DOE Office of Electricity TRAC

Peer Review

U.S. DEPARTMENT OF ENERGY | OFFICE OF ELECTRICITY

PROJECT SUMMARY

Scalable Hybrid Large-Scale dc-ac Grid Analysis Methods

Develop characterization methods and tools to evaluate reliability, transient stability, and economics of large-scale dc architectures in ac grids. Approach uses (i) advanced fast-acting control in HVdc substations for improved reliability, (ii) high-fidelity EMT models of dc scenarios (with specialized numerical simulation algorithms), (iii) scalable hybrid simulation of PSCAD-PSS®E (EMT and TS dynamics) through E-TRAN, and (iv) economic benefits quantification of dc architectures.

PRINCIPAL INVESTIGATORS

Dr. Suman Debnath, R&D Staff, Oak Ridge National Laboratory
Dr. Jiazi Zhang, Research Engineer, National Renewable Energy Laboratory
Dr. Marcelo Elizondo, Power System Researcher, Pacific Northwest National Laboratory
Dr. Joshua Novacheck, Electric System Research Engineer, National Renewable Energy Laboratory

Project Overview

DOE PROGRAM OFFICE:
OE – Transformer Resilience and Advanced Components (TRAC)

FUNDING OPPORTUNITY:
Lab Call

LOCATION:
Oak Ridge, TN
Seattle, WA
Denver, CO

PROJECT TERM:
10/01/2021 to 01/01/2023 (Budget Period 1 [BP1] of three BPs)

PROJECT STATUS:
Ongoing

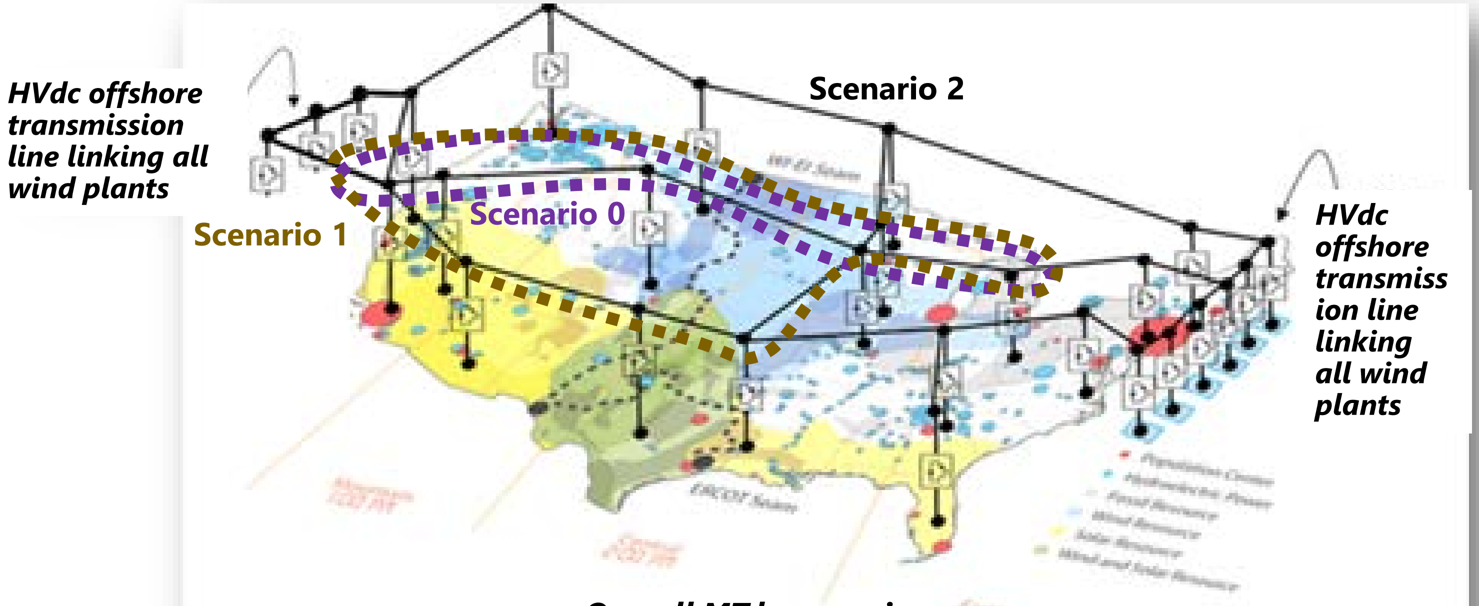
AWARD AMOUNT (DOE CONTRIBUTION):
$960,000 (BP1)

AWARDEE CONTRIBUTION (COST SHARE):
N/A

Primary Innovation

- **Advanced simulation algorithms** for fast simulation of high-fidelity models of scalable dc architectures to **enhance number of nodes** studied in dc architectures (ORNL),
- **Library** of dc network components' **EMT** models (vendor agnostic HVdc converter substations, breakers, dc line/cable, scalable radial MTdc, meshed MTdc, and MTdc grid architectures) (ORNL),

- Control algorithms in scalable dc architectures and individual HVdc converter substations to introduce **reliability-by-design** (ORNL),
- **Hybrid EMT-TS simulation** methods for scalable dc-ac architecture studies including event analysis on dc architectures (ORNL-PNNL)) and system wide feasibility and control benefits from MTdc (PNNL-ORNL),
- **Economic quantification** methods to quantify benefits from enhanced reliability and high bandwidth control introduced by dc architectures (NREL with inputs from ORNL) and by system wide MTdc control (NREL with input from PNNL),
- Assessment of **resilience support** provided by MTdc support (NREL-PNNL),



Overall MTdc scenario
*(with incremental build out of dc architectures from **scenario 0** to **scenario 1** to **scenario 2** [with examples of the scenarios shown in the figure above] to be studied in this project over three budget period)*

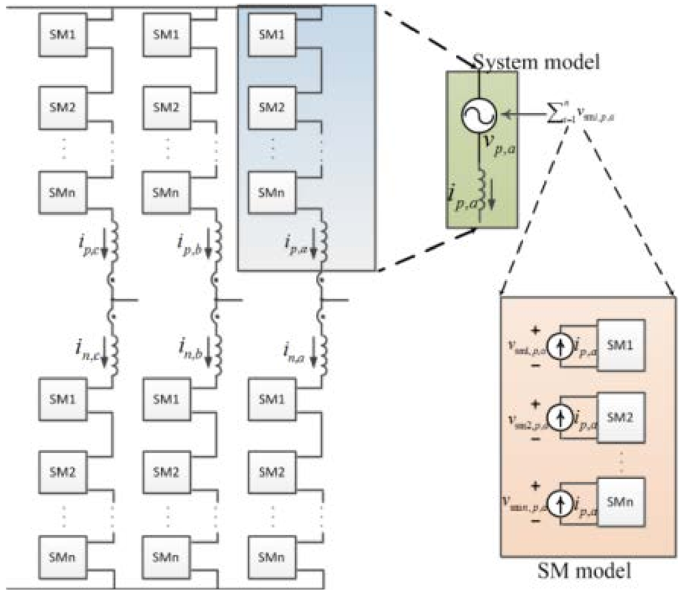
- Development of MTdc **TS dynamic models** consistent with ORNL's EMT model and for grid-forming and grid-following controls to serve as comparison base of performance, and to inform about limitations and uses of TS base models (PNNL-ORNL),
- Incremental development of dc architecture scenarios (from *scenario 0* to *scenario 1* to *scenario 2* marked in the figure – the exact scenarios to be identified in the project (NREL-ORNL-PNNL))
- **Recommendations and guidelines** for use of EMT models, TS models, and hybrid EMT-TS models (ORNL-PNNL).

Impact

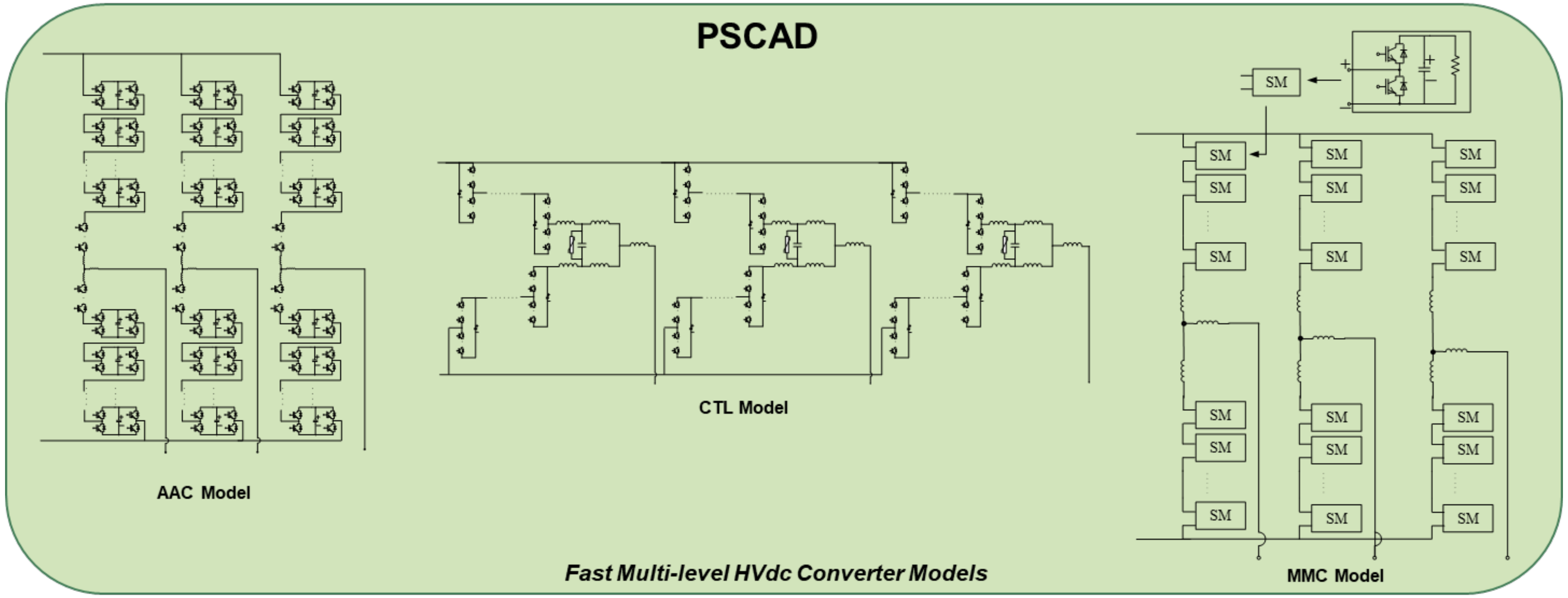
- Inform policy makers of the pathway to introduce infrastructure upgrades in existing ac grids.
- Tools and methods developed to enable reliable and resilient integration of clean energy, aligning with goals of meeting 100% clean energy target by 2035 (and 100% renewables by 2050).
- Disseminate information to industry and educate planners on methods applied for studying future ac-dc power grids.
- Provide industry with reliability-by-design approach in control systems for different MTdc architectures in US: radial, meshed, and grid architectures of MTdc. Quantify gaps in existing control systems.

