Wind farm integration with the objective of transmission expansion power in South Africa

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ABSTRACT

Growing renewable energy (RE) use mitigates climate change. The integration of large-scale intermittent renewable energy resources (RER) like wind energy into electrical networks has increased during the past decade. However, careful planning is needed to accommodate the long-term energy demand increase. Transmission network expansion planning (TNEP) is the methodical and profitable process of increasing power infrastructure to meet predicted electricity demand while preserving reliability. This article is for those interested in integrating renewable energy sources (RES) into HVTL to increase power availability and decrease losses. The Eros-Vuyani-Neptune 400 kV transmission powerline connecting KwaZulu-Natal to the Eastern Cape is used in this study. It was implemented during the transfer of affected residents in the Ingquza Hill Local Municipality, which includes Lusikisiki and Flagstaff villages. This study connects the existing Metro wind farm to the Vuyani substation, which is connected to the Eros substation through a 400 kV transmission line. This research enhanced transmission line power while preserving grid stability with a 27 MW wind farm, and also increased external grid reserve capacity for future usage or unexpected power demand. This paper outlines TNEP's significant advances using classic (mathematical) and advanced (heuristic and meta-heuristic) optimization approaches.

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1. INTRODUCTION

Electricity generation, transmission, and consumption contribute significantly to the socio-economic and infrastructure development of a developing nation [1]. South Africa is Africa's leading energy user and one of the continent's most industrialized countries [2]. The growing recognition of the significant pollutants generated by coal, as well as the depletion of these sources, has compelled energy firms to explore alternative and sustainable energy sources, known as renewable energy resources (RERs) which may play a big role in reducing load shedding [3]. Moreover as a viable alternative to the depleting and environment unfriendly fossil fuels [4], [5]. They are being introduced to reduce emissions, lower maintenance, storage capabilities, and costs associated with generation facilities [6]. However, the presence of inherent uncertainties in RERs adds complexity to optimization challenges [7]. The transmission system plays a crucial role in power networks [8]. Figure 1 shows South Africa's installed capacity, with thermal power the highest. Thus, most of our power plants generate energy from coal. Statistics show that South Africa does not use oil or fuel for power. Renewable energy (RE) sources like solar and wind power have increased in potential again. This study suggests using RE to improve transmission line power accessibility. The Figure uses data from numerous sources [9].

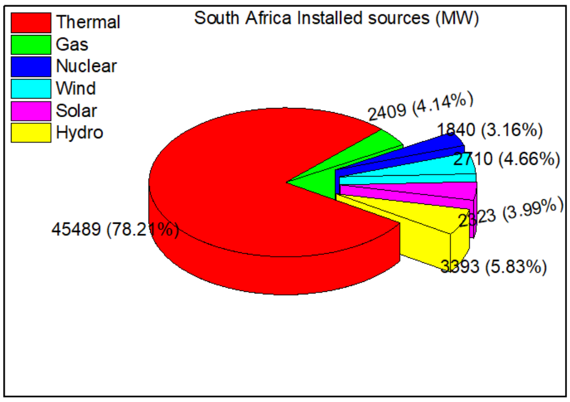


Figure 1. Installed capacity in South Africa

The transmission expansion planning (TEP) problem in modern power networks is a complex, non-linear, mixed-integer, and non-convex problem [10]. TEP aims to develop and fortify the transmission network to meet future energy demand, integrate new power plants, and ensure efficient system operation [11]. TEP aims to increase power system capacity to meet future demand. The TEP specifies the location, timing, and number of new power lines needed to meet network demand. Current and future electrical networks require more precise models to address the TNEP issue due to their complexity [12]. The South African electricity grid needs to be expanded to fulfill the demand growth and the RE integration objective [13]. Other models include investment and operational expenses when choosing transmission lines. The TEP model optimization is hampered by the non-convex and non-linear AC power flow equations. Existing methodologies cannot ensure the optimal global answer [14]. The TEP issue is a complicated and non-convex problem that is both nondeterministic and polynomial time (NP)-hard. It may be expressed as a mixed-integer non-linear programming (MINLP) problem [15]. The MINLP problem can be addressed by the utilization of mathematical methods that employ commercial solvers, or through the application of metaheuristic algorithms such as genetic algorithm (GA), tabu search, particle swarm optimization (PSO) [16]. Furthermore, stochastic programming or robust optimization (RO) methodologies may be employed to consider the pertinent uncertainties associated with the TEP problem, including power consumption, pricing, and renewable energy sources (RES), among other factors [17]. The incorporation of security and dependability aspects into the TNEP problem has been addressed through the development of several approaches [18]. A new 400/132 kV substation, named Vuyani, was necessary in Mthatha to resolve issues of low voltages and overloading on the distribution network [19]. This is the first 400 kV transmission line in the former Transkei region, facilitating an enhanced capacity for power transfer in the area. 400 kV transmission lines efficiently deliver a substantial amount of electricity to supply a significant number of consumers and can provide sufficient power for a whole town [20].

As power plants have grown larger and further away from population centers, the need for efficient ways to move electricity over long distances has become increasingly important. generating a large amount of electricity is a massive endeavor that necessitates a large initial investment as well as continuous costs for maintenance, operation, and fuel. The challenge is that most power plants are typically located far away from populated areas for a variety of reasons, including lower land costs in rural areas, the need for large cooling ponds in many plants, and most people do not want to live near large industrial facilities that require massive amounts of electricity to be transported over long distances. The apparent answer to this problem is power transmission lines, this results in a significant need for transmission lines that can provide sufficient power and maintain stability in the face of unexpected disruptions that may arise in the grid, as well as the losses that occur over long distances.

It is imperative that we do not delay our focus on RE until coal reserves are exhausted. Academics and businesses are focusing on RE. This research examines RE's utilization of HV transmission lines to increase capacity. This study integrates the implementation of the existing wind farm using the DigSilent PowerFactory software tool into the existing SA HV transmission network to promote RE consumption using the Newton-Raphson method in load flow analysis. This study conducts transient stability analysis and n-1 contingency analysis to evaluate the stability of the network when a wind farm is introduced to the transmission lines. it reviews the most effective ways to locate and size new transmission lines in large, complicated networks with many lines. These solutions reduce losses, stabilize voltage, and lower investment costs.

