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TOGETS Task Force

Grid Enhancing Technologies Modeling Methodology

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Modeling Objectives

Assess Grid Enhancing Technologies in transmission planning by **coupling economic and reliability analysis** over an entire time horizon rather than a few dispatch conditions.

1. Develop novel methods to link economic and reliability transmission planning tools
2. Consider the flexible nature of GETs across wide ranges of system conditions
3. Evaluate how GETs can be used to defer, reduce, and potentially eliminate the need for new transmission upgrades

This document focuses on the modeling methodology and the ***process*** of evaluating possible transmission upgrades. As part of the overall project, this process was applied to both a test system and a model of the New England power system. The analysis results are in a separate document.

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Pre-Read Materials and Knowledge Disclaimer

This document assumes that the reader is familiar with some transmission planning concepts, including:

- Locational Marginal Pricing
- Transmission Congestion
- A/C and D/C Power Flows
- Contingency Analysis (N-1 power system planning)
- Economic Dispatch

If any of these concepts are unfamiliar, the reader is encouraged to stop and review introductory material for these concepts. Rather than attempt to recreate such introductions here, the reader should begin with [1] and [2], which do thorough exploration of the topics.

[1] Planning Electric Transmission Lines: A Review of Recent Regional Transmission Plans. Joseph H. Eto. LBNL. 2016.
https://www.energy.gov/sites/prod/files/2017/01/f34/Planning%20Electric%20Transmission%20Lines--A%20Review%20of%20Recent%20Regional%20Transmission%20Plans.pdf

[2] Grid-Enhancing Technologies: A Case Study on Ratepayer Impact. US. Department of Energy. February 2022.

https://www.energy.gov/sites/default/files/2022-04/Grid%20Enhancing%20Technologies%20-%20A%20Case%20Study%20on%20Ratepayer%20Impact%20-%20February%202022%20CLEAN%20as%20of%20032322.pdf

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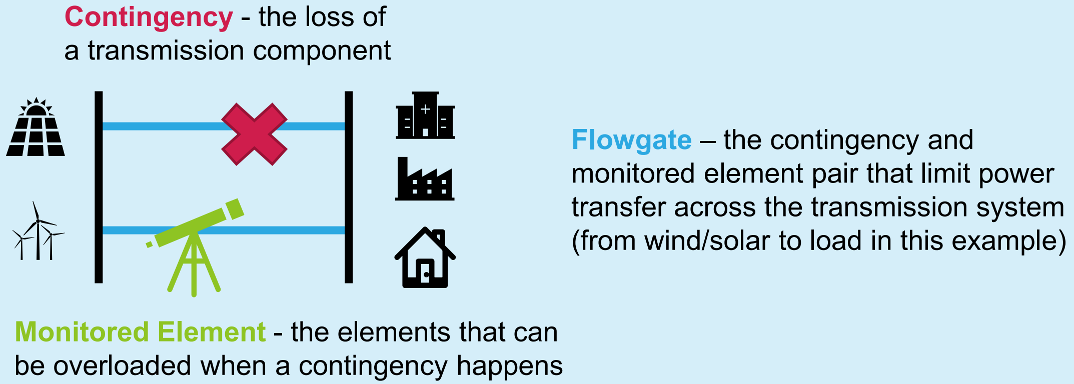
Acronyms and Defining Flowgates

Acronym	Definition
A/C	Alternating Current
AAR	Ambient Adjusted Rating
D/C	Direct Current
DLR	Dynamic Line Rating
EI MMWG	Eastern Interconnect Multiregional Modeling Working Group
FERC	Federal Energy Regulatory Commission
GETs	Grid Enhancing Technologies
ISO-NE	Independent System Operator of New England
kV	kilovolt
LBW	Land-Based Wind
MW	Megawatt
N-1	"N minus 1" (Typically, refers to system condition assessments)
NERC	National Energy Regulatory Commission
NYISO	New York Independent System Operator
OSW	Offshore Wind
PFC	Power Flow Control
PLEXOS	Energy market simulation software tool
RTO	Regional Transmission Operator
SEMA	Southeastern Massachusetts
SLR	Static Line Rating
TARA	Transmission Adequacy and Reliability Assessment software tool

In transmission system planning, ensuring safe power flows across transmission facilities relies on a variety of system ratings. Dynamic Line Ratings (DLR) aim to take advantage of inherent capability in the physical properties of the conductor. However, these line ratings can be limited by the physical properties of nearby elements (such as circuit breakers) or by system security concerns. A key concept in system security is N-1 security, wherein the system remains secure even if one element is lost. This N-1 security is sometimes maintained through definition of flowgates: “A transmission facility or transmission element(s) that has been identified as limiting the amount of power that can be reliably transferred over the bulk transmission system.”[1] In the context of this work, flowgates are used to limit the power transfer across contingency and monitored element pairs as explained in the graphic below. They are a proxy for other types of limits, such as voltage or stability limits. Note that the formal NERC definitions[2] and specific implementations across the country may differ slightly from how these terms are defined in the below. In particular, a flowgate can be a single element in formal definitions.



[1] https://www.spp.org/glossary/?term=Flowgate
[2] https://www.nerc.com/pa/Stand/Project%20200607%20MODV0Revision%20DL/MOD-030-1_Project2006-07_clean_30-day_Pre-ballot_18Jun08.pdf

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Grid Enhancing Technologies Overview

Grid Enhancing Technologies (GETs) include, but are not limited to:

1. ***Power Flow Control (PFC)*** and transmission switching equipment
2. Storage technologies
3. Advanced line rating management
   - ***Ambient Adjusted Ratings (AAR)***
   - ***Dynamic Line Ratings (DLR)***

This effort is primarily focused on the items in ***red*** above.

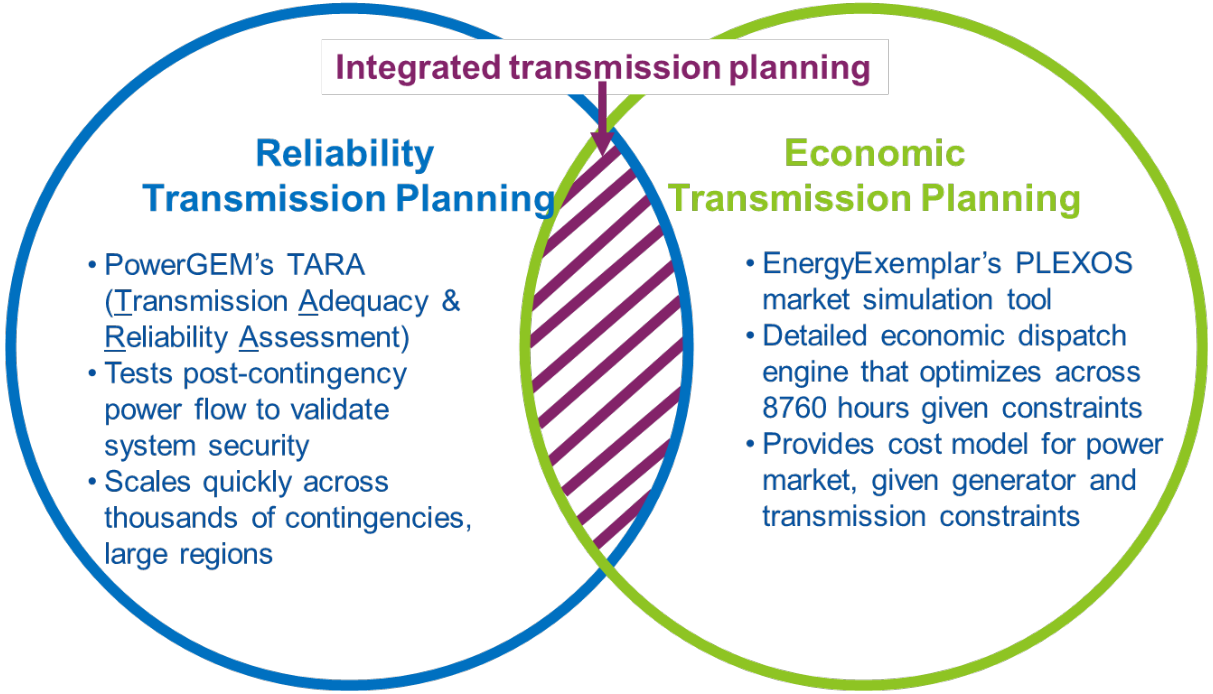
Power Flow Control is a set of technologies that push or shift power away from overloaded lines and onto underutilized lines/corridors within the existing transmission network. Multiple power flow control solutions exist.

Dynamic Line Ratings (and Ambient Adjusted Ratings) adjust thermal line ratings based on actual weather conditions including, ambient air temperature, wind speed/direction, and solar irradiance, in conjunction with real-time monitoring.

GETs definition from FERC Notice to Convene a Workshop on Grid-Enhancing Technologies: https://cms.ferc.gov/media/7198

Modeling and Simulation – Why?

Transmission planning needs are changing due to the changing resource mix, the rapid interconnection of inverter-based resources like wind, solar, and battery storage, and increasing options of grid enhancing technologies. Given the variability and physical properties of these resources, new approaches towards transmission planning are needed. Detailed AC power flow solutions, while computationally detailed, help to analyze the system reliability but only across a small subset of potential operating conditions. Production cost modeling assesses how changes in the system might be reflected in the economics of operating the power system and capture a broader set of conditions across an entire year(s) of operations. However, Production Cost Modeling often uses simplified power flow, which may miss reliability risks. This project proposed to combine the best of two industry leading tools (PLEXOS and TARA) to analyze GETs. This allows the analysis to capture the dynamic and variable nature of these technologies across a range of operating conditions, while also capturing important engineering details.



Integrated Reliability & Economic Planning

- Combined reliability analysis with economic planning will highlight full benefits of GETs and other transmission upgrades
- Reliability analysis in TARA informs PLEXOS contingency modeling and dispatch
- Reliability analysis in TARA paired with PLEXOS congestion costs informs PFC placement

Tool linking is necessary for GETs

The tight coupling of engineering tools and market tools like TARA and PLEXOS is at the leading edge of the industry's efforts to plan for an increasingly dynamic and technologically diverse grid while maintaining the reliability and economics expected from the power system. The key insights here are gleaned from the pairing of traditionally disparate tools. Solutions identified in one model may be unnecessary in another. By pairing the two models in planning the power system, complex system dynamics can be evaluated across a variety of dimensions throughout the process.

What is PLEXOS?

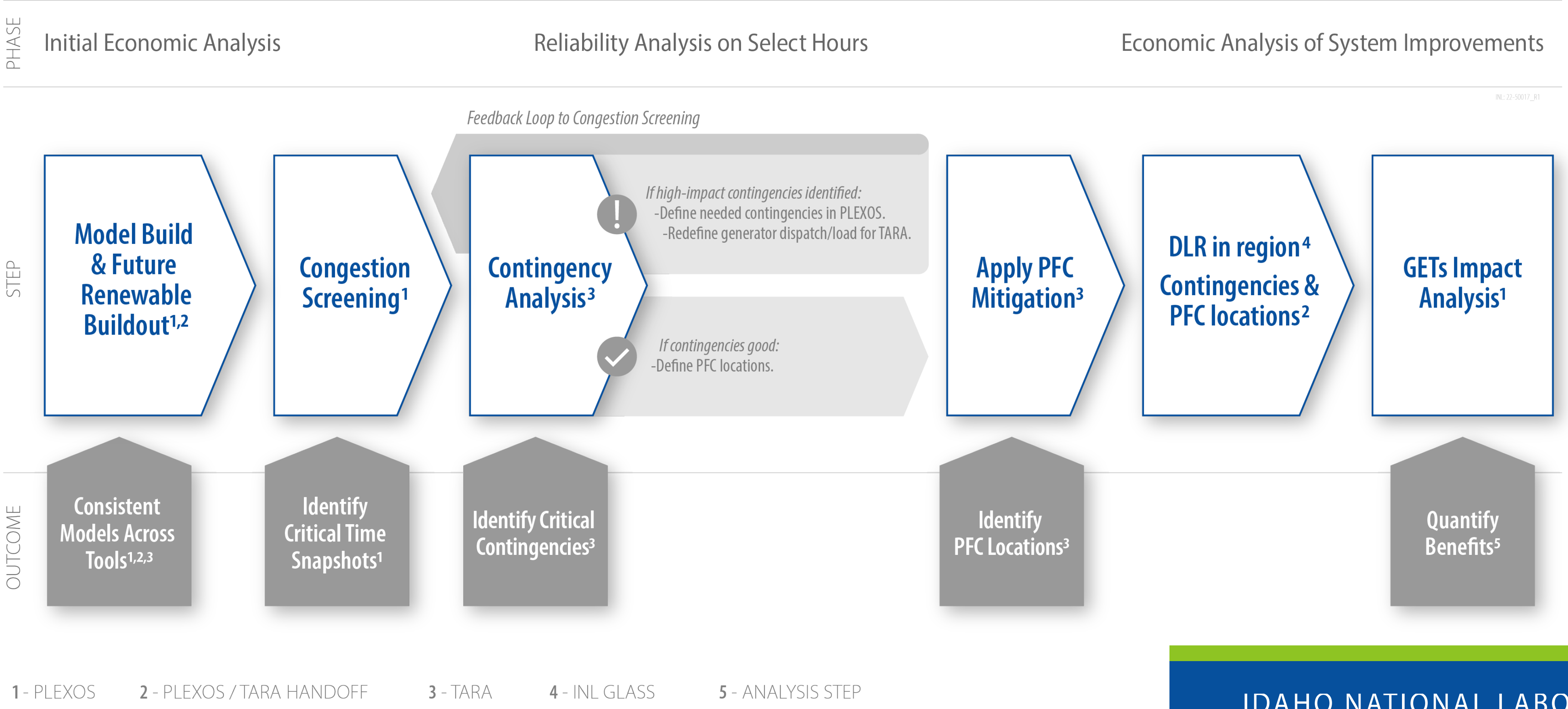
- Software Developer: Energy Exemplar
- Used for: Production Cost Modeling
- DC Optimal Power Flow
  - Simplified Network Solution
  - Ignores Voltage Impacts
- Entire year(s) of simulation
- Economic unit commitment & dispatch
- Identifies transmission congestion that should be resolved to reduce costs
- Quantifies system operating costs & benefits

