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EPRI-CPLANET: Controlled Planning Expansion Tool with Corrective and Preventive Control

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SUMMARY

The end-use energy consumption is on an upward trend, forcing us to have increased electricity generation and the structure to support that capacity. With this ever-growing electricity demand and supply, planning and expansion of the transmission system have become a more challenging issue in recent years. The high-performing transmission grid of the future will have to be more flexible to host a diverse supply of renewable generation resources, more adaptable to accommodate changes in systems conditions with fewer cost penalties to customers, and highly responsive to maintain operability and security under unexpected severe and widespread impacts. Even though transmission expansion projects will continue to be the backbone of grid development, advanced transmission technologies, such as power flow controllers and FACTS devices, can be used to fulfill these highly demanding requirements at a lower cost and higher efficiency. With increased penetration of distributed energy renewable resources, storage devices such as batteries are also trending as viable options for transmission system support.

To design and evaluate transmission solutions that combine in an effective manner, the capability of various transmission technologies, proper analytical methods, and tools for optimization and simulation analysis are needed. EPRI has developed a software tool (CPLANET for Controlled Planning Expansion Tool) [1] that helps identify effective and low-cost solutions for mitigating thermal overloads in a power system over various operating scenarios. The solution is determined from a given set of candidate projects that may include power flow controllers (Phase-shifting transformers (PSTs), fixed series reactors), energy storage, as well as traditional expansion projects such as new and/or upgraded transmission lines and substations.

The software uses a mix-integer optimization engine to identify the least-cost solution among the candidate projects, subject to the grid's different physical and operational characteristics. The tool provides not only cost-effective solutions to the transmission planners, which make the network more stable, reliable, and resilient but also offers different operating setpoints for the devices that need control (e.g., PSTs). This paper showcases the CPLANET capabilities and discusses the formulation and optimization algorithm used to develop the tool. The planning

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problem is formulated as a single-stage optimization problem. It captures project investment and operation costs and includes the system operation under different operating conditions. Finally, extensive results are presented using an IEEE case and a utility case to validate the tool.

KEYWORDS

Transmission Planning, Expansion Planning Tool, Phase Shift Transformers, Series Reactors, New Transmission Lines, Upgrade Existing Transmission Lines, Batteries, Modular, Scalable.

1 INTRODUCTION

The power system is snowballing. It is getting highly complex with an increased variety of demand and sources such as renewables. To accommodate this change, better planning is necessary. As such, transmission expansion planning is need of an hour in power system planning. It is essential to use the existing transmission system efficiently and, at the same time, make economic and insightful decisions to expand the system. The transmission expansion planning problem aims to minimize the investment and operating cost while meeting the system needs under various operating conditions. A variety of options have become available that can help in the expansion and efficient use of the transmission system. Traditional technology solutions to control power flow—such as phase-shifting transformers (PSTs)—have been used extensively to reduce loop flows or maintain scheduled power flow on specific paths. They have also been used in some cases to minimize overloads by diverting power flow from heavily loaded lines to other lines with spare capacity, increasing the utilization of existing transmission assets and reducing the need for certain transmission upgrades.

In recent years, the development of new power flow control (PFC) technologies has grown under the auspice of the U.S. Department of Energy. There is also a rise in the number of private developers for these devices. Relative to the more traditional power flow technologies such as PSTs, Flexible AC Transmission Systems (FACTS), and high voltage direct current (HVDC) technologies, the new PFC devices are more straightforward and compact scalable. Some of these new PFCs have great potential but still are at an intermediate stage of development. In contrast, others are already commercially available, such as the distributed series compensator (DSC) technology, developed and commercialized by Smart Wires, Inc.

The applications of PFCs include, but are not limited to, loop flow control, congestion reduction, deferral of transmission expansion, overload mitigation, increased asset utilization, increased flexibility of system operations, and improved flexibility of transmission expansion. Also, some new technologies, specifically DSCs, are modular and can be gradually installed over time as the need arises. They can also be moved from one location of the grid to another in a relatively straightforward manner. These characteristics provide great flexibility and make the technology useful for other additional purposes, such as interim solutions to operational issues or mitigation solutions that can be implemented until strategic transmission projects are in service.