Primary Innovation Proposed (ORNL in BP1)

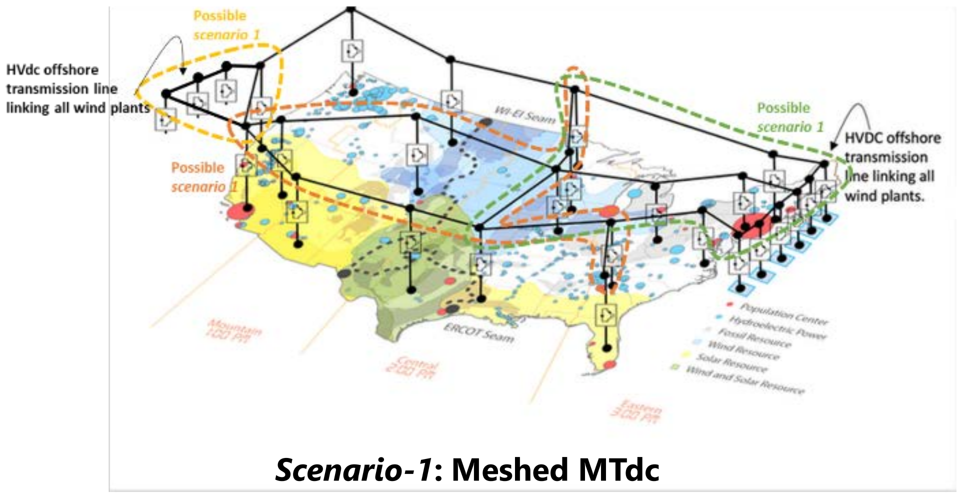
- *Advanced simulation algorithms* for fast simulation of high-fidelity models of scalable dc architectures to enhance number of nodes studied in dc architectures,
- *Library of dc network components'* models (vendor agnostic HVdc converter substations, breakers, dc line/cable, scalable radial MTdc, meshed MTdc, and MTdc grid architectures)



High-Voltage direct current (HVdc) substation: example simulation algorithm



Existing library of converter models (dc substations)



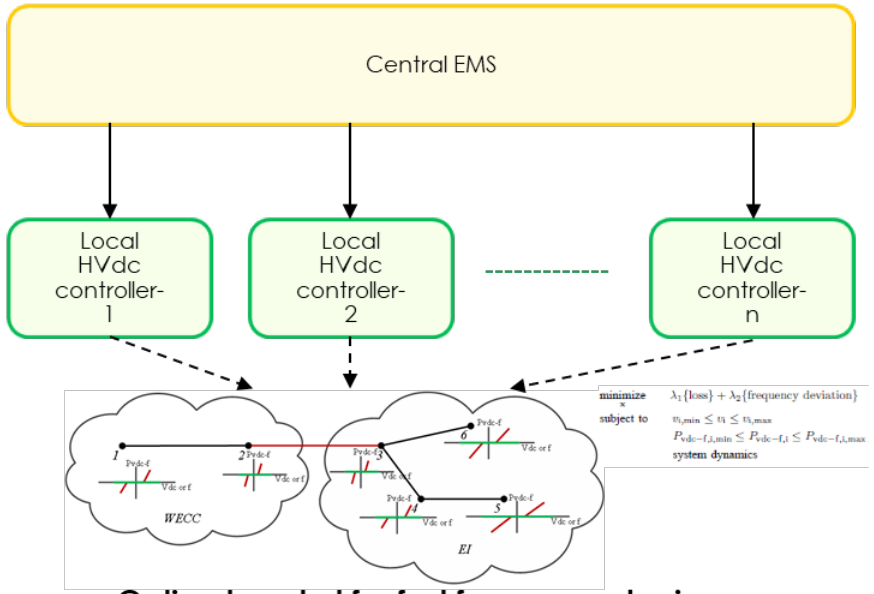
***Scenario-1*: Meshed MTdc**

Primary Innovation Proposed (ORNL in BP1)

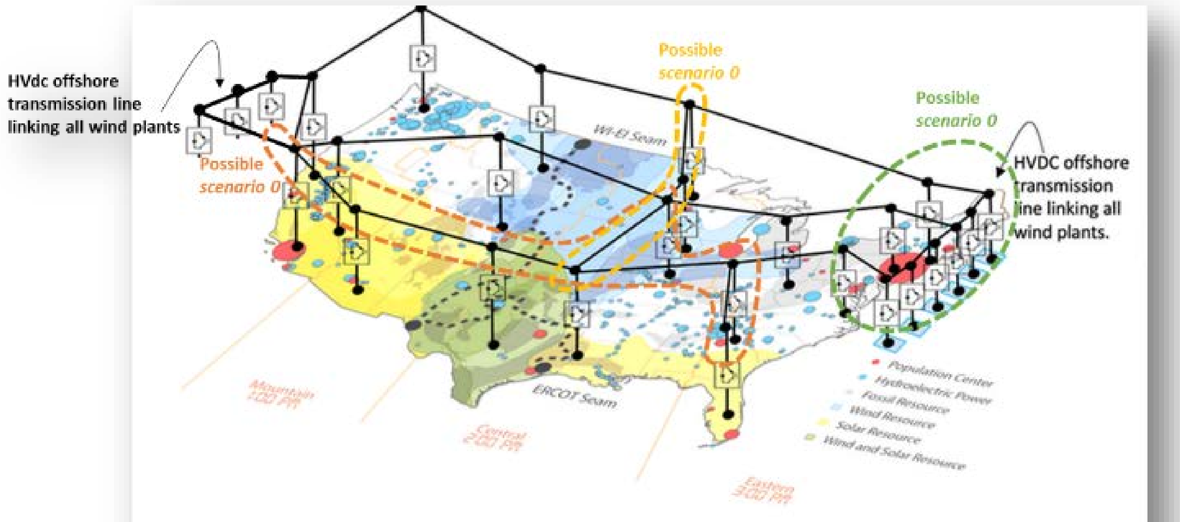
- *Control algorithms* in scalable dc architectures and individual HVdc converter substations to introduce reliability-by-design,
- *Hybrid EMT-TS simulation methods* for scalable dc-ac architecture studies including event analysis on dc architectures) and system wide feasibility and control benefits from MTdc (in collaboration with PNNL)

PSSE ⟺ (E-TRAN) ⟺ PSCAD *Fast HVdc Converter Models High-Fidelity Model*

Control System Managing MTdc System



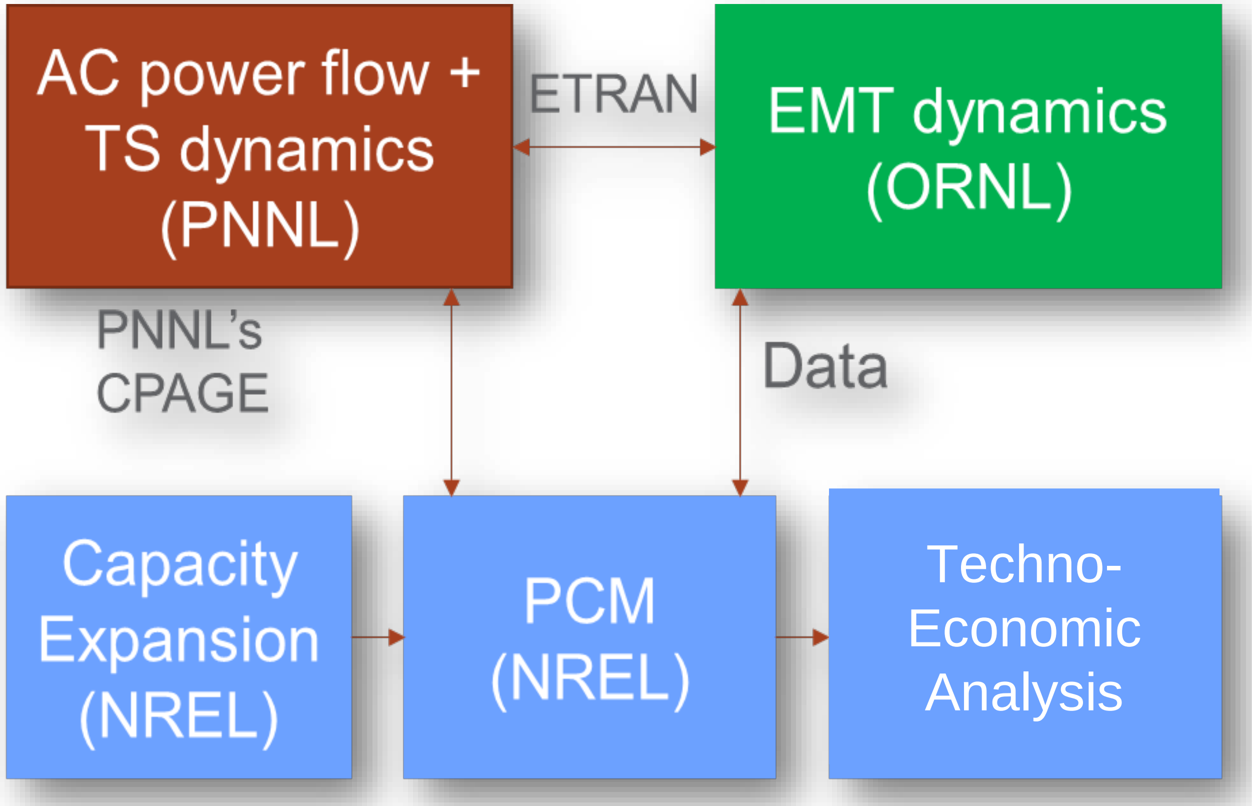
Optimal control for fast frequency sharing



***Scenario-0*: Radial MTdc**

Primary Innovation Proposed (NREL in BP1)

- Collaborate to identify scenarios
- Develop MTdc capacity expansion model and PCM for Scenarios 0 and 1
- Develop MTdc network component and advanced control/protection models in PCM
- Develop the economic quantification methods
- Collaborate to identify the long-term impact of the advanced controls