What is TARA?

- Software Developer: PowerGEM
- Used for: Steady State Analysis
- AC Power Flow
  - Complete Network Solution
  - Incorporates Voltage Impacts
- Single Dispatch Conditions
- Analyzes post-contingency power flows
- Identifies transmission overloads and voltage violations that need to be resolved for reliability

Process Design Pairing Economic and Reliability Analyses

The detailed methodology below was developed in order to combine these tools and more completely evaluate the potential benefits of GETs. The process begins with an initial economic analysis, then moves into a reliability analysis on select hours, and ultimately moves back to a (more accurate) security-constrained economic analysis of multiple potential system improvements. Detailed explanations are provided in subsequent slides.



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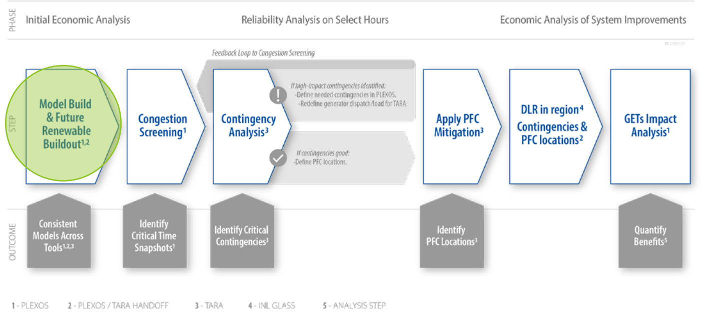


Model Build

Pick a Region and Examine Factors

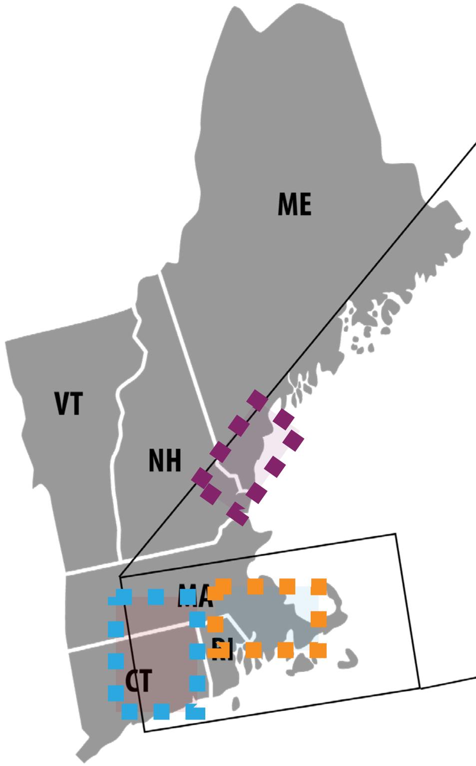
The 2022 Report to Congress on Grid Enhancing Technologies[1] identified six key indicators for GETs value:

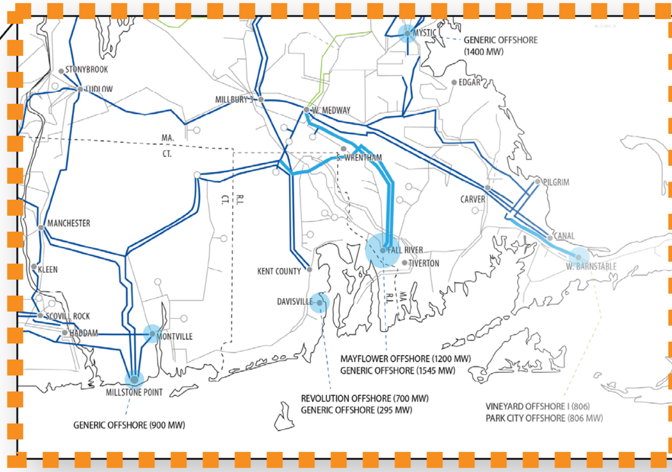
1. Wind and Solar Share
2. Renewable Curtailment
3. Transmission Congestion
4. Price Differentials
5. Proposed Transmission
6. Proposed Renewables

Within that context, 3 locations within ISO-NE were identified as potentially well-suited for GETs:

- **Maine-Greater Boston**
  - ☑ Addresses Land Based Wind Integration
  - ☑ Challenges today expected to worsen with electrification
  - ⊖ Minimal paths for PFC optimization (Mostly NE/SW)
- **Southeast Massachusetts (SEMA)**
  - ☑ Multiple Offshore Wind (OSW) integration points
  - ☑ Multiple paths, voltages (345 & 115 kV), orientations (N/S, E/W)
  - ☑ Impacts both New England and New York power systems
- **Eastern Connecticut (ECT)**
  - ⊖ Single OSW landing spot
  - ⊖ Multiple 345 kV paths
  - ☑ Impacts both New England and New York power systems

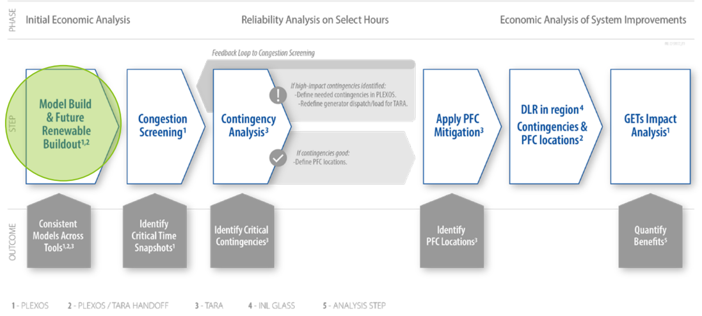
Selected Southeast Massachusetts (SEMA) for detailed modeling region





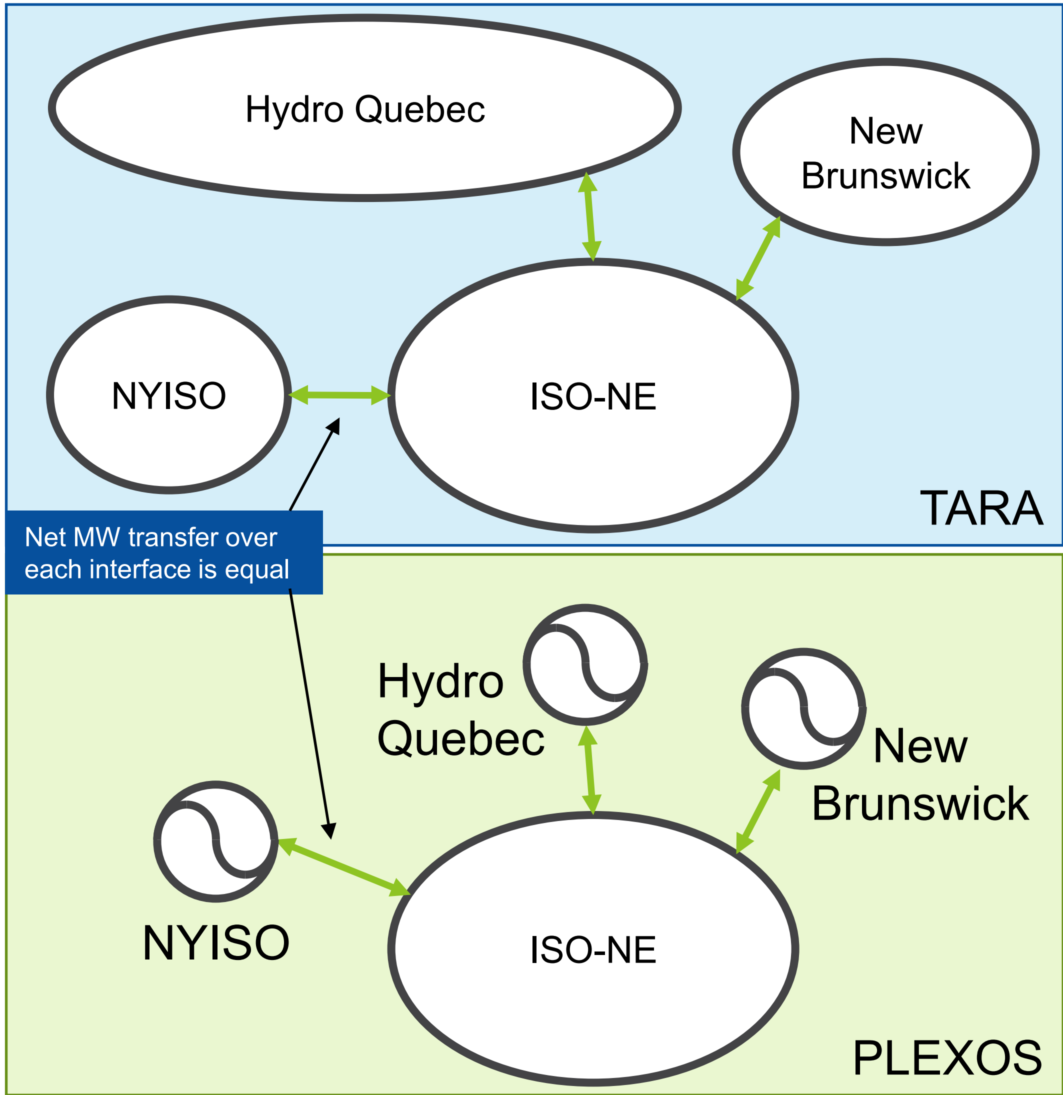
[1] https://www.energy.gov/sites/default/files/2022-04/Grid%20Enhancing% 20Technologies%20-%20A%20Case%20Study%20on%20Ratepayer%20Impact%20-%20February%202022%20CLEAN%20as%20of%20032322.pdf

Model Build
PLEXOS vs TARA Comparison

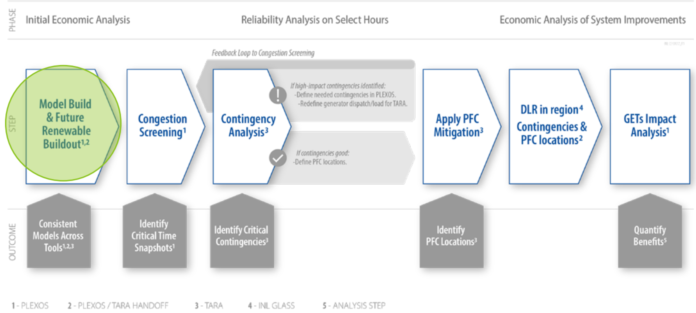


Because these tools were built to study different things, there are certain simplifications that are made with respect to the power system. Below is a sampling of the types of decisions required for alignment on system characteristics.