On the other hand, when planning or evaluating the need for a transmission facility, transmission planners are facing pressing needs from regulatory directives to assess the value of deploying non-wire solutions—including PFC technologies. PFC technologies are not intended to displace but complement conventional transmission infrastructure. As such, PFC should be considered options in a portfolio of transmission infrastructure necessary for the efficient and reliable supply of electricity to customers.

Storage is gaining traction as transmission assets. One of the reasons is their decreasing costs and increasing penetration. Planners need appropriate models, analytics methods, and tools to determine the best locations to install one or a combination of these components. These different types of devices solve various problems in transmission systems; therefore, there is no unique approach to designing an effective solution. The challenge is to develop a methodology tailored to the specific case.

In this paper, we consider mitigating overloads as the primary objective. The solution identifies the least-cost alternative that satisfies all the operating conditions. Finding a solution with multiple choices of these components that meet all the slated requirements through trial and error and manual inspection is a challenging task. E.g., in a highly meshed network, PFCs can impact neighboring lines, not just the selected location. These devices can highly interact, and the analysis done with one component at a time may not be feasible. Therefore, an analytical approach is needed to find a viable solution.

There is a lot of research done around planning problems. Reference [2] provides an optimization method to place new transmission lines to alleviate congestion. Reference [3] considers PSTs as new elements along with traditional components such as transmission lines and conventional transformers. However, it forms a mixed-integer nonlinear problem (MINLP) and employs a genetic algorithm. Reference [4] considers variable series reactors are considered in a multi-stage N-1-secure transmission expansion planning problem. A DC model and other linearization techniques are used to cast the problem as a mixed-integer linear program (MILP), which is solved using a decomposition approach. It is observed that the variable series reactor allocations add flexibility to the system at a reduced planning cost. In reference [5], PSTs are considered along with other flexibility-providing resources such as energy storage and demand-side management for long-term system planning under uncertainty. The problem is formulated as a MILP using a dc model. It is shown that the flexible technologies considered are valuable investment options when facing uncertainties from future renewable generation developments.

The CPLANET tool [1] proposed in this work extends all this research into a user-friendly graphical tool with a unique optimization approach. It is unique in that it simultaneously considers all the operating conditions and scenarios, all the different types of devices, such as phase shift transformers, transmission lines, and batteries. It provides the least cost solution accounting for all these different combinations to mitigate thermal overloads across all operating scenarios. Additionally, it offers the option to consider preventive or corrective control for the optimization of devices with control settings such as phase shift transformers, batteries, etc.

The remainder of this paper is organized as follows: Section 2 provides an overview of the CPLANET infrastructure and the methodology behind the engine. Section 3 validates the tool through extensive results. Section 4 discusses concluding remarks and future work insights.

2 EPRI-CPLANET TOOL

In this section, we discuss the general overview of CPLANET, define the optimization problem used in the tool, and some key definitions used in the rest of the literature.

2.1 CPLANET Overview

The overview of the tool structure is shown in Figure 1. The tool needs three sets of input files as described below:

1) Operating Scenarios – A collation of power flow case files that correspond to the operating conditions under which the system will be analyzed. These files can be PSS®E raw files.
2) List of Monitored lines – A file that provides information regarding the transmission lines in the system for which thermal overloads need to be monitored and mitigated.
3) List of Candidates – List various candidates for each type of device the user wants to consider for optimization. The devices supported are phase shift transformers, reactors, new lines, upgrades of existing lines, and batteries.

These input files are then loaded into the optimization module, which performs the least cost solution optimization (briefly discussed in the next section) to mitigate thermal overloads in the operating scenarios and spit out the output. The output files contain the detailed report of selected devices for installation, their estimated cost, and the size of the devices where applicable, and additionally provide individual operating setpoint for each device for each scenario under consideration. The tool also provides the final output scenario files with the installed devices, which one can use for further analysis. In the next section, we briefly discuss the optimization module.

