Reliability-Driven Planning of a Campus Auxiliary Power Grid with Renewable Upgrades

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Abstract— The College of New Jersey (TCNJ) operates an auxiliary power microgrid for which dedicated funding is available and must be optimally invested. Traditionally, such investment decisions are guided primarily by financial considerations. This paper extends that framework by explicitly incorporating system reliability and renewable energy integration into a unified planning analysis. A detailed model of the TCNJ auxiliary grid was developed in MATLAB and Simulink and evaluated using single and double contingency analysis. Candidate upgrades, including additional transmission lines and distributed solar generation, were assessed through a cost function that accounts for capital investment, operating cost, renewable contribution, and penalties associated with unserved load. Due to the computational complexity of exhaustive contingency testing, simulations were executed using TCNJ's high-performance computing cluster. Results demonstrate that distributed solar generation provides greater reliability improvement per unit cost than transmission line additions for this system, highlighting the importance of reliability-driven planning for campus auxiliary grids.

Keywords— auxiliary grid optimization, renewable energy integration, contingency analysis

I. Introduction

As institutions intensify their commitment to renewable energy and sustainability, the central challenge is often not the level of investment but the effectiveness of that investment. Many college campuses support large solar installations that improve environmental metrics yet offer limited gains in cost efficiency or operational reliability [1]. This paper adopts an alternative strategy, one tasked with improving 1) system reliability, 2) support of essential loads, and 3) reduction of long-term operating costs. Its primary objective is to achieve these goals through MATLAB Simulink-based contingency analysis to facilitate the required planning-level evaluation. The College of New Jersey's auxiliary grid is used as a case study. The system is modeled to reflect real operational constraints, enabling quantification of reliability, cost, and renewable integration.

This study is intended as a planning-level evaluation of discrete upgrade options, rather than a continuous real-time optimization or operational control framework. While the college does not currently face threats of thermal overload or voltage violations, campus expansion would increase the probability of these problems occurring. Given that funding is currently available, it should be utilized to address both current and anticipated future issues.

The proposed method identifies the optimal placement and configuration of additional lines and switches, distributed solar generation, and energy storage capacity. Secondary objectives include:

- Formulate and implement a specialized cost function that accounts for both capital and operational expenditures, tailored for TCNJ;
- Model and simulate TCNJ's auxiliary power system using MATLAB, Simulink, and Simscape to quantify the technical and economic impact of each proposed upgrade scenario;
- Compare alternative investment strategies to identify upgrade configurations that provide the highest reliability improvement per unit cost.

In this paper, *optimal* refers to the best-performing configuration among a finite candidate set evaluated through exhaustive simulation.

II. Innovation

The resulting methodology enables decision-makers to make informed choices regarding campus power system modernization, balancing cost, reliability, and renewable energy adoption within realistic budgetary constraints. The most innovative aspects of this work include:

- Cost-function formulation that links renewable investments directly to contingency-derived reliability penalties;
- Upgrade evaluation framework for campus auxiliary grids that do not operate fully islanded;
- Real-system validation process using MATLAB supported by a high-performance computing cluster.

While existing auxiliary grid studies optimize energy management, hybrid renewable penetration, or cost, few institutions incorporate an organization's specific operational structure and constraints into their analysis.

III. Literature Review

The authors reviewed several works. Agustriadi et al. discuss how contingency analysis is utilized to test the reliability of a power grid, identifying areas with higher blackout probability following transmission line or generator failure [3]. Tang et al. demonstrate that explicitly incorporating reliability into cost equations is essential when upgrading systems with multiple energy sources [4]. Liu et al. show that introducing penalty costs for bus outages increases the fidelity of cost-based

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comparisons [5]. Umunnakwe et al. examine similar reliability-cost tradeoffs under constrained funding conditions [6].

IV. Network Model Reconfiguration

One of the first steps in this research was to meet with TCNJ facilities' staff to gather the information needed to mathematically describe the distribution auxiliary grid. The authors already had experience modeling traditional terrestrial transmission and distribution systems, but determining the appropriate level of detail and resolution for the college's distribution system required some iterative design. The campus auxiliary grid is not normally self-sufficient and relies on locally generating units only during stressed or emergency conditions. All power supplied to TCNJ passes through a substation called the *Power House Facility* before being distributed to various campus buildings, most of which are academic facilities or residence halls [7]. The Power House Facility operates like a substation with a co-generation plant.

