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Geospatial Analysis of a Medium Voltage Distribution Network Expansion Planning

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ABSTRACT

The current transition toward carbon neutrality creates several previously unforeseen challenges. The intermittent and unpredictable nature of renewable energy can potentially be harmful regarding important factors such as flexibility. The most recent report by the International Energy Agency guarantees an absolute need to double infrastructure equipment by 2030, and they also predict that the system flexibility will need to almost double by the same time. Thus, planning network expansions appropriately is key. This paper will focus on the geospatial analysis of terrain according to several environmental, soil, location, social, and technical constraints. This task is often overlooked in theoretical network planning papers, but it is extremely crucial to showcase practical applicability. For an exposition case study, an excerpt of a real 180-bus network in Portugal will be used and analyzed for a potential expansion.

Keywords: Distribution Network Expansion, Geospatial Analysis, Geospatial Visualization, Landscape Analysis, Natural Constraints, Optimal Planning

1. INTRODUCTION

To meet the desired target of 42.5% renewable energy source (RES) penetration by 2030, the International Energy Agency assures a need to double network flexibility and network investment alike [1]. While there are multiple studies that tackle the necessity for optimal network planning, almost all completely disregard the practicality of their approaches, and stick to analyzing the theoretical possibilities. Several viewpoints need to be regarded when considering the expansion of a network, such as the fact that the terrain obviously needs to be appropriate [2] for the placement of support poles and should not have a high terrain slope to allow for proper installation and maintenance. Some works have broadly approached this issue, such as [3], where the authors present a GIS-based method for optimizing electric line routing, considering environmental, operational, and cost factors, using dynamic programming to identify economic corridors and optimal paths for new power lines. In [4], the authors present a GIS framework for planning electrification in developing countries, focusing on the cost-effectiveness of grid, mini-grid, and home systems based on community and household distribution patterns in rural sub-Saharan Africa. In [5], the authors evaluate the sustainability of power line routing in Brazil, proposing an alternative route with a higher sustainability index, while considering environmental, social, and economic impacts using GIS and MCDA.

Fig. 1 showcases the framework of the proposed method, which aims to advance the state-of-the -art.

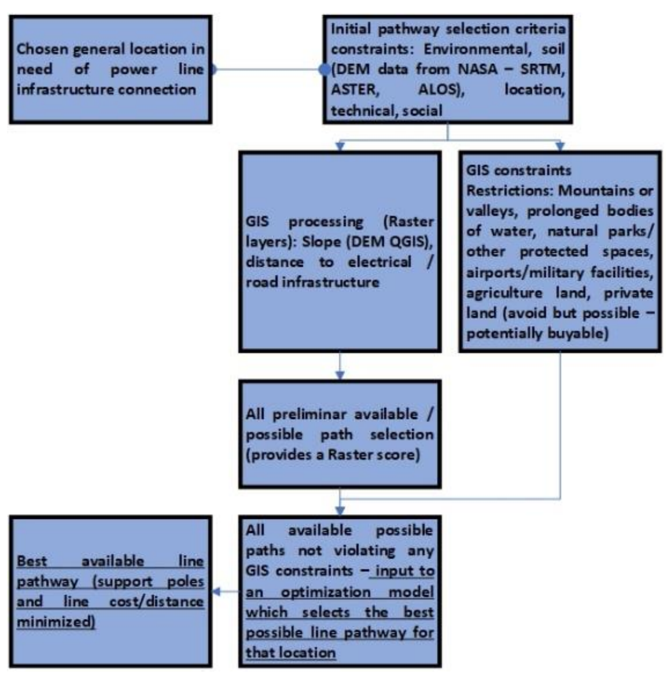

Fig. 1 Flowchart of the method

[1]This is a paper for the 16th International Conference on Applied Energy (ICAE2024), Sep. 1-5, 2024, Niigata, Japan.

2. PROPOSED METHODOLOGY AND CASE STUDY

The proposed state-of-the-art advancement corresponds to a novel approach to general geospatial analysis, focused on expansion network planning, in this specific case for medium voltage distribution networks, using a real network.

To achieve this analysis, localized data is collected and processed. Digital elevation models (DEM) were collected from open sources, such as NASA's earth dataset [6]. There were several void pixels, which were filled via interpolation using "Gdal_fillnodata". The data was then mapped to the Portugal location using "Gdalwarp" [7].

These datasets were then inserted into QGIS, and slope and terrain for the desired area was analyzed and visualized.

