Sequential Integrated Analysis of Distributed Energy Resources in Distribution and Bulk Power Systems

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Agenda

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- Sequential Integrative Modeling (SIM)
- Indiana case study: introduction
- Model input components
- Distribution system technical results
- Generation-transmission technical results
- Cost results and rate impacts

Modeling for planning

Bulk Power System Planning	Distribution Planning	Demand-side Planning
• Decisions: investment in supply side technologies and transmission lines/substations • Models: capacity expansion models (e.g., Aurora); production cost (dispatch) models used for verification	• Decisions: grid investments to maintain distribution reliability • Models: power flow models (e.g., CYME) to identify technical issues; then manual upgrades, with non-wires alternatives used by some utilities	• Decisions: investment in behind-the-meter (BTM) distributed energy resources (DERs) to maximize customer value; occasionally dispatch of BTM DERs for system benefits • Models: DER value maximization models (e.g., DER-CAM, ReOpt)

What is sequential integrative modeling (SIM)?

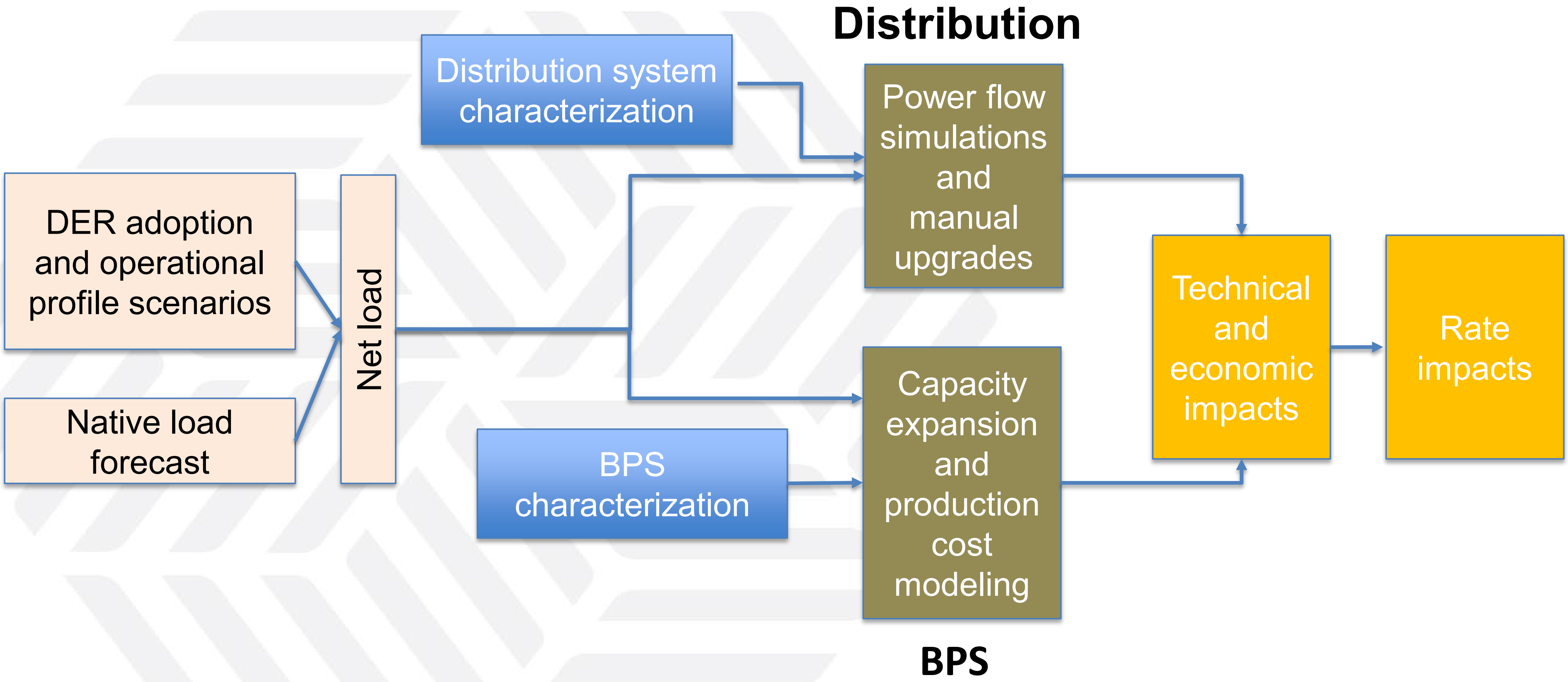
- Regulators and system planners want to understand the impacts of DERs across domains in the power system: distribution and bulk power system (BPS—generation+transmission)

- DER impact assessments are usually constrained to one domain (distribution or BPS) based on analyses developed in planning processes—distribution planning, integrated resource planning (IRP), cost-benefit analysis

- Joint simulation of distribution system and BPS is possible, but can be challenging:
  - Requires substantial computational capacity
  - Makes potentially unrealistic assumptions about investment coordination across power system domains
  - Uses nascent tools, not industry-standard

- SIM is a method to simulate the impacts of DER across the whole electric value chain employing industry standard tools

SIM framework overview



SIM case study: state of Indiana

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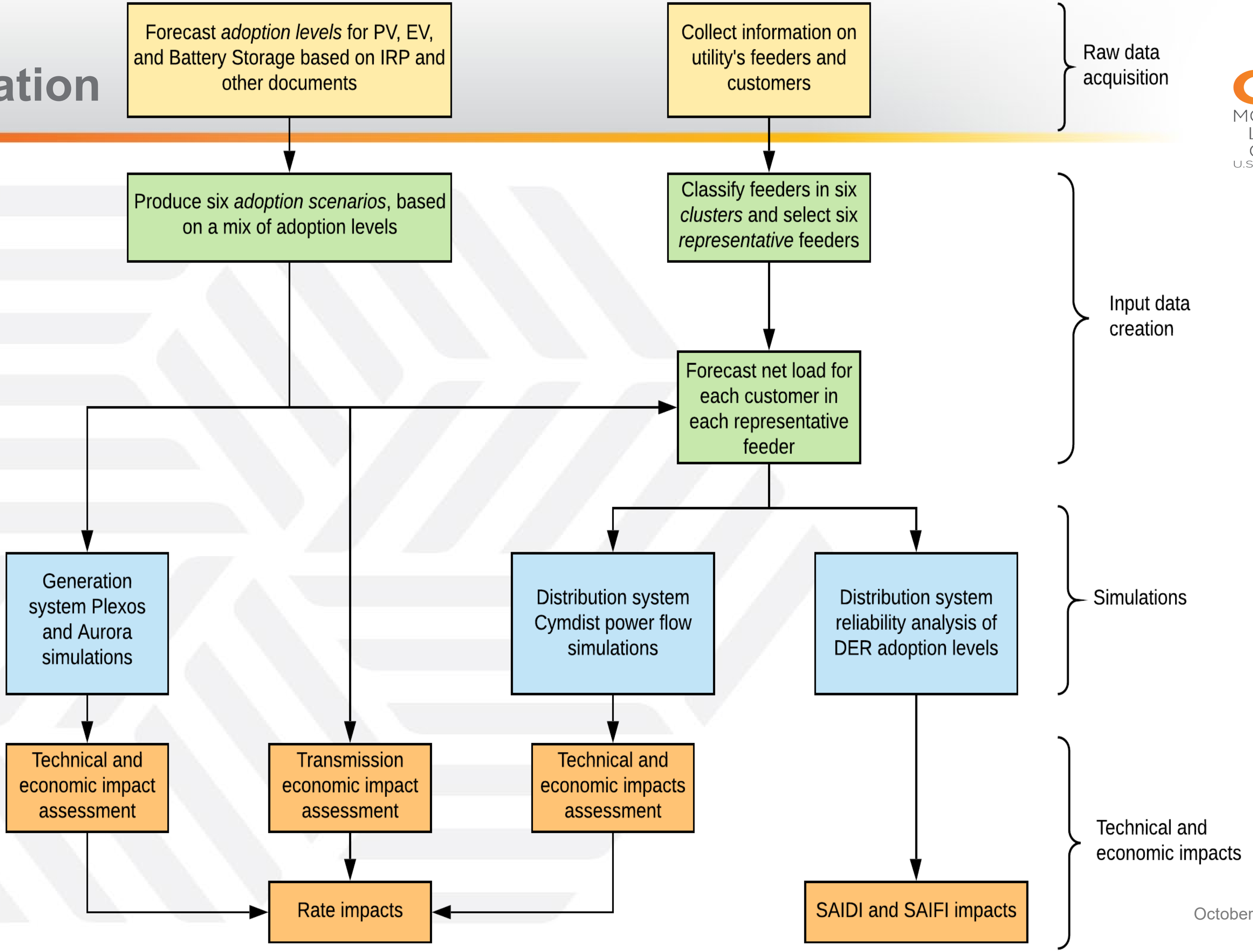
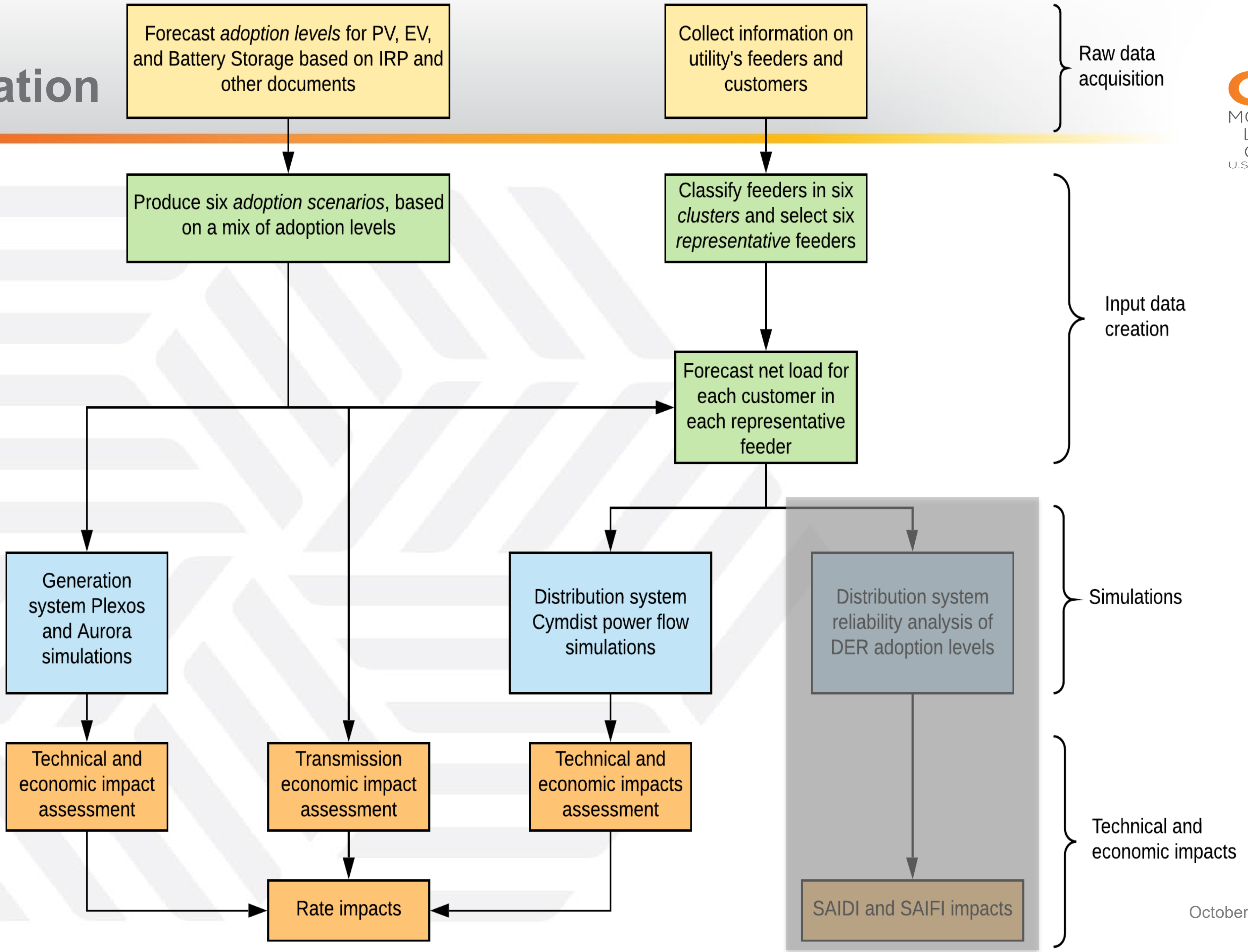
Indiana implementation