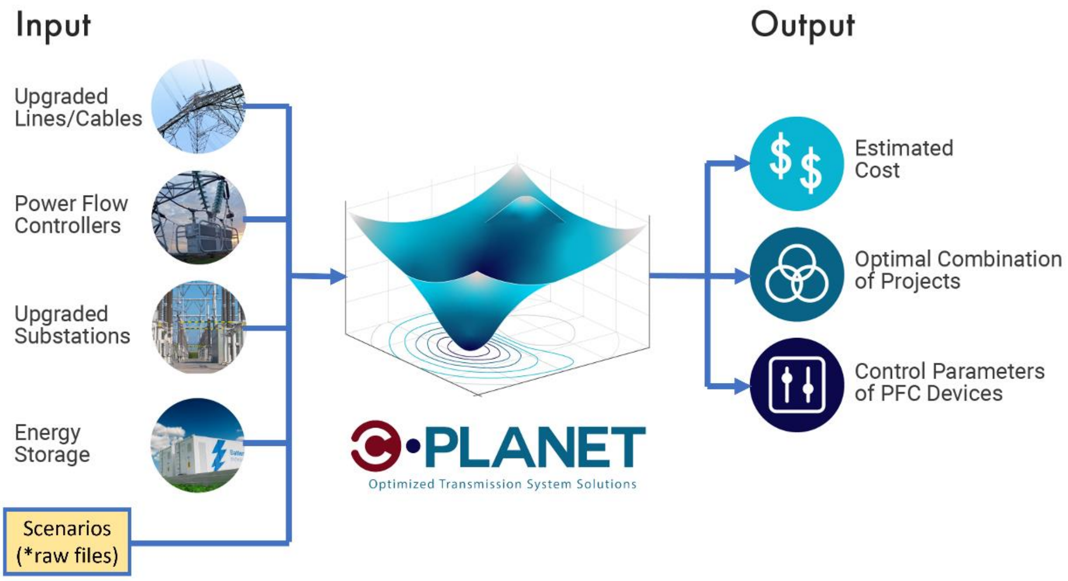

Figure 1: CPLANET Overview

2.2 Objective

The objective is to determine the minimum-cost investment of devices that allows for eliminating thermal overloads under various operating conditions. The devices include PSTs, and it determines their location, sizes, and setpoints for each scenario. It also includes locating new lines or recommending an upgrade of existing lines. Lastly, it also considers batteries and determines their location, sizes, and setpoints for each scenario. The investment decisions determine whether to purchase and install any of these devices. It is noteworthy to mention that, for each operating scenario considered, the phase shifts of these PSTs and injection/withdrawal of power from the battery can be adjusted independently of other scenarios to alleviate the overloads. Mathematically, this investment planning problem can be represented as shown in Figure 2.

$$\underset{\alpha,\beta,\zeta,\psi,\xi}{\text{minimize}} \quad \overbrace{\sum_{(i,j)\in\Omega_p} \left(\alpha_{ij}A_{ij} + B_{ij}\beta_{ij}\right)}^{\text{PSTs}} + \overbrace{\sum_{(i,j)\in\Omega_c} \zeta_{ij}D_{ij}}^{\text{New Lines}} + \overbrace{\sum_{(i,j)\in\Omega_u} \zeta_{ij}E_{ij}}^{\text{Upgrade lines}} + \overbrace{\sum_{i\in\Omega_b} \left(\psi_i U_i + V_i\xi_i\right)}^{\text{Batteries}} + \overbrace{\sum_{w=1}^{|\mathcal{W}|} \sum_{(i,j)\in(\Omega_m\cup\Omega_c\cup\Omega_u)} C\bar{f}_{ij}}^{\text{Thermal Overloads}}$$

Figure 2: Objective function

Where α represents decisions of purchasing and installing PSTs on candidate transmission lines denoted by Ω_p, β represents maximum phase shift angles of PSTs, A and B are location-specific cost coefficients for PST investments, ζ represents the decision to install a new transmission line or upgrade an existing one, D represents the associated cost of installing or upgrading the transmission line, ψ represents decisions of purchasing and installing batteries on candidate buses denoted by Ω_b, ξ represents the maximum size of the battery (rating), U and V are location-specific cost coefficients for Battery investments,$|\mathcal{W}|$ is the number of operating scenarios, $\Omega_c, \Omega_u, \Omega_m$ represents set of candidate new lines, candidate lines considered for an upgrade, and set of monitored lines for thermal overloads, respectively, C is a large positive constant that penalizes the thermal overloads, $\overline{f}$ captures thermal overloads.