Tools such as Google Maps and Google Earth were used to understand the precise proximity and existing constraints such as the ones specified in Fig. 1. Since the final line destination was preemptively decided, there is a need to analyze the optimized way to reach that place.

Fig. 2 shows the existing line infrastructure in the place, and the point to which the line needs to be expanded to. The bigger yellow round markers are line support poles, and the ones filled in red are the selected potential exit points where the line can be extended to the desired "Expansion Location".

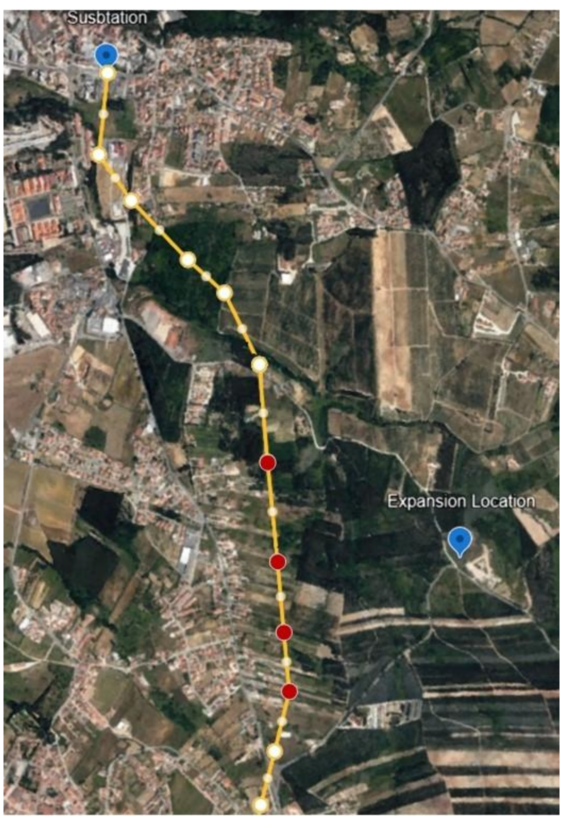

Fig. 2 Line expansion location and start points

The shown line infrastructure is part of a 180-bus network. The full data for the 180-bus network can be found in [8]. The area between the selected branching points and the "Expansion Location" will then be analyzed for potential restrictions according to the definitions in Fig. 1. While this is a small example, on a larger scale, there could potentially be numerous branching possibilities and trajectories.

After this brief analysis the data is implemented into an optimization model which will determine the optimal location by minimizing the investments (lines, support poles, transformers, etc.), while choosing a viable route. Inputs include total trajectory distance via vector analysis of areas, line costs, pole costs (to consider harsh direction changes and longer straight distances), among others. When crossing terrain that appears to be private, a heavy penalty is inferred (implying buying the terrain), for that whole aggregated area. However, this can potentially be slightly misleading as multiple lumps of terrain can be of the same owner.

Fig. 3 shows the unifilar network configuration.

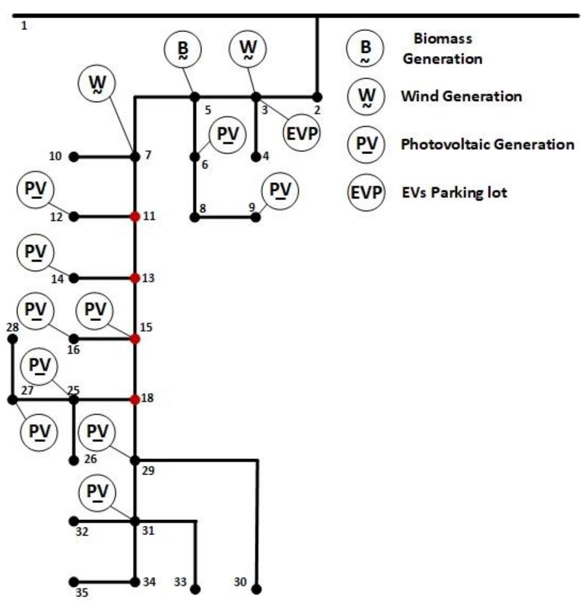

Fig. 3 Unifilar line configuration

Regarding the model inputs, these values are highly uncertain and heavily depend on region and other factors. For this study, the values were arbitrated to be 2,500 m.u. per pole, 1,500 m.u. for additional equipment per pole (such as isolation, etc.), 750 m.u. for taxes, licenses, and periodic maintenance and 1,000 m.u. for installation labor. All these costs are per pole installed. Additionally, it was decided that the cost per line meter would be 30 m.u. and the normalized distance per pole would be 150 m.