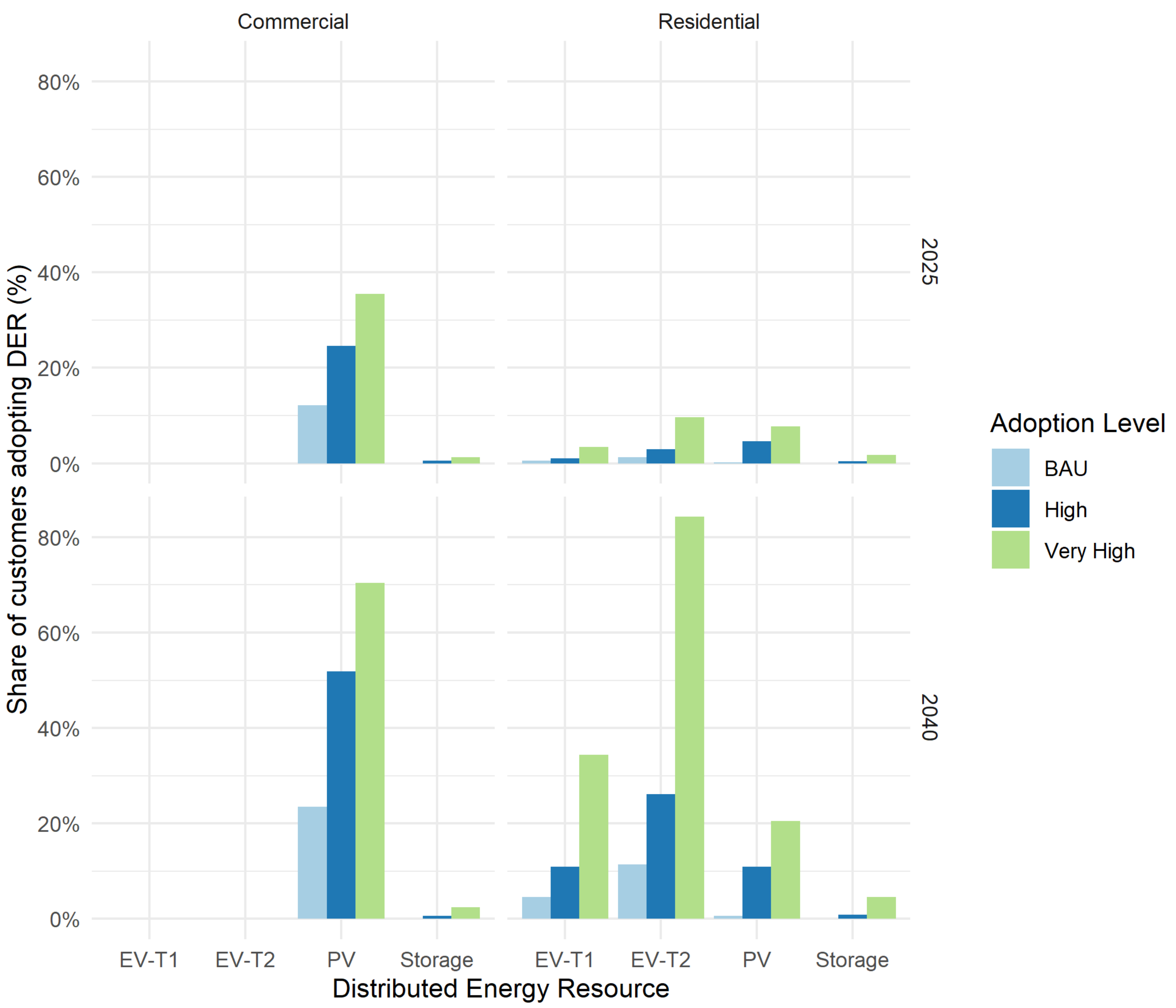


Indiana implementation



DER adoption levels

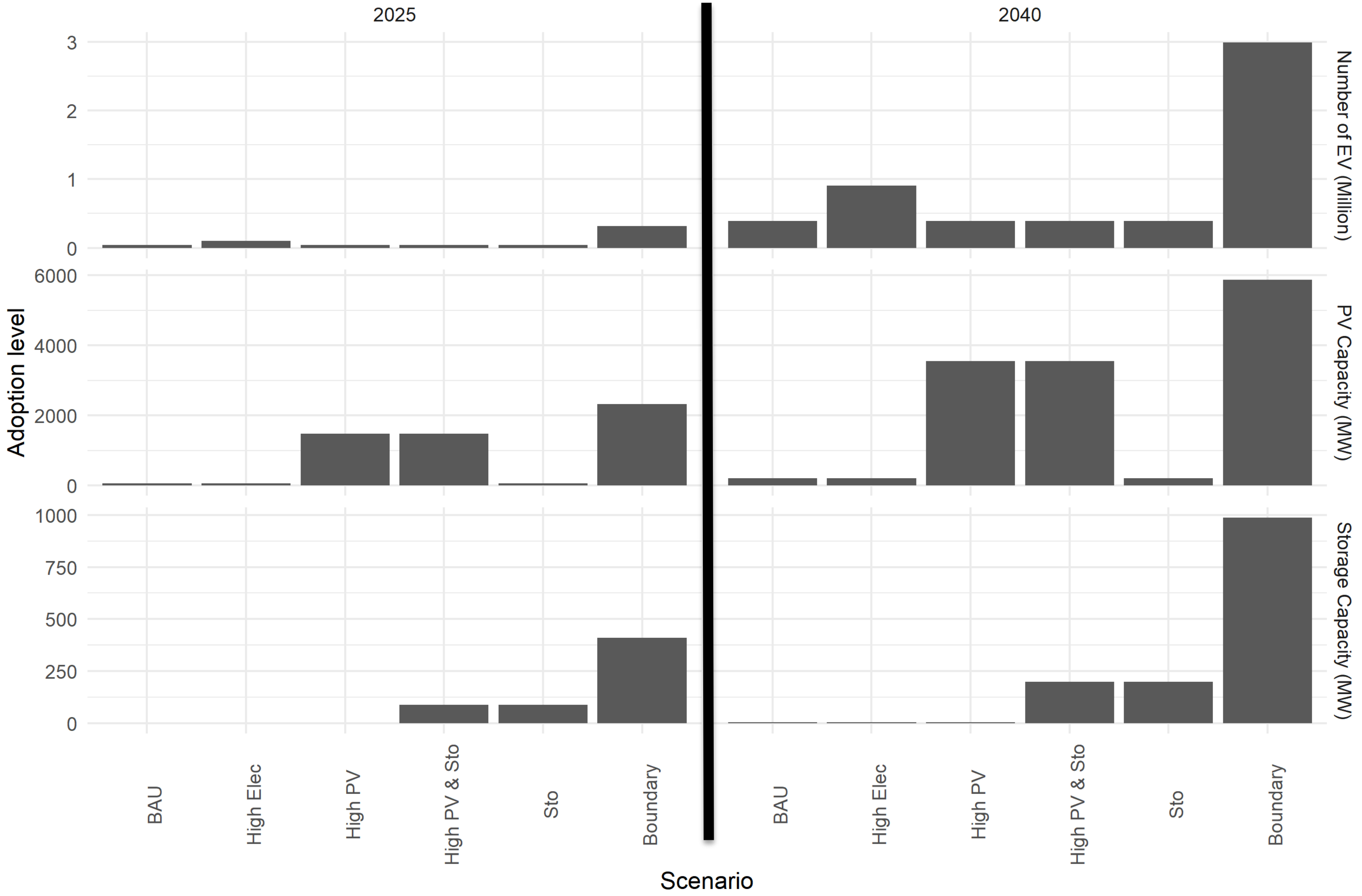
- Business as usual (BAU) adoption levels based on Indiana IRPs are very modest.
- High and Very High levels for various types of DERs based on the following:
  - EV: MISO EV adoption scenarios
  - PV: IP&L (now AES Indiana) IRP
  - Storage: Estimated at 1% and 5% of customers



DER adoption scenarios for 2025 and 2040

Adoption Level
- BAU
- High
- Very High

Scenario	PV	Storage	EV
1: Base	BAU	BAU	BAU
2: High Electrification	BAU	BAU	High
3: High PV Stress Test	High	BAU	BAU
4: High PV and Battery Storage	High	High	BAU
5: Battery Storage Arbitrage	BAU	High	BAU
6: Boundary Case	Very High	Very High	Very High



Distribution system characterization: Representative feeders

- Objective: determine a minimum number of representative feeders that can be used for power flow simulations and represent large portions of the existing customer base