Most power sources are located on terrain far from the city. Reliable transmission networks are necessary for connecting power sources to load centers [21]. The state-owned electricity provider Eskom is vertically integrated. Nearly 95% of South Africa's energy comes from it, and it generates electricity across Africa. It trades power with Botswana, Lesotho, Mozambique, Namibia, Eswatini, Zimbabwe, and Zambia [22]. Determining the optimal timing and location for the installation of transmission lines, cables, and transformers onto the power grid is the objective of the TEP problem [23]. Figure 2 shows the integration of RE into the transmission line. It demonstrates the process of stepping up power for transmission purposes and stepping it down for distribution purposes. Based on the diagram, it is evident that this wind can serve as a supplementary source for strengthening and extending the power in the transmission lines.

The establishment of the transmission line in the Eastern Cape was prompted by the fact that the quantity of electricity required in Port Elizabeth and the adjacent areas is rapidly approaching capacity [24]. The 400 kV transmission line goes from Eros Substation in Harding, KwaZulu-Natal, to Grassridge Substation in Port Elizabeth. Construction of the line was meant to provide electrical supplies to other major Eastern Cape cities. The mountainous terrain made this project difficult. It is also considered one of South Africa's hardest lines. In these difficult terrains, helicopter aerial construction is needed to complete this magnitude of building. Additionally, many tower constructions require hand assembly. Due to the steep terrain, this line has some of the longest tower lengths, up to 1.5 km [25]

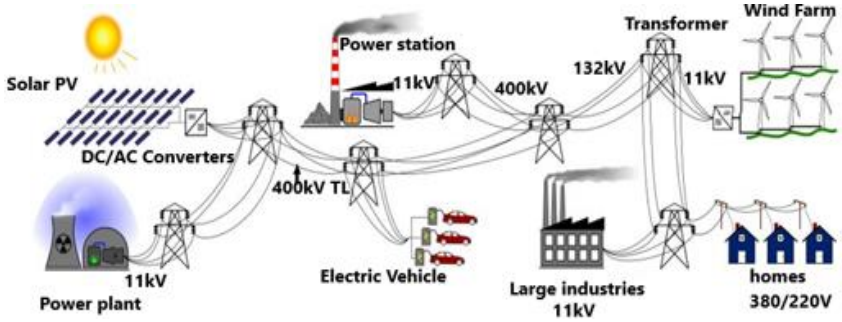


Figure 2. Generation, transmission, and distribution network with re integration

2. MATERIALS AND METHODS

As illustrated in Figure 3, the Vuyani-Eros 400 kV transmission line with two SS and the Metro wind farm was constructed and simulated by employing the DigSilent PowerFactory software and previously gathered data. Transformers are built-in power plants to elevate the voltage of the electricity to a level that is appropriate for long-distance transmission. These transformers increase the voltage from 22 kV to higher levels such as 220 kV, 275 kV, 400 kV, or 765 kV, and supply the energy to Eskom's national grid. The voltage is ultimately reduced to a level that is suitable for the customer. In major enterprises, the voltage may reach 11 kV, whereas in stores and households, it is often 380/220 volts [9]. The construction involves the installation of a 400 kV transmission line that runs approximately 150 kilometers, connecting Tower 211 to the Vuyani Substation. The line will go from Vuyani to Eros. The present study employed the Newton-Raphson method to analyze load flow in networks. The suggested transmission network for this research is the current transmission line, which is the Eros-Vuyani 400 kV transmission line located between KwaZulu-Natal and the Eastern Cape. The purpose of this line is to transfer electrical power from Vuyani SS to Eros Substation, as shown in Figure 3 and Figure 4. Vuyani SS is connected to the Metro wind farm by a step-down transformer with a voltage ratio of 132/22 kV. Alongside it, the voltage levels are displayed, encompassing the entire range of voltages utilized within the system, ranging from 22 kV to 400 kV. Additionally, this display indicates the operational status of the system.

This study employs loadflow analysis using the Newton-Raphson method to effectively construct and integrate two substations, load demand, external grid and a transmission line. A wind farm has been incorporated into the system to acknowledge the substantial utilization of RE in the transmission line and enhance power accessibility in the network. Transient stability study was conducted aunder load-flow analysis. The analysis involved defining the short circuit event and switch event, calculating initial conditions, and defining the variable that must be monitored. Finally, the n-1 contingency analysis was successfully conducted by performing load flow calculations utilizing fault cases in the contingency definition command. This analysis is carried out by evaluating the stability of the network in the event of unexpected disturbances, such as a power outage in a line or a malfunctioning generator.

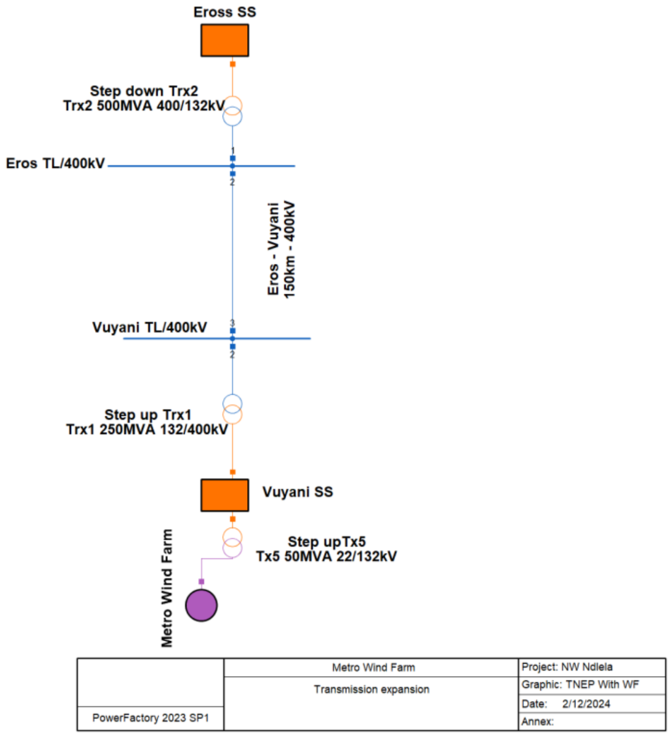


Figure 3. Vuyani-Eros 400 kV transmission network with Metro wind farm integration