- External Interfaces Representation
  - PLEXOS uses an accurate system model of ISO-NE with large generators representing neighboring systems
  - TARA uses the FERC 715 EI MMWG[1] dataset complete with explicit representation of ISO-NE and neighboring systems
  - When building a TARA model from a PLEXOS case, generation and load are scaled such that the net MW transfer over each interface is equal
- Aggregated Generation and Nodal Load Allocation
  - There are multiple ways to locate new and distributed generation across buses in a region when its eventual location is unknown.
  - It's important that both systems understand the siting and scale of new generation relative to aggregated representations attributed to certain nodes. Effectively, elegant simplification in one model can cause a stumbling block in the other model.
- Future Generators
  - Certain assumptions are required about the capabilities of future generators, including their reactive power contribution in TARA.



[1] https://rfirst.org/ProgramAreas/ESP/ERAG/MMWG/ERAG%20%20MMWG%20Library/MMWG%20Charter%20-%20November%209%202020.pdf



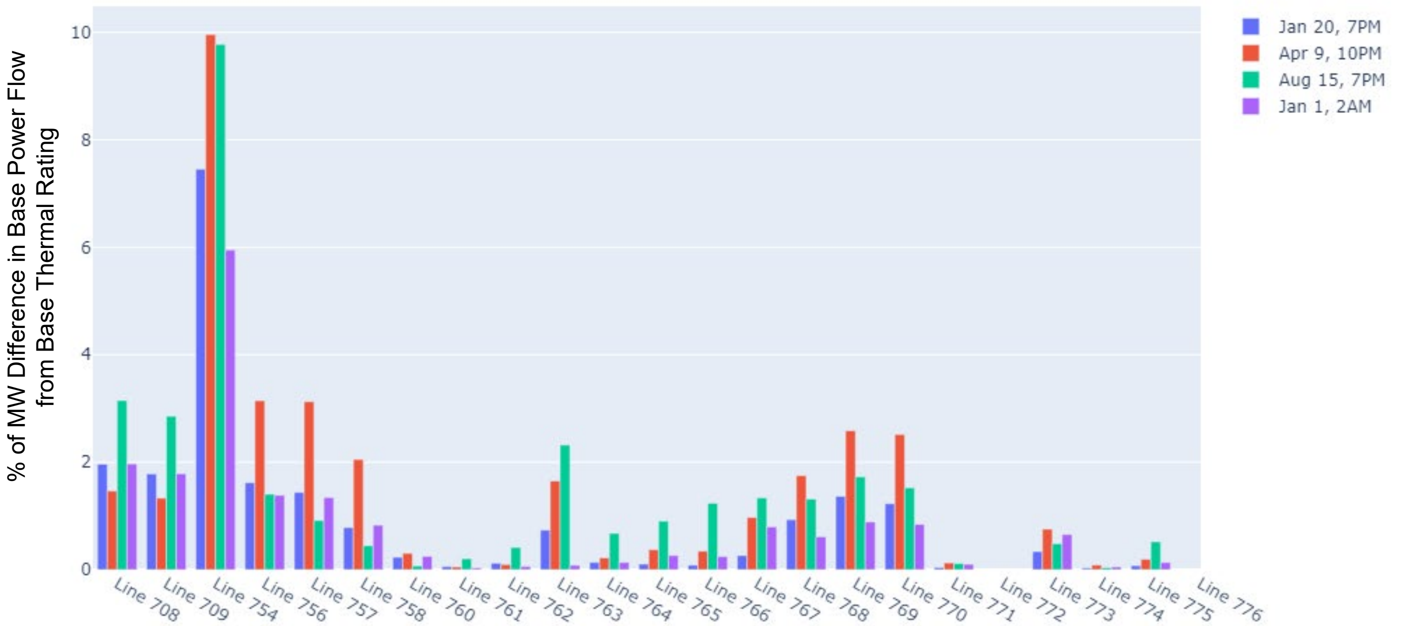
Model Build

Getting different tools to agree

In building different models, assumptions must be made with respect to the detail about system facilities from one model not available in the other and the interties with adjacent systems.

- It is expected that these models will not converge on exactly the same solution, in part because PLEXOS solves power flow using a DC representation, but TARA's key insights require the full AC representation of the system. [1]
  - It is important to understand the causes of divergence along different lines when both models are analyzing the same dispatch conditions
  - It was observed that many of the lines with low reactance had significant discrepancy between TARA and PLEXOS solutions.[2]
- Ultimately, the definition of "acceptable" divergence between the models is at the discretion of the modeling team and is subject to the accuracy required by the study objectives.

The figure below shows what was deemed "acceptable" model divergence for the New England power system. Across a variety of hours, only one line experienced MW line flows that differed by as much as 4%.



[1] TARA is capable of running power flow using a DC representation. Early testing and model building may find this feature helpful to in building model alignment.
[2] These were typically jumper cables with no impact on system congestion.

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Congestion Screening

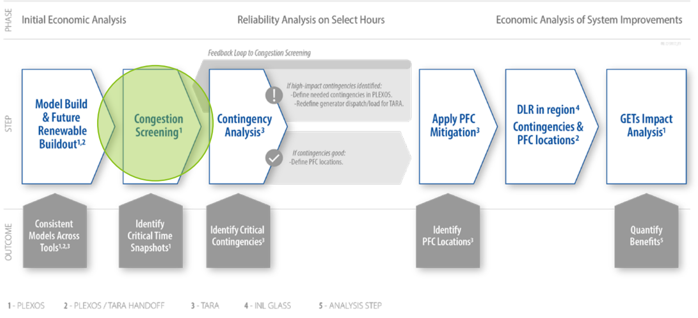
Understanding the initial buildout

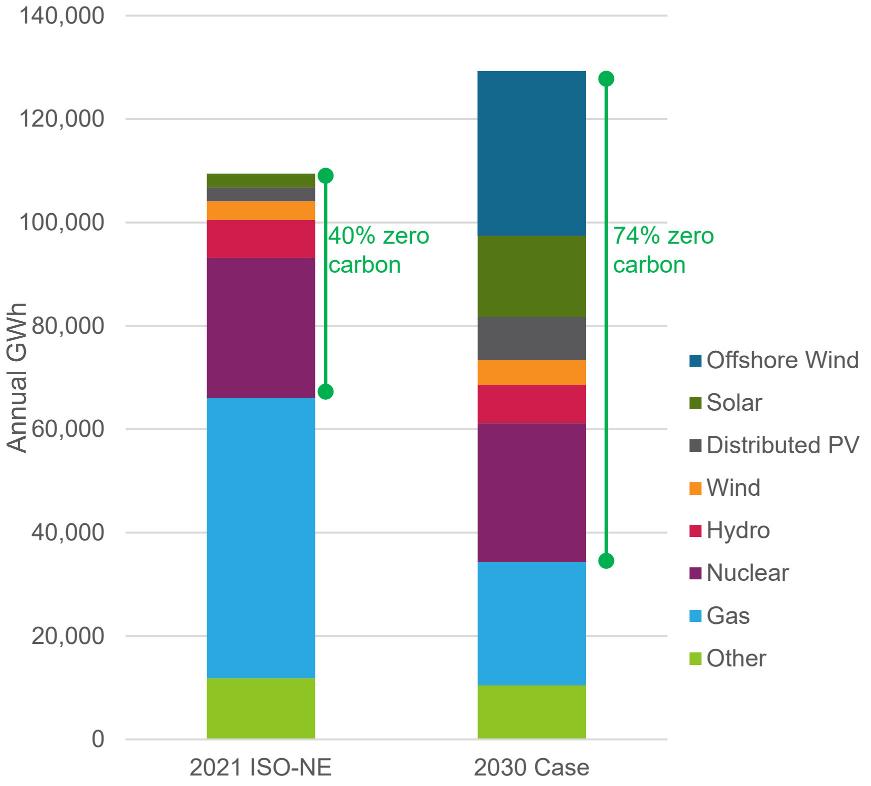
The initial model build and congestion screening are intertwined. On this slide, the resource mix that made up the study year is characterized. From a process perspective, it's important to note that the initial PLEXOS model saw minimal congestion across the year in N-0 conditions, but adding N-1 contingencies (flowgates) through integration with TARA identified areas of system congestion.

The Telos Energy team reviewed public planning documents from ISO-NE as well as referenced the interconnection queue to build a realistic 2030 scenario for resource and load mix. The base model included:

- Siting assumptions for 7,690 MW of offshore wind placed across the southeast Massachusetts region
  - Aligns with the Status Quo approach in ISO-NE's Pathways Study [1]
- Announced thermal generator retirements
- Load forecast from ISO-NE's Forecast Report of Capacity, Energy, Loads, and Transmission (CELT) [2]

Consistent with current ISONE congestion, under the no-contingency (N-0) operating conditions, this base model saw minimal congestion across the full 8760 operating hours of the year.





[1] ISO-NE Pathways Study: https://www.iso-ne.com/static-assets/documents/2022/04/schatzki-et-al-pathways-final.pdf
[2] ISO-NE CELT Report: https://www.iso-ne.com/system-planning/system-plans-studies/celt/

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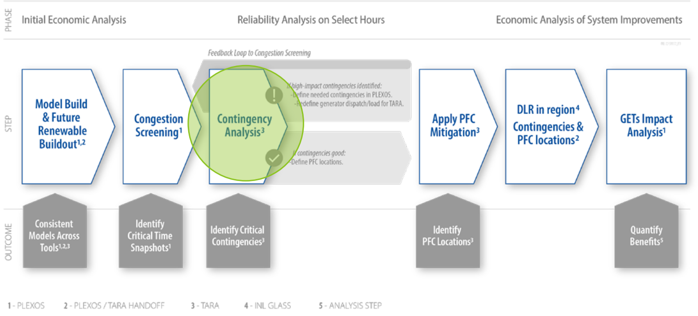
Contingency Analysis

Leveraging tools for their purpose



The most suitable and tractable solution for linking TARA and PLEXOS is to allow PLEXOS to monitor as many high voltage transmission flowgates as possible while allowing TARA to fill in the gaps at lower voltages in the study area.

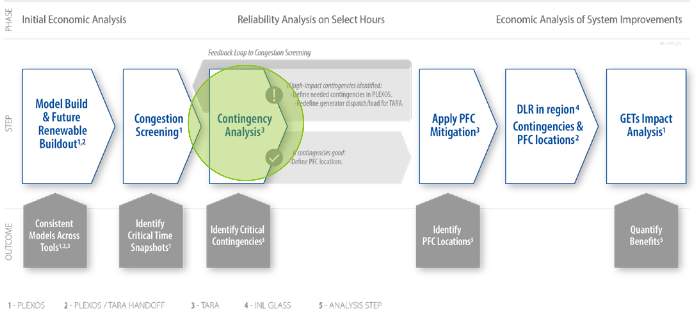
There are overlapping capabilities across most power system modeling tools. PLEXOS and TARA can both identify and monitor flowgate impact

- PLEXOS can perform a DC power flow to monitor all flowgates based on contingency and monitored element voltages
- TARA can perform AC power flow on select hours across the system quickly

For the ISO-NE system, two tools were used together. By using TARA to inform PLEXOS of the most important flowgates to monitor, the final evaluation of technology solutions is informed by a better and more manageable representation of system security constraints at lower voltages. The methodology for accomplishing this is discussed further in the following slides.

	The Good	The Struggle
PLEXOS	System-wide economic dispatch	Runtimes get unwieldy when monitoring lower voltages
TARA	System-wide reliability analysis	Ingesting multiple PLEXOS dispatch hours (DC) can create AC power flow convergence challenges

	Contingency	Monitored Elements	Final Flowgates in PLEXOS
PLEXOS	230+ kV	115+ kV	Select 69+ kV
TARA	69+ kV	69+ kV	Select 69+ kV

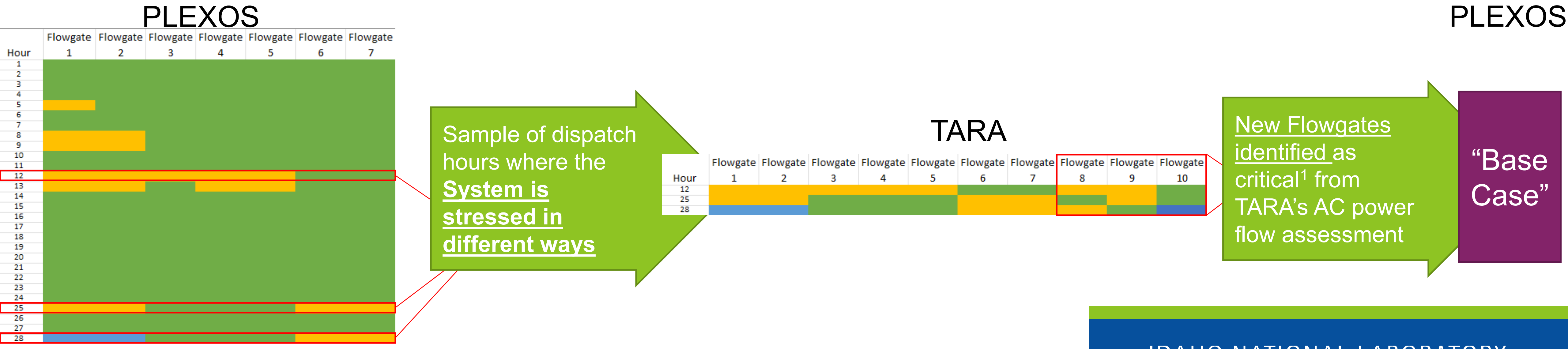


Identify Critical Snapshots

Pick hours for TARA to perform reliability analysis?