It is subjected to the following constraints (in generic form for brevity),

$$g(x) = 0$$

$$h(x) \leq 0$$

where g(x) includes all equality equations such as power balance equations, etc. h(x) provides inequality equations that account for thermal limits, etc. To resolve the non-linearity, DC power flow model is used for power balance, and the big-M technique [6] is used to resolve some of the nonlinear mixed integer constraints. The final problem formed is a MILP (mixed integer linear problem). The following section describes various optimization parameters the tool offers as flexibility for the user to select.

2.3 Alternatives

Once the input files are loaded into the tool, the user can set different parameters for the optimization, as shown in Figure 3.

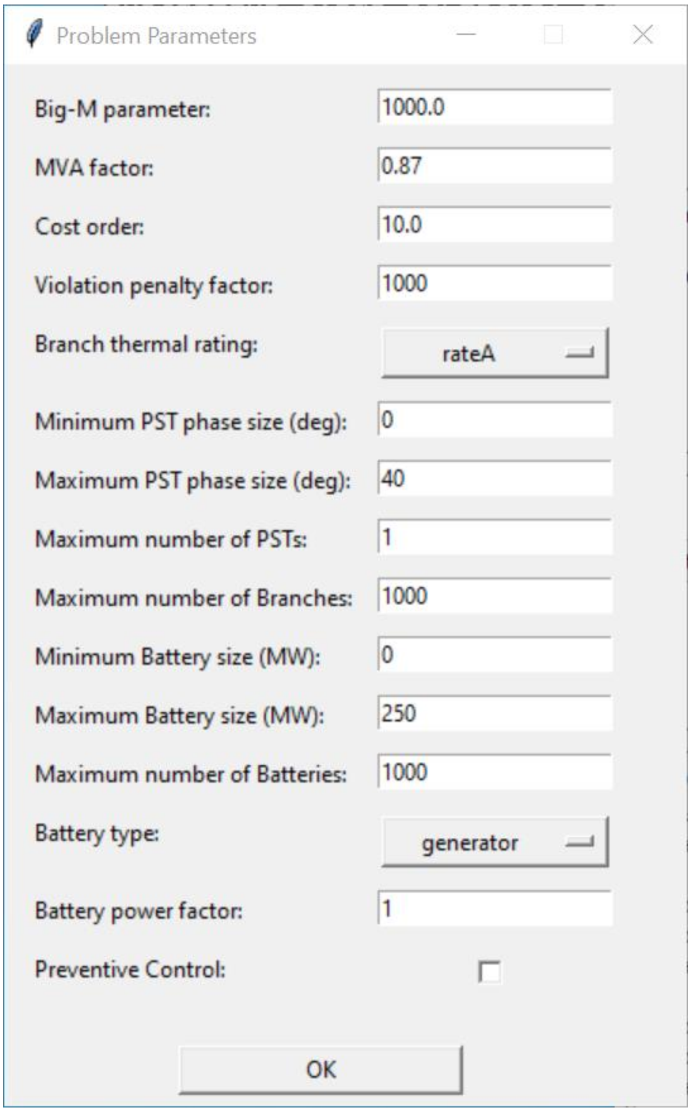

Figure 3: Optimization Parameters

The user can perform different types of studies by choosing a different set of parameters for every analysis and possibly selecting a subset of candidate projects. Each such possible subset of candidate projects or parameter selection is defined as an alternative. Depending on the application and the need, users can analyze a few alternatives and choose the best one that suits their requirements. The preventive control setting is to be used when the system needs to be prepared for the most critical contingency considered. However, the device itself may be active all the time and may be a non-optimal solution from the viewpoint of transmission capability. This setting is applicable only to PST devices. The following section discusses a few results to show the prowess of the tool.