From the four potential exit points defined in Fig. 2, a total of 12 potential paths were defined that respected the GIS constraints in Fig. 1. They were input into the optimization model.

The model is as follows in Eqs. (1)-(7).

Eq. (1) shows the objective function which aims to minimize all potential costs.

$$Min\ Z = \sum_{p \in P} x_p \left(\sum_{s \in S_p} \left(\begin{array}{l} C_{line_{meter}} \cdot d_{PS} + \\ \left(C_{pole} + C_E + C_{AE} + C_T \right) \cdot y_P \end{array} \right) \right) \quad (1)$$

Apart from the GIS constraints in Fig. 1, the model abides by some mathematical constraints. Eq. (2) shows that out of all the input paths only one must be selected.

$$\sum_{p \in P} x_p = 1 \quad (2)$$

Eqs. (3) and (4) shows that poles must be placed at a direction change if needed.

$$y_{ps} \geq z_{ps} \quad \forall_p \in P, \quad \forall_s \in S \quad (3)$$

$$z_{ps} \geq T_{ps} \quad \forall_p \in P, \quad \forall_s \in S \quad (4)$$

Eq. (5) internally connects the path selection to the number of poles.

$$y_{ps} \leq M \cdot x_p \quad (5)$$

Eq. (6) ensures that poles are placed at appropriate distances. When the remaining total distance is less than the normalized distance per pole, *D*, the model places a pole at the end. When the total remaining distance is more than *D*, but less than 2*D*, the model places a pole halfway, and then at the end (for example, if 200 meters were left, with 150 meters being the normalized distance, the model would place a pole at 100 meters and one at the end). If the remaining distance is more than 2*D* the model places a pole every 150 meters until the distance is 2*D* or less.

$$y_{ps} \geq \left\lceil \frac{d_{ps}}{D} \right\rceil + \left\lceil \frac{d_{ps} - \left\lceil \frac{d_{ps}}{D} \right\rceil \cdot D}{D} \right\rceil + 1 \quad (6)$$

$$\forall_p \in P, \quad \forall_s \in S$$

Finally, when the model places a pole, it needs to update the distance to recalibrate, as in Eq. (7).

$$Pd_{ps} \geq d_{ps} - \sum_{s' < s} y_{ps'} \cdot D \quad (7)$$

$$\forall_p \in P, \quad \forall_s \in S$$

3. RESULTS AND DISCUSSION

This model is part of the expansion planning of a distribution network, which is then input into a full planning model [9].

This geospatial analysis model was implemented into a computer using Windows 11 Education, with an Intel Core i9 13900KF CPU and 32GB of RAM. It was built using Pyomo [10] and solved using the Gurobi [11] solver, written in Python.

Of the 12 possible pathways exiting the existing infrastructure (Fig. 2), the model chose the pathway to be as chosen in Fig. 3. Even in this specific path, there was a forced direction change (leading to more support poles needed) as there was a steep slope followed by a dense tree agglomerate which made going in a straight line impossible. The full red dots on the pathway are the placement of the support poles needed for this expansion, noting that only one direction change was necessary.

Fig. 3 Optimal line expansion path

In this path, to its right was a high slope, not allowing a straight line. As such, the path was of 268 meters before it needed a direction changed, and then a straight line of 466 meters after the direction change. To breakdown the innings of the model, this was how the poles were placed: in the first segment of this path (268 meters), the distance was higher than *D*, but lower than 2*D*, meaning the model placed a pole at 134 meters, and one at 268 meters. In the second segment, the distance left was 466 meters, higher than 2*D*, so the model placed a pole at 418 meters (268+150-normalized distance), leaving the total remaining distance as 316 meters (still higher than 2*D*), thus placing another at 568 meters, leaving 166 meters (between *D* and 2*D*), thus placing a pole halfway, at 651 meters, and a pole at the end, 734 meters. As such, six poles were needed.

The full cost details can be seen in Table I.

Table I. Cost and pole placement details

Pole cost (m.u.)	15,000
Additional Equipment (Isolation,etc.) (m.u.)	9,000
Taxes, licenses and maintenance (m.u.)	4,500
Installation labor (m.u.)	6,000
Excavations and structures (m.u.)	6,000
Cost of lines (m.u.)	22,020
Total cost (m.u.)	**62,520**

4. CONCLUSION

The shift towards achieving carbon neutrality presents unprecedented challenges that demand careful consideration and strategic planning. The intermittent and unpredictable nature of RES introduces complexities that can impact system flexibility, a critical factor in ensuring stable and reliable energy supply.