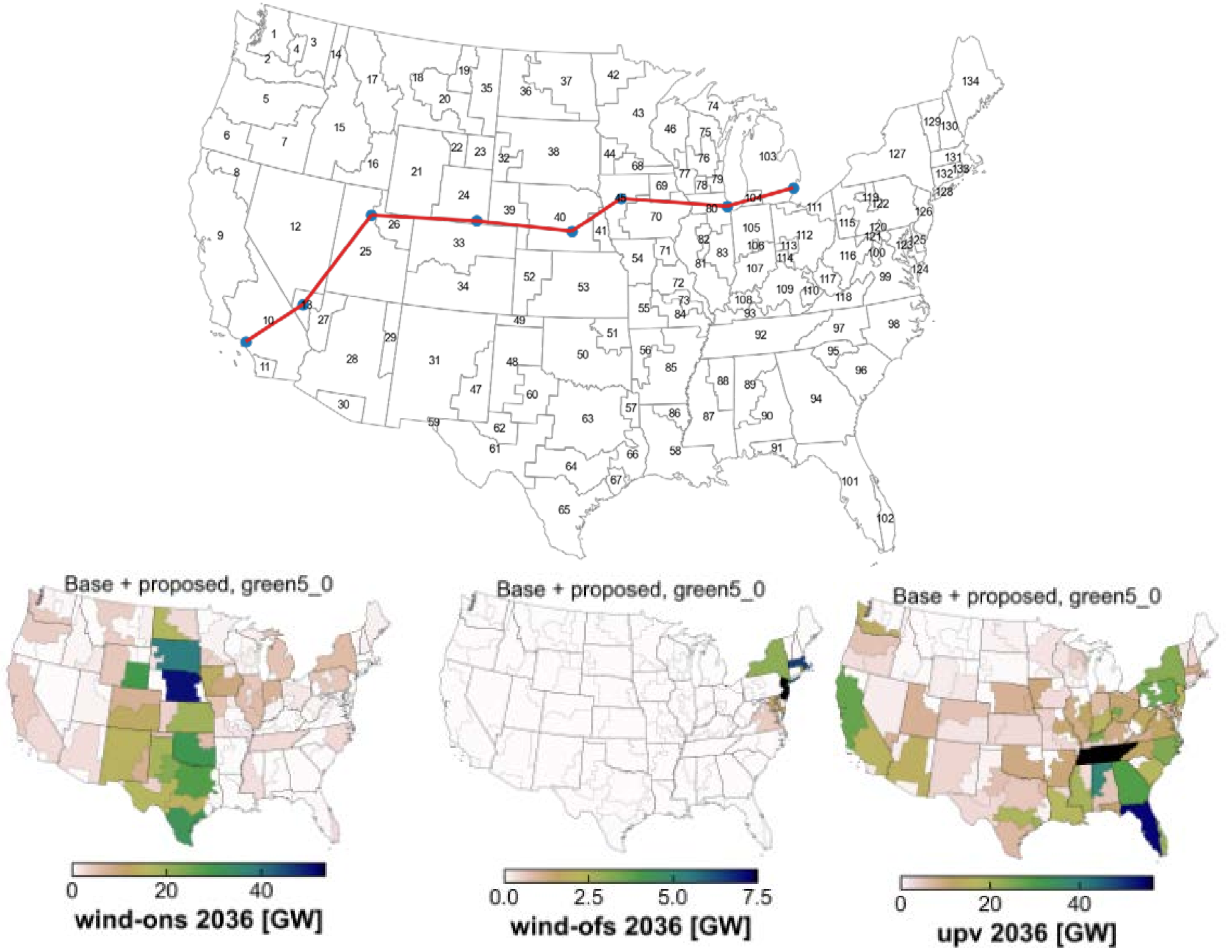
Innovation Updates (NREL in BP1)

- NREL team leveraged existing ReEDS model and developed capacity expansion models for VSC macrogrid design.
- NREL team developed the capacity expansion models of:
  - baseline system without macrogrid design
  - baseline system with proposed industry HVDC projects before 2026
  - 5 potential options of radial MTdc system in near-term future (Scenario 0)
  - 3 potential options of meshed MTdc in mid-term future (Scenario 1)
- Based on the system cost, wind and PV capacity expansion results, we provide the most valuable Scenarios 0 and 1 design options (and is iterating with ORNL and PNNL).
- NREL coordinate with PNNL to identify the PCM and AC power flow baseline cases using WECC 2028 ADS and MMWG EI 2026 raw cases connected with B2B HVDC lines.

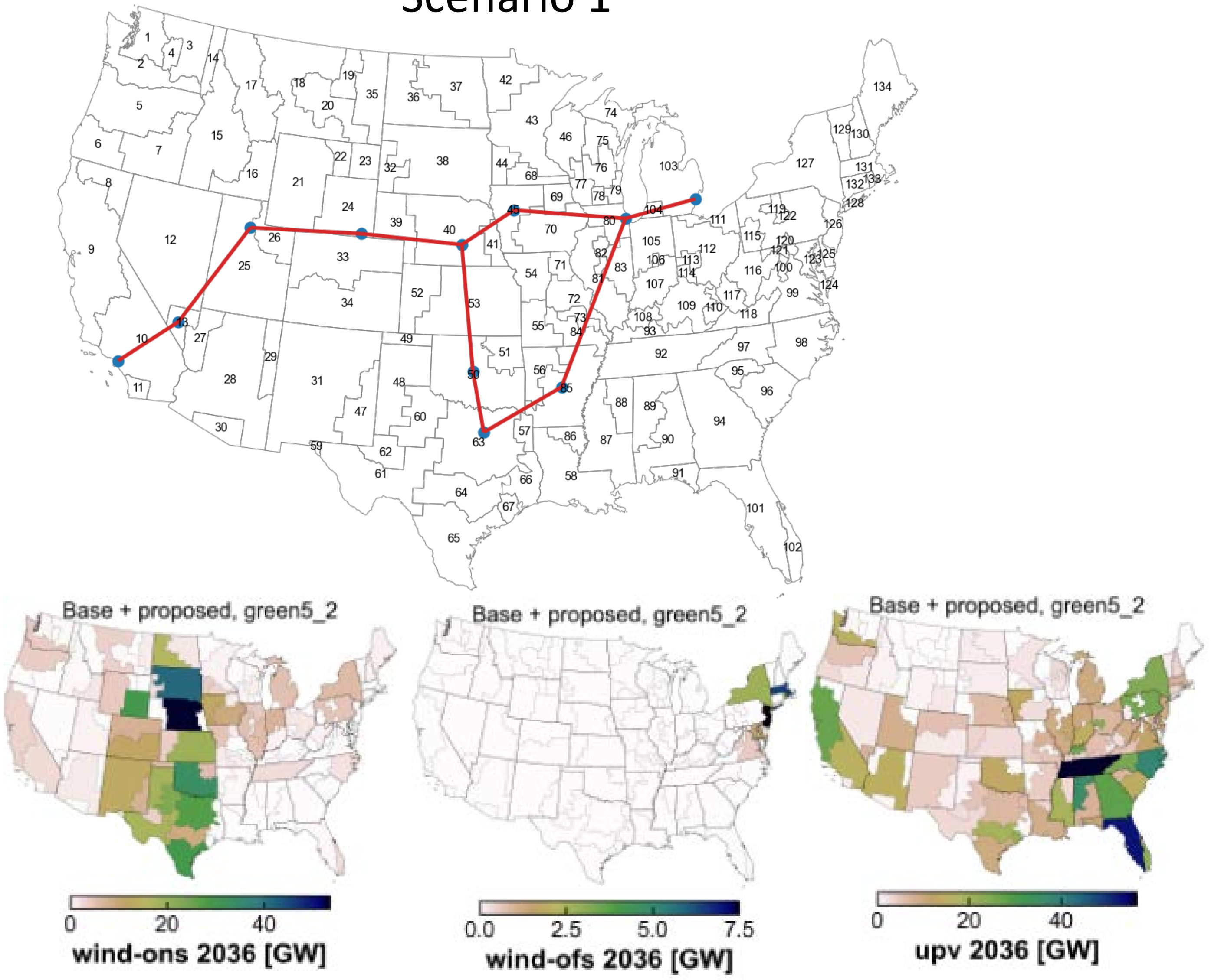
Innovation Updates: Scenarios

- Most valuable Scenarios 0 and 1 design and the associated VRE capacity expansion maps