TARA scales to assess a few dispatch hours, PLEXOS has 8760 hours. Because TARA only analyzes a few hours for system reliability analysis, selecting hours representative of a range of dispatch conditions for security assessment is vital.

- There are options for how to identify the critical snapshots. The method used herein is fairly manual but could be automated and programmed. Critical snapshots are passed from PLEXOS to TARA based on:
  - Flowgate performance (see below)
  - Peak and minimum load
  - High and low offshore wind generation
  - Imports/Exports, particularly the DC ties
- There are times when TARA may not see PLEXOS's initially defined flowgates as critical, but those high voltage flowgates remain in the base model because of the impact of high voltage system security and the possibility that the Critical snapshot selection missed the hours when those flowgates are most important.



[1] Defined as any monitored element overload greater than 90% of the contingency rating

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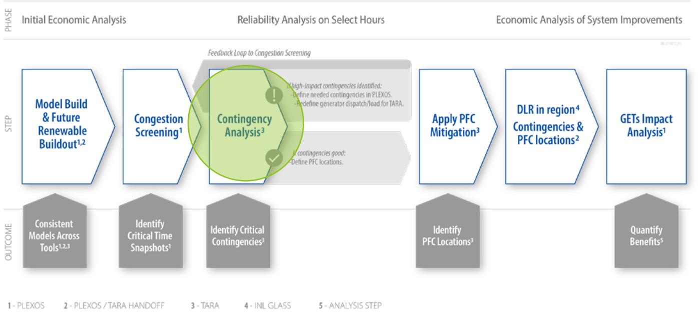
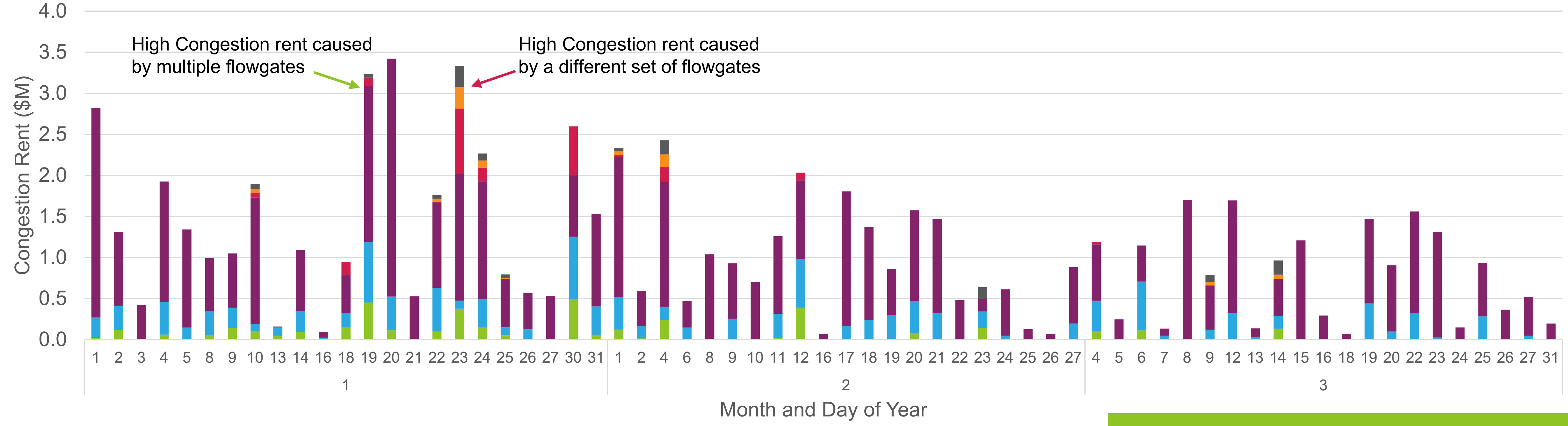


Identify Critical Snapshots

Pick hours for TARA to perform reliability analysis?

In complex systems, it can be hard to disentangle the cause of system stress. For that reason, critical snapshot hours are taken from days with largest the amount of congestion rent and with a diverse set of flowgates forcing the congestion rent higher[1]. By analyzing the system in this fashion, different system stress conditions can be evaluated, rather than worrying about a representative “low load” condition or a “maximum output from offshore wind” hour, or how those intersect. The various potential system stressors will be reflected in the flowgate congestion rent. There may be other system conditions where risk is high that are not captured in the congestion and flowgate pairing, such as reserves. In an analysis of reserves strategy, a different methodology may be better suited for selecting critical hours.

Daily Congestion Rent by Flowgate[2]



[1] In theory, congestion can be defined on a system-wide basis as “the difference in what load pays vs. what generation is paid.” This difference makes up “Congestion Rents.”

[2] Note: This analysis was performed for a full year but only 3 months are shown on this graph for illustration purposes.

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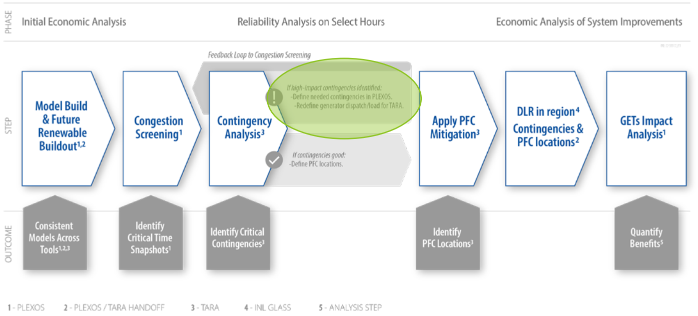
Contingency Analysis



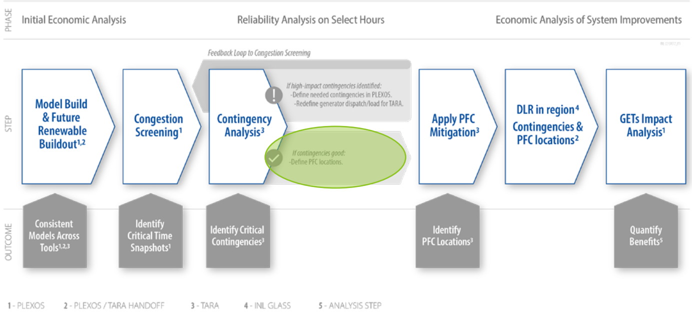
Multiple roundtrips should be performed to ensure that the reliability considerations have been captured in the economic dispatch engine.

- Round-trip modeling is necessary because the new flowgates that have been identified will shift the dispatch in the economic engine (PLEXOS) and potentially reveal new important flowgates
- One could continue the roundtrip activity in perpetuity, or otherwise loosen the definition of what flowgates should be incorporated in PLEXOS.
  - Critical flowgates are defined by a threshold wherein the monitored element reaches at least 90% of its thermal rating in post-contingency conditions
- Ultimately, there will be a point wherein the value of incorporating new flowgates begins to diminish. This could be apparent through
  - Fewer critical flowgates identified
  - Minimal impact on production cost and congestion from the new flowgates that are included

PLEXOS-TARA Roundtrip	Flowgates Identified	Flowgates that add new congestion to dispatch	Dispatch Hours passed to TARA	Base Case Dispatch Hours that solve in TARA's AC power Flow
0	0	0	3	3
1	6	5	3	3
2	5	2	5	5
3	3	1	6	6
4	2	0	Analysis Complete (new flowgates did not add new congestion)	

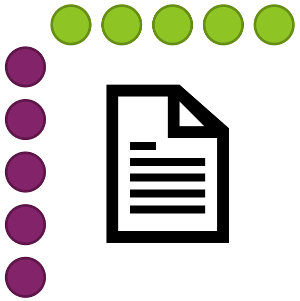
Representative example of the key statistics from the TARA and PLEXOS flowgate-specifying roundtrips.

Identify PFC Placement

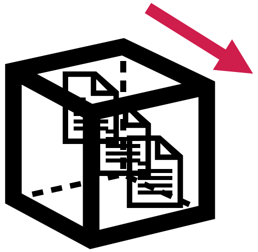


Once a base case model is developed that includes the important flowgates in the economic dispatch optimization, the grid enhancing technology strategy options for the region should be defined. This includes identification of where to locate power flow controllers. With respect to PFC placement, there is a ***Dimensionality Problem.*** In this planning context, PFC's should be placed in a manner that addresses the (1) overloaded elements during (2) different contingencies at (3) different hours of the year that (4) have the highest impact on costs and (5) consider other GETs.

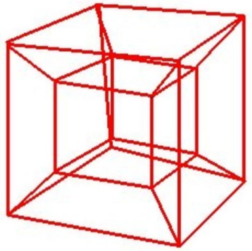
Elements
associated w/ congestion



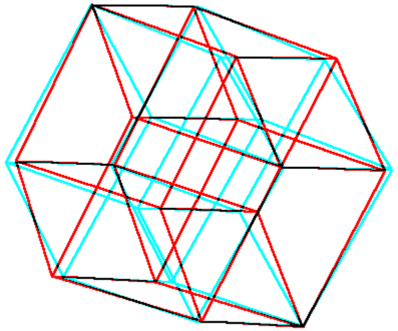
Contingencies
Inform Overloading Situations



Snapshots
Different Hours' Dispatch capture the likelihood of certain conditions



Economic Dispatch
Refine PFC placement based on economic impact.



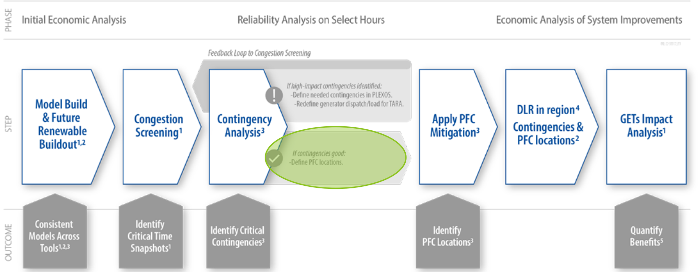
GETs Co-Optimization
Adjust PFC placement based on DLR and storage.

Engineering Optimization
PFC placed based on highest impact in addressing N-1 planning criteria at different times of the year

Economic Validation
PFC placement modeled to confirm impact on the security constrained economic dispatch

GETs Planned Together
PFC placement modeled based on unaddressed congestion after DLR implementation

Where can PFCs help us?



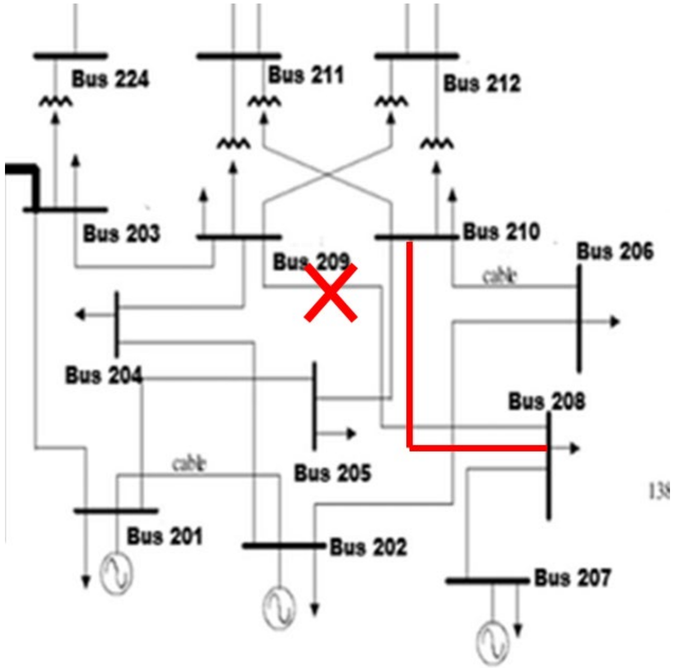
PFCs can help us mitigate overloads on non-radial elements. An example of a radial element is presented in the below, from the RTS-GMLC test system[1]. In that system, the economic dispatch PLEXOS frequently sees overloads on 208-210-1 for loss of 208-209-1. However, this is a poor candidate for PFC placement because the loss of 208-209-1 means that the only line that feeds 208 is from Bus 210.