This paper underscores the significance of geospatial analysis in addressing the complexities of network planning amidst environmental, soil, locational, social, and technical constraints. While often overlooked in theoretical network planning studies, this approach is indispensable for demonstrating practical applicability and ensuring sustainable energy solutions. The model minimized all potential costs, totaling 62,520 m.u. as expenses and six necessary support poles.

As future perspectives to evolve this model, the authors plan to have better precision on input parameters (namely the predefined costs), and to apply this model on a bigger scale.

NOMENCLATURE

Indices and Sets

p	Line path
s_P	Line segments in path, P (m)
Ω_P	Set of line paths
Ω_S	Set of segments within path P

Parameters

C_{AE}	Cost of added equipment (isolation, etc.) (m.u.)
C_{line_meter}	Cost per meter of line (m.u./m)
C_E	Cost of excavations/structure (m.u.)
C_{pole}	Cost per pole (m.u.)
C_T	Cost of taxes/licenses (m.u.)
D	Distance per pole normalized (m)
d_{PS}	Distance of segment, s, in path, o (m)
T_{PS}	Binary direction change indicator for segment *s*, in path, *p*

Variables

Pd_{ps}	Distance where the *n*-th pole is place in segment, *s,* of path, *p* (m)
X_p	Binary variable that indicates if path *p* is selected
y_p	Integer variable indicating the total number of poles placed in segment, *s*, of path, *p* (m)
z_p	Binary variable indicating if segment, *s*, in path, *p*, requires a direction change pole

REFERENCE

[1] IEA, “Electricity Grids and Secure Energy Transitions,” IEA, Paris. Accessed: Apr. 08, 2024. [Online]. Available: https://www.iea.org/reports/electricity-grids-and-secure-energy-transitions ; License: CC BY 4.0

[2] S. Zambrano-Asanza, W. E. Chumbi, J. F. Franco, and A. Padilha-Feltrin, “Multicriteria Decision Analysis in Geographic Information Systems for Identifying Ideal Locations for New Substations,” *Journal of Control, Automation and Electrical Systems*, vol. 32, no. 5, pp. 1305–1316, Oct. 2021, doi: 10.1007/s40313-021-00738-5.

[3] C. Monteiro, I. J. Ramirez-Rosado, V. Miranda, P. J. Zorzano-Santamaria, E. Garcia-Garrido, and L. A. Fernandez-Jimenez, “GIS Spatial Analysis Applied to Electric Line Routing Optimization,” *IEEE Transactions on Power Delivery*, vol. 20, no. 2, pp. 934–942, Apr. 2005, doi: 10.1109/TPWRD.2004.839724.

[4] J. E. Adkins *et al.*, “A geospatial framework for electrification planning in developing countries,” in *2017 IEEE Global Humanitarian Technology Conference (GHTC)*, IEEE, Oct. 2017, pp. 1–10. doi: 10.1109/GHTC.2017.8239293.

[5] G. Castiglio, J. Klas, M. Dal Forno, and M. Resener, “Power Line Routing Considering Aspects of Sustainable Development and Complex Environments,” in *2021 IEEE PES Innovative Smart Grid Technologies Conference - Latin America (ISGT Latin America)*, IEEE, Sep. 2021, pp. 1–5. doi: 10.1109/ISGTLatinAmerica52371.2021.9543060.

[6] NASA - The National Aeronautics and Space Administration, “NASA Earth Data.” Accessed: Jun. 06, 2024. [Online]. Available: https://www.earthdata.nasa.gov

[7] Ciimar, “DEM data.” Accessed: Jun. 06, 2024. [Online]. Available: https://gis.ciimar.up.pt/gisData/dems/

[8] F. Castro, B. Canizes, J. Soares, J. Almeida, B. Francois, and Z. Vale, “180-Bus Medium Voltage Distribution Network Data.” Accessed: Jan. 15, 2024. [Online]. Available: https://zenodo.org/records/10371848

[9] F. Castro, B. Canizes, J. Soares, J. Almeida, and Z. Vale, “Comprehensive Framework for Distribution Network Multi-Investment Expansion Planning: Emissions, Uncertainty, and Resource Remuneration Integration,” *Energy Convers Manag*, vol. 316, p. 118734, Sep. 2024, doi: 10.1016/j.enconman.2024.118734.

[10] M. L. Bynum *et al.*, *Pyomo — Optimization Modeling in Python*, vol. 67. Cham: Springer International Publishing, 2021. doi: 10.1007/978-3-030-68928-5.