- Approach:
  - Collect data to characterize feeders (e.g., overhead and underground circuit length, number of customers by segment, SAIDI/SAIFI, peak demand, etc.)
  - Process data to produce a set of feeders with a balance of valid fields and utilities represented
  - Use statistical methods to process the data and cluster feeders
  - Run sensitivities on clusters
  - Determine final clusters and qualitatively characterize them

Distribution system characterization: Clusters – Feeder selection

Cluster	General description of feeders in cluster	Average customer number	Average total length (miles)	Average CAIDI (min)	Share of installed capacity (residential)	Share of installed capacity (commercial)	Share of installed capacity (industrial)	Share of circuit length that is underground
1	Short and high commercial, about 1/3 underground	445	9.5	145.1	25%	58%	6%	30%
2	Short, urban residential	567	11.5	142.4	77%	17%	2%	19%
3	Suburban mostly overhead, residential, relatively dense	1,472	21.7	135.4	70%	21%	7%	20%
4	Very long residential mostly rural	1,133	59.3	148.5	78%	15%	3%	19%
5	Suburban underground residential relatively dense	1,535	26.2	121.4	77%	17%	5%	67%
6	Short, heavy industrial, substantial underground	463	10.0	120.8	15%	31%	51%	39%

Distribution system analysis

Method – Distribution system analysis

- Translate state-wide penetration scenarios to feeder-level customer adoption:
  - Develop scaling factors from feeder-level to cluster-level
  - Develop an adoption logic for each connected customer

- Hourly production
  - PV systems from NREL's PVWatts for several Indiana locations; use average since clusters are not necessarily geographically split
  - EV charging assumed "charge as available," mostly after work
  - Storage operation designed to maximize netting of PV production, subject to a minimum charge of 25%

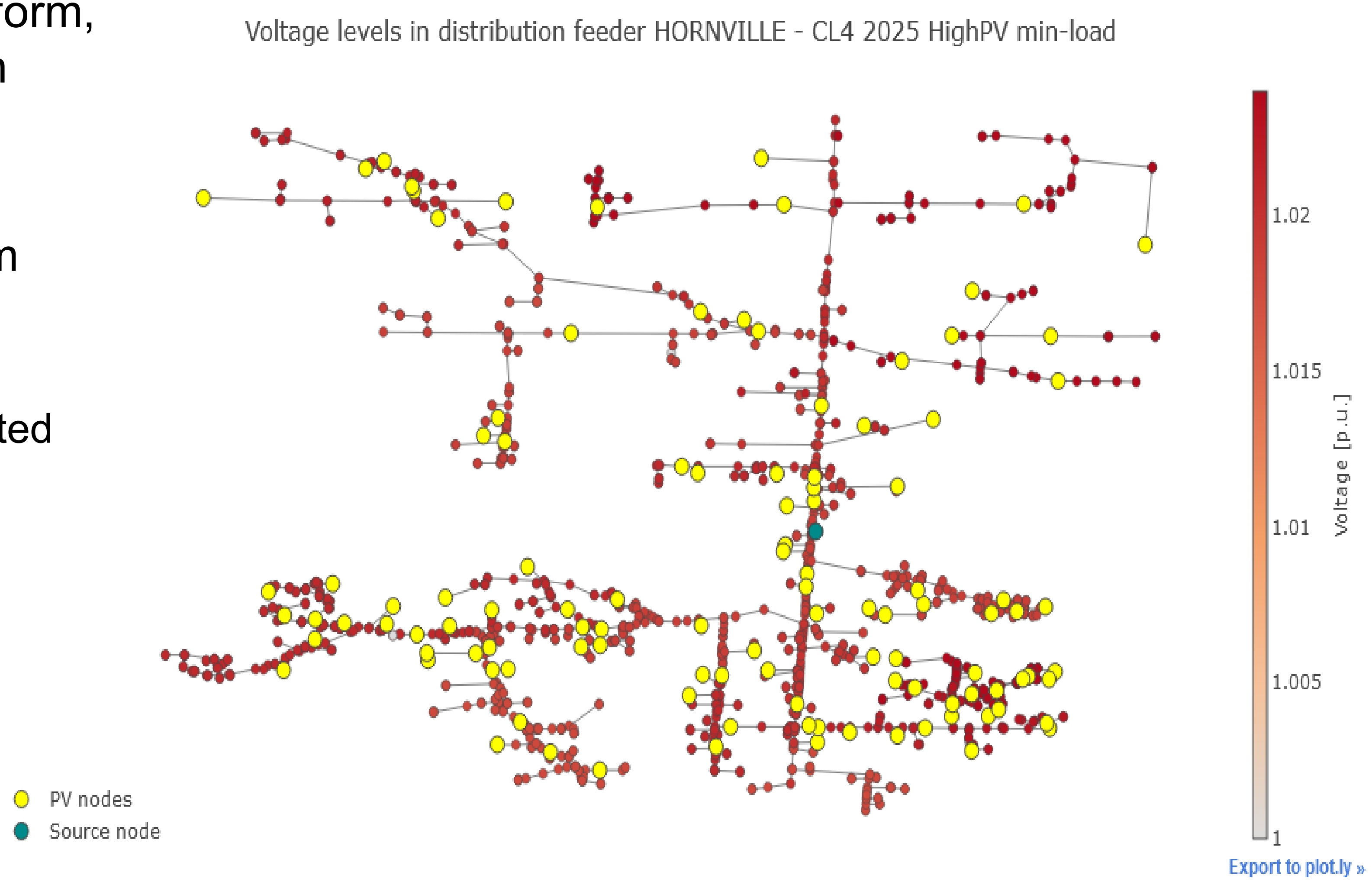
Method – Distribution system analysis

- Assumed size for DER systems by customer segment

DER System	Residential	Commercial	Industrial
Rooftop PV	• 8 kW	• 16 kW	N/A
Battery storage	• 7 kW max discharge capacity • 12 kWh storage capacity • 90% roundtrip efficiency • 25% maximum discharge level	• 14 kW max discharge capacity • 0.1% of annual kWh consumption of storage capacity • 90% roundtrip efficiency • 25% maximum discharge level	N/A
Electric vehicle charging	• T1 charger: 1.75 kW peak capacity • T2 charger: 5.25 kW peak capacity	N/A	N/A

Power flow simulation

- Use API-enabled CYMDIST platform, which allows users to “batch” run simulations
- Simulate maximum and minimum load days, for each cluster/ scenario/year combination
  - About 3,500 power flows simulated

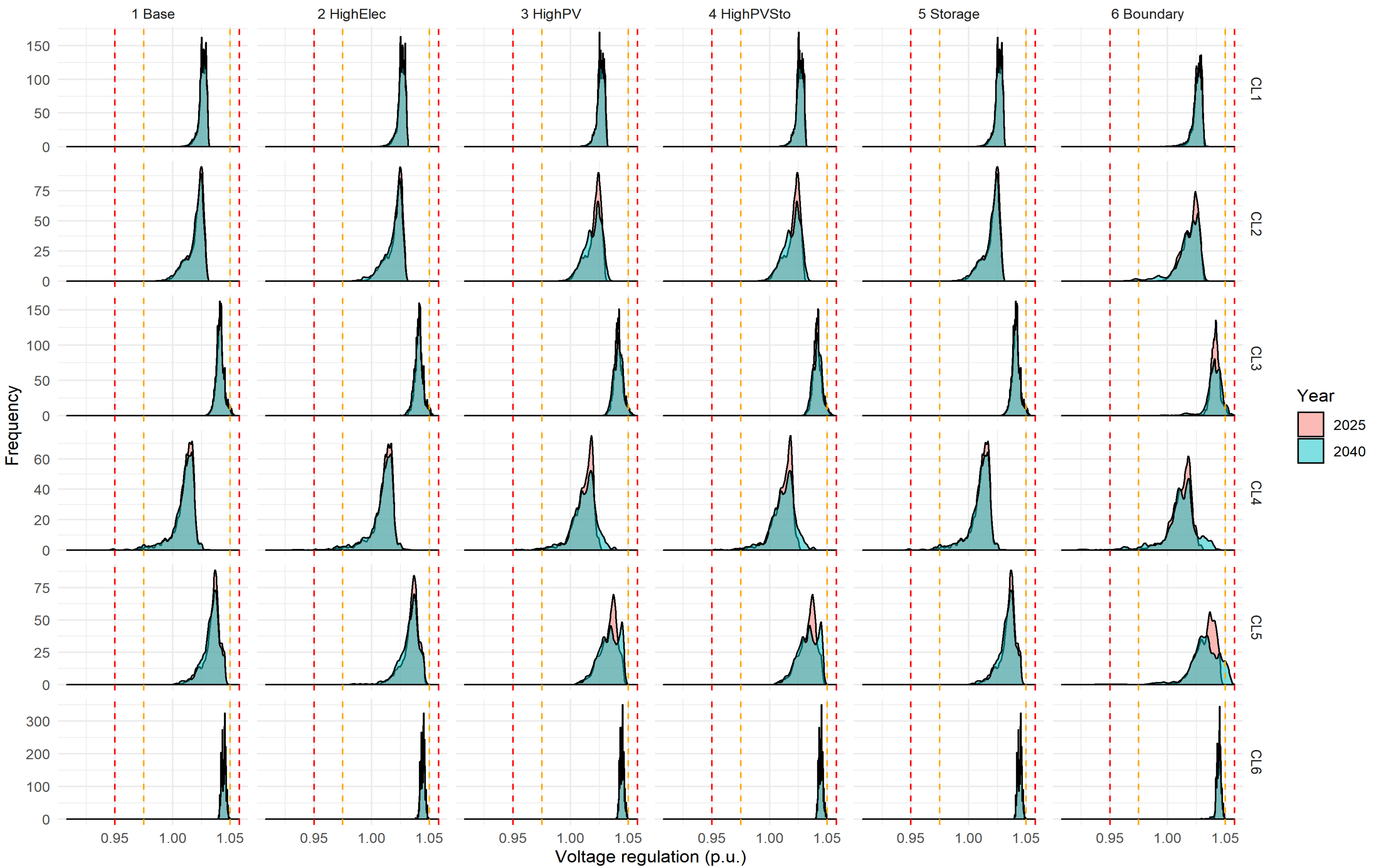


Method – Distribution cost impacts

- Use power flow simulations to track three metrics:
  - Voltage issues
  - Line loading issues
  - Line losses