In (1) represents the mathematical expression used to compute the total power available in both the two substations and the wind farm.

$$P_T = P_{Vgen} + P_{Egen} + P_{wf} \tag{1}$$

In (2) demonstrates the ability of these three substations to generate power without any loss across the cable that connects to the wind turbine.

$$P_T = \sum_{k=1}^{r} P_{Vgen} + \sum_{k=1}^{r} P_{Egen} + \sum_{i=1}^{n} P_{wt} \tag{2}$$

In (3) represents the maximum amount of power that can be obtained from the Eros load. It is derived from (6)-(9), considering all available power in the system and taking into consideration any losses that occur in a network.

$$P_{E.load} = (\sum_{k=1}^{r} P_{Vgen} + P_{wf}) - P_{TL} + \sum_{k=1}^{r} P_{Egen} \tag{3}$$

In (4) and (5) depict the active power in the entire network when the external grid P_{EG} is present, as illustrated in Figure 3.

$$P_{T.Network} = (\sum_{k=1}^{r} P_{Vgen} + P_{wf}) - P_{TL} + \sum_{k=1}^{r} P_{Egen} + P_{EG} \text{ or} \tag{4}$$

$$P_{T.Network} = P_{E.load} + P_{EG} \tag{5}$$

The (6) is used to calculate the active power available in the Vuyani SS inside the two generators that are accessible as power sources, as shown in Figure 4(a).

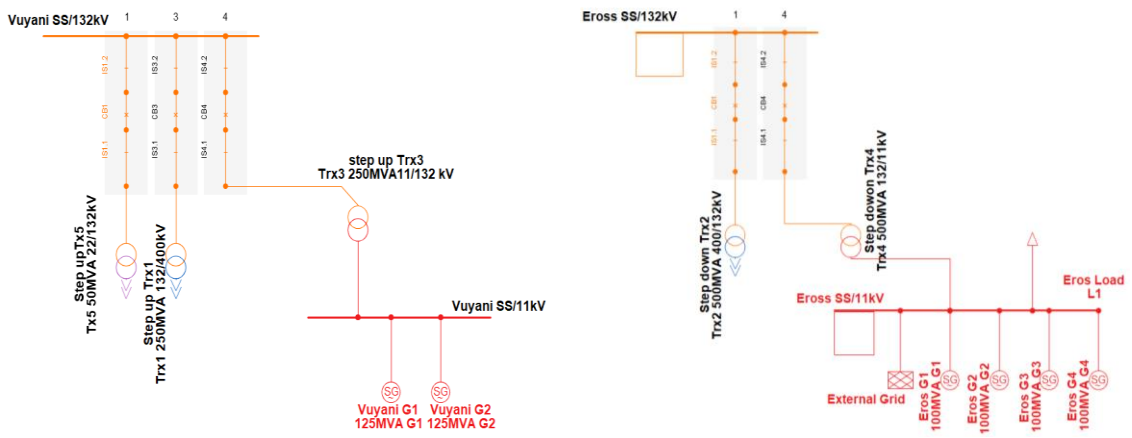
$$P_{T.Vgen} = \sum_{k=1}^{r} P_{Vgen} \tag{6}$$

Where,
- $P_{T.Vgen}$ is the sum of Vuyani's active power available in generators.
- r is the total number of generators in Vuyani SS.
- P_{Vgen} is available power in each generator in Vuyani SS.

The eros substation, located in Kwazulu Natal, is utilized in conjunction with the substation in the Eastern Cape through a 400 kV transmission line, as shown in Figure 4(b). This substation is equipped with a 500 MVA transformer with a step-down ratio of 400/132 kV, enabling the transmission of an active power of 400 MW. Additionally, Eros SS is equipped with an external grid that stores surplus power for power demand purposes and a load capacity that indicates the amount of power available for distribution purposes. The procedure for estimating power available in the Eros SS is nearly identical to the one for calculating power for the Vuyani SS in (2); the only difference is the number generator utilized.

$$P_{T.Egen} = \sum_{k=1}^{r} P_{Egen} \tag{7}$$

Where,
- $P_{T.Egen}$ is the sum of Eros SS active power available in generators.
- r is the total number of generators in Vuyani SS.
- P_{Egen} is available power in each generator in Eros SS.



(a) (b)

Figure 4. The current transmission line, (a) Vuyani SS and (b) Eros SS

Figure 5 depicts the Metro wind farm, which is located in the eastern cape. In this research, the farm is connected to the transmission line of Vuyani-Eros, a 400 kV transmission line, with the aim of expanding power access in the transmission line. The farm comprises 9 wind turbines, each of which has 3 MW active power. These turbines are linked together using 8 cables that are 1km apart. This wind farm is connected to a 50 MVA, 22/132 kV step-up transformer, which steps up the voltage from 22 kV to 132 kV for transmission purposes. Subsequently, it is transformed to a voltage of 400 kV for the purpose of transmission.

The total active power in the wind turbine can be computed using (8).

$$P_{Twt} = \sum_{i=1}^{n} P_{wt} \tag{8}$$

Where,
- n is the total number of wind turbines in a wind farm.
- P_{Twt} is the total active power for all the wind turbines in a wind farm.
- p_{wt} is the active power in each wind turbine.

$$P_{wf} = P_{Twt} - P_{c.l} \tag{9}$$

Where, $P_{c.l}$ are the losses occurring in the cables connecting the transmission line.