Scenario 0



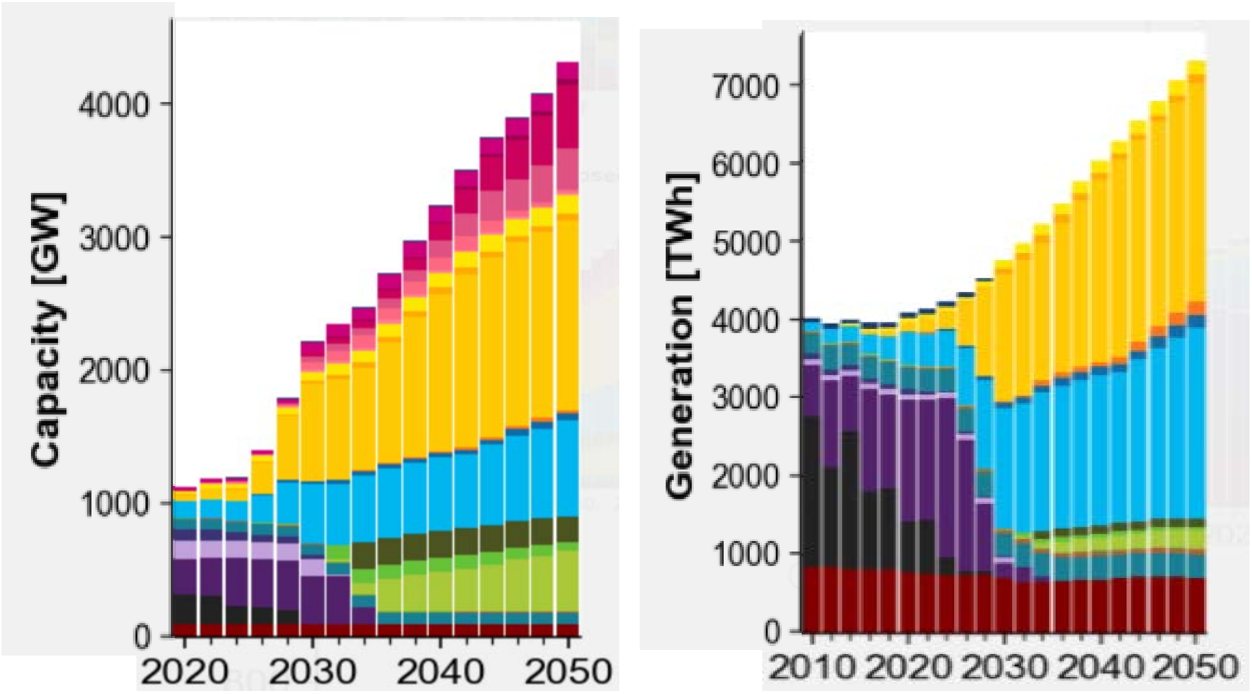
Scenario 1



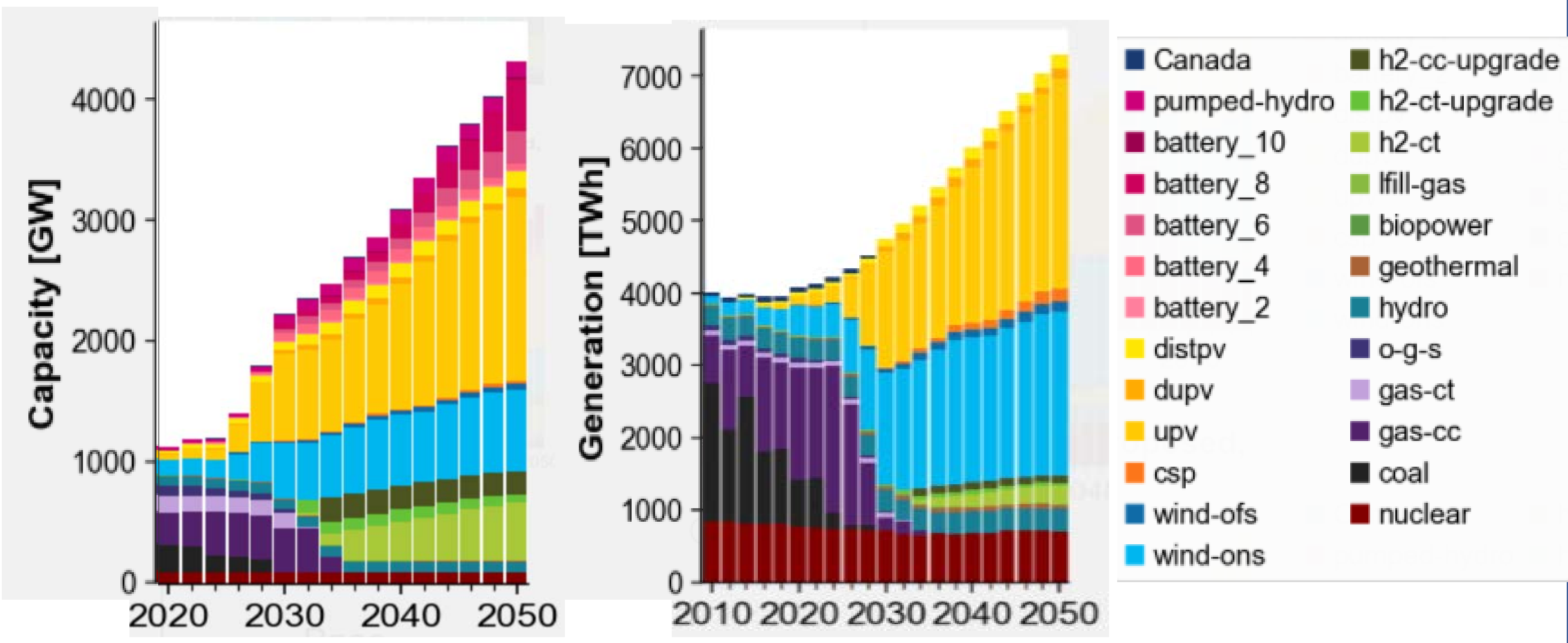
Innovation Updates: Scenarios

- **Most valuable Scenarios 0 and 1 design and the associated capacity and generation data**

Scenario 0



Scenario 1



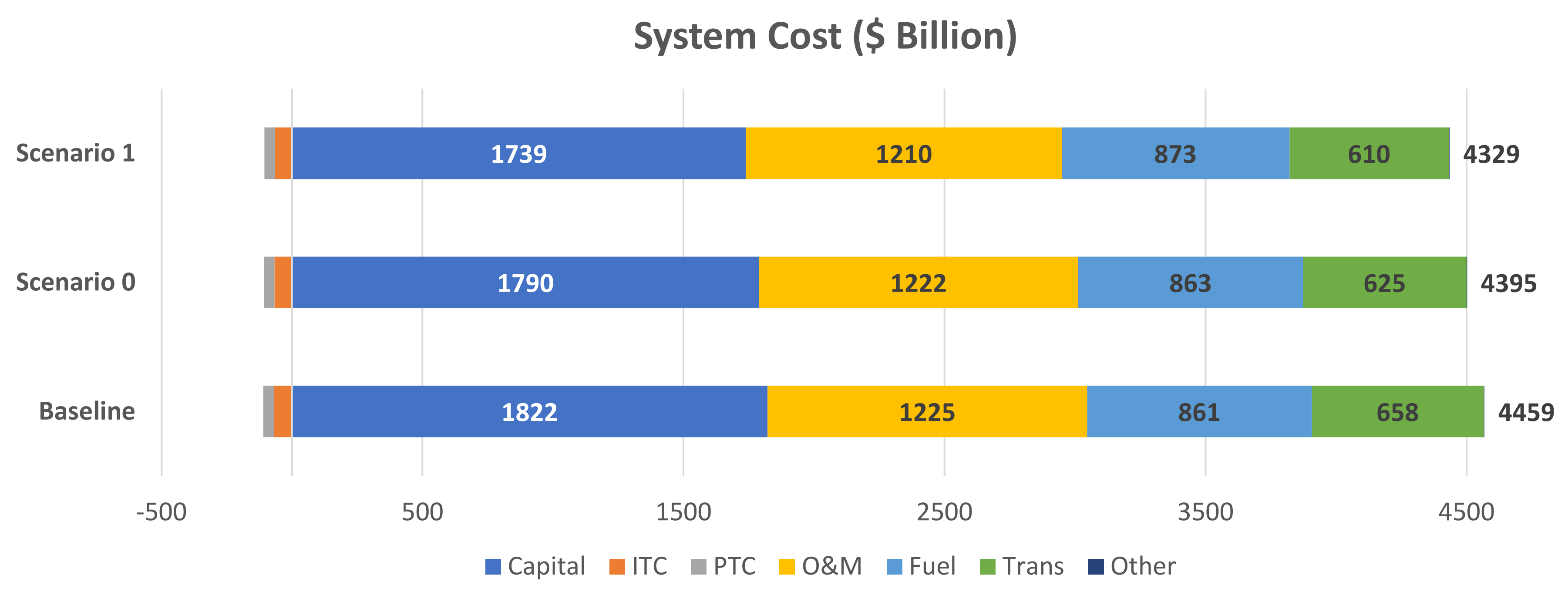
Installed Wind/PV Capacity in 2036 (GW)

Resource	Scenario 0	Scenario 1
upv	901.87	848.44
wind-ons	519.52	538.15
wind-ofs	31.90	32.06

The Generation % from Renewable Resources (exclude hydro)

Resource	Scenario 0	Scenario 1
2026	32.69%	32.72%
2036	82.34%	82.56%
2050	85.55%	85.68%

Innovation Updates: Characterization of Scenarios



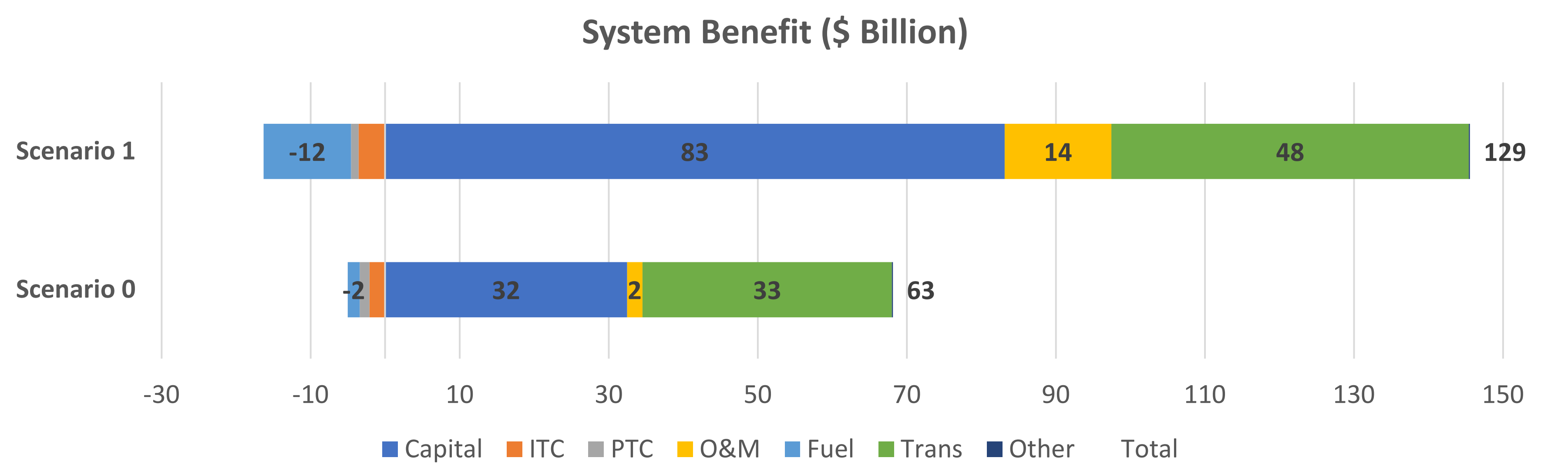
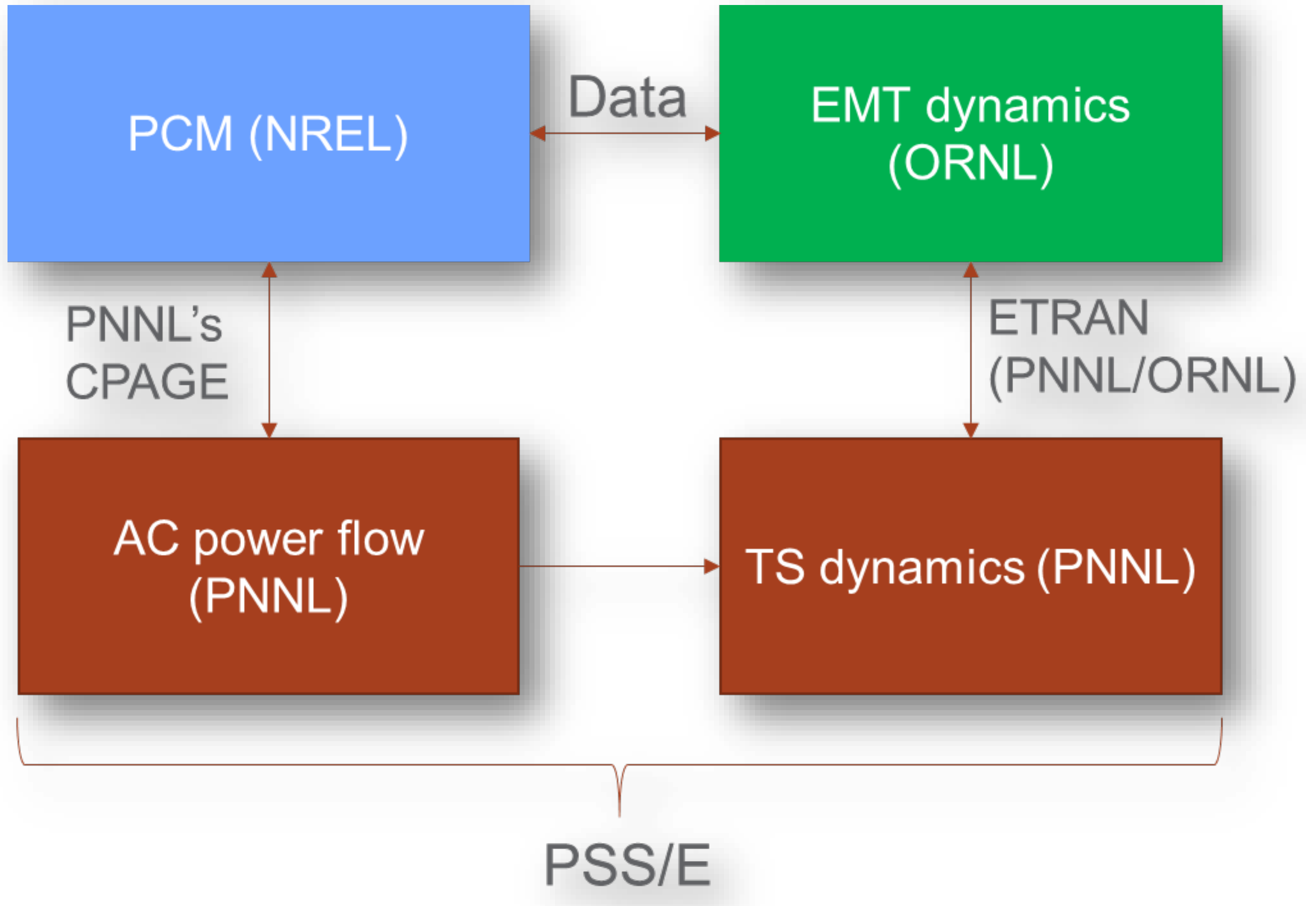