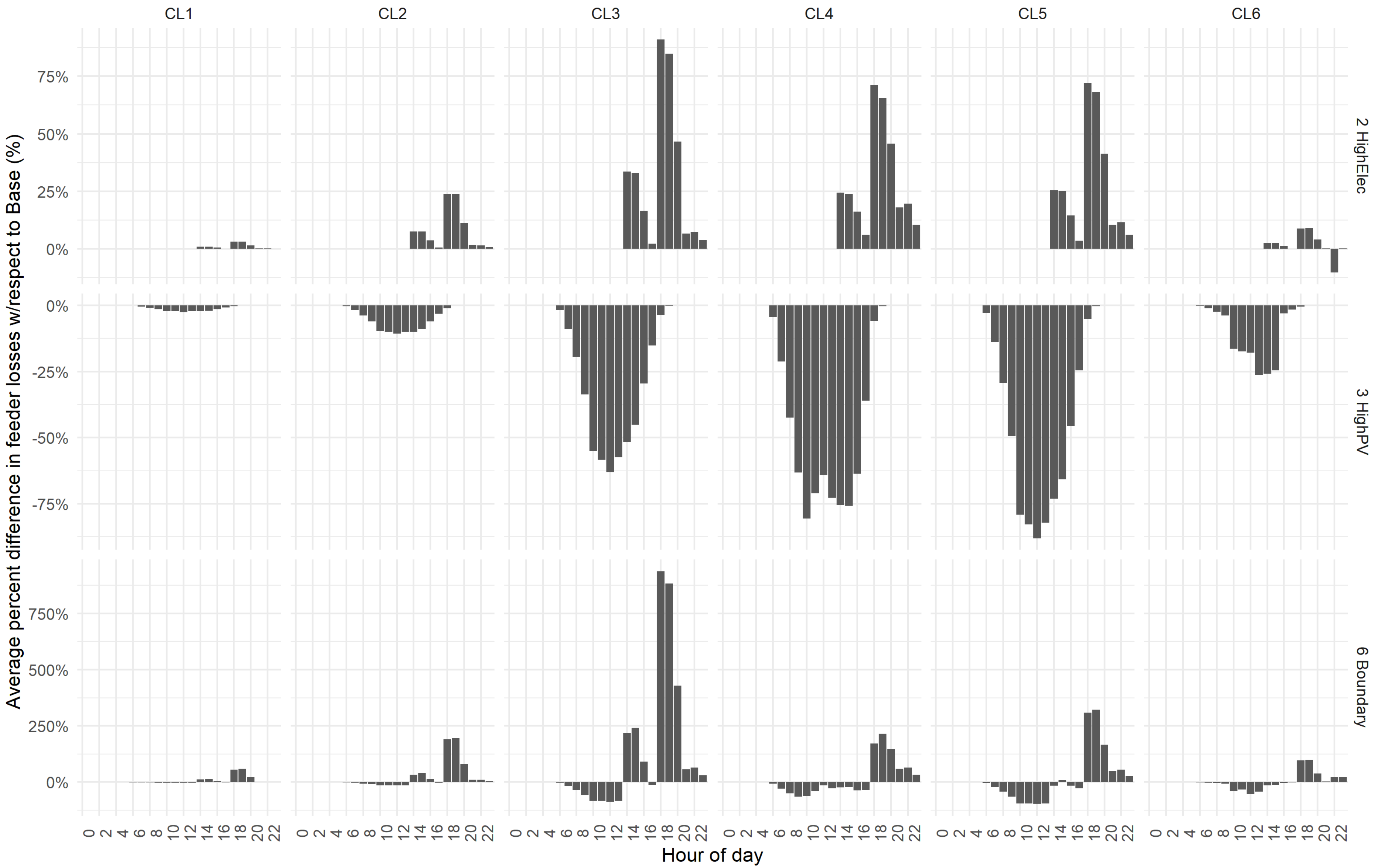
- Strategies to mitigate voltage and loading impact:
  - Volt/Var control in PV smart inverters (automatic)
  - Line reconductoring (manual)
  - Install tap changers in feeder heads (manual)
  - Install voltage regulators (manual)

Results – Voltage Violations



Results – Line losses changes relative to Base

- In High Electricity scenario, increase in losses tied to EV charging especially in long, sparse feeders
- In High PV scenario, substantial loss reduction during PV production hours
- In Boundary scenario, losses dominated by uncontrolled EV charging



Results – Cost impacts

- Voltage regulation
  - Smart inverters (assumed installed by default)
  - ~$10M annual cost to equip substations with load tap changers
- Line loading
  - ~$12.5M and $70M annual cost
  for High Electricity and Boundary scenarios
- Line losses
  - Between -$2M to $12M annual cost in energy losses
  - Negative range comes from reduction in losses due to lower current flows driven by PV operation

	Underground Cable Length (feet)		Overhead Line Length (feet)	
Cluster	Copper	Aluminum	Copper	Aluminum
3	0	0	0	3,634
4	57	0	2,386	0
5	172	0	0	6,461

Generation and transmission assessment

Method – Generation and transmission impacts

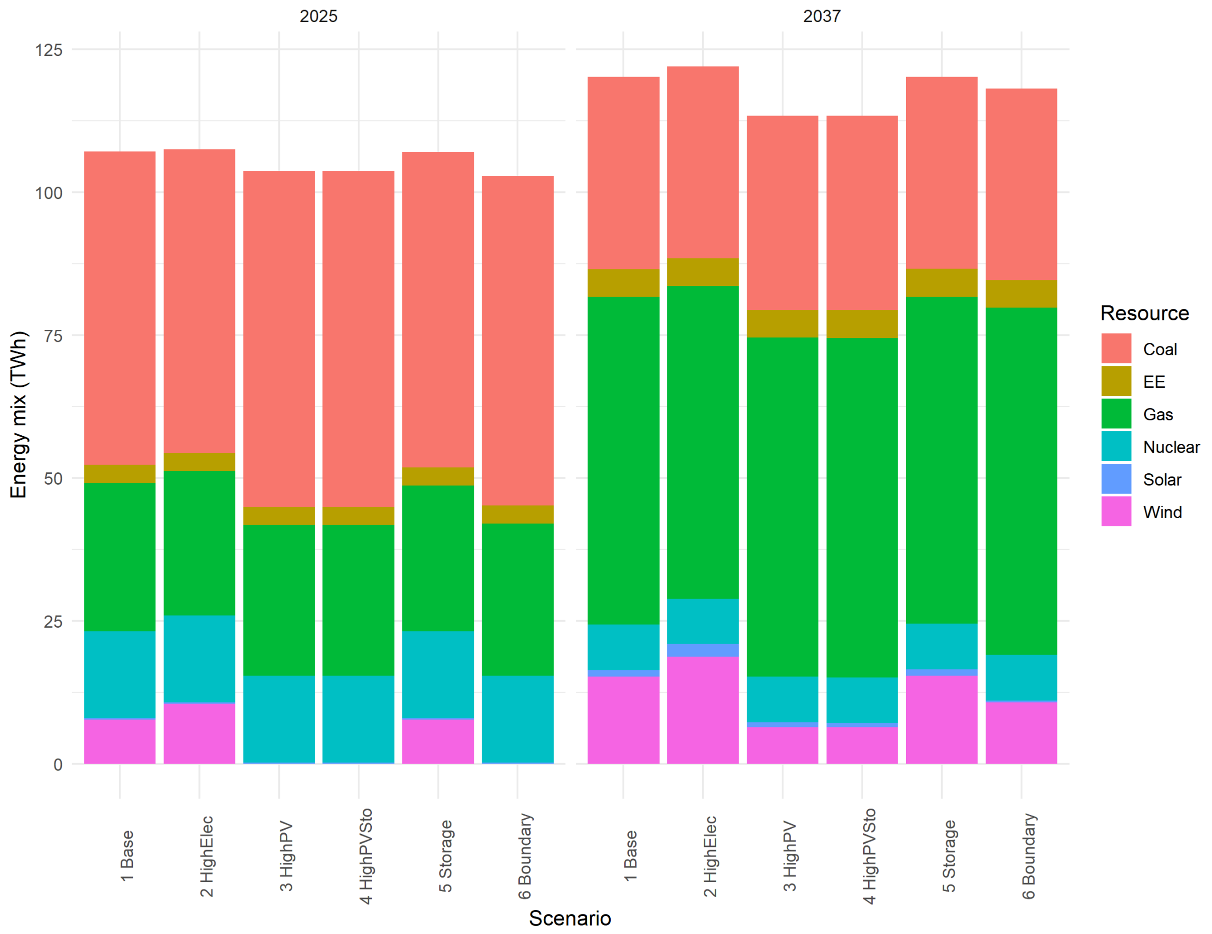
- Employ Aurora capacity expansion model and Plexos production cost model. Analysis developed by Purdue University's State Utility Forecasting Group (SUFG)
  - Models produce capital and operational cost estimates for scenarios
- Input data
  - Scale the hourly customer-level net demand profile to the cluster-level, and then to the state-wide level
  - Express the hourly net-demand as a % variation of the Base scenario to minimize distortions with the data that SUFG uses to calibrate their models
  - Apply the % hourly variation over the SUFG baseline scenario, verify that baseline scenarios are compatible
- Transmission impact very simplified, based on increase in peak demand and average cost of transmission buildout per MW

Results – Generation mix

- Energy levels in Boundary scenario balance PV and EV adoption; low capacity impact

