSS into the LV network area. New DSS are placed at the chosen CP, connection lines to the corresponding feeders are added and sectionalization is performed, creating a new viable radial topology for all LV networks. All individual LV networks in the LV network area are then fed into the automated planning tool to compare needed expansion with and without new DSS.

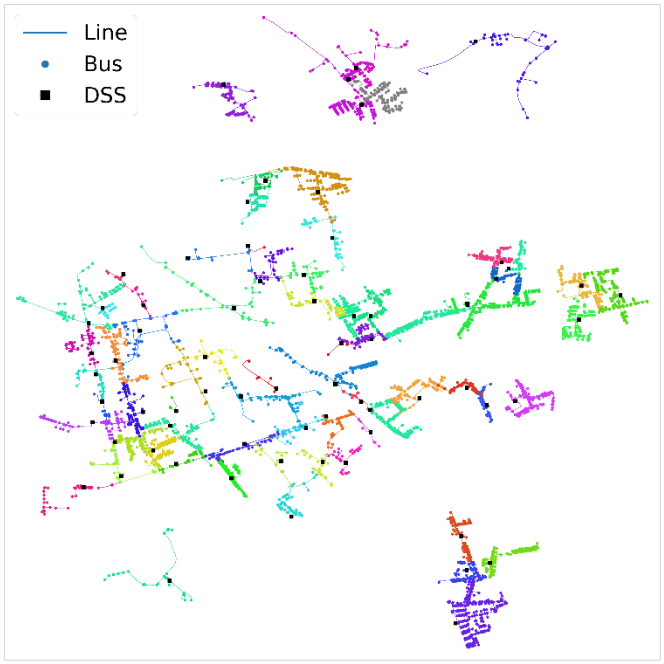


Figure 7 LV network study area with new DSS fully integrated after applying the method

Results for expansion costs determined by the automated planning for both cases of planning are shown in Table 1. As 7 new DSS were integrated in previous steps, the planning results are for 63 individual LV networks in the base case and 70 individual LV networks in the case of new DSS integrated, consisting of the 63 original LV networks and the 7 new networks supplied by the new DSS. While the new DSS add new cost categories (new DSS enclosure, new DSS transformers and integration costs for new DSS) that are not relevant for the base planning case, conventional expansion of transformers and lines for existing networks is significantly lower. Total investment there differs by 460,176.00 €, meaning a 10.3 % reduction with new DSS compared to the base topology.

Table 1 Comparison of expansion costs for LV network area with and without new DSS integrated

Cost Category	**LV network area base case**	**LV network area new DSS case**
Transformer reinforcement	1,235,000 €	935,000 €
Line reinforcement	3,235,330 €	2,391,645 €
New DSS enclosure	0 €	340,000 €
New DSS transformer	0 €	245,000 €
New DSS integration	0 €	98,509 €
Total Investment	4,470,330 €	4,010,154 €

The most notable difference lies in costs for line reinforcement. The costs for line reinforcement are reduced by 843,685.00 €, meaning a 26.1 % reduction. This translates to a lower required length of line measures and therefore also civil engineering measures, visualised in Figure 8.

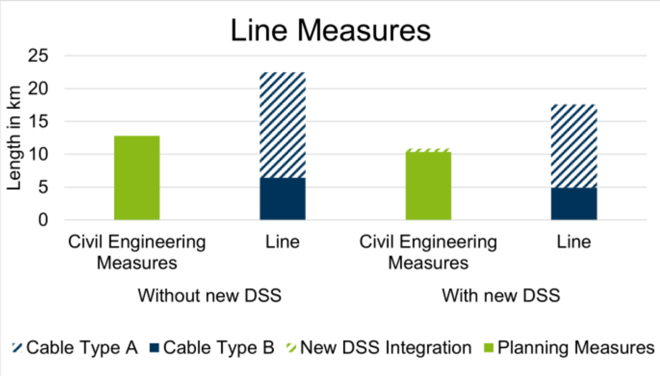


Figure 8 Comparison of line expansion length and for study area with and without new DSS integrated

4 Conclusion

This contribution presented a novel, automated method to address the increasing planning demand in LV networks driven by the energy transition. The proposed method systematically identifies the cost-optimal placement of new DSS through a two-step process. First, a comprehensive analysis of public geospatial data filters the entire study area for physically and legally feasible installation sites. Second, an iterative, economic-driven algorithm evaluates each CP by calculating its net economic benefit.

The application of this method to a large-scale, real-world LV network area of a German DSO demonstrates its effectiveness. Multiple worthwhile CP for new DSS could be identified and DSS were successfully integrated into the existing topology. This way, significant reductions in total expansion costs were achieved. The primary driver for these savings is the substantial reduction in required conventional line reinforcement measures.