TABLE INFORMATION:

- The tables demonstrate the total system cost of the baseline, the selected Scenarios 0 and 1 design and the system benefit (avoided cost) of the 2 scenarios
- Scenarios 0 and 1 will both introduce system benefit to the baseline
- Comparing with the total system cost, the benefit portion is relatively small since the capacity expansion model can only roughly estimate the operation cost
- Detailed system cost-effectiveness study will be performed using the PCM in the next quarter

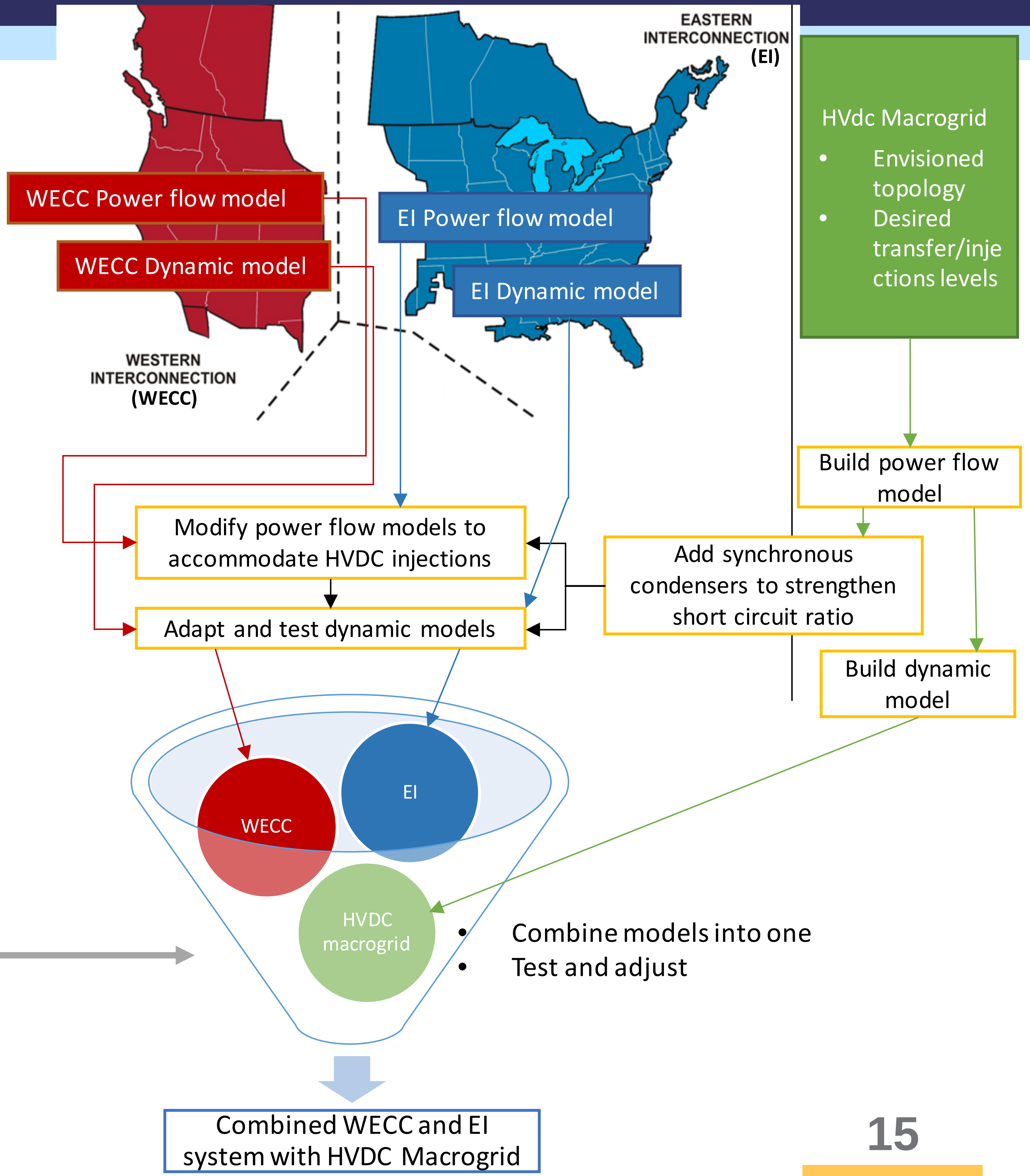
Primary Innovation Proposed (PNNL in BP1)

- Collaborate to identify scenarios
- Develop continental-level ac power flow models
- Adapt industry-grade TS dynamics for full continental-level system
- Develop MTdc phasor-based TS dynamic models
- Simulate hybrid PSSE-PSCAD with ETRAN



Primary Innovation Proposed (PNNL): Continental Scale Model

- Develop ac power flow (PF) and transient stability model (TS) to be used in the HVdc planning studies
  - Models coordinated with NREL's PCM
  - HVdc topologies from NREL's ReEDS, and input from IAB
  - TS MTdc model developed by PNNL
- Industry-grade power flow models + transient stability dynamic models
  - Western Interconnection (WECC)
  - Eastern Interconnection
- Process to combine 3 models



Elizondo et al, "HVdc macrogrid modeling for power-flow and transient stability studies in North American continental-level interconnections," CSEE Journal of Power and Energy Systems, Dec. 2017

Primary Innovation (PNNL): Dynamic Modeling

Transient Stability

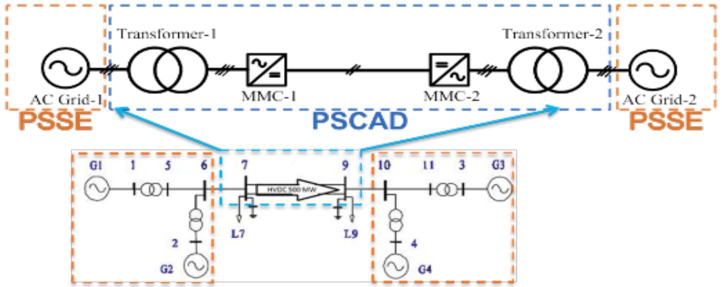
Electromechanical phenomenon

- Transient stability studies
- Governor control (frequency response)
- Transmission planning studies
- Simplified HVdc converters

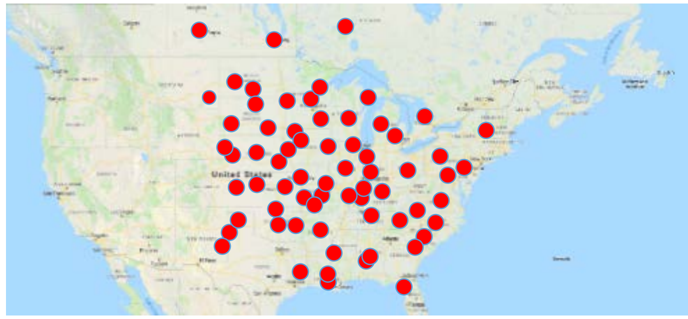
Less detail – larger area

PNNL will develop MTdc phasor-based TS dynamic models

Hybrid Simulation

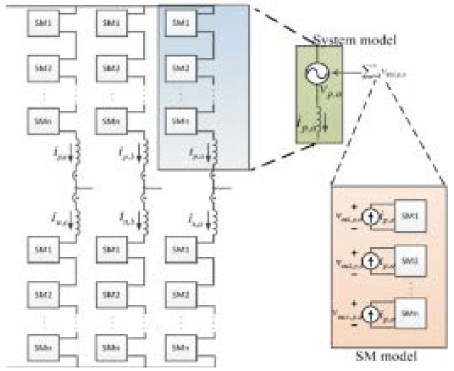


Lumped models



Middle ground

Electromagnetic Transients



Electromagnetic phenomenon

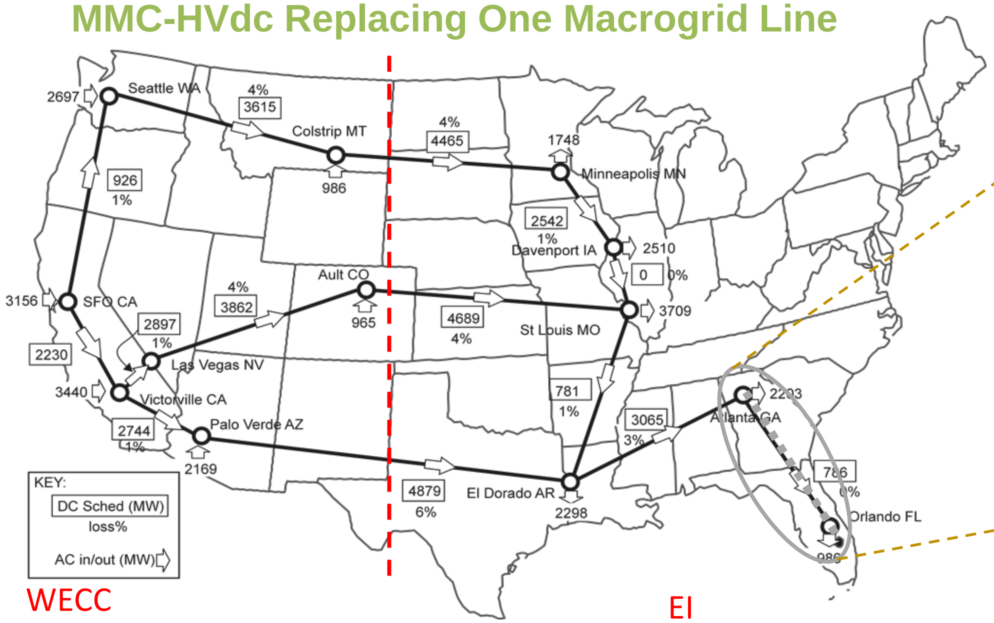
- Switching surges
- Sub-synchronous resonance
- Detailed HVdc converters
- Current interest in large scale EMT models to study high penetration of IBR