- Distributed solar crowds out utility-scale solar

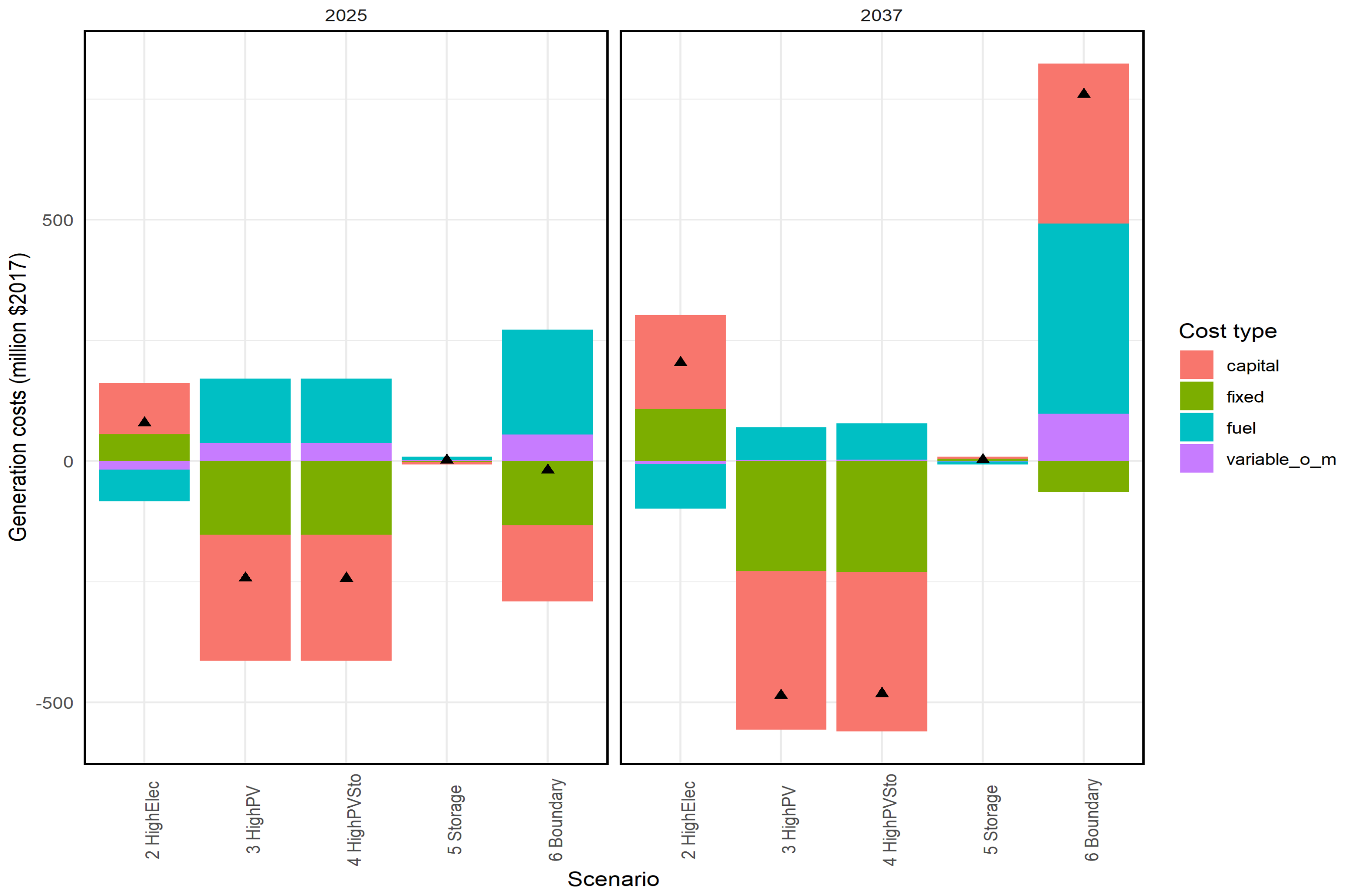
- Note: Model does not assess utility-scale storage



Results - Generation costs

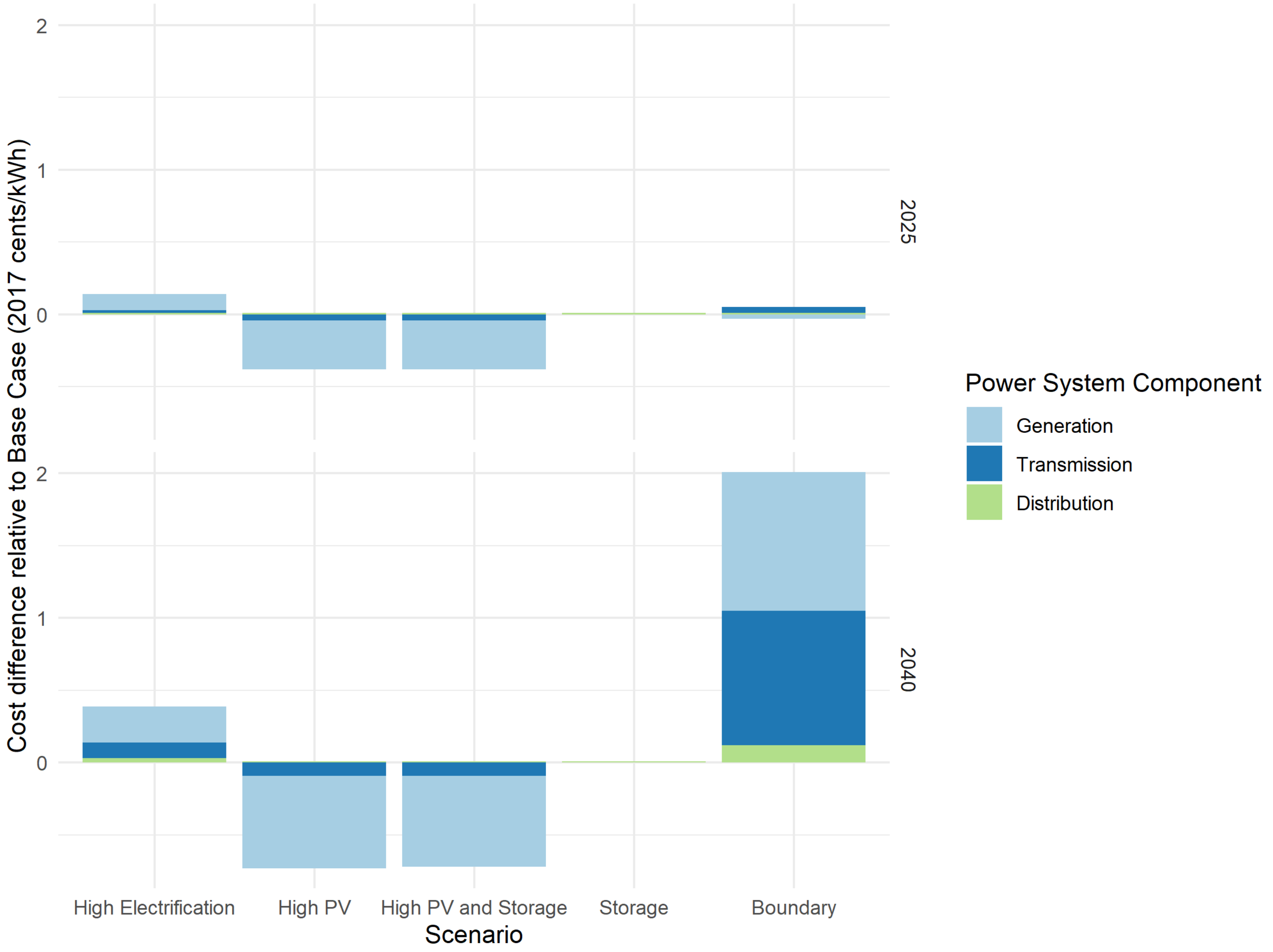
- Savings largely driven by demand reduction

- Boundary scenario has low energy impact, but very high capacity impact; model deploys natural gas peaker plants



Results – Aggregate cost impacts

- Non-boundary scenarios have cost savings in generation driven by PV adoption
- Boundary scenario has high cost impacts in generation and transmission, mostly from unmanaged EV charging
- Very low distribution cost impacts



Results – All-in average rate impacts

	2025 Rate Change Relative to Base				2040 Rate Change Relative to Base			
Scenario	Residential	Commercial	Industrial	Average	Residential	Commercial	Industrial	Average
High Electrification	0.25¢	0.24¢	0.19¢	0.22¢	-0.03¢	0.05¢	0.14¢	0.06¢
High PV	-0.06¢	-0.10¢	-0.19¢	-0.13¢	1.01¢	0.73¢	0.23¢	0.59¢
High PV and Storage	-0.06¢	-0.10¢	-0.19¢	-0.13¢	1.00¢	0.71¢	0.22¢	0.58¢
Storage	0.00¢	0.00¢	0.00¢	0.00¢	0.05¢	0.05¢	0.01¢	0.03¢
Boundary	0.52¢	0.47¢	0.18¢	0.35¢	1.88¢	1.96¢	1.46¢	1.70¢

Summary of SIM for Indiana

- Expected DER penetration levels in Indiana will have minor technical and economic impacts on the distribution system.
- Most impacts of DER penetration are on generation and transmission costs, especially capacity to meet demand from unmanaged EV charging.
- Rate impacts continue to be positive, mostly due to assumptions about future utility “fixed costs” and rate increases needed to pay for them as retail sales decline due to DERs.
- Feeder clustering represents vast portions of the distribution system with a few representative feeders, allowing for detailed simulations.
- This framework could serve as a blueprint for joint distribution-BPS planning studies in other states.

Summary of framework

- The SIM framework develops integrated analyses of DER impacts on distribution, transmission, and generation domains of the power system and at the technical, economic (cost), and rate levels.

- The SIM approach addresses computational and regulatory challenges by:
  - Developing detailed adoption and operational profiles for DERs
  - Characterizing the distribution system through representative feeders that enable rigorous modeling of distribution system impacts across vast territories with reasonable fidelity
  - Applying a standard method for assigning DERs to customers and customers to feeders, and scaling feeders to the state level or other aggregations, which allows modeling and analysis in the absence of detailed customer data

- The framework can produce feeder-level and statewide estimates for DER-avoided or driven costs across all three domains of the power system.

Questions states can ask

- How consistent are assumptions for native load and DER adoption and operation between: (1) distribution planning studies and (2) bulk power system studies?
- How is DER adoption modeled in distribution planning processes?
  - What assumptions are made about drivers of adoption in terms of costs, incentives, and behavior?
  - Where applicable, how do these assumptions map to bulk power system assumptions for similar technologies such as solar PV and storage?
- How is DER operation modeled in distribution planning processes?
  - What drives different operational patterns for each type of DER?
  - How diverse are the operational patterns?
  - How are these patterns reflected at the bulk power system level?
- How would a whole-system planning analysis — including upstream benefits of DER — result in different non-wires alternative decisions for utilities compared to localized benefit-cost analyses, (assuming consistent assumptions)?
- Has the utility conducted analysis to identify feeders representative of the distribution system? How diverse are feeders on the utility's distribution system? For example, how many long rural feeders compared to shorter, urban, mostly underground feeders are there?