By lowering the amount of required line reinforcement and therefore also civil engineering measures, a direct contribution to the overarching goal of a zero-carbon society by enhancing the energy efficiency of network expansion is made. Conventional line reinforcements are intrinsically linked to high energy consumption and CO_2 emissions through extensive civil engineering works, including excavation, manufacturing of materials, and transportation. By minimising these activities, the proposed method actively reduces the carbon footprint associated with necessary network expansion. It therefore provides a pathway to decarbonize not only the energy supply but also the construction and maintenance of the infrastructure required for it.

While the method proves effective, its current implementation approximates the consequential costs on the overlying MV network via a fixed cost buffer. Future research should therefore focus on a more detailed, coupled simulation and optimization of both the LV and MV network levels. A holistic integration would allow for a more precise quantification of costs and technical impacts on the MV network level, further refining the economic evaluation and leading to even more robust and systemically optimal planning decisions.

References

[1] United Nations Treaty Collection, "Paris Agreement,"

[2] P. Wintzek, S. Alsayed Ali, M. Zdrallek, J. Monscheidt, B. Gemsjäger, and A. Slupinski, "Development of Planning and Operation Guidelines for Strategic Grid Planning of Urban Low-Voltage Grids with a New Supply Task," *Electricity*, pp. 614–652, 2021.

[3] S. Corigliano, F. Rosato, C. Ortiz Dominguez and M. Merlo, "Clustering Techniques for Secondary Substations Siting." *Energies*, 14, no. 4, 2021, DOI: https://doi.org/10.3390/en14041028

[4] El-Fouly et al., "A new optimization model for distribution substation siting, sizing, and timing," *Int. J. Elec. Power Energy Syst.,* 30(5), pp. 308–315, 2008

[5] F. Meisam, M. B. B. Sharifian, R. Esmaeilzadeh, "A Novel Method for Optimal Location and Expansion of Subtransmission Substations Considering Existing Medium-Voltage Distribution Feeders," *American Journal of Applied Sciences. 6.*, 2009, DOI: 10.3844/ajassp.2009.368.379.

[6] L. Wang, Y. Wang, K. Yang, S. Yang, and C. Luo, "An Approach of Substation Location and Capacity Planning Considering Geographical Constraints," *2023 8th Asia Conference on Power and Electrical Engineering (ACPEE)*, 2023.

[7] M.-R. Haghifam, M.Esmaeeli, A. Kazemi, and H. Shayanfar, "Optimal Placement of the Distribution Substations to Improve Reliability Under Load Growth," 2015 IEEE Power & Energy Society General Meeting, 2015

[8] F. Barrera, J. Brito, E. Moreno and J. Munoz, "Optimal integrated planning of MV–LV distribution systems using DPSO," *Elect. Power Syst. Res.*, vol. 81, no. 10, pp. 1905–1914, Oct. 2011.

[9] S. Heidari and M. Fotuhi-Firuzabad, "Integrated Planning for Distribution Automation and Network Capacity Expansion," IEEE Transactions on Smart Grid, no. 10, pp. 4279–4288, 2019.

[10] Rebentisch, T.; Becker, C.; Riedlinger, T.; Zdrallek, M.; Tracht, A.; Körner, P., "Two-stage method for optimal placement and integration of distribution substations in low voltage networks," *Proceedings of the 28th International Conference on Electricity Distribution (CIRED 2025)*, Geneva (2025)

[11] T. Riedlinger, B. B. Wierzba, M. Zdrallek, and S. Plötz," Analysis of a support-year-based and an end-year-based optimization in automated network planning," *Proceedings of the International ETG Congress 2023*, Kassel (2023).

[12] T. Riedlinger, B. B. Wierzba, M. Zdrallek, L. Lohrberg, and D. Wolter, "Integration of Renewal Planning Results in an Automated Strategic Power Grid Planning," in *Mediterranean Conference on Power Generation, Transmission, Distribution and Energy Conversion (MEDPOWER)*, Valletta, Malta, 2022.

[13] ABB, Technical guide: MV/LV transformer substations, 5th ed., ABB SACE Division, 2022. [Online]. Available: https://library.e.abb.com/public/5fa84c2f08dd4e4ea7c94a98de0ebea3/MV_LV_Transformer_Substations_EN.pdf

[14] Geobasis NRW – Open Data, "ALKIS cadastre data NRW," 2025. [Online]. Available: https://www.opengeodata.nrw.de

[15] OpenStreetMap contributors, OpenStreetMap. Accessed: Jan. 16 2025. [Online]. Available: https://www.openstreetmap.org/

[16] Kopernikus-Projekt Ariadne Potsdam-Institut für Klimafolgenforschung (PIK), Ed., "Kopernikus-Projekt Ariadne (2021): Ariadne-Report: Deutschland auf dem Weg zur Klimaneutralität 2045: Szenarien und Pfade im Modellvergleich," Oct. 2021.

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