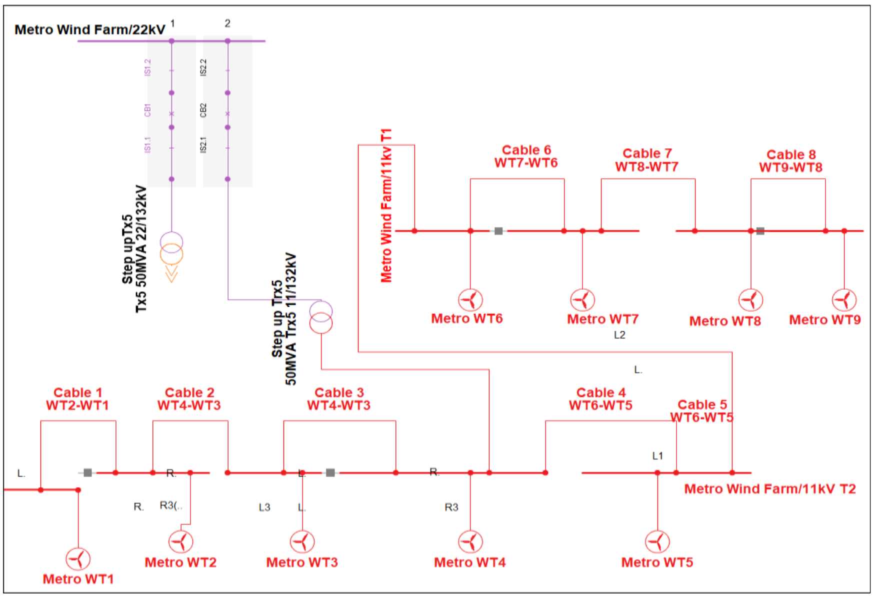


Figure 5. Metro wind farm

3. RESULTS

Vuyani SS in Figure 6 utilizes a 400 kV bursar equipped with a transformer that has ratings of 250 MVA. This transformer is a step-up transformer with a ratio of 132/400 kV, enabling a maximum power flow of 200 MW. Vuyani SS is equipped with two generators that serve as power sources, with each generator producing 100 MW of active electricity that can be distributed. For distribution purposes, Vuyani SS is utilized in this study to transmit power to Eros SS through a 150-km transmission line. Vuyani SS consists of three transformers, the first of which steps up the voltage from 11 kV/132 kV from the Vuyani SS/11 kV BB, the second of which steps up the voltage from 11 kV/22 kV from the Metro wind farm, and the last of which steps up the voltage from 132 kV/400 kV for the transmission line network.

This part demonstrates the utilization of the data gathered in Chapter 3 for the Eros-Vuyani transmission network. The network was simulated using DigSilent software to emphasize the significance of integrating RE into the transmission line. This study utilizes wind energy from the Metro wind farm, situated at the eastern cape. During normal operation, the bus bar must remain within the permitted range of values, as displayed in Figure 6(a), which was generated using DigSilent PowerFactory software. For a healthy network performance, the voltage range should be maintained between 0.95 and 1.05 per unit (p.u). A lower voltage range is considered below 0.95 p.u, while an upper voltage range is beyond 1.05 p.u. Additionally, the maximum thermal loading of transformers, generators, lines, and wind turbines should be kept between 80% and 100%.

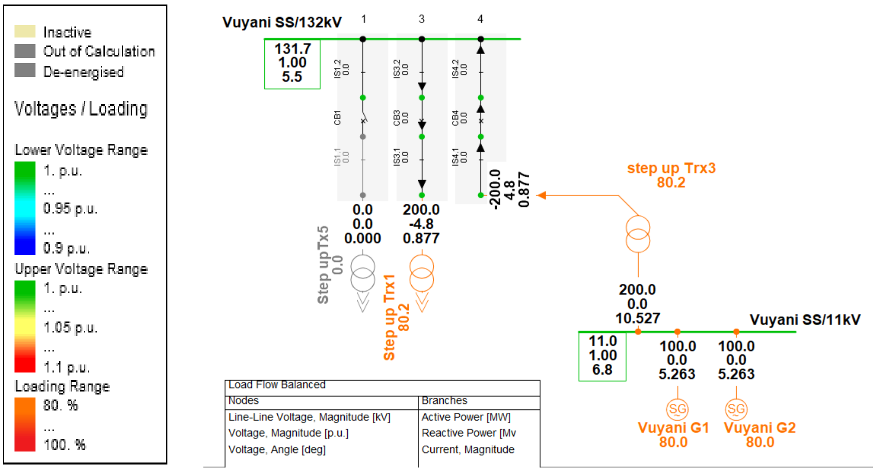
In (10) represents the computation of thermal loading for a current. It can be utilized to overload in transformers and generators.

$$Thermal.loading = \frac{Iload}{Irated} X100\% \quad (10)$$

Figure 6(b) illustrates the Vuyani SS prior to the implementation of the wind farm. At present, the Vuyani SS produces 200 MW of power at an 11 kV busbar. This 200 MW is then transmitted to a 400 kV transmission line through the utilization of a 132/400 kV step-up transformer. The thermal loading of Vuyani generators and transformers lies within the allowed range of 80-100%. The Eros substation, shown in Figure 7, utilizes an 11 kV busbar and consists of four generating units. Each generating unit has a capacity of 100 MW and operates within an 80% loading range. Additionally, it features an external grid for storing excess electricity in the event of increased demand or for future purposes. The substation includes an Eros load, which indicates the amount of power available for distribution purposes