Resources for more information

- Overview of Power Sector modeling (DOE): https://www.energy.gov/sites/prod/files/2016/02/f29/EPSA_Power_Sector_Modeling_020416.pdf
- SIM-Indiana: Full LBNL-Nexant report https://emp.lbl.gov/publications/indiana-21st-century-energy-policy
- Indiana's 21st Century Energy Policy Task Force, for which the Indiana SIM was developed: https://www.in.gov/iurc/research-policy-and-planning-division/hea-1278-energy-study/
- SIM-LA100: The LA 100 project developed by LADWP and the City of Los Angeles with support from NREL is another SIM example: https://maps.nrel.gov/la100/report

Contact

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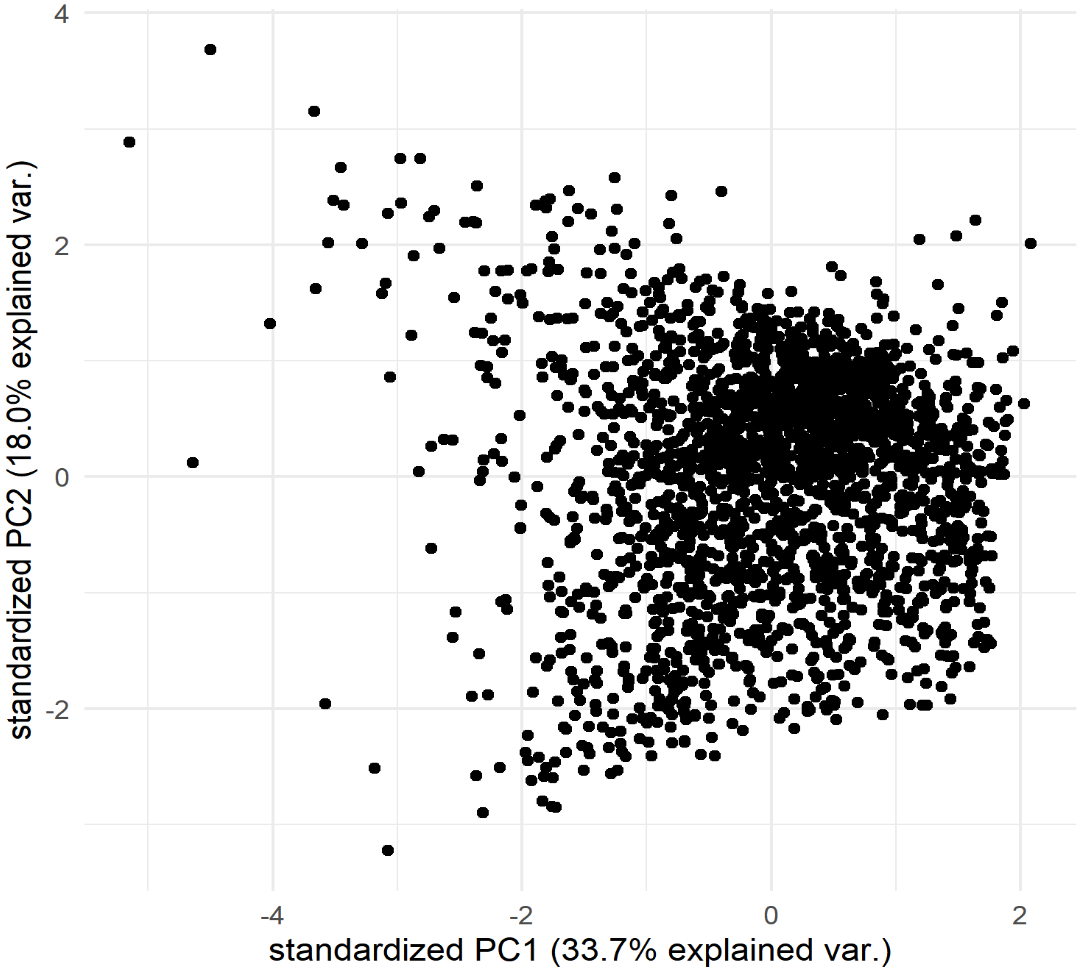
Extra Slides

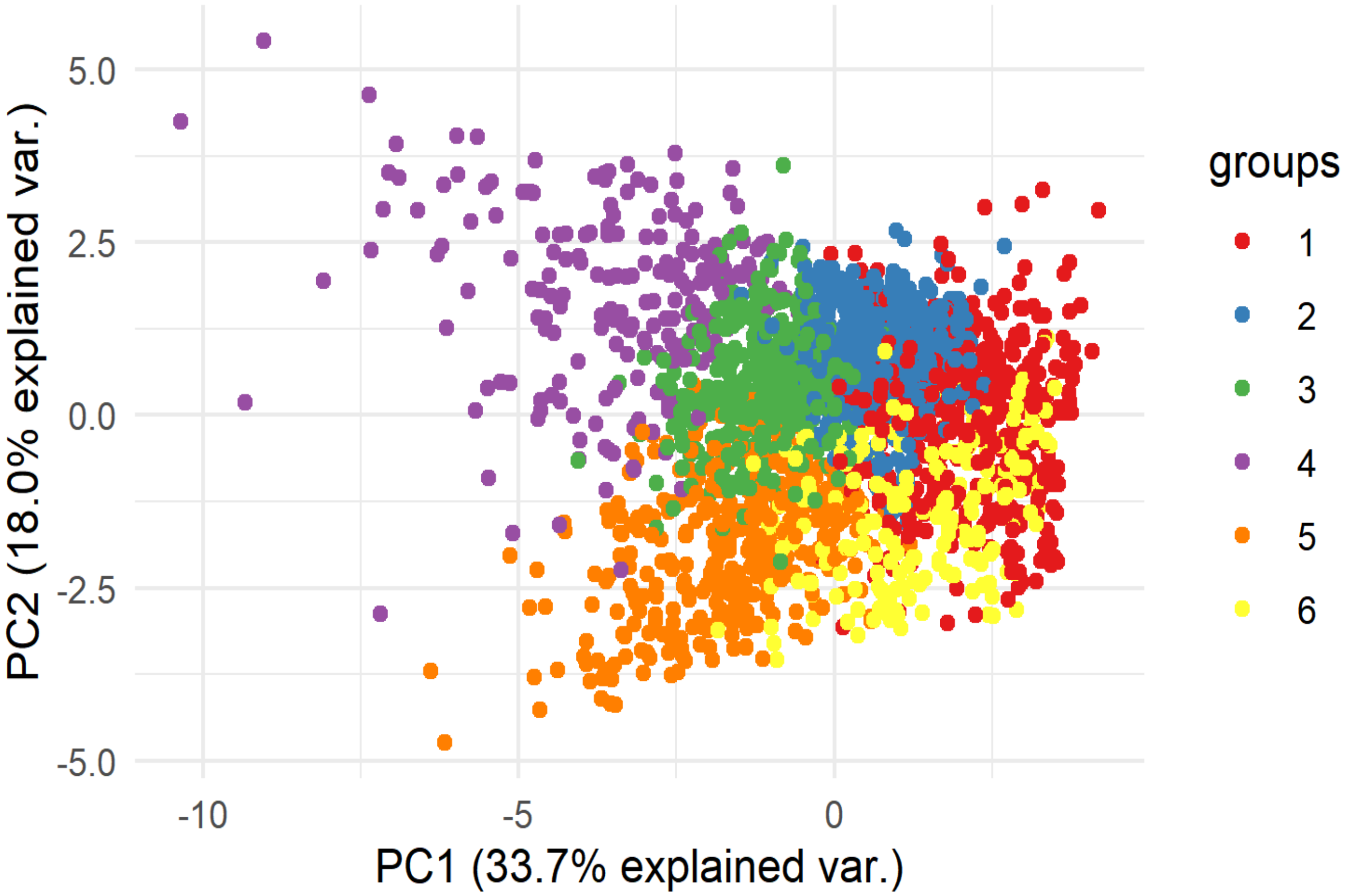
Feeder clustering – Pre-processing

- Pre-processing: Principal Component Analysis (PCA).
  - PCA is a method designed to extract and display the systematic variation in a data set (Broderick and Williams, 2013)
  - “PCA provides a roadmap for how to reduce a complex data set to a lower dimension to reveal the sometimes hidden, simplified structure that often underlie it.” (Shlens, 2005)
- Outlier detection using Mahalanobis distance



Feeder clustering - Results

- Partitioning Around Medoids (PAM) algorithm used to group feeders and create clusters.
- Used in similar work by Cale et. al (2014)



Selected feeder parameters for clustering

Parameter name	Description	Count	Mean	Standard deviation
poles	Number of poles	2,252	549	474
len_oh	Total overhead circuit length (miles)	2,252	13	14
len_ug	Total underground circuit length (miles)	2,252	6	8
agg_tr_cap	Aggregate MV/LV transformer capacity (MVA)	2,252	13,485	8,385
sh_cap_res	Share of connected capacity, residential customers	2,252	57%	30%
sh_cap_com	Share of connected capacity, commercial customers	2,252	29%	23%
sh_cap_ind	Share of connected capacity, industrial customers	2,252	9%	17%
sh_cap_other	Share of connected capacity, other customers	2,252	5%	10%
avg_caidi	Average feeder CAIDI (2014-2018)	2,252	137	55
num_cust_tot	Total number of customers in feeder	2,252	902	659
tot_len	Total feeder circuit length (Derived)	2,252	19	17
sh_len_und	Share of underground length from total length (Derived)	2,252	32%	26%

Annual energy consumption thresholds for DER adoption

		Residential		Commercial	
DER	Adoption level	2025 threshold level (kWh)	2040 threshold level (kWh)	2025 threshold level (kWh)	2040 threshold level (kWh)
PV	Base	50,000	41,000	75,000	34,000
PV	High	24,500	18,500	32,000	7,600
PV	Very High	21,000	14,250	18,000	3,000
EV-T1	Base	44,000	24,500	N/A	N/A
EV-T1	High	36,000	18,500	N/A	N/A
EV-T1	Very High	27,000	11,000	N/A	N/A
EV-T2	Base	34,500	18,100	N/A	N/A
EV-T2	High	28,200	12,800	N/A	N/A
EV-T2	Very High	19,350	4,700	N/A	N/A
Storage	Base	N/A	140,000	N/A	N/A
Storage	High	46,500	37,000	700,000	600,000
Storage	Very High	32,000	24,500	400,000	220,000

Method – Reliability impacts

- Reanalysis of historical outage data based on storage adoption levels, consumption levels, outage onset hour, and storage operational mode

Grouped circuits by cluster to examine outages by cluster → Applied customer types by circuit → Applied battery adoption assumptions by cluster, customer type, and scenario → Reduced individual outages by applying battery assumptions by:
- Onset hour
- Scenario
- Mode of operation