Ultimately, PFC locations are evaluated based on their potential impact to post-contingency system overloads, ignoring radial overloads. DLR could be a good candidate to assist in radial overloads, depending on many factors including the nature of the overload.

Loss of 208-209-1 makes buses 208 and 207 radial

PFCs can not mitigate the overload on 208-210-1

This is a common circumstance – a large chunk of overloads can be radial for a given contingency analysis



Monitored Element		Contingency		Creates Radial Situation?	Good Candidate for PFC?
FromBus	ToBus	FromBus	ToBus		
208	209	208	210	Yes	No
206	210	206	210	Yes	No
208	207	208	209	Yes	No
208	207	209	203	No	Maybe
208	209	208	210	No	Maybe

PFC's are of minimal value to address flowgates that create radial situations. Additional investigation is necessary to qualify the location for PFC's to address the remaining flowgates.

[1] IEEE RTS-GMLC: Barrows, C. *Reliability Test System of the Grid Modernization Laboratory Consortium (RTS-GMLC)*

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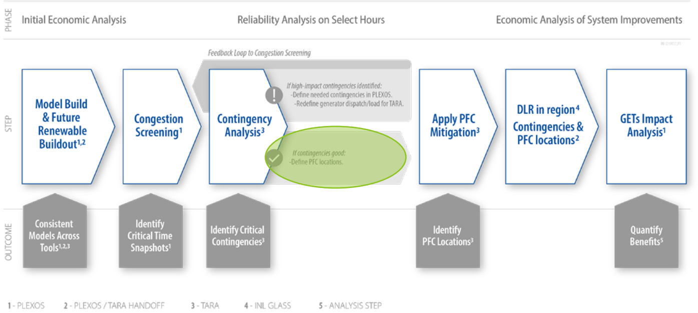
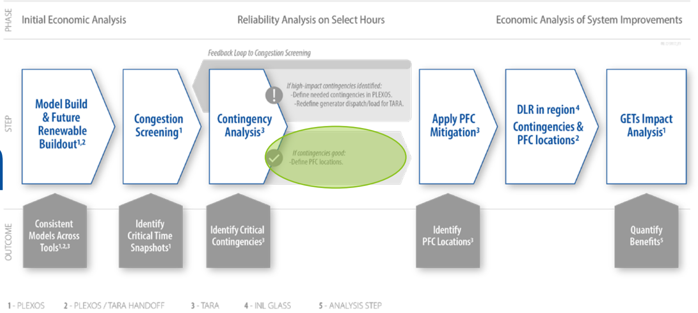
Measuring PFC Impact Using TARA

Engineering Optimization



To address the ***Dimensionality Problem,*** a process is required that assesses the system-wide impact of PFC's placed at different locations given different dispatch conditions, different contingencies, and ultimately screen those locations for impact on system costs. Note that this process ultimately yields a PFC location, assuming that the size (and associated angle change) is equal across all possible locations. That process is included in the below 5 step process and covered in more detail in the slides that follow.

1. PLEXOS runs a full year of dispatch and several key hours of generation and load information are selected for evaluation in TARA
2. TARA runs AC contingency analysis to determine relevant contingencies and monitored elements
3. In TARA, add PFCs at potential locations and measure the impact of a small change in angle for every combination of hour & contingency
4. Measure the change in MW flow and change in MW overload on each monitored element
   - Radial overloads will have near-zero MW change
5. Combine the MW overload impact across several key hours

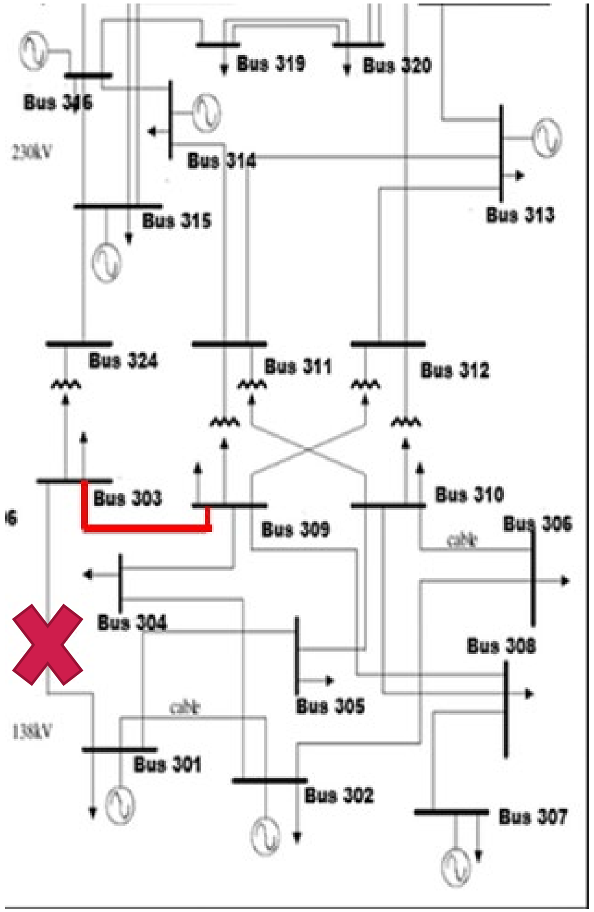


PFC Siting Methodology in a Test System

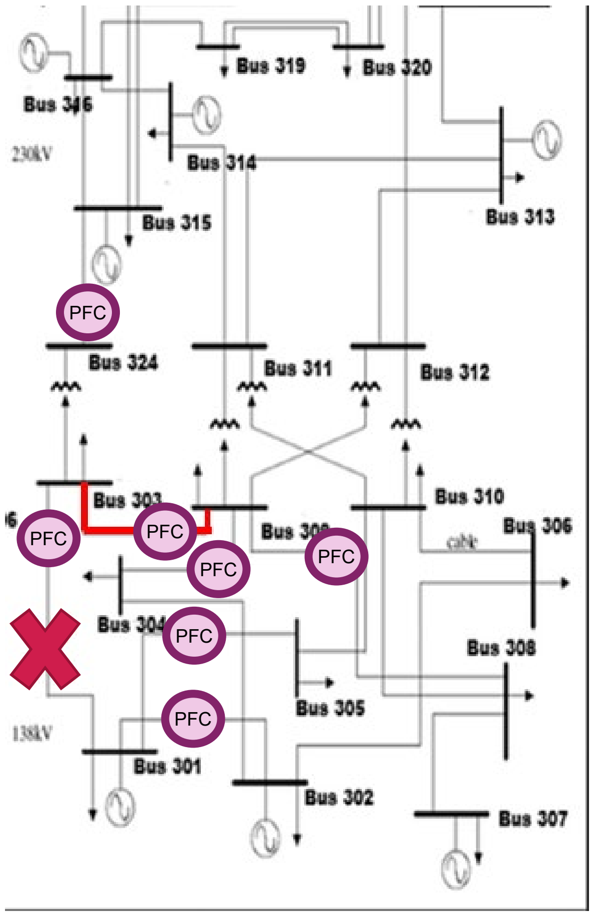
Steps 1-4a

Step 1) PLEXOS runs a full year and selects multiple critical hours to analyze further (see earlier slides for this methodology)

Step 2) For a specific hour and loss of 301-303-1, 303-309-1 is overloaded by ~80 MW



Step 3) Test PFC locations within 2 branches of bus 303



Step 4a) What is the potential impact of a small change at each PFC location on the 303-309-1 overload?

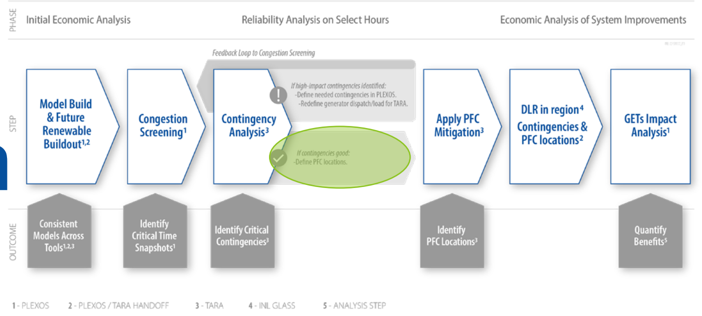
		MW Overload on 303-309-1
Ctg	PFCLocation	
301-303-1	301-302-1	-0.54
	301-303-1	-0.06
	301-305-1	0.45
	303-309-1	9.82
	304-309-1	-0.93
	308-309-1	-0.93
	315-324-1	9.74
	NoPerturbance	0.00

Candidate locations

This MW Overload metric shows us how much the PFC helped at each location. Each value represents a MW change, so the larger the value, the more it helped. Note that the directionalityy assumption informing the positive/negative numbers is addressed on the next slide.

PFC Siting Methodology in a Test System

Step 4b – Single System-Wide Metric



For a specific hour and contingency, a PFC location could increase MW overloads on one branch and decrease MW overloads on another. For that reason, the impact of the PFC on the entire system should be assessed.

From there, each row is summed before the absolute value is taken to get net impact of each PFC location on overloads for the specific hour and contingency.

		Monitored Elements - Compare MW Overload with Base Case									
	FromBus	301			303		304	308	309		315
	ToBus	302	303	305	309	324	309	309	311	312	324
	ID	1	1	1	1	1	1	1	1	1	1
Ctg	PFCLocation										
301-303-1	301-302-1	0.00	0.00	0.00	-0.54	0.00	0.00	0.00	0.00	0.00	0.00
	301-303-1	0.00	0.00	0.00	-0.06	0.00	0.00	0.00	0.00	0.00	0.00
	301-305-1	0.00	0.00	0.00	0.45	0.00	0.00	0.00	0.00	0.00	0.00
	303-309-1	0.00	0.00	0.00	9.82	0.00	0.00	0.00	0.00	0.00	0.00
	304-309-1	0.00	0.00	0.00	-0.93	0.00	0.00	0.00	0.00	0.00	0.00
	308-309-1	0.00	0.00	0.00	-0.93	0.00	0.00	0.00	0.00	0.00	0.00
	315-324-1	0.00	0.00	0.00	9.74	0.00	0.00	-4.87	0.00	0.00	0.00
	NoPerturbance	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

PFCLocation	MWOverload Metric
301-302-1	0.54
301-303-1	0.06
301-305-1	0.45
303-309-1	9.82
304-309-1	0.93
308-309-1	0.93
315-324-1	4.87
NoPerturbance	0

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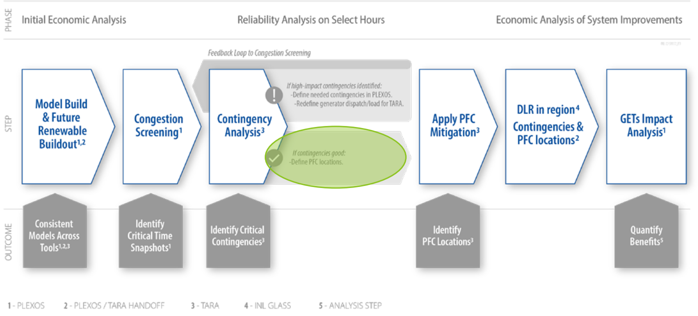
PFC Siting Methodology in a Test System

(Optional) Step 4c – Weighting the Reliability Metric by cost



Not all PFC locations will have the same impact on system dispatch decisions. While a given location may address a flowgate from a reliability perspective, the system may not have the generation flexibility to take advantage of the PFC capabilities. Therefore, as an optional step in determining PFC location suitability, a weighting to each potential PFC location can be applied based on the total congestion rent accumulated by each flowgate. By including this consideration, an economic signal is included in the PFC siting methodology, which can be confirmed through PLEXOS simulation validation.