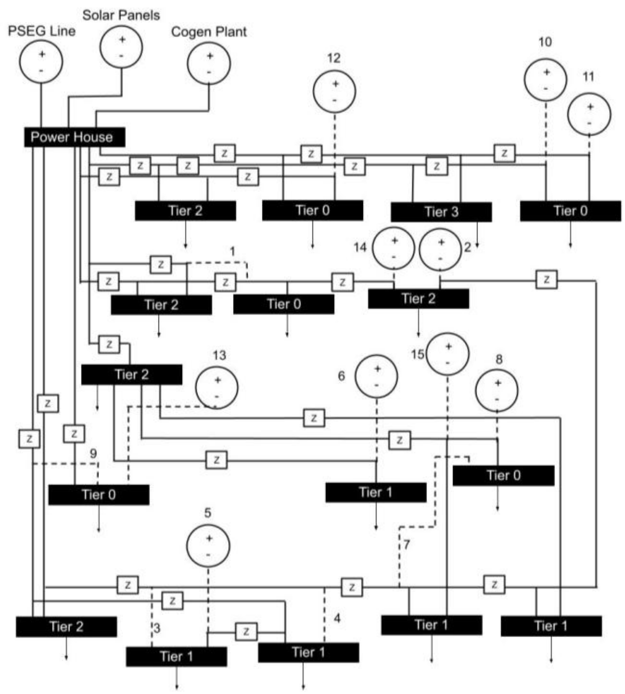

Figure 1: One-Line Diagram Describing TCNJ Power Auxiliary Grid

After several iterations, the authors developed a model of the TCNJ grid in MATLAB Simulink, with each node representing between one and nine buildings. Aggregation choices were based on building size, load characteristics, and importance to overall campus operations. Buildings located within 500*ft* of each other that were connected in series were combined. The type and size of building was also considered. Buildings with drastically different load types, academic versus residential, were not combined to maintain the integrity of the system. The one-line diagram below illustrates the grid used for simulation. All analysis procedures were automated through a MATLAB script that disconnected and reconnected transmission lines to simulate single and double contingency conditions. The results of each test were then recorded and analyzed to identify system vulnerabilities and evaluate upgrade scenarios. Figure 1 presents the system model in Simulink as well as the candidate upgrades to be considered via simulation in this work.

As reliability is a major factor in this analysis as well as a direct input to the cost function referenced below, this paper employs contingency analysis to quantify how different network upgrades affect system performance. Consistent with the broader literature on auxiliary grid reliability and hybrid-energy optimization, both single and double contingencies are examined to capture realistic failure scenarios and the system's ability to maintain service under stressed operating conditions [8]. Recent work on auxiliary grid energy management highlights that reliability must be evaluated not only through steady state feasibility but also through the system's response to element outages, line failures, and uncertainty in renewable production [9].

For contingency analysis, a matrix containing the status of all possible transmission lines, $\mathbf{L}_{\mathbf{org}}$ is changed. An element in the matrix can be changed from one to zero without modifying the $\mathbf{Y}^{\mathbf{Bus}}$ matrix directly. This action automatically opens the corresponding line and prevents current flow according to the implementation. A single contingency analysis examines the effect of changing any one element within the upper half (diagonal and above) of the $\mathbf{L}_{\mathbf{org}}$ matrix, since it is symmetric. A double contingency analysis evaluates the effect of changing any two such elements, analogous to the higher order disturbance scenarios explored in recent multi auxiliary grid modeling studies.

To complete a contingency analysis, the following system variables must be known: the admittance bus $\mathbf{Y}^{\mathbf{Bus}}_{\mathbf{org}}$, the status of all possible transmission lines $\mathbf{L}_{\mathbf{org}}$, and the number of individual solar generating stations connected in the distribution portion of the grid, s_{org}. These quantities are consistent with the state descriptions used in recent hybrid auxiliary grid optimization literature, where structural parameters, component condition, and renewable availability define the feasible operating set. For a system with *n*-buses, $\mathbf{Y}^{\mathbf{Bus}}_{\mathbf{org}}$ and $\mathbf{L}_{\mathbf{org}}$ are $[n \times n]$ matrices, and s_{org} is a single scalar value. The matrix $\mathbf{L}_{\mathbf{org}}$ encodes connectivity; for example, if buses three and seven are connected, then $\mathbf{L}_{\mathbf{org}}(\mathbf{3}, \mathbf{7}) = 1$. If they are not connected, the value is zero [10].