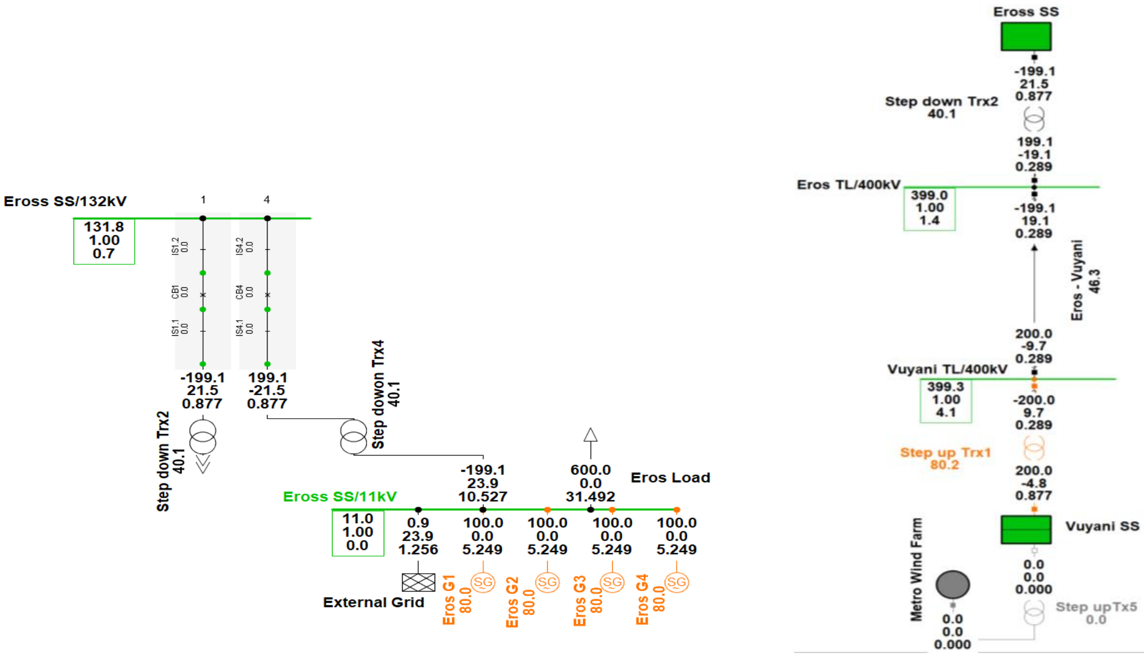
Figure 7(a) illustrates that the Eros substation can provide a total of 600 MW, with 200 MW coming from the Vuyani SS and 400 MW from the Eros substation. Additionally, the figure indicates that there is a 0.9 MW loss on the transmission line, resulting in a shortage of power on the external grid. Additionally, it is equipped with two step-down transformers, the first of which reduces the voltage from 400/132 kV to 132/11 kV, as illustrated in the figure.

The diagram in Figure 7(b) illustrates the complete structure of the Vuyani-Eros transmission network prior to its integration with the wind farm. The Vuyani SS sends 200 MW of power along a 400 kV transmission line that runs 150 km. During transmission, there is a loss of 0.9 MW, resulting in Eros SS receiving 199.1 MW, as shown in Figure 7(b). The entire structure is functioning within the permitted range and limits, as illustrated in Figure 7(b). Consequently, Eros SS is capable of receiving 199.1 MW from the Vuyani SS for the purpose of distribution.



(a) (b)

Figure 6. Metro wind farm (a) thermal loading and p.u and (b) Vuyani SS network simulation



(a) (b)

Figure 7. Eros substation (a) Eros SS network simulation and (b)Vuyani - Eros 400 kV transmission network

Figure 8 shows the Metro wind farm, consisting of 9 wind turbines, each capable of generating 3 MW of power. This results in a total power output of 27 MW. However, 1 MW is lost during the transmission through the connection cables. It is evident that cable 7 is receiving 6 MW of power and transmitting 5.9 MW. In total, 26 MW of the generated power is available for transmission to Vuyani SS. The wind farm utilizes a combination of three double busbars and three single busbars, all functioning at a voltage of 11 kV. The busbars connecting Metro WT9 to Metro WT6 indicate grid instability, since they operate outside the permitted range, as shown in Figure 6(a). This poses a threat to the overall stability of the system. The wind farm has two step-up transformers. The first transformer has a voltage ratio of 11/22 kV and is connected to the wind farm. The second transformer has a voltage ratio of 22/132 kV and is used to increase the voltage before transmitting the power to the Vuyani SS substation. The purpose of this setup is to enhance power accessibility in the transmission line.

Figure 9 shows the identical network as Figure 6(a), except for an additional power source of 26 MW from the Metro wind farm. This 26 MW is combined with the existing 200 MW from the Vuyani SS/11 kV busbar. Consequently, the Vuyani SS is currently transferring a total of 226 MW through a transmission line, which will be supplied to the Eros SS.