Example Cost Table

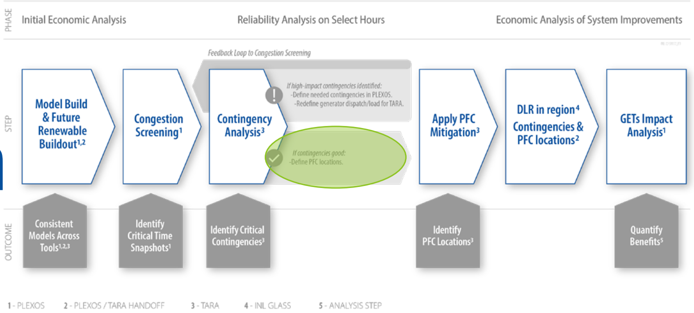
Contingency	Monitored Element	Congestion Rent from Initial Case
301-303-1	303-309-1	$3,117,740.00
301-303-1	308-309-1	$38,307,694.61

		Monitored Elements - Compare MW Overload with Base Case									
	FromBus	301			303		304	308	309		315
	ToBus	302	303	305	309	324	309	309	311	312	324
	ID	1	1	1	1	1	1	1	1	1	1
Ctg	PFCLocation										
301-303-1	301-302-1	0.00	0.00	0.00	-0.54	0.00	0.00	0.00	0.00	0.00	0.00
	301-303-1	0.00	0.00	0.00	-0.06	0.00	0.00	0.00	0.00	0.00	0.00
	301-305-1	0.00	0.00	0.00	0.45	0.00	0.00	0.00	0.00	0.00	0.00
	303-309-1	0.00	0.00	0.00	9.82	0.00	0.00	0.00	0.00	0.00	0.00
	304-309-1	0.00	0.00	0.00	-0.93	0.00	0.00	0.00	0.00	0.00	0.00
	308-309-1	0.00	0.00	0.00	-0.93	0.00	0.00	0.00	0.00	0.00	0.00
	315-324-1	0.00	0.00	0.00	9.74	0.00	0.00	-4.87	0.00	0.00	0.00
	NoPerturbance	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

	FromBus	301			303		304	308	309		315
	ToBus	302	303	305	309	324	309	309	311	312	324
	ID	1	1	1	1	1	1	1	1	1	1
Ctg	PFCLocation										
301-303-1	301-302-1	0.00	0.00	0.00	-1.68E+06	0.00	0.00	0.00	0.00	0.00	0.00
	301-303-1	0.00	0.00	0.00	-1.87E+05	0.00	0.00	0.00	0.00	0.00	0.00
	301-305-1	0.00	0.00	0.00	1.40E+06	0.00	0.00	0.00	0.00	0.00	0.00
	303-309-1	0.00	0.00	0.00	3.06E+07	0.00	0.00	0.00	0.00	0.00	0.00
	304-309-1	0.00	0.00	0.00	-2.90E+06	0.00	0.00	0.00	0.00	0.00	0.00
	308-309-1	0.00	0.00	0.00	-2.90E+06	0.00	0.00	0.00	0.00	0.00	0.00
	315-324-1	0.00	0.00	0.00	3.04E+07	0.00	0.00	-1.87E+08	0.00	0.00	0.00
	NoPerturbance	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

PFC Siting Methodology in a Test System

Step 5 – Summing Across Multiple Hours



A ranked list of PFC locations for every hour and every contingency based on their impact to system overloads is created by applying steps 1-4 to multiple dispatch hours.

PFCLocation	MWOverload Metric
301-302-1	0.54
301-303-1	0.06
301-305-1	0.45
303-309-1	9.82
304-309-1	0.93
308-309-1	0.93
315-324-1	9.74
NoPerturbance	0

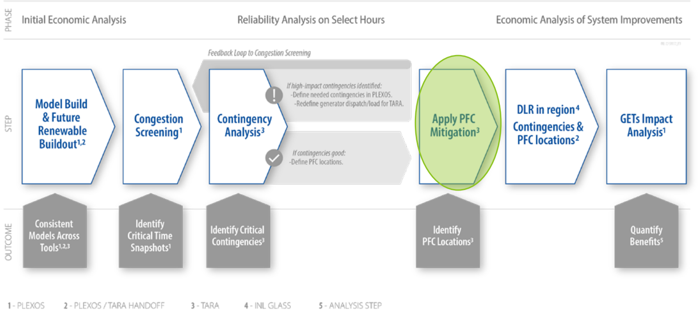
Add values for all hours and all contingencies

Assuming all hours and all contingencies are valued equally, sum results to get a ranked list of PFC locations. This provides an engineering MW Overload Impact metric ("Unweighted Reliability") that can be combined with future economic analysis to determine quality PFC siting locations. Should those future economic analyses be infeasible, or simply require more signal, the congestion-rent-weighted metric can be informative with respect to identifying the PFC placements.

PFCLocation	UnweightedReliability
301-302-1	23.83
301-303-1	33.27
301-305-1	25.96
303-309-1	101.29
304-309-1	30.06
308-309-1	21.54
315-324-1	78.84
NoPerturbance	0

PFCLocation	Congestion-Rent Weighted Reliability
303-309-1	1.93E+09
315-324-1	1.07E+09
301-303-1	7.32E+08
301-302-1	6.76E+08
304-309-1	5.90E+08
301-305-1	4.24E+08
308-309-1	3.58E+08
NoPerturbance	0.00E+00

PFC locations are ranked according to the weighted reliability metric



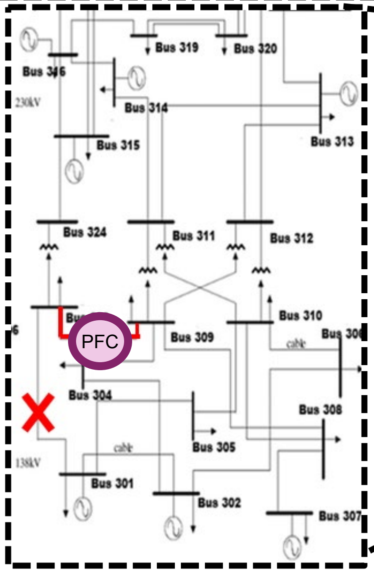
Applying the PFC Device in PLEXOS

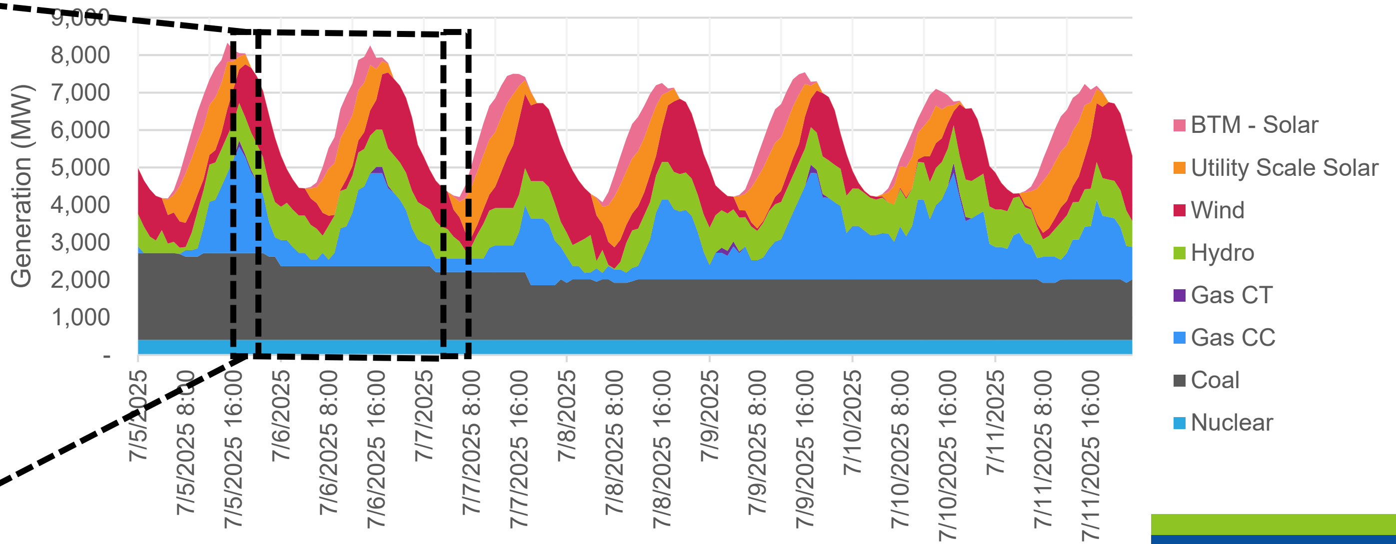
After the PFC device location has been identified based on reliability improvement opportunities, the PFC is then used in the hourly market simulation to identify how the system may be dispatched differently with the new flexibility afforded from the PFC.

- The hourly chronological simulation (PLEXOS) is expected to dispatch the PFC (adjust the PFC angle to manipulate power flow) in much the same fashion that the reliability tools identified. This is accomplished through the economic penalties associated with reliability problems in PLEXOS.
- By allowing PLEXOS to optimize the PFC setpoint, the reliability benefit for the critical hours is achieved and additional economic benefit is available via system flexibility in all other hours. Note that PLEXOS sets the PFC angle to be N-1 secure and that the PFC setpoint is assumed to remain unchanged post-contingency[1].

The PFC device is placed based on a sampling of hours.

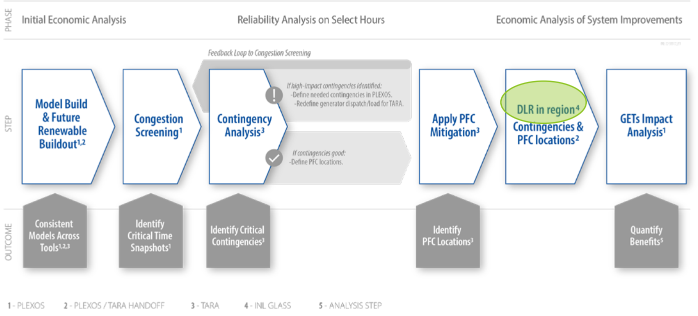
PLEXOS is still free to dispatch the PFC as part of the economic optimization throughout the year



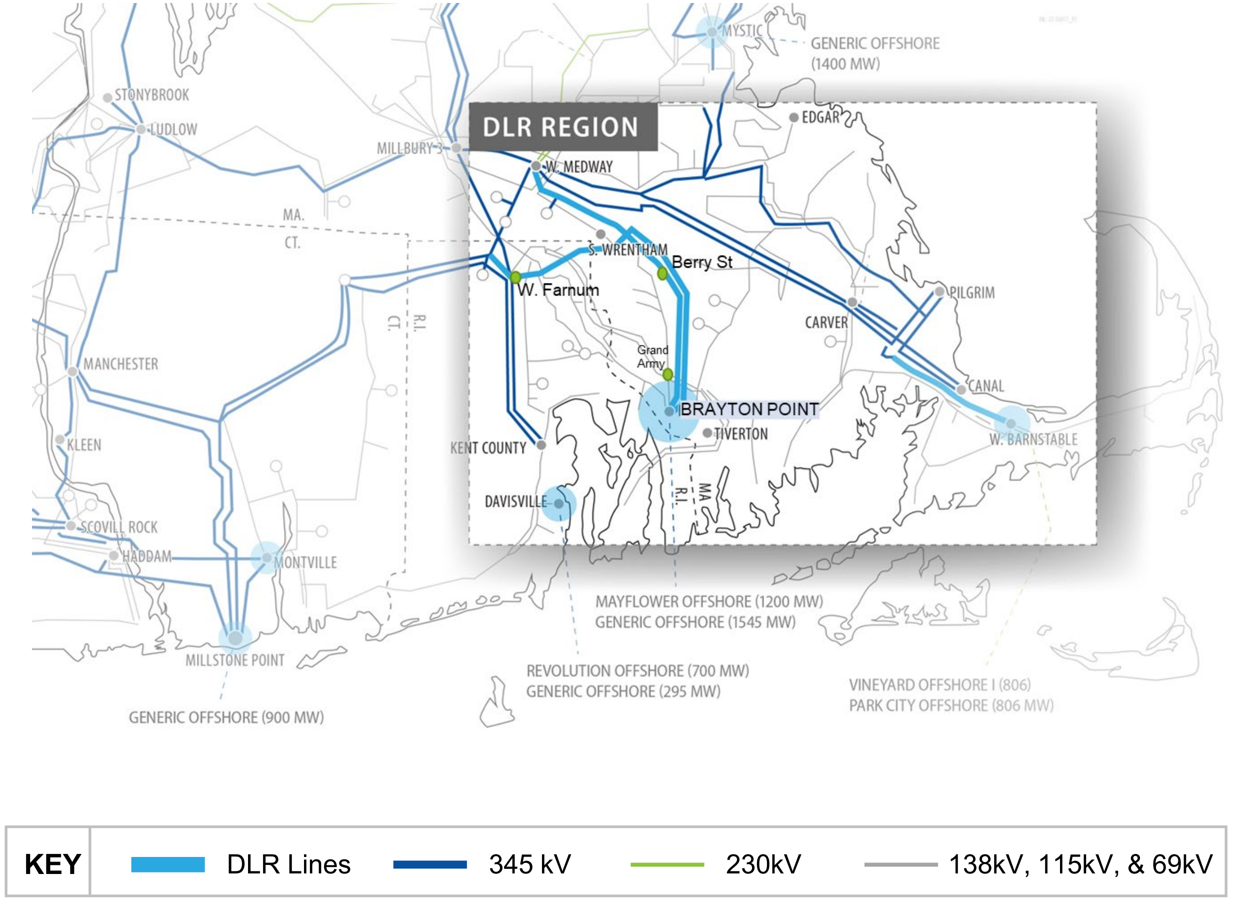


1. This has minimal impact on the hour-to-hour dispatch decisions on PLEXOS. Rather, it makes it difficult to assess if and how PLEXOS would use the PFC in post-contingency operations (like is observed in TARA). This could be solved by removing a line from service in PLEXOS and assessing PFC value while operating in that N-1 state for a short period of time.