Each test in a single or double contingency analysis is completed by changing the contents of the matrix $\mathbf{L}$. Matrix $\mathbf{L}$ is initially equal to $\mathbf{L}_{\mathbf{org}}$ and retains its symmetry as lines are removed. For each transmission line removed, $\mathbf{L}$ is updated to reflect the new network condition. A new $\mathbf{Y}^{\mathbf{Bus}}$ is then created for each modified instance of $\mathbf{L}$ using the following equation:

$$\mathbf{Y}^{Bus} = \boldsymbol{f}_Y\left(\mathbf{Y}^{Bus}_{Org}, \mathbf{L}\right) \quad (1)$$

Function $\boldsymbol{f}_Y$ accepts the original (base case) admittance matrix $\mathbf{Y}^{\mathbf{Bus}}_{\mathbf{org}}$ and generates a modified version $\mathbf{Y}^{\mathbf{Bus}}$ suitable for the specific contingency scenario. This follows the same philosophy observed in multi objective auxiliary grid models, where structural modifications or component failures trigger recalculation of feasible power flow states. The nominal system-wide served load can be calculated using the equation below.

$$P^{Nom} = \sum \boldsymbol{P}_c\left(\boldsymbol{f}_Y\left(\mathbf{Y}^{Bus}_{Org}, \mathbf{L}\right)\right) \quad (2)$$

$\boldsymbol{P}^{\boldsymbol{Nom}}$ is a scalar representing the maximum known system-wide load served when all buses receive rated power. The

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function $\boldsymbol{P_c}$ calculates a $[n\times1]$ vector that defines the power flowing to each individual bus, as dictated by the power flow equations. Under ideal conditions, $\boldsymbol{P^{Nom}}$ and the sum of $\boldsymbol{P_c}$ should equal; this indicates that no load service has been lost.

If $\boldsymbol{P^{Nom}}$ and the sum of $\boldsymbol{P_c}$ are equal for a given contingency, then all buses receive power under that condition. If they remain equal for all tested contingencies, then the grid is fully reliable for the analysis case set. This reliability characterization parallels the System Reliability Index (SRI) used in recent auxiliary grid planning and hybrid energy optimization studies, though here it is simplified to a binary load service measure. A matrix indicating which buses receive power can be generated using the equation below.

$$P_b = \boldsymbol{binary}(P_c) \tag{3}$$

The function ***binary*** converts the vector $\boldsymbol{P_c}$ into ones or zeros. If an element of $\boldsymbol{P_c}$ is greater than zero without triggering voltage collapse or overloads, the corresponding element of $\mathbf{P_b}$ becomes one; otherwise, it becomes zero. Matrix $\mathbf{P_b}$ is an $[n\times1]$ vector. This classification aligns with the service feasibility indicators applied in multi objective dispatch models, where each bus's served or unserved state informs cost, emissions, and reliability tradeoffs.

Improving system reliability requires both additional transmission lines and additional power generation sources (e.g., solar). New transmission lines enhance reliability by increasing the number of electrically independent paths between buses, which reduces the probability of load loss under single or double contingencies. Likewise, adding new solar installations increases the number of distributed energy resources supplying the grid, which aligns with standard auxiliary grid design principles: reliability improves when supply is diversified and sufficient local generation exists to cover demand during stressed operating conditions [11]. Recent auxiliary grid studies confirm that reliability is strongly tied to both structural redundancy and the availability of on-site renewable resources during contingency events. When a new transmission line or generator is added, the matrices $\mathbf{Y_{org}^{Bus}}$ and $\mathbf{L_{org}}$ are updated in a similar manner.

For this work, the authors devoted most of their efforts to accurate and practical modeling of the TCNJ auxiliary grid. As such, they have not yet significantly explored innovative ways to optimize this model. Currently, they employ a basic exhaustive search. However, the authors are currently working on a Lagrange approach to this constrained optimization problem. This will be more beneficial as the system size grows as well as modeling accuracy and complexity [5].

V. Cost Analysis

One innovative contribution of this work is a cost function tailored for a medium-sized commercial and academic facility with specific reliability and renewable energy objectives. This structure mirrors modern auxiliary grid energy management frameworks, where investment cost, renewable utilization, operation cost, and outage penalties are combined into a single optimization problem. As is common in recent auxiliary grid studies, the objective evaluates each candidate configuration by balancing capital additions, energy supply costs, and the economic impact of lost load under contingency conditions. The primary objective function is presented below. $\boldsymbol{f_{OBJ}}$ is the final cost represented in dollars ($).

$$\boldsymbol{f_{OBJ}(L,s)} = \mathrm{c_{Line}} + \mathrm{c_{Solar}} + c_{Power} + \mathrm{c_{Blackout}} \tag{4}$$

The cost of adding a transmission line is presented below.

$$\mathrm{c_{Line}} = \mathbf{c_L}\left(\mathbf{L} - \mathbf{L_{org}}\right) \tag{5}$$