More detail – smaller area

Primary Innovation (PNNL-ORNL): Hybrid Simulation

- Study the HVdc's control responses to different contingencies and grid events
- Investigate the interactions of modular multilevel converter (MMC) – based MTdc system with bulk power system.
  - Radial (scenario 0) and meshed (scenario 1) topologies
- **Approach**: hybrid electro-magnetic transient (EMT) – transient stability (TS) co-simulation
- **Expected Accomplishment**: co-simulation framework to integrate the EMT models of MMC-MTdc system and the TS continental model eastern and western interconnections

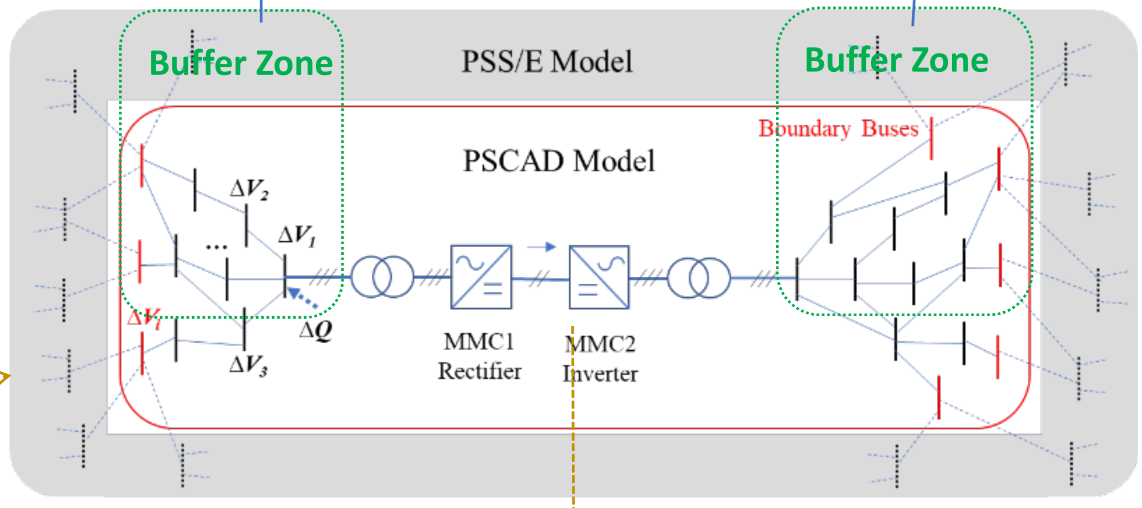
MMC-HVdc Replacing One Macrogrid Line



WECC
(equivalent power injection at HVdc terminals)

EI
(full dynamic model)

The size is determined by VAr injection approach



PSS/E

E-TRAN

PSCAD
High-Fidelity HVdc Converter Model

Images from previous work: Liu et al, "Hybrid EMT-TS Simulation Strategies to Study High Bandwidth MMC-Based HVdc Systems" IEEE PES GM, Aug. 2020

Acronyms

HVdc: High-Voltage dc

EMT: Electro-Magnetic Transients

TS: Transient Stability

MTdc: Multi-Terminal dc

MISO: Midcontinent Independent System Operator

PCM: Production Cost Model

PF: Power Flow

VSC: Voltage Source Converter

ReEDS: Regional Energy Deployment System

THANK YOU

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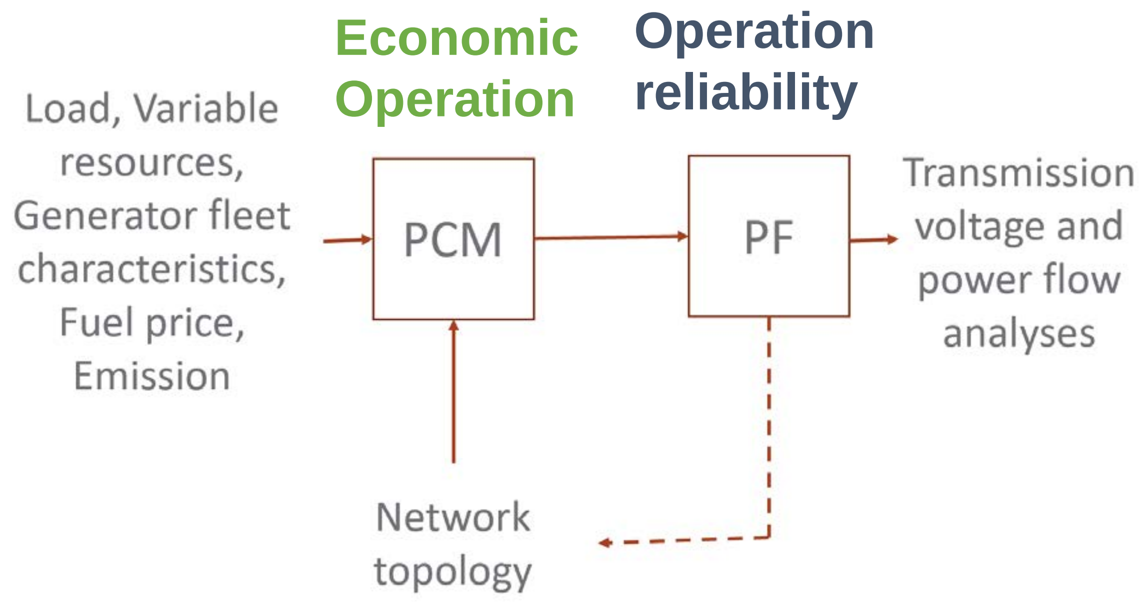
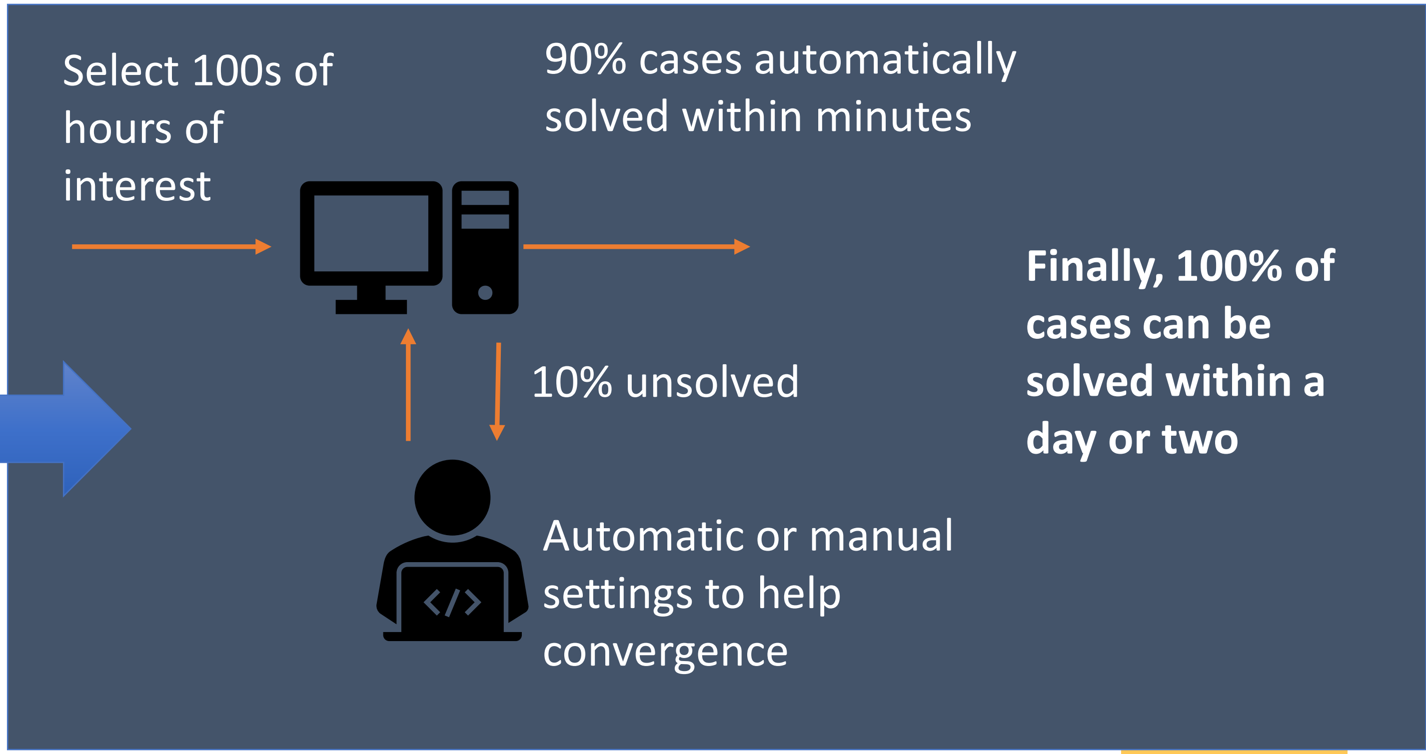
PNNL's C-PAGE tool



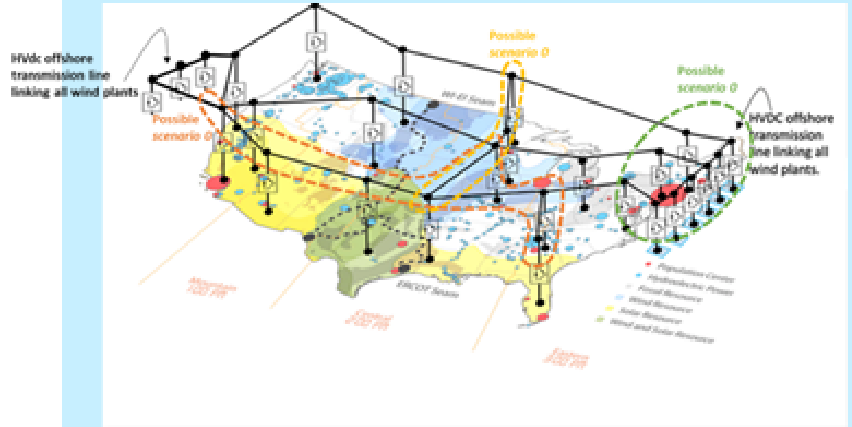
- **Why round trip PCM to (AC)PF:** Planning issues that cannot be dealt with only PCM or PF
  - PCM: cannot deal with voltage stability
  - PF: cannot deal with resource adequacy, flexibility requirement
- **Challenges to perform round trip**
  - DC to AC power flow conversion
  - Time consuming: Typically, it takes several days to months to create a base AC power flow case from PCM data

- **To address this challenge, we have developed C-PAGE**
  - C-PAGE uses AI/ML, combined with PCM and PF tools, to discover critical contingencies as they unfold over time.
  - Used C-PAGE to develop the WECC 2028 ADS cases
  - Leading WECC's Anchor Power Flow Work Group (APFWG) in the "Round-Trip" capability
  - EPRI and GridView to adopt C-PAGE