3 RESULTS AND DISCUSSIONS

The tool is validated extensively using different generic cases and real utility cases. Here two of those case studies are presented. First, the IEEE reliability test system with 96 buses (RTS 96) is used to showcase the application of the tool. Second, a utility case study with Great River Energy Transmission System.

3.1 IEEE RTS-96 Bus System

The generation dispatch, load dispatch, and line ratings were modified for the purposes of this case study. Following are the set of input files used for this study:

1. Operating Scenarios – Five scenarios representing different system conditions were simulated. These five scenarios included the base case with no contingency plus four different N-1 branch contingencies, as shown in Figure 4.
2. Monitored lines – Power flows on all the 230 kV branches (45 lines + Transformers) were monitored for any Rate A thermal violations.
3. Candidate devices – A choice of 19 bus locations for batteries, 10 new lines, 11 locations for installing PSTs were selected for this study. Reference costs for PST devices were calculated using the data provided by Siemens. The cost of new transmission lines has been estimated using the reference costs provided in [7].

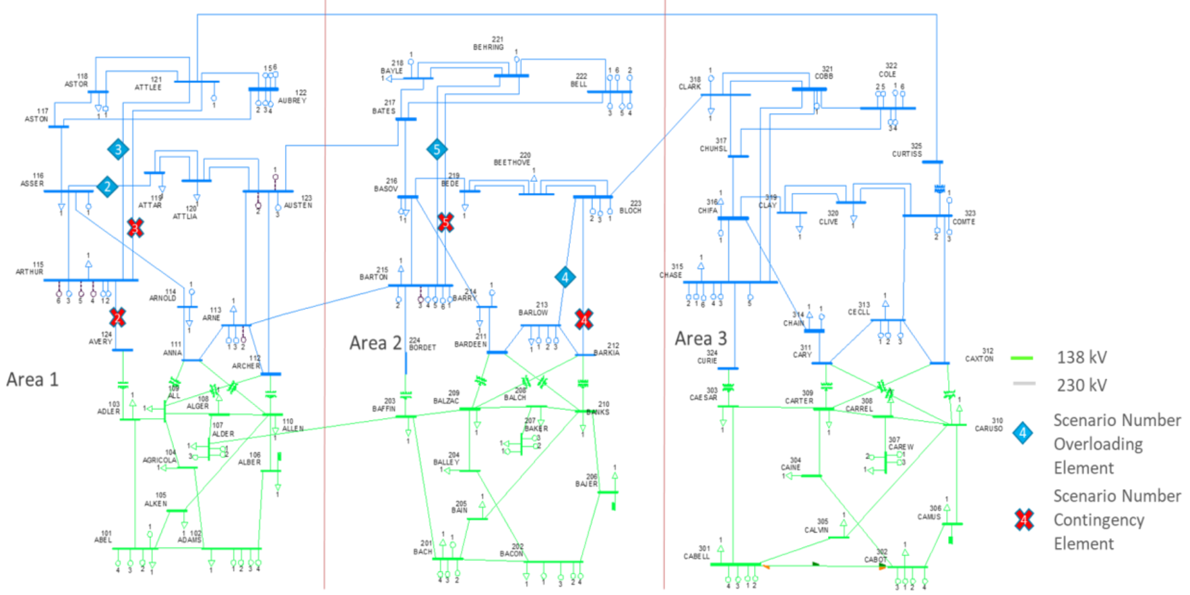

Figure 4: IEEE RTS-96 Operating Scenarios

The initial transmission line overloads are shown in Table 1.

								Line Loading Before Installing New Devices [%]				
From bus	From bus name	From bus kV	To bus	To bus name	To bus kV	id	Rating (pu)	Sce1	Sce2	Sce3	Sce4	Sce5
115	ARTHUR	230	121	ATTLEE	230	1	5	70.9	111.4	64.6	73.6	71.4
116	ASSER	230	119	ATTAR	230	1	5	69.8	68.5	100.8	74.1	69.2
213	BARLOW	230	223	BLOCH	230	1	5	65.4	66.5	67	100.8	66.2
215	BARTON	230	221	BEHRING	230	1	4.5	70.7	71	72.3	72.4	109.6

Table 1: [Case A] Initial Transmission Line Overloads

Three alternative choices were analyzed, as shown in Table 2.