This term models the direct investment needed to introduce new paths into the network [12]. Note that the authors assume that the original number of solar panels (s_{org}) is zero.

$$c_{Solar} = c_s(s) \tag{6}$$

The coefficient c_s is a constant representing the cost of each additional solar installation. Because this study considers only one panel size, c_s remains constant and includes all required components except any new transmission lines, already accounted for in c_{Line}. Each installation is assumed to be placed near its connection point to minimize losses [13]. The cost difference between power consumed and power generated is shown below.

$$\mathrm{c_{Power}} = (\alpha)\Delta\mathrm{t}\left[\boldsymbol{P}_c\left(\boldsymbol{f}_Y\left(\mathbf{Y}_{Org}^{Bus}, \mathbf{L}\right)\right) - \mathrm{P_s(s)}\right] \tag{7}$$

Here α converts Watts to dollars and represents the average cost of energy per kilowatt hour. Variable Δt is the analysis window in hours; P_s is the power produced by the solar units, which is subtracted from total consumption to determine remaining demand. Together, α and Δt convert this net demand into cost. This structure aligns with the economic dispatch terms used in recent multi-objective auxiliary grid studies, where the optimization seeks to minimize the energy purchased from external sources while maximizing renewable utilization [14]. Although this paper focuses on solar generation, the underlying formulation is consistent with hybrid-resource models that include wind turbines, fuel cells, and energy storage systems.

The penalty associated with a blackout is shown below.

$$\mathrm{c_{Blackout}} = \boldsymbol{c_{out}}\left(\boldsymbol{P_b^{-1}}\right) \tag{8}$$

The $\mathbf{c_{Out}}$ assigns a cost to each building's outage, weighted by tier. The function $\boldsymbol{P_b^{-1}}$ is the inverse of $\mathbf{P_b}$ and serves as a simple indicator of unsupplied load. This reliability-oriented term is consistent with outage management strategies discussed extensively in the uploaded papers, where the economic consequence of unserved energy is central to evaluating system resilience. Putting these components together yields the full objective function below.

$$\begin{aligned}\boldsymbol{f_{OBJ}(L,s)} &= \mathbf{c_L}\left(\boldsymbol{L} - \mathbf{L_{org}}\right) + \mathrm{c_s(s)} \\ &+ (\alpha)\Delta t\left[\boldsymbol{P}_c\left(\boldsymbol{f}_Y\left(\mathbf{Y}_{Org}^{Bus}, \mathbf{L}\right)\right) - \mathrm{P_s(s)}\right] + \mathbf{c_{out}}(\overline{\mathbf{P_b}})\end{aligned} \tag{9}$$

The objective function is minimized while reliability is maximized. A complete cost evaluation is performed for every test case. This structure captures the essential features found across modern auxiliary grid optimization efforts: 1) a capital term for new assets, 2) an operational term for imported energy, 3) a renewable benefit term, and 4) an outage penalty reflecting resilience. Although the multi-objective formulations in the uploaded literature often include additional factors such as emission penalties, power losses, voltage regulation, or demand

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response, the simplified cost model employed here follows the same conceptual design [15]. It provides a practical framework for evaluating upgrade strategies and for comparing the relative value of increased renewable penetration, expanded network connectivity, and improved contingency performance in an auxiliary grid environment.

VI. Tools and Challenges

In the early stages of testing, simulation time was a significant concern. A full double contingency analysis of the TCNJ simulation model required approximately two hours to complete. To reduce computation time and enable simulation of larger networks, several adjustments were made to both the Simulink model and the accompanying MATLAB script. Within the model, all small (as compared to rest of the network) impedances were assumed to be zero, including those on switches and transmission lines. This form of model reduction is consistent with practices found in recent auxiliary grid studies, where eliminating negligible impedance terms can substantially improve computational performance without compromising the fidelity of the results. The MATLAB Script was also modified to take advantage of parallel processing through the Parallel Computing Toolbox. This allowed multiple contingency cases to be evaluated simultaneously. After these changes, the total simulation time dropped to 23 minutes. As the system was expanded, several buildings were aggregated into combined nodes. This reduction in network granularity further improved computation time while preserving the accuracy of the electrical behavior, a strategy commonly used in auxiliary grid management when full-resolution modeling is unnecessary for system-level analysis [16]

Finally, TCNJ's ELSA High-Performance Computing Cluster (HPC) was employed. The HPC environment provided additional processing cores, enabling a greater number of simultaneous executions. Using eight cores, the simulation time for the same nine node system decreased to roughly 20 minutes. This aligns with observations in large scale auxiliary grid optimization literature, where parallelism and distributed computation are essential for managing the increased complexity associated with contingency modeling and multi-objective analysis [17].