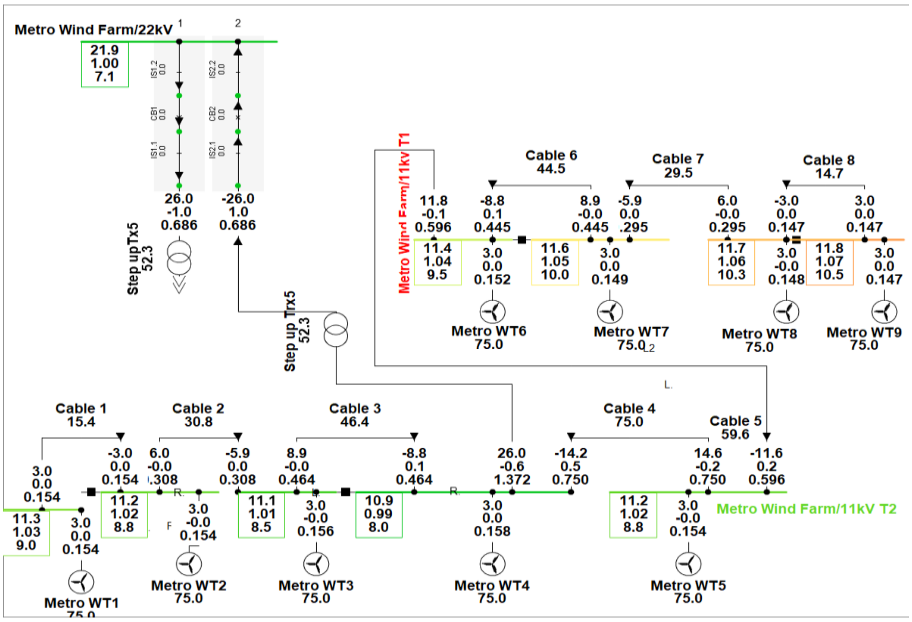


Figure 8. Metro wind farm simulation network

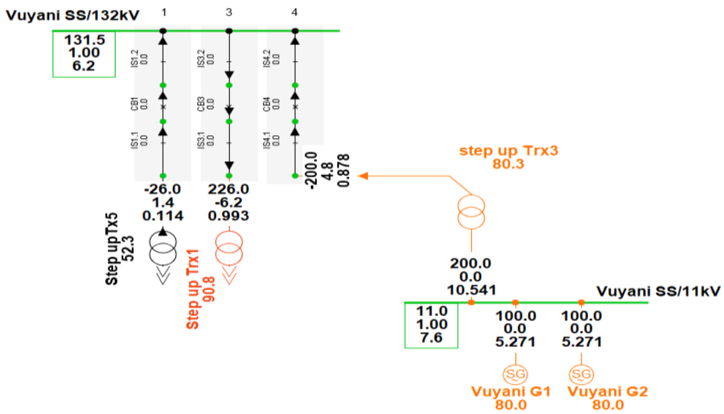


Figure 9. Vuyani SS with Metro wind farm

The Eros SS, which is identical to the network in Figure 7(a), functions as a receiving substation. The distinction lies in the integration of the Metro wind farm at present. It is apparent from Figure 10 that the substation offers the capability to meet the demand for 600 MW, with an additional 24.9 MW being observed in the external grid. As depicted in Figure 8, the implementation of a wind farm within this transmission line significantly enhanced power accessibility, thereby positively impacting the power demand of Eros.

With regard to voltage restrictions and load range, this network continues to function within the allowed parameters.

Figure 11 shows the integrated model of the Vuyani SS and the Metro wind farm, showcasing the growth of transmission. It is evident from the Figure that the Vuyani SS is currently transmitting 226 MW, compared to 200 MW in Figure 7(b). An additional 26 MW is being generated by the wind farm. It is observed from the transmission line that out of the 226 MW supplied to the Vuyani TL, 224.9 MW is received by the Eros TL. This indicates an increase in losses to 1.1 MW compared to the previous Figure 7(b) when losses were measured at 0.9 MW. Upon examining step-up Trx1, it is observed that the loading range has elevated from 80.2% to 90.8%, indicating an increase in the load on the transformer. Furthermore, this study demonstrates that the utilization of RE will significantly improve power accessibility in the transmission line, with the minimum rise in power losses.

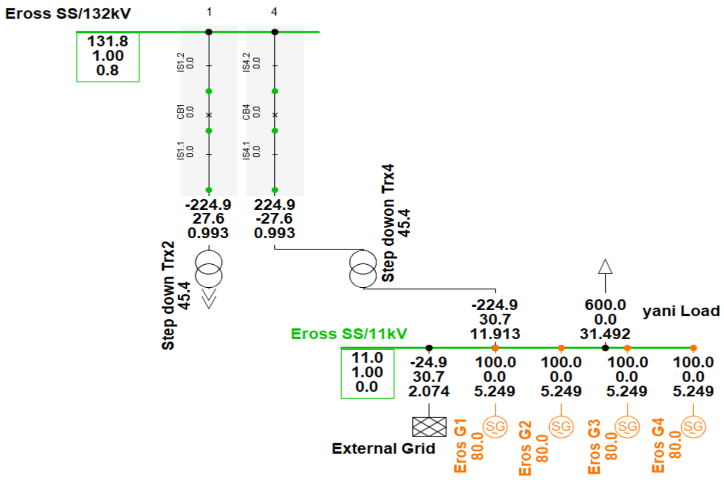


Figure 10. Eros SS with Metro wind farm

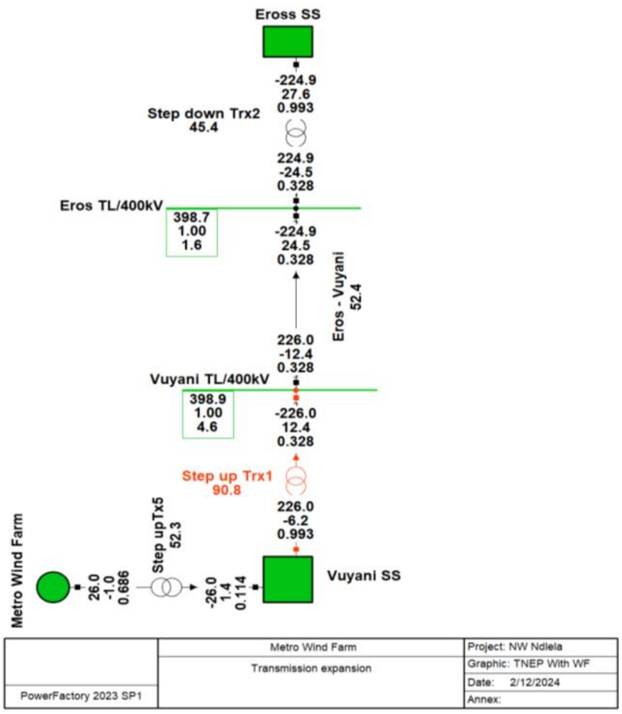


Figure 11. The complete model of Vuyani-Eros TL with Metro wind farm

Figure 12 is a graph illustrating the transient stability study. The graph showcases four Eros generators operating in parallel, all having equal capacity, along with one Vuyani generator. The purpose of the analysis is to examine the dynamic behavior during transient conditions for a period of 10 seconds.