Alternative	Description
1	Only PSTs and Transmission lines are considered for the optimization
2	Same as 1, but the maximum number of PSTs was restricted to 1
3	Only batteries are considered for the optimization, with maximum battery size restricted to 250 MW

Table 2: [Case A] List of Alternatives

3.1.1 Alternative 1 Results

CPLANET selected five PST devices, as shown in Table 3. The corresponding operating setpoint for each scenario is shown in Table 4. This solution indicates that all the overloads can be mitigated using these devices, and there was no need for a new transmission line. It can be noted that PSTs 2 and 5 have zero-degree phase shifts. For practical purposes, it can be considered that a reactor is installed rather than a PST. The new overloading of the transmission lines after installing these devices is shown in Table 5, and as can be seen, all thermal overloads have been mitigated.

PST	From bus	Name	kV	To bus	Name	kV	id	Size (deg)	Cost ($)
1	115	ARTHUR	230	121	ATTLEE	230	1	1.58	666,385.9
2	116	ASSER	230	119	ATTAR	230	1	0	260,416.0
3	211	BARDEEN	230	213	BARLOW	230	1	1.22	573,886.5
4	215	BARTON	230	221	BEHRING	230	1	5.14	1,475,699.0
5	217	BATES	230	218	BAYLE	230	1	0	243,055.0

Table 3: [Case A] PST Solution for Alternative 1 (Location and Reference Cost)

		PST Angle Setting (deg)				
PST	Max Angle	Sc. 1	Sc. 2	Sc. 3	Sc. 4	Sc. 5
1	1.58	1.58	-1.58	-1.58	1.58	-1.58
2	0	0	0	0	0	0
3	1.22	1.22	1.22	1.22	-1.22	1.22
4	5.14	5.14	-3.64	-3.27	5.14	-5.14
5	0	0	0	0	0	0

Table 4: [Case A] PST Solution for Alternative 1 (Operating Setpoints)

3.1.2 Alternative 2 Results

In this alternative, the solution was forced to consider a maximum of 1 PST device, this led to the selection of 3 new transmission lines to resolve all the overloads along with the single PST device. The new line solution is shown in Table 6.

								Line Loading After Installing New Devices [%]				
From bus	From bus name	From bus kV	To bus	To bus name	To bus kV	id	Rating (pu)	Sce1	Sce2	Sce3	Sce4	Sce5
115	ARTHUR	230	121	ATTLEE	230	1	5	68.4	97.7	50.3	70.8	56.8
116	ASSER	230	119	ATTAR	230	1	5	66.6	64.3	96.1	71	65.6
213	BARLOW	230	223	BLOCH	230	1	5	65.7	67.1	67.4	99	67
215	BARTON	230	221	BEHRING	230	1	4.5	86	48.4	51.1	86.6	90.3

Table 5: [Case A] Transmission Line Loadings with PSTs for Alternative 1

Line	From bus	Name	kV	To bus	Name	kV	id	Cost ($)
1	116	ASSER	230	120	ATTLIA	230	1	41,746,950.0
2	116	ASSER	230	121	ATTLEE	230	1	23,032,800.0
3	215	BARTON	230	221	BEHRING	230	3	32,629,800.0

Table 6: [Case A] New Lines for Alternative 2 (Location and Reference Cost)

3.1.3 Alternative 3 Results

This type of alternative analysis is proper when exploring non-wire alternative solutions in correspondence to conventional projects such as new transmission lines to mitigate thermal overloads. CPLANET determined the installation of three new battery devices with one battery capped to the maximum limit set as a parameter for this alternative as shown in Table 7.

Selected Energy Storage Devices				Injection/withdrawal for operating scenarios [MW]				
Battery	Bus name	Bus kV	Capacity [MW]	Sc. 1	Sc. 2	Sc. 3	Sc. 4	Sc. 5
1	ARTHUR	230	44.09	44.09	44.09	-44.09	44.09	-44.09
2	BATES	230	62.21	62.21	62.21	62.21	62.21	-62.21
3	BAYLE	230	250	-250	250	250	250	-250

Table 7: [Case A] Selected Batteries for Alternative 3

3.2 Great River Energy Transmission System

The data and information details have been obfuscated to protect CEII and sensitive information. The scenarios include one summer peak and two winter peak cases. Forty-seven transmission lines in the region were monitored for overloads above Rate A. Three different alternatives were simulated as summarized in Table 8.