→ Calculated SAIDI, SAIFI, CAIDI reductions from baseline level

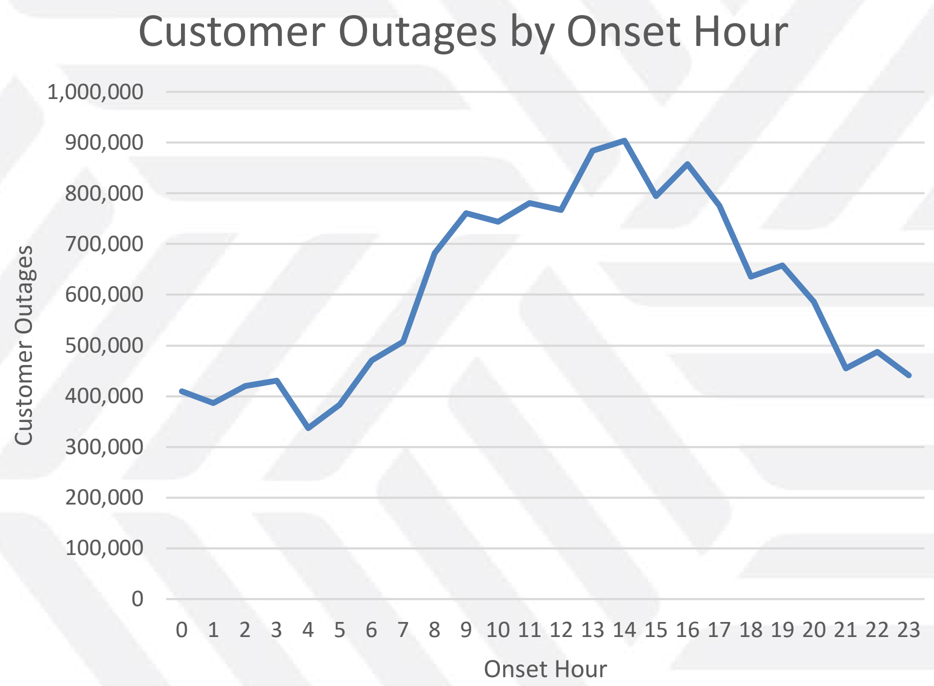
- Output: reliability impacts from a customer's perspective
- Assumes:
  - Only storage has a meaningful impact on reliability levels
  - No changes in consumption patterns during an outage (no conservation)
  - Base scenario electrification (very few EV)
  - A PV system for every storage system

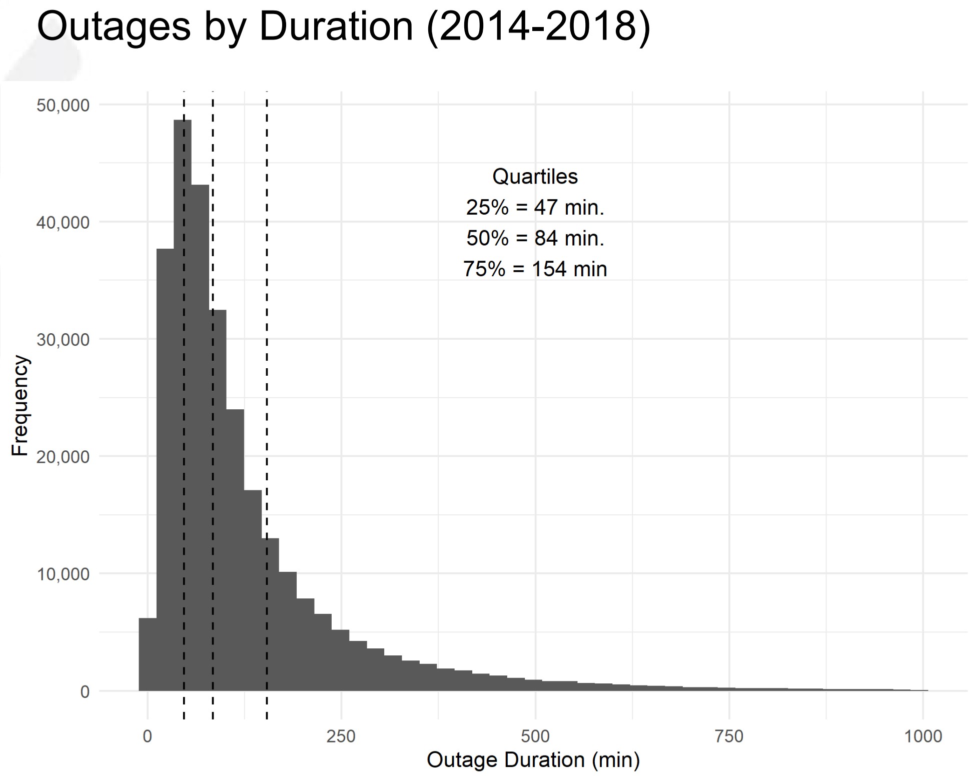
Method - Reliability Data Processing

- ► Five years of outage data + circuit characteristics from each utility
  - ■ Each row is an outage
  - ■ Each outage has a circuit or feeder, cause, number of customers affected, duration, etc.
- ► Cleaned data
  - ■ Uniformity: outage types, included/excluded outages, time frame (2014-2018)
  - ■ Removed outliers, momentary outages (<5 min.), major event days (MEDs)

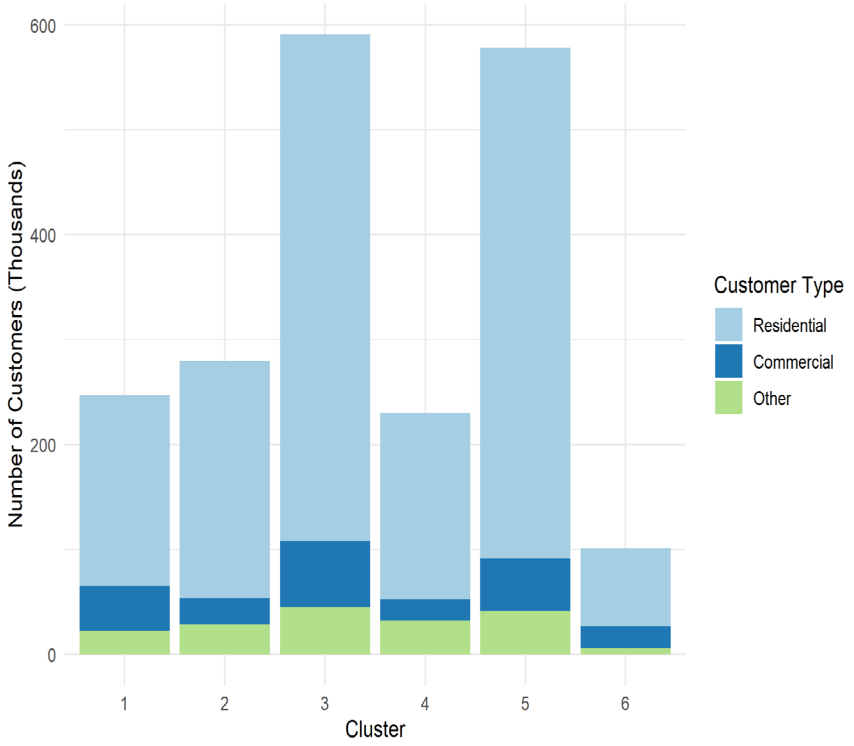
Outage Characteristics - Statewide

- ► More customer-outages occur mid-day than at other hours
- ► Outage duration has a long tail to the right