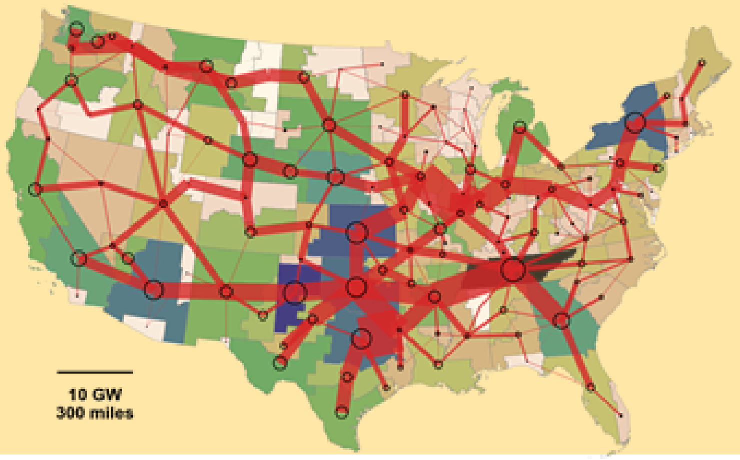


NREL Workflow and Existing Capabilities

Scenario development survey with IAB

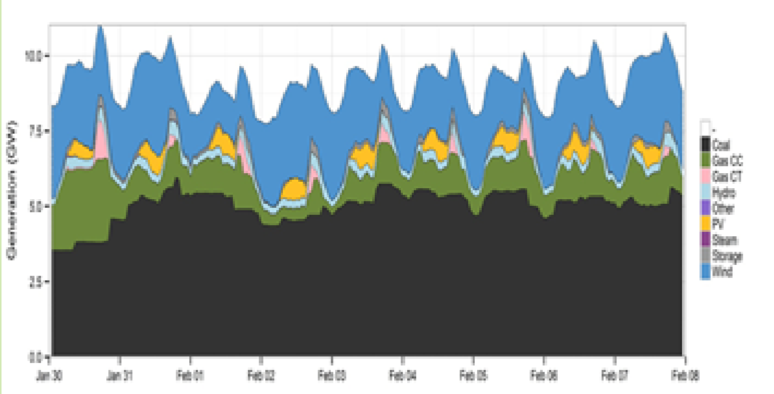


Use ReEDS to develop capacity expansion models for Scenarios 0 - 2



ReEDS-to-PLEXOS link

Use PLEXOS to develop PCMs for Scenarios 0 – 2



constraints

constraints

Power flow case

Pacific Northwest NATIONAL LABORATORY

Power flow case

OAK RIDGE National Laboratory

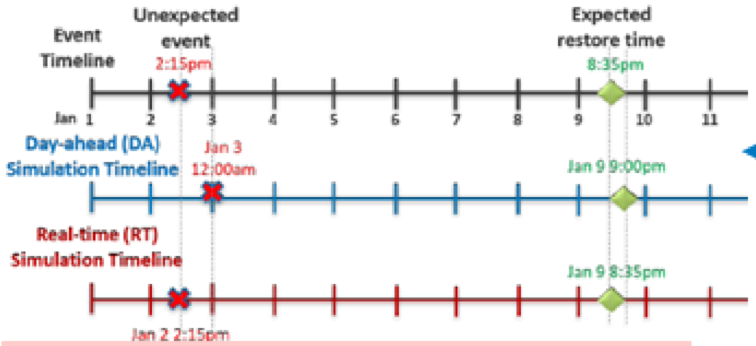
Use PLEXOS-PowerWorld tool to identify vulnerable operating conditions

Target Timestamps	Updated raw file with target operating power flow
2020-03-29 02:00:00	RTS-GMLC_Y2020M03D29HH02MM00.raw
2020-06-01 05:00:00	RTS-GMLC_Y2020M06D01HH05MM00.raw
2020-06-14 05:00:00	RTS-GMLC_Y2020M06D14HH05MM00.raw
2020-06-29 16:00:00	RTS-GMLC_Y2020M06D29HH16MM00.raw
2020-06-29 17:00:00	RTS-GMLC_Y2020M06D29HH17MM00.raw
2020-07-20 15:00:00	RTS-GMLC_Y2020M07D20HH15MM00.raw
	RTS-GMLC_Y2020M07D20HH20MM00.raw
	RTS-GMLC_Y2020M07D20HH21MM00.raw

Benefit Evaluation

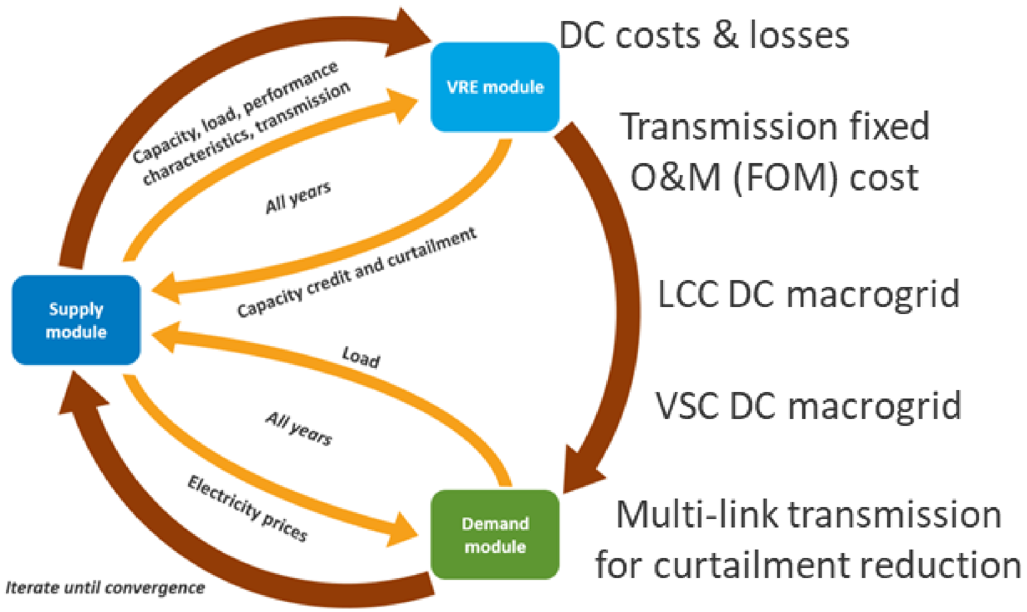
Valuation Metric of Interest
Cost-benefit ratio
Efficient use of resources
Congestion Management
Dynamic Frequency Support
Capacity Value