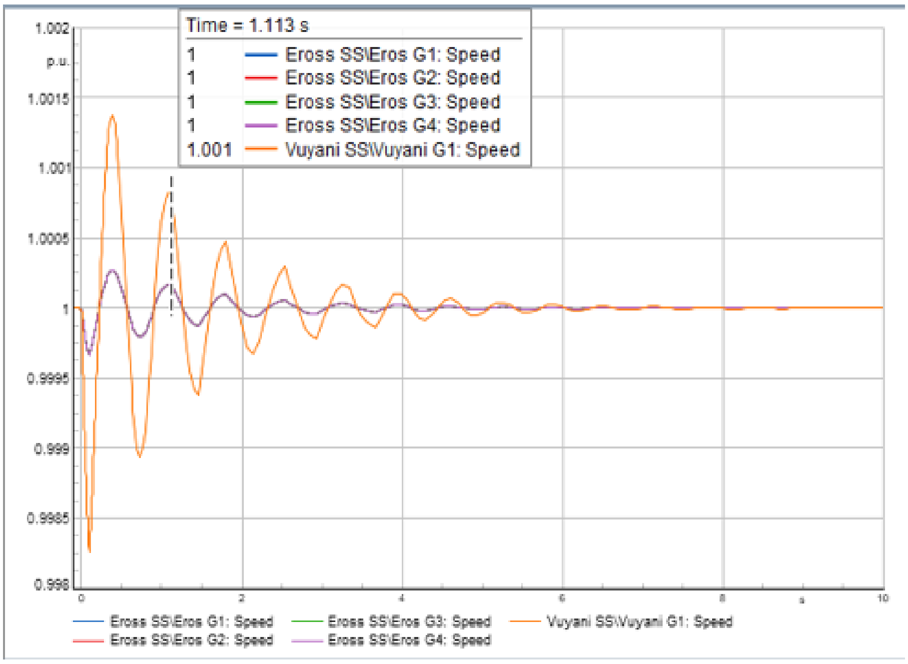


Figure 12. transient stability analysis

4. RESULTS DISCUSSION

The main objective of this study is to conduct a load flow analysis on the existing transmission lines in SA to incorporate RE into the transmission system and enhance the supply of electricity. The Digsilent PowerFactory tool was utilized in this study to construct each Substation and wind farm, as depicted in Figure 4 and Figure 5. Subsequently, these individual SS were interconnected to create a unified transmission network, as depicted in Figure 3. The loadflow research was conducted using a load demand of 600 MW, as depicted in Figure 7(a). It is observed that whereas Vuyani SS generates 200 MW and Eros SS generates 400 MW, the load demand requires only 0.9 MW to meet its requirements due to losses in the transmission line. By incorporating a wind farm with a capacity of 26 MW, as depicted in Figure 8, the system is now capable of meeting the demand of 600 MW and has an excess of power that may be utilized for future purposes. Despite the increased thermal loading observed in Figure 11 when compared to Figure 7(b) due to the loading of the transmission line, it remains within the permitted range, as indicated in Figure 6(a). The comparison is further elucidated in Table 1. The two analyses, transient stability analysis, and contingency analysis were conducted in Figure 12 and Table 2, respectively. These analyses aim to evaluate the network's performance in the presence of any disturbances. The comparison is further elucidated in Table 1. The two analyses, namely transient stability analysis, and contingency analysis, were conducted in Figure 12 and Table 2 to assess the network's response to any disruption. Figure 12 demonstrates that the system can achieve stability even during transient conditions. Table 2 illustrates that the system can operate reliably within permitted values throughout contingencies when comparing continuous loading and base case loading. This study holds significant importance due to the depletion of coal, the aging infrastructure of power plants, and the increasing demand. This study also emphasizes the significance of employing methods to identify the appropriate position and size of additional transmission lines in a large network, as well as approaches to managing the uncertainty associated with RE.

Table 1. Evaluation and comparison of two network system

System network	TL (MW)	Load (MW)	Losses (MW)	External grid (MW)	Trx1 loading (%)	Line loading (%)
Network without wind farm	200-199.1	600	0.9	-0.9	80.2	46.3
Network with wind farm	226-224.9	600	1.1	24.9	90.8	52.4

Table 2. Contingency analysis

Component	Branch, substation or site	Loading continuous [%]	Loading short-term [%]	Loading base case [%]	Contingency number	Contingency name	Base and continuous loading [0.0% - 90%]
Step up Trx1		9.079.137.144	9.079.137.144	9.079.137.144	-1	Base case	
Step up Trx3	Vuyani SS	8.023.683.122	8.023.683.122	8.023.683.122	-1	Base case	
Step up Trx3	Vuyani SS	8.022.531.382	8.022.531.382	8.023.683.122	48	Step up Trx5 (Metro wind farm)	
Step up Trx1		8.022.531.382	8.022.531.382	9.079.137.144	49	Step up Trx5 (Metro wind Farm)	
Step up Trx1		8.022.531.382	8.022.531.382	9.079.137.144	43	Metro WTG (Metro wind farm)	

5. CONCLUSION

This study emphasizes the significance of RE, specifically in terms of integrating it into transmission lines. The main objective of this research is to enhance power accessibility in existing transmission lines by incorporating RES due to their advantageous characteristics. It is important to note that the grid is still working within acceptable limits. This analysis demonstrates the need to incorporate RE into transmission lines. Such integration would yield significant advantages, including enhanced power capacity and the utilization of environmentally sustainable sources, while also minimizing maintenance expenses. This research utilizes the pre-existing SA transmission line to incorporate it with the existing wind farm to enhance power accessibility in the transmission line. It conducts transient stability analysis and contingency analysis to analyze the stability of the system. In the future, this study aims to incorporate various RES into a large network with multiple transmission lines. The study reviews established techniques that are commonly used to address TEP problems such as to locate and size transmission lines to be added which will help to reduce losses, voltage instability, and investment cost, as well as the techniques that reduce uncertainty that come with RE introduction. This project aims to implement these strategies on a wide network as it plans to integrate RE into transmission lines.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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Musasa Kabeya	✓					✓	✓	✓		✓	✓	✓	✓	✓

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

REFERENCES

[1] O. M. Akinbami, S. R. Oke, and M. O. Bodunrin, "The state of renewable energy development in South Africa: an overview," *Alexandria Engineering Journal*, vol. 60, no. 6, pp. 5077-5093, 2021, doi: 10.1016/j.aej.2021.03.065.