Picking Lines for DLR/AAR in the Region

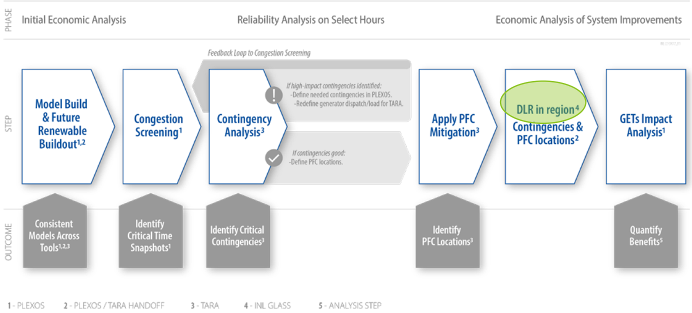


- Dynamic Line Ratings (DLR) and Ambient Adjusted Ratings (AAR) in the study region are generally applied directly to the lines that are experiencing congestion, but the benefits of this are extremely system specific.
  - In some cases, the congestion is caused by voltage constraints, system security constraints (N-1), or at hours for which DLR is below Static Line Rating (SLR).
  - Analysis of the shift factors[1] associated with certain buses will reveal how even increased thermal ratings may not directly lead to avoiding local wind and solar curtailment.
- When planning PFC and DLR together, it becomes obvious that DLR's are particularly useful in radial situations, where PFC's ability to shift power to adjacent lines is muted.

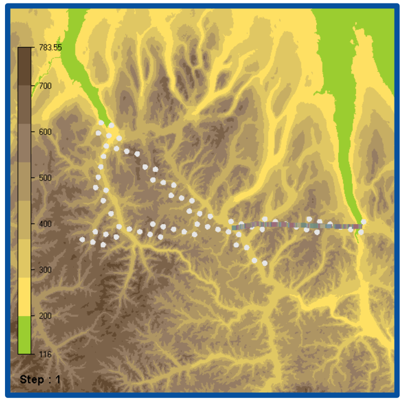


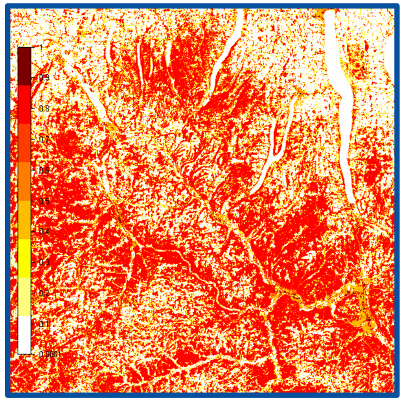
[1] Shift factors quantify the sensitivity of the line flows to the change in injections at different buses.

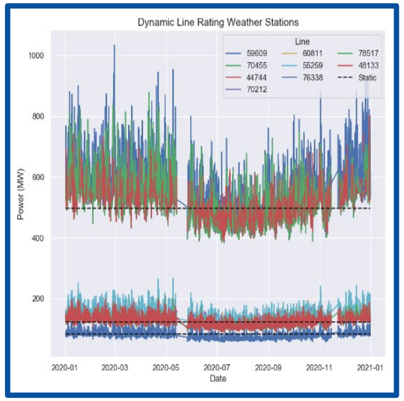
DLR in the Region



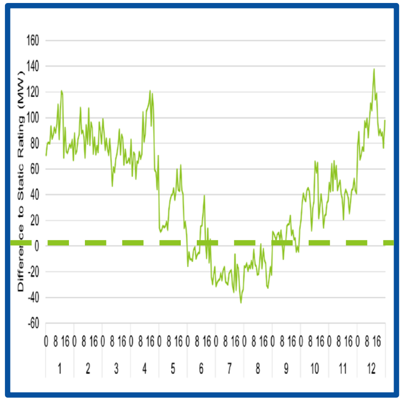
DLR's were developed specifically for this region using established weather-based methods by INL

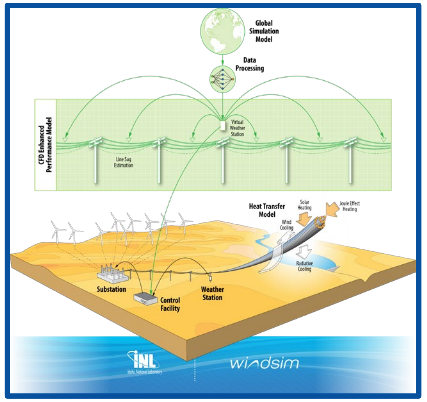

Topology


Roughness



Power


Single Line relative to SLR



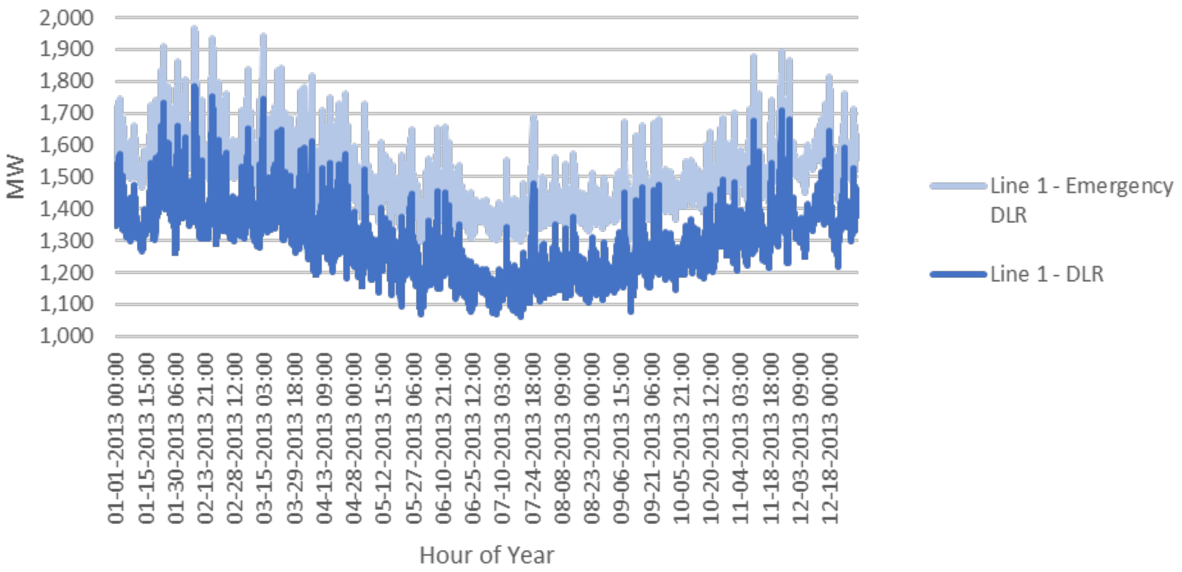
Weather Forecast Mapping

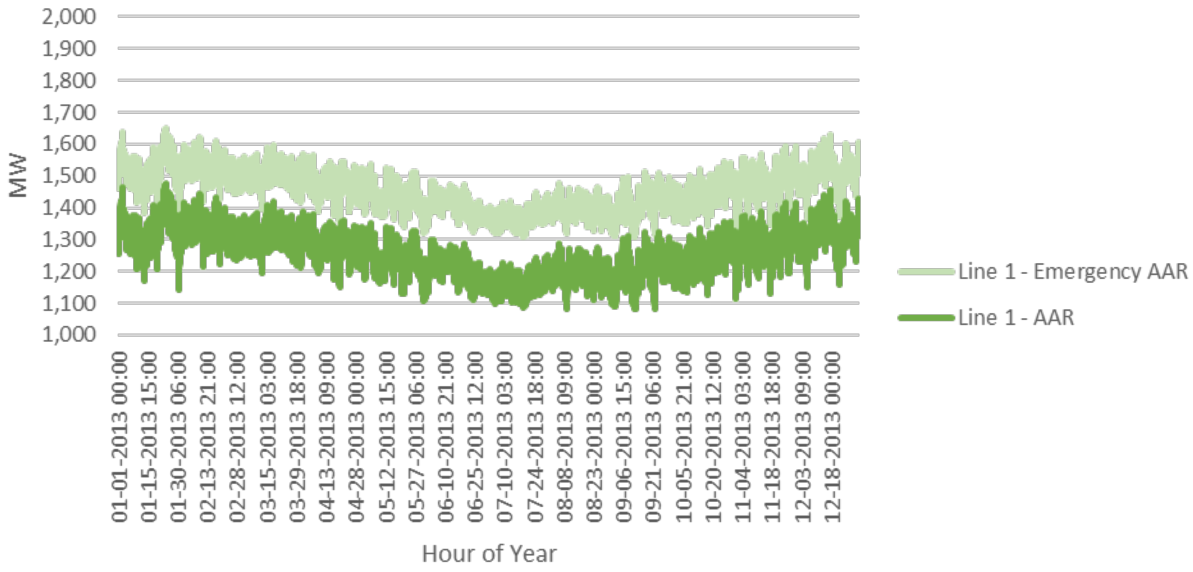
DLR process results in increased line ratings and enhanced operational awareness for increased reliability

Emergency DLR

In power system dispatch, there is often an emergency rating that can be applied in N-1 conditions or other high stress events. PLEXOS allows us to define that emergency rating for analysis of post-contingency system conditions.

- The emergency DLR/AAR were calculated as a conductor temperature of 115°C vs. the normal conductor temperature rating of 100°C.
- When using particularly high temperature, and low emissivity conductors, it is particularly important to use the conductor temperature models to define emergency ratings (rather than X percentage of the normal rating assumptions) because the ratings derived from heat transfer equations become non-linear with respect to ambient conditions.





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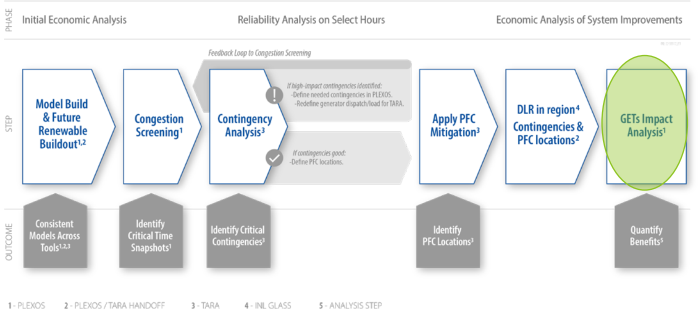
GETs Impact Analysis



Once the models are built, including a future resource mix and flowgate combination that capture a potential future system that would be wise to upgrade, technology strategies can be assessed using the economic simulation tool. That tool will be able to assess the impacts of different technology strategies across multiple metrics.