Alternative	Description
1	• There is no restriction on the number of batteries that the optimization solution can select from the given battery candidates to resolve the thermal overloads. • The battery size range was set from a minimum of 0 MW to a maximum of 250 MW capacity.
2	• The number of batteries that the optimization solution can select from the given battery candidates to resolve the thermal overloads was restricted to **2**. • The battery size range was set from a minimum of 1 MW to a maximum of 250 MW capacity.
3	• The number of batteries that the optimization solution can select from the given battery candidates to resolve the thermal overloads was restricted to **1**. • The battery size range was set from a minimum of 1 MW to a maximum of 250 MW capacity.

Table 8: [Case B] Alternatives for Great River Energy System

The tool determined three battery locations for alternative 1 with a total capacity of 44 MW. This is summarized in Table 9. Table 10 shows the loading of the transmission lines for the three scenarios with the Batteries installed as a generator with a 0.95 power factor. As seen, the thermal overloads are mitigated in all three alternatives. The red shading indicates line loading greater than 100%. The light color shading indicates line-loading that ranges 95-100%. Similar results were observed for other alternatives. A summary of all three alternative results is presented in Table 11.

Selected Energy Storage Devices					Injection/withdrawal for operating scenarios [MW]		
Battery	**Bus Number**	**Bus name**	**Bus kV**	**Capacity [MW]**	**Scenario 1**	**Scenario 2**	**Scenario 3**
1	1	***	***	5	4	5	0
2	2	***	***	15	0	15	10
3	3	***	***	24	0	24	2
			Total	**44**			

Table 9: [Case B] Battery solution for Alternative 1

	Line Loading Before Installing New Devices [%]			Line Loading After Installing New Devices [%]		
	Scenario 1	Scenario 2	Scenario 3	Scenario 1	Scenario 2	Scenario 3
Line 1	104.2	16.9	77.6	99.4	16.9	76.3
Line 2	38.3	113.2	103.7	38.3	100	99.3
Line 3	54.6	103.6	98.3	54.6	94.2	95.2
Line 4	29.9	100.6	88.3	29.9	98.3	91.3

Table 10: [Case B] Transmission lines loading with installed batteries for Alternative 1

Alternative	Description	Number of batteries selected in the optimum solution	Total Battery Size (MW)	Total Cost (M$)
1	There was no restriction on the number of candidate battery locations optimization could select.	3	44	96.8
2	The number of candidates optimization can select is restricted to a maximum of 2.	2	46	101.2
3	The number of candidates optimization can select is restricted to a maximum of 1	1	66	145.2

Table 11: [Case B] Summary of Alternatives

The total capacity of the batteries increases as we reduce the flexibility of the number of batteries, increasing the cost. Although expense increases as we move from alternative 1 to 3, it might be easier to control as there are fewer batteries. The final choice would then depend on the physical limitations and other aspects related to the system. The individual scenario battery setpoints are the amount of MW power injected/withdrawn by the battery if that scenario (contingency) occurs to prevent thermal overloads. A cost factor of 2.2M$/MW is used to calculate the total cost obtained from the EPRI BESS Energy Storage Costs Table [8]. In the next section, we discuss some ongoing and future works under consideration.

4 CONCLUDING REMARKS AND FUTURE WORK

This paper showcases the CPLANET tool developed to provide the least-cost solutions to system planners selected among a pool of enormous possible options across various operating conditions. Since the tool uses an approximate model for the power flow, a detailed engineering analysis is finally needed to refine the solutions. The future work involves improving CPLANET capabilities with new optimization algorithms and introducing more types of devices, such as non-wire alternative solutions such as SmartValve devices. Furthermore, exploit the modular and re-deployable features of devices such as batteries and Smart Wires.

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