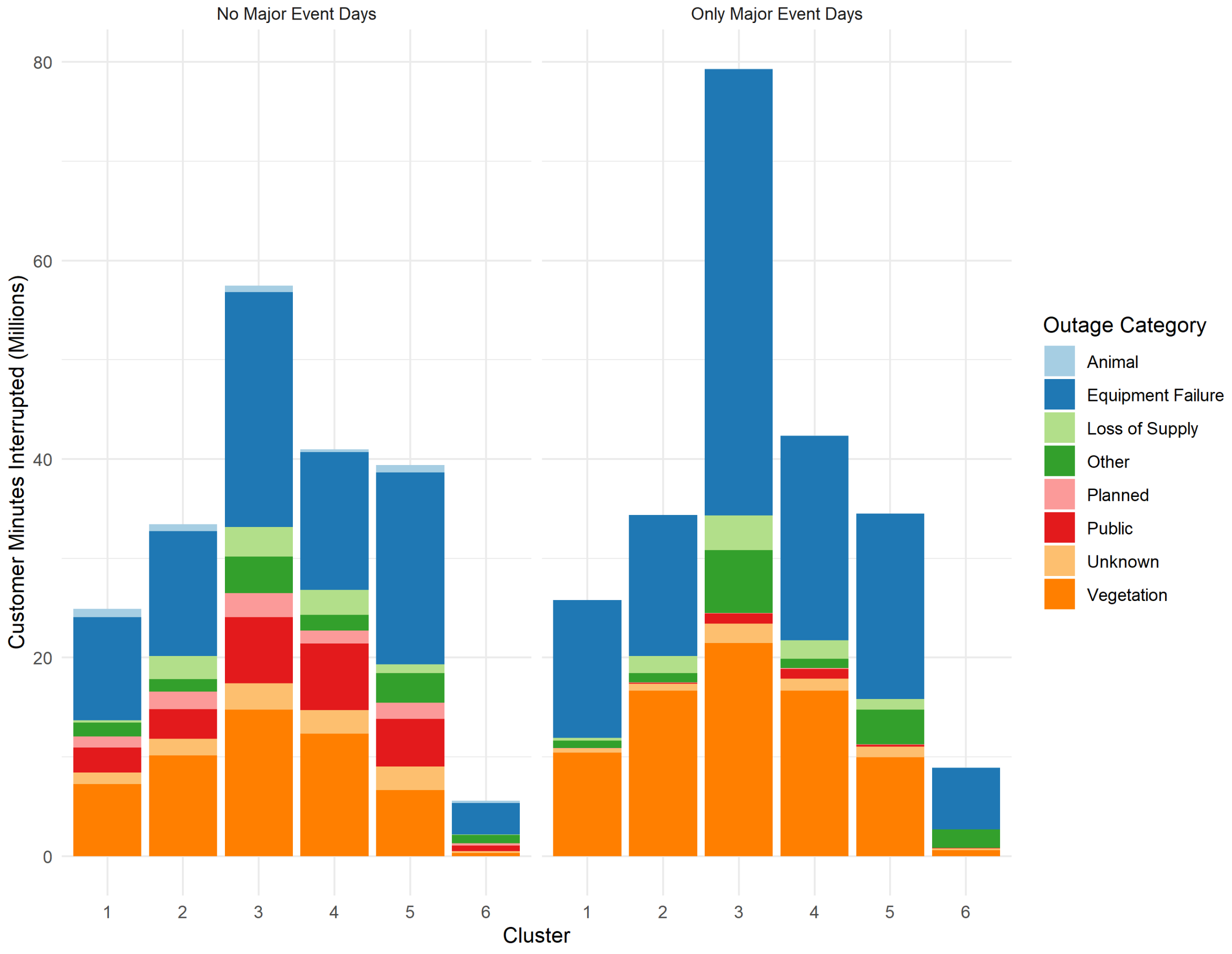




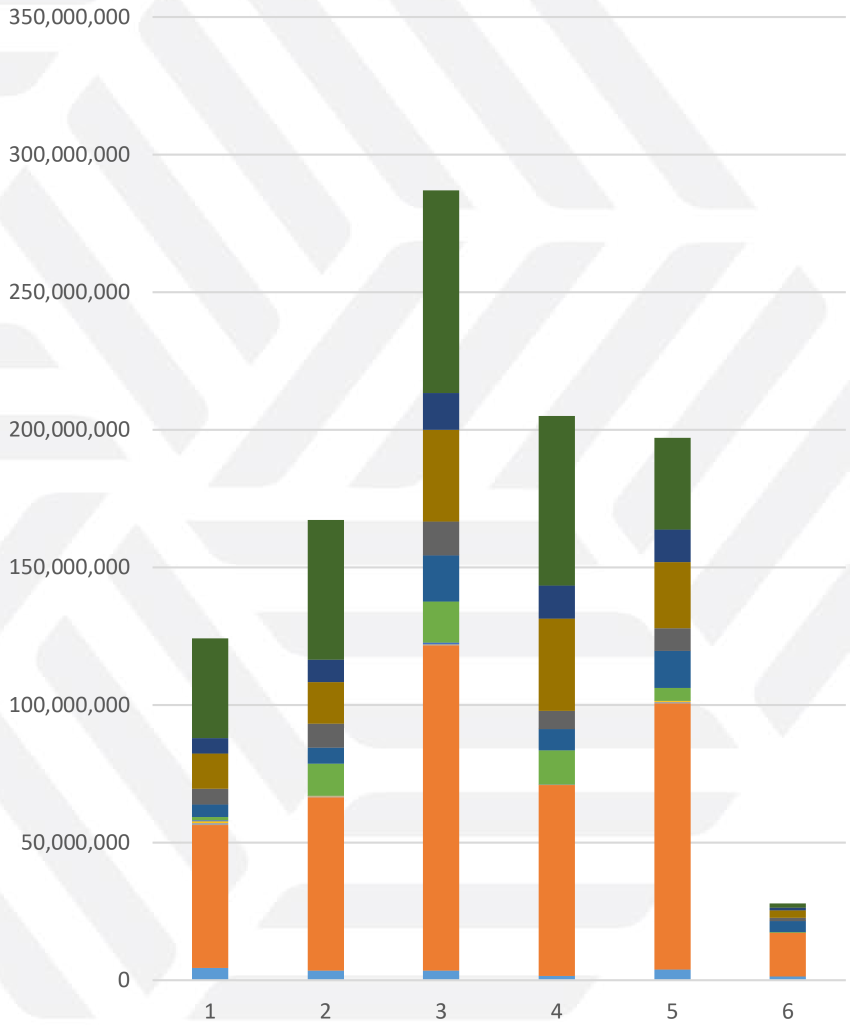
Outages by Cluster and Type (2014-2018)



Customer-Outages by Outage Type



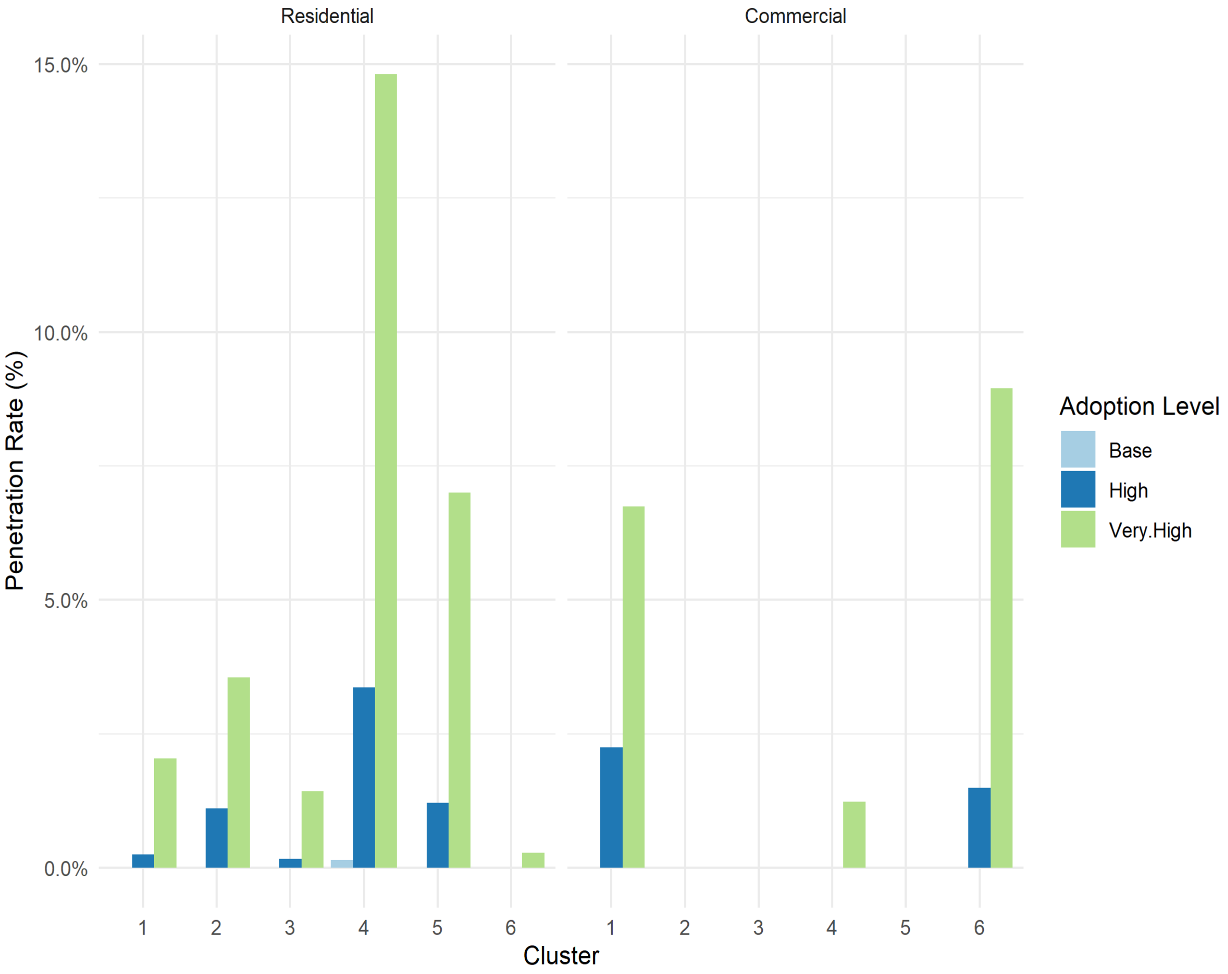
Customer Minutes Interrupted by Outage Type



Results Setup

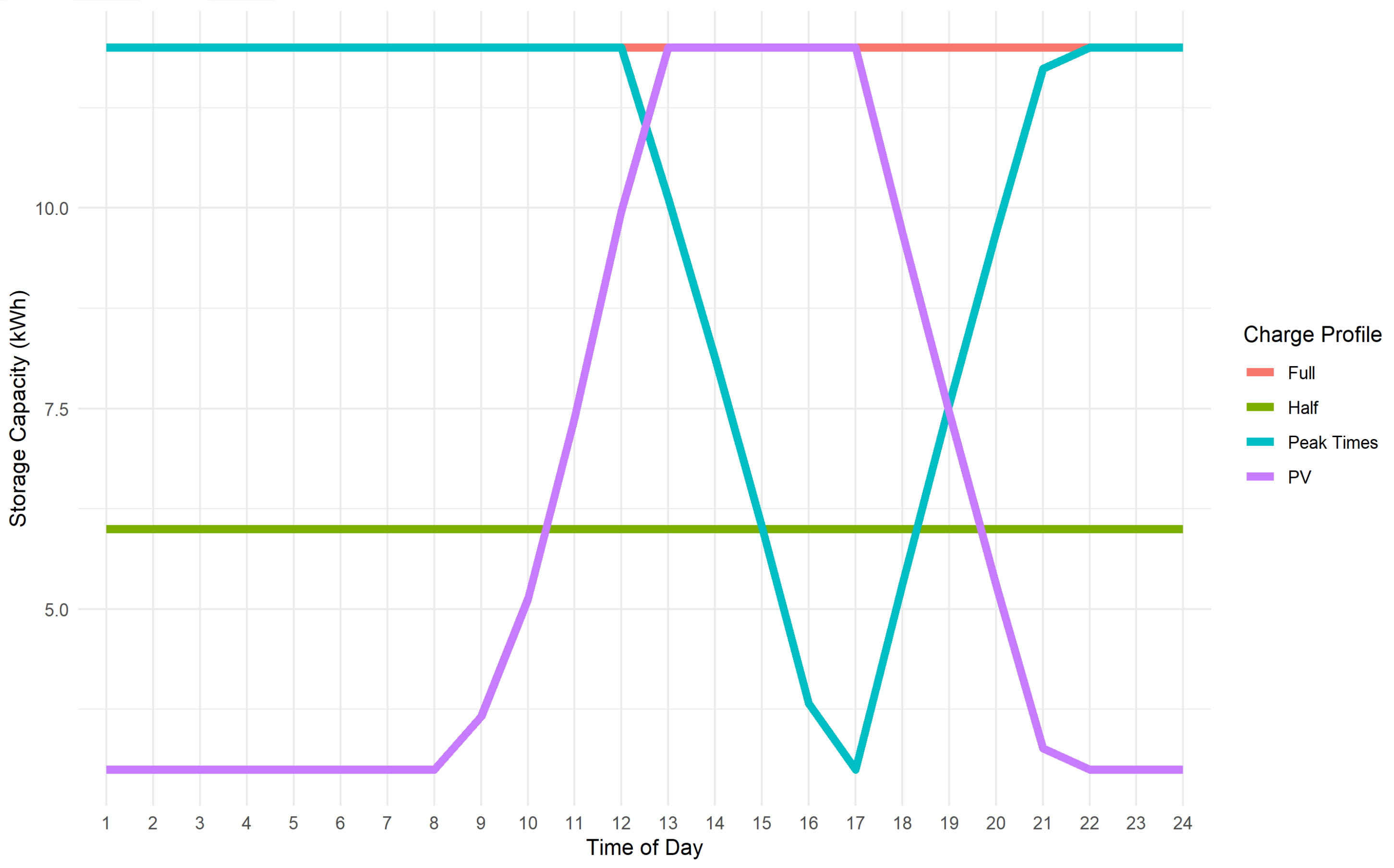
- 3 levels of storage adoption corresponding to the levels in the scenarios
  - Baseline/BAU: 0.01% overall
    - Scenarios 1, 2, 3
  - High: 1% overall
    - Scenarios 4, 5
  - Very High: 5% overall
    - Scenario 6
- Assumed battery capacity of:
  - 12 kWh for residential
  - 20 kWh for commercial

Storage Adoption by Cluster and Scenario