It is recommended that at least following Technology Strategies are assessed:

1. Base Case: establish baseline performance
2. Traditional Upgrades: could include reconductoring, building a new substation, creating new lines, etc.
3. GETs Cases:
   a) DLR (rather than SLR)
   b) AAR (rather than SLR)
   c) PFC placement (multiple cases to assess interactive effects)
   d) DLR+PFC (with PFC placement based on post-DLR line limits)
4. GETs + Traditional: leverages some combination of PFCs, DLRs, and traditional upgrade options

Impact Assessment Metrics

- **Production Cost**– The cost to produce electricity to serve the region. Production cost includes startup costs, fuel costs, and other operational costs.
- **Net Imports Cost**– The region under study may transact energy with its neighbors. To the extent that the projects affect imports and exports, those cost savings can be quantified
- **Renewable Generation Increase**– Renewable generation is sometimes curtailed because of system constraints. Any increase of renewable generation that is available to serve customers as the result of the technology strategy can be quantified.
- **Congestion Rent –** The congestion rent is usually reflected in the production cost savings, but it is sometimes useful to analyze the causes of cost increases independently.

Areas for Improvement

As with any methodology, there is always room for improvement. Opportunities for improvement in the study methodology is listed below:

1. **Analysis of post-contingency PFC value –** There is a slight disconnect in how PFC's are placed based on post-contingency conditions, and the economic dispatch engine assuming that the dispatch remains the same in its post-contingency flow reporting. By adjusting some system characteristics from the outset, the value of PFC's in contingency situations could be assessed.
2. **Evaluate different resource deployment scenarios** – By looking at generation resource and transmission planning together, "no-regrets" GETS investments could be identified that will be helpful regardless of how the resource mix may change over time (more off-shore wind, etc.).
3. **Improve the snapshot selection methodology for reliability analysis –** The current methodology relies on engineering judgement, but the groundwork is in place to formalize the contingency combination methodology to systemically identify different system stress conditions.
4. **Forecasted DLR impact on reliability/unit commitment decisions –** The current methodology performs a unit commitment and economic dispatch based on DLRs in place of SLRs with no forecast error. By including forecast error in DLR (as well as solar, wind, load, etc.), system reliability concerns with relying upon DLR in operations can be evaluated.

Some Technical Lessons Learned

Lessons Learned are sprinkled throughout this methodology report. Numerous failed attempts at joining two tools were performed prior to the methodology that made its way into this report. Still, it’s worth calling out a few modeling notes that may save future engineers some headache:

- Loss Modeling: Modeling losses in PLEXOS would improve TARA case convergence because AC power flow includes losses while a PLEXOS DC power flow typically does not. In the work on the RTS-GMLC model, adding losses increased line flow convergence between TARA and PLEXOS as well as TARA case convergence. However, including losses in PLEXOS also significantly increased unserved energy in the PLEXOS solution. Removing the unserved energy in the PLEXOS solution caused by the addition of losses required significant tinkering with the dispatch parameters in PLEXOS and a large amount of time. Rather than adding losses in the PLEXOS model, when the case is passed to TARA, TARA should lower the load to reach case convergence. The load data used in PLEXOS models typically comes from state estimator load data from an RTO or Balancing Authority. State estimator load data from an RTO or Balancing Authority typically includes losses. Thus, when running a PLEXOS simulation, using the state estimator load already accounts for losses. No extra loss modeling should be added.
- Flow Divergence: A large cause of the flow divergence between PLEXOS and TARA is AC power low voltage divergence from the DC power flow assumption of 1 p.u. voltage. In cases where local voltages are well above or below 1 p.u., the DC power flow approximation significantly diverges from the AC power flow. Divergence is also more likely to occur on elements with a low reactance because voltage magnitude changes will be more pronounced for these elements.
- Power Transfer Distribution Factor (PTDF) Threshold: The PLEXOS “PTDF Threshold” setting in the Transmission object determines which generators are included in the power flow formulation for a given transmission element. This is effectively a “shift factor” threshold to understand how a given generator’s output changes flows on a given line. In this project, a value of .001 has been utilized for the PTDF threshold and has yielded consistent line flows between TARA and PLEXOS.

Summary

- Traditionally siloed analyses in engineering and economic planning have been paired to assess Grid Enhancing Technologies, such as PFC and DLR. This methodology was tested in a test system and analyzed on the New England grid to better understand how GETs could help bring gigawatts of offshore wind into the ISO-NE system to meet the region’s clean energy and policy goals.
- The methodology aims to capture the key considerations for the type of N-1 planning required to interconnect large amounts of new generation. While not every type of analysis required to interconnect new generation is covered herein, this methodology should prove useful in thinking through the reliability and economic benefits of new transmission amid a rapidly changing resource mix.
- Other studies across the country have touched on the need for proactive and master planning of the transmission system to facilitate the renewable build-out underway. This methodology should help to expedite some of the key considerations that are often apparent after preliminary screening. By spending the time upfront to get accurate system representations across 2 different tools, potential long-term projects can be analyzed more quickly.

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Backup Slides

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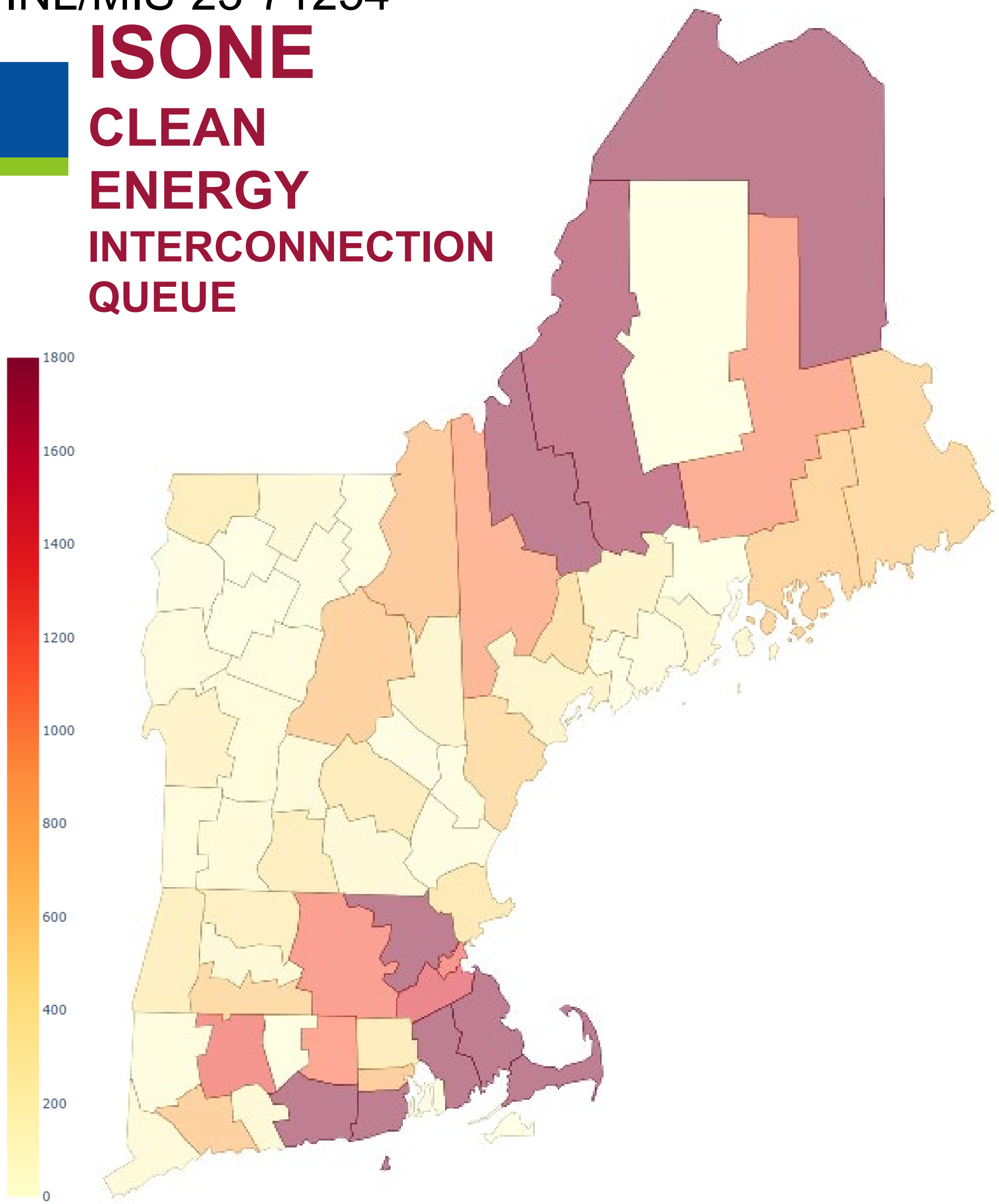
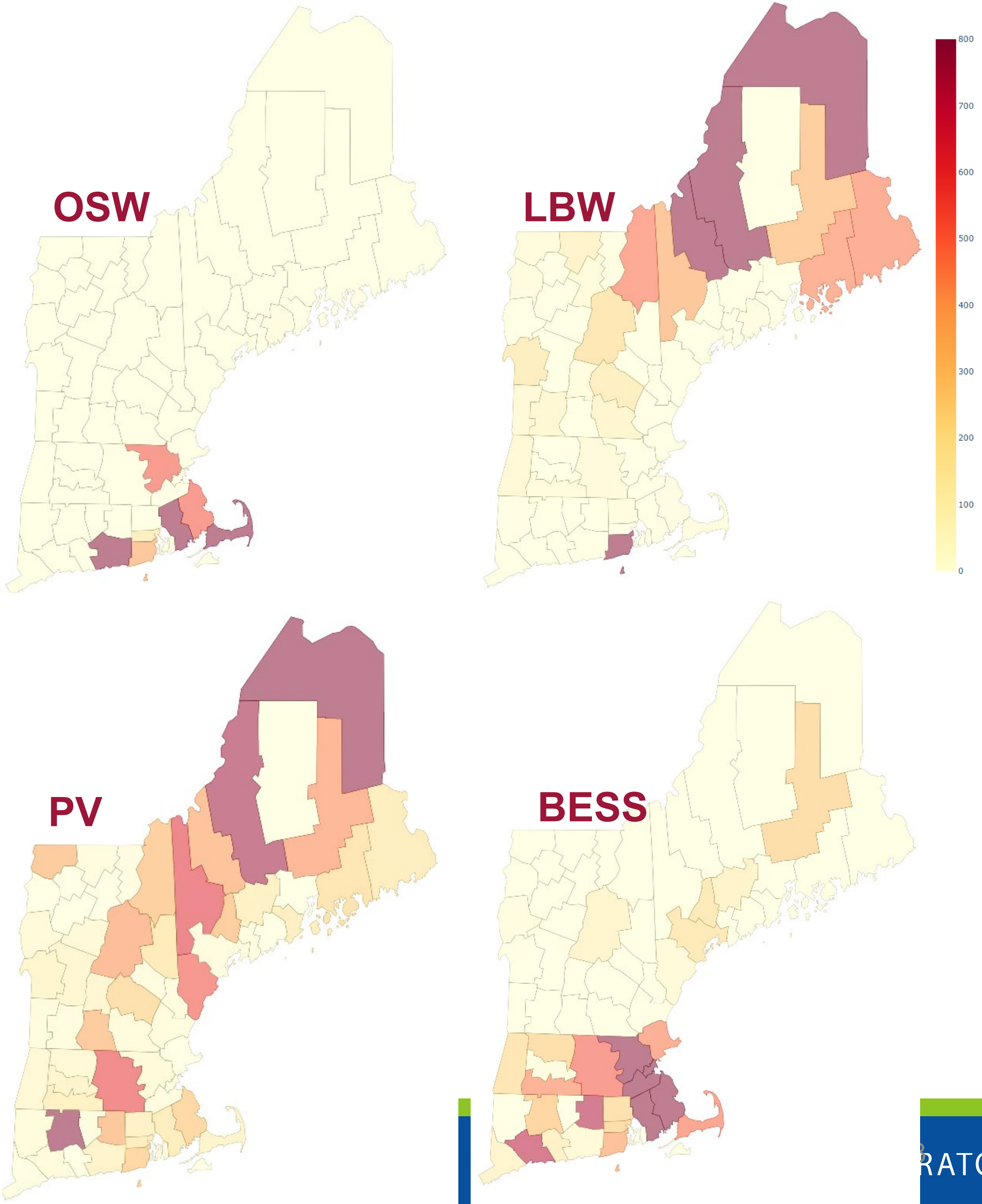
ISONE

CLEAN ENERGY INTERCONNECTION QUEUE





TELOS ENERGY

RATORY