[2] G. Mutezo and J. Mulopo, "A review of Africa's transition from fossil fuels to renewable energy using circular economy principles," *Renewable and Sustainable Energy Reviews*, vol. 137, p. 110609, 2021, doi: 10.1016/j.rser.2020.110609.

[3] M. Ntombela, K. Musasa, and K. Moloi, "A comprehensive review of the incorporation of electric vehicles and renewable energy distributed generation regarding smart grids," *World Electric Vehicle Journal*, vol. 14, no. 7, p. 176, 2023, doi: 10.3390/wevj14070176.

[4] T. Keokhoungning *et al.*, "Transmission network expansion planning with high-penetration solar energy using particle swarm optimization in Lao PDR toward 2030," *Energies*, vol. 15, no. 22, p. 8359, 2022, doi: 10.3390/en15228359.

[5] K. R. Abbasi, M. Shahbaz, J. Zhang, M. Irfan, and R. Alvarado, "Analyze the environmental sustainability factors of China: the role of fossil fuel energy and renewable energy," *Renewable Energy*, vol. 187, pp. 390-402, 2022,doi: doi: 10.1016/j.renene.2022.01.066.

[6] S. W. Ali *et al.*, "Offshore wind farm-grid integration: A review on infrastructure, challenges, and grid solutions," *IEEE Access*, vol. 9, pp. 102811-102827, 2021, doi: 10.1109/ACCESS.2021.3098705.

[7] M. H. Lipu *et al.*, "Data-driven hybrid approaches for renewable power prediction toward grid decarbonization: applications, issues and suggestions," *Journal of Cleaner Production*, vol. 328, p. 129476, 2021, doi: 10.1016/j.jclepro.2021.129476.

[8] Z. Zhu, "Applications of reinforcement learning on deregulated active distribution networks," PhD, Electrical Engineering, Hong Kong Polytechnic University, Hong Kong, 2023.

[9] Eskom, "Transmission and distribution of electricity," Eskom Generation Communication, South Africa, 2023.

[10] H. Zhang, V. Vittal, G. T. Heydt, and J. Quintero, "A mixed-integer linear programming approach for multi-stage security-constrained transmission expansion planning," *IEEE Transactions on Power Systems*, vol. 27, no. 2, pp. 1125-1133, 2011, doi: 10.1109/TPWRS.2011.2178000.

[11] A. S. Dagoumas and N. E. Koltsaklis, "Review of models for integrating renewable energy in the generation expansion planning," *Applied Energy*, vol. 242, pp. 1573-1587, 2019, doi: 10.1016/j.apenergy.2019.03.194.

[12] E. G. Morquecho *et al.*, "Comparison of an improved metaheuristic and mathematical optimization based methods to solve the static AC TNEP Problem," *IEEE Transactions on Power Systems*, 2024, doi: 10.1109/TPWRS.2023.3305431.

[13] S. E. Uhunamure and K. Shale, "A SWOT analysis approach for a sustainable transition to renewable energy in South Africa," *Sustainability*, vol. 13, no. 7, p. 3933, 2021, doi: 10.3390/su13073933.

[14] S. Goodarzi, M. Gitizadeh, and A. R. Abbasi, "Efficient linear network model for TEP based on piecewise McCormick relaxation," *IET Generation, Transmission & Distribution*, vol. 13, no. 23, p. 10, 2019, doi: 10.1049/iet-gtd.2019.0878.

[15] U. Shahzad, "A review of challenges for security-constrained transmission expansion planning," *Journal of Electrical Engineering, Electronics, Control and Computer Science*, vol. 7, no. 2, pp. 21-30, 2021.

[16] M. M. Hussain *et al.*, "SONG: a multi-objective evolutionary algorithm for delay and energy aware facility location in vehicular fog networks," *Sensors*, vol. 23, no. 2, p. 667, 2023, doi: 10.3390/s23020667.

[17] J. M. Ramirez, A. Hernandez-Tolentino, and J. A. Marmolejo-Saucedo, "A stochastic robust approach to deal with the generation and transmission expansion planning problem embedding renewable sources," in *Uncertainties in Modern Power Systems*: Elsevier, 2021, pp. 57-91, doi: 10.1016/B978-0-12-820491-7.00003-7.

[18] G. Chicco and A. Mazza, "Metaheuristics for transmission network expansion planning," in *Transmission Expansion Planning: The Network Challenges of the Energy Transition*. Torino, Italy: Springer, 2021, pp. 13-38.

[19] K. K. Makhanya, "An evaluation of development-induced relocation process in the ingquza hill local municipality," Master of science, environmental management, University of South Africa, South Africa, 109, 2015.

[20] CONCO, "400 kV transmission line spanning 89km's – a significant achievement for Eskom and CONCO," Vorna Valley, Johannesburg, 2023.

[21] Y. Wang, C. Xu, and P. Yuan, "Is there a grid-connected effect of grid infrastructure on renewable energy generation? Evidence from China's upgrading transmission lines," *Energy & Environment*, vol. 33, no. 5, pp. 975-995, 2022, doi: 10.1177/0958305X211031.

[22] C. D. Justo, J. E. Tafula, and P. Moura, "Planning sustainable energy systems in the Southern African Development Community: a review of power systems planning approaches," *Energies*, vol. 15, no. 21, p. 7860, 2022, doi: 10.3390/en15217860.

[23] P. V. Gomes and J. T. Saraiva, "State-of-the-art of transmission expansion planning: A survey from restructuring to renewable and distributed electricity markets," *International Journal of Electrical Power & Energy Systems*, vol. 111, pp. 411-424, 2019, doi: 10.1016/j.ijepes.2019.04.035.

[24] Eskom, "Eros- Neptune - Grassridge 400 kV transmission line," Eskom, Grahamastown, 2003.

[25] Optipower, "Eros – Vuyani 400 kV Line (Section B)," Murray & Roberts, Boulevard, Bedfordview, 2022.

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