VII. Testing And Results

Figure 1 presents the Simunlink Model employed for these simulations. To evaluate the proposed methods and identify an optimal upgrade plan for the TCNJ auxiliary grid, the authors followed a structured assessment approach that parallels contemporary auxiliary grid studies in literature. First, fifteen candidate upgrade plans were defined, each introducing either one additional transmission line or one distributed solar generator into the base configuration. Similar scenario-based evaluations are widely used in community auxiliary grid research, where incremental additions of renewable resources or network assets are tested to quantify their effects on system performance and cost. Second, each upgraded configuration was simulated using the MATLAB model, and the resulting operational behavior was recorded with respect to energy efficiency and reliability, with particular attention paid to whether any buses approached voltage collapse. This mirrors standard reliability metrics used in multi-energy auxiliary grid evaluations, where system stability under modified resource portfolios is a primary measure of feasibility. Third, the simulation outcomes were supplied to the cost function defined in (9), consistent with techno-economic analyses employed in recent hybrid auxiliary grid optimization studies.

Table 1: TCNJ Cost and Reliability Study Results

Trial Number	Upgrade Type	Avg Number of Buses Without Power	Normalized Total Cost
6	Solar	0.698	0.580
15	Solar	0.725	0.581
7	Line	0.830	0.585
8	Solar	0.830	0.585
14	Solar	0.872	0.585
5	Solar	0.850	0.586
13	Solar	0.926	0.587
2	Solar	0.916	0.588
11	Solar	0.963	0.589
10	Solar	0.968	0.589
12	Solar	0.995	0.590
4	Line	0.875	0.913
3	Line	0.875	0.914
1	Line	0.907	0.915
9	Line	0.941	0.916
Baseline	n/a	1.201	2.072

Table 1 presents the corresponding simulation results. The table reports the upgrade type, the average number of buses not supplied with power across all single and double contingency cases, and the total cost as defined by (9). Results are sorted from lowest to highest cost. The outcomes indicate that:

- Distributed solar generation generally provides more favorable performance than added transmission lines, improving both cost metrics and system resilience.
- Solar panels installed toward the end of a feeder increase reliability more than panels placed near the middle or beginning of the line.
- Additional transmission lines located closer to the source tend to yield smaller reliability improvements compared to other upgrade options.

While all evaluated upgrades increase system reliability, certain configurations provide substantially greater improvements than others. Selecting upgrades that maximize reliability while minimizing cost is therefore essential for effective institutional planning.

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VIII. Conclusion

This paper does not represent the end point of this research. Although it is informative to examine how MATLAB-based simulation coupled with contingency analysis may be used to evaluate the impact of specific upgrades on overall cost, the long-term objective is to apply sensitivity analysis directly to (9) in order to predict which network upgrades from the full candidate set will yield the most optimal results. Recent work in auxiliary grid optimization has shown that fully nonlinear power system models often limit the ability to compute meaningful sensitivities, particularly in the presence of renewable generation variability and load uncertainty. As such, the authors are currently investigating model simplifications that permit tractable analysis, including variations of decoupled power flow methods, similar in spirit to the reduced-order and scenario-based approaches seen in contemporary auxiliary grid energy management research. These reduced formulations have been used to support optimization in hybrid renewable systems, community auxiliary grids, and multi-energy auxiliary grids when full AC models become impractical. The authors anticipate that these simplified formulations will enable a sensitivity-driven search across a broader set of candidate upgrades, with results to be presented alongside the findings reported in this work.

This paper presented a method for determining the combination of transmission lines and distributed generators that yields the least expensive and most reliable configuration for the TCNJ auxiliary grid. Single and double contingency analysis methods were employed to identify network vulnerabilities, consistent with reliability-oriented evaluations used in recent multi-auxiliary grid and community auxiliary grid studies. These weak points served as a guide for proposing targeted upgrade options. The least expensive combination of upgrades was then identified using the cost analysis formulation, which includes a penalty term associated with any building failing to receive adequate service. Similar penalty mechanisms appear in modern auxiliary grid energy management formulations, where unserved energy, load shedding, or service interruptions must be explicitly discouraged. This term prevents solutions that permit frequent service loss and reinforces the importance of selecting upgrades that enhance reliability across the entire network. Overall, the approach aligns with broader trends in auxiliary grid optimization literature, emphasizing reliability-driven planning guided by scenario evaluation, contingency assessment, and multi-criteria cost analysis.

IX. Acknowledgments

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X. References

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