Resilience Assessment



Capacity Expansion Models

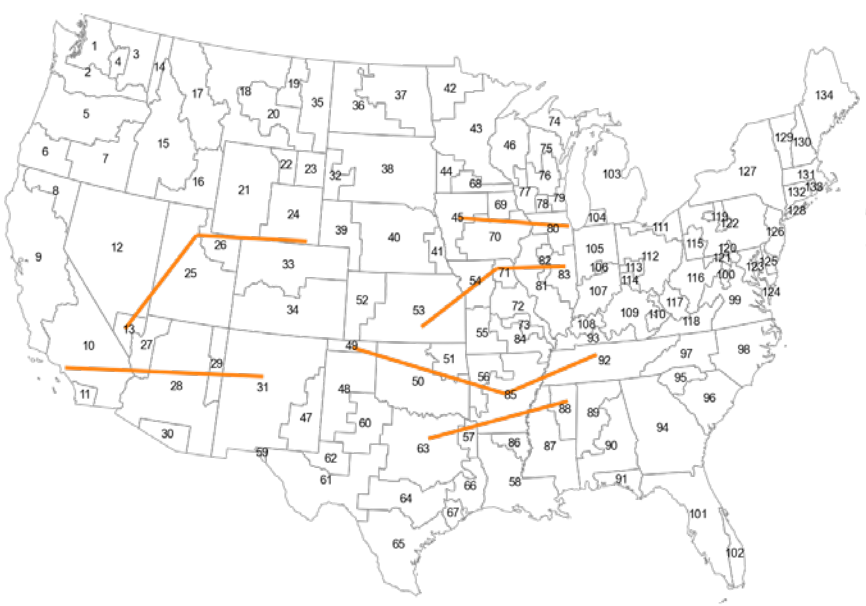
ReEDS with transmission updates



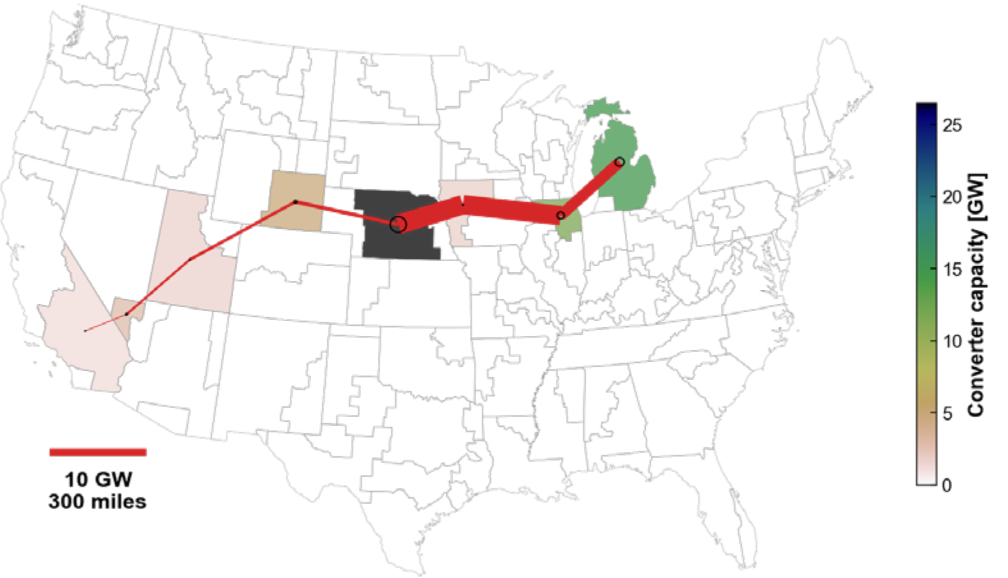
Existing Industry HVDC project modeling

Proposed VSC route and substation optimization function

Existing Industry HVDC Projects Map



Scenario 0 Design

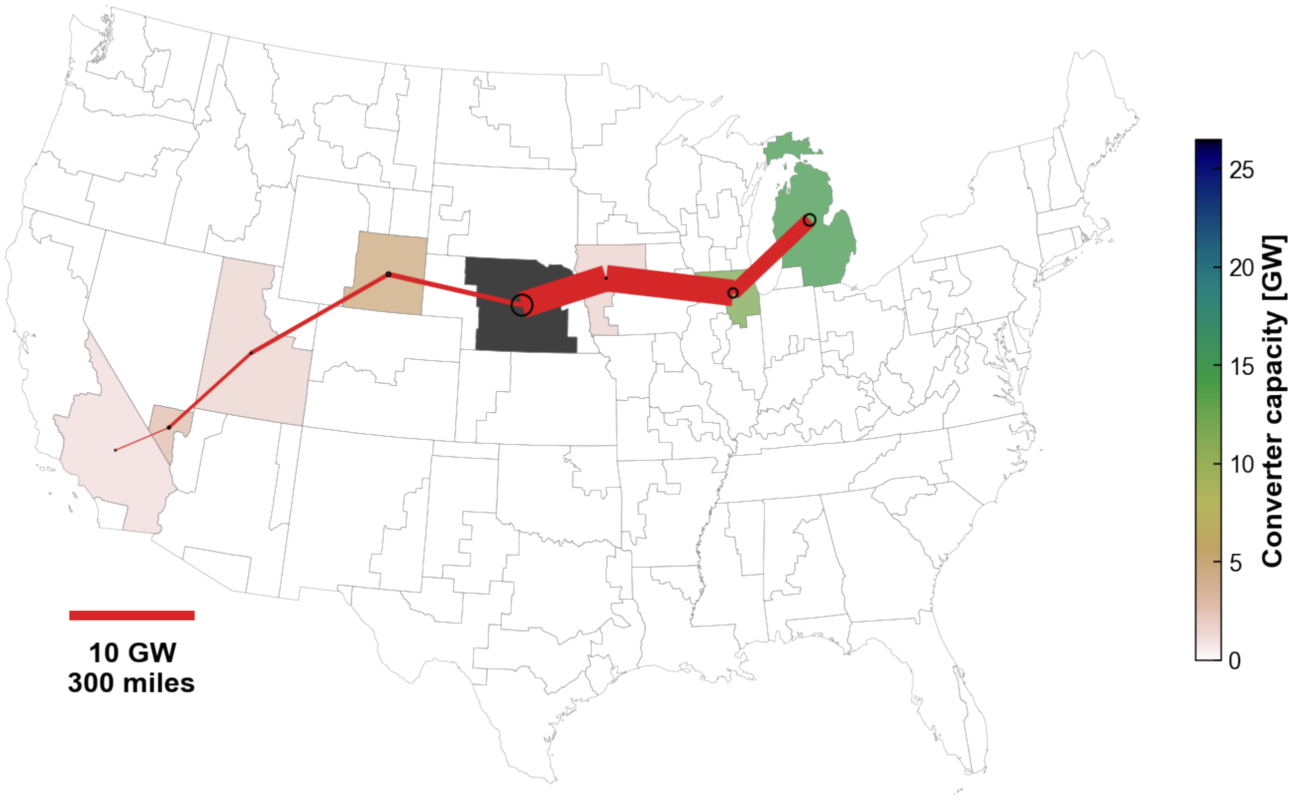


- ReEDS is a capacity expansion and dispatch model that relies on system-wide least cost optimization to estimate the type and location of future generation and transmission capacity.
- ReEDS with transmission updates can generate scenarios with VSC macrogrid designs
  - VSC: 1) Meshed HVDC network; 2) Converter and line capacity independently optimized
- Existing industry HVDC project modeling and proposed VSC route and substation optimization functions have been added to ReEDS model in Q1 for scenario selection.

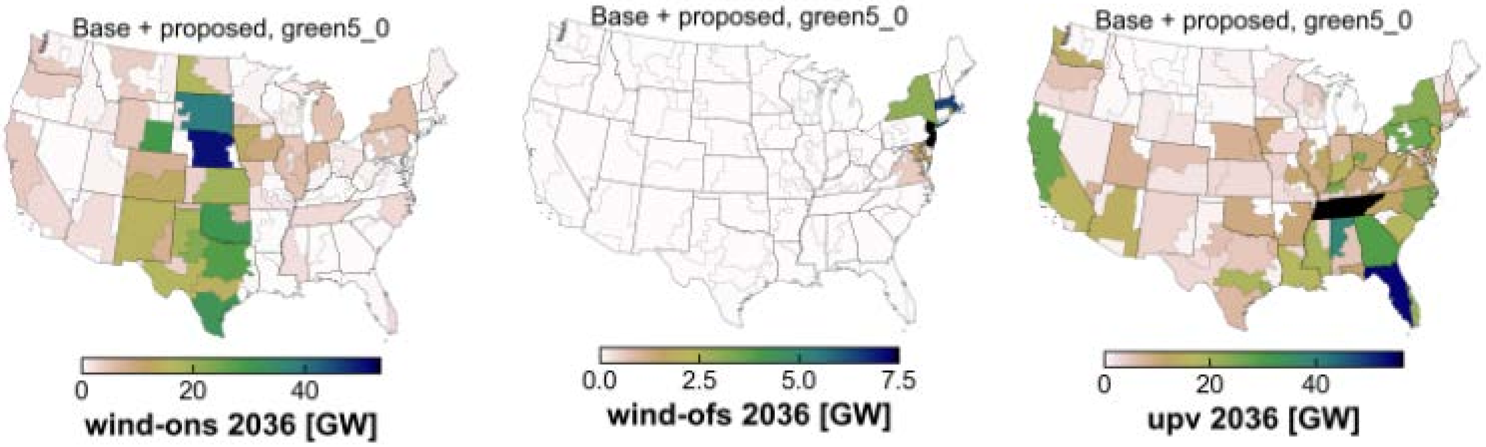
Scenario 0

- NREL has developed capacity expansion models of 5 potential radial MTdc system options in 2026 and selected the optimal one

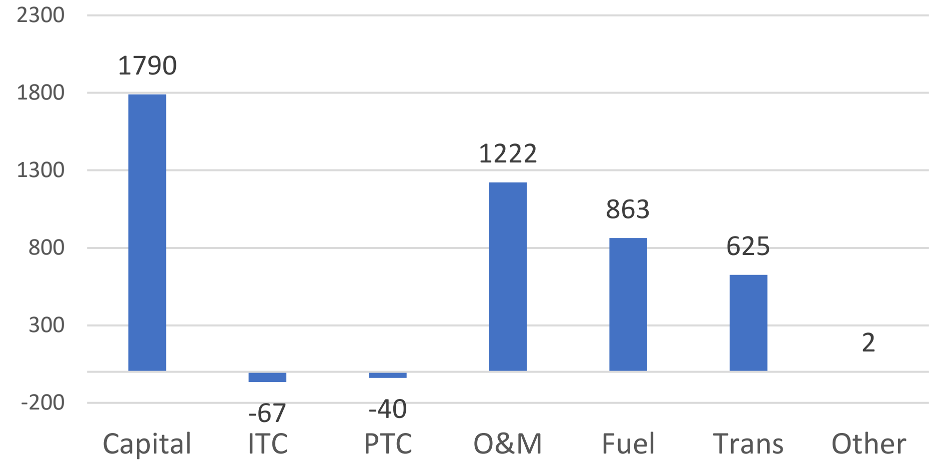
Scenario 0 VSC Line and Substation Map



Scenario 0 Onshore, Offshore Wind and UPV Capacity Map



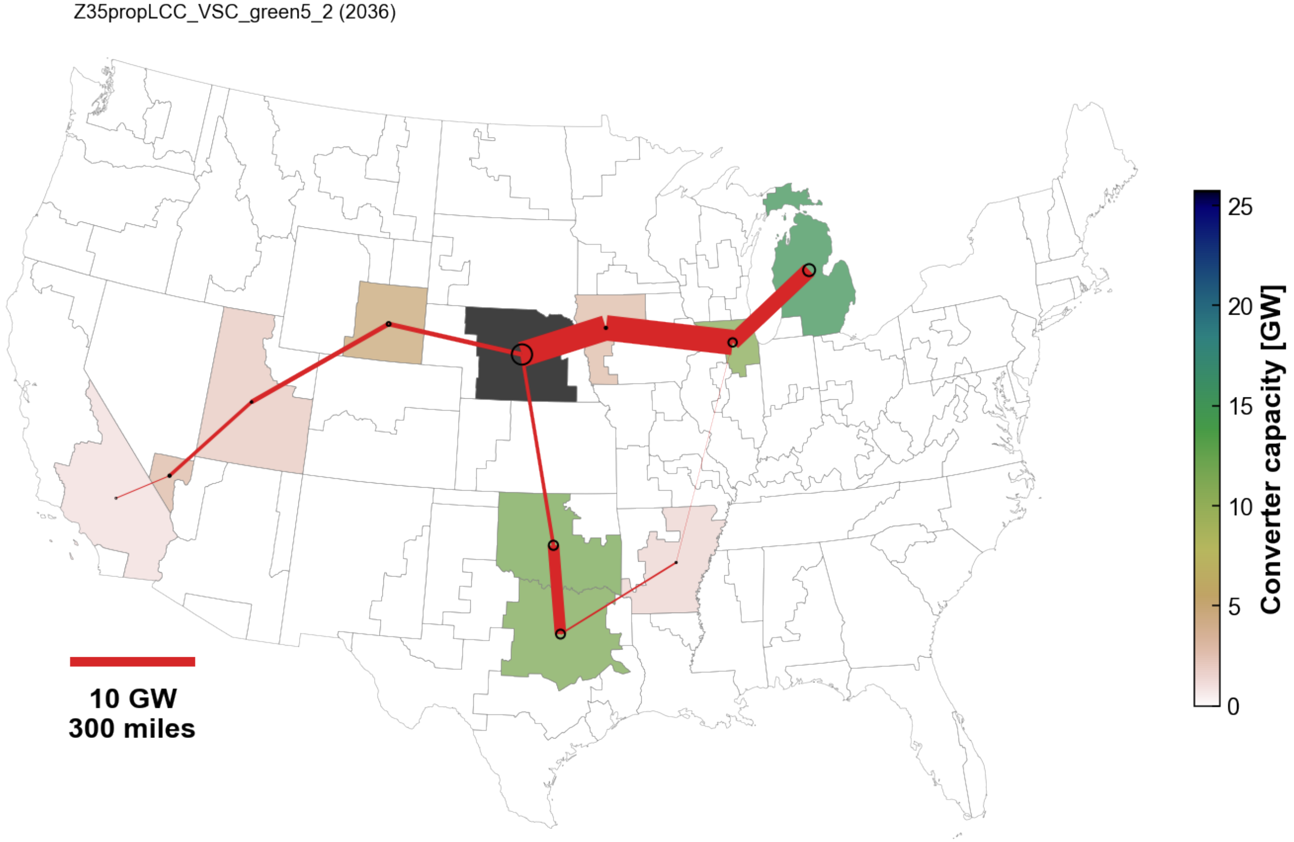
Scenario 0 System Cost ($ Billion)



Scenario 1

- NREL has developed capacity expansion models of 3 potential meshed MTdc system options in 2036 and selected the optimal one

Scenario 0 VSC Line and Substation Map



Scenario 0 Onshore, Offshore Wind and UPV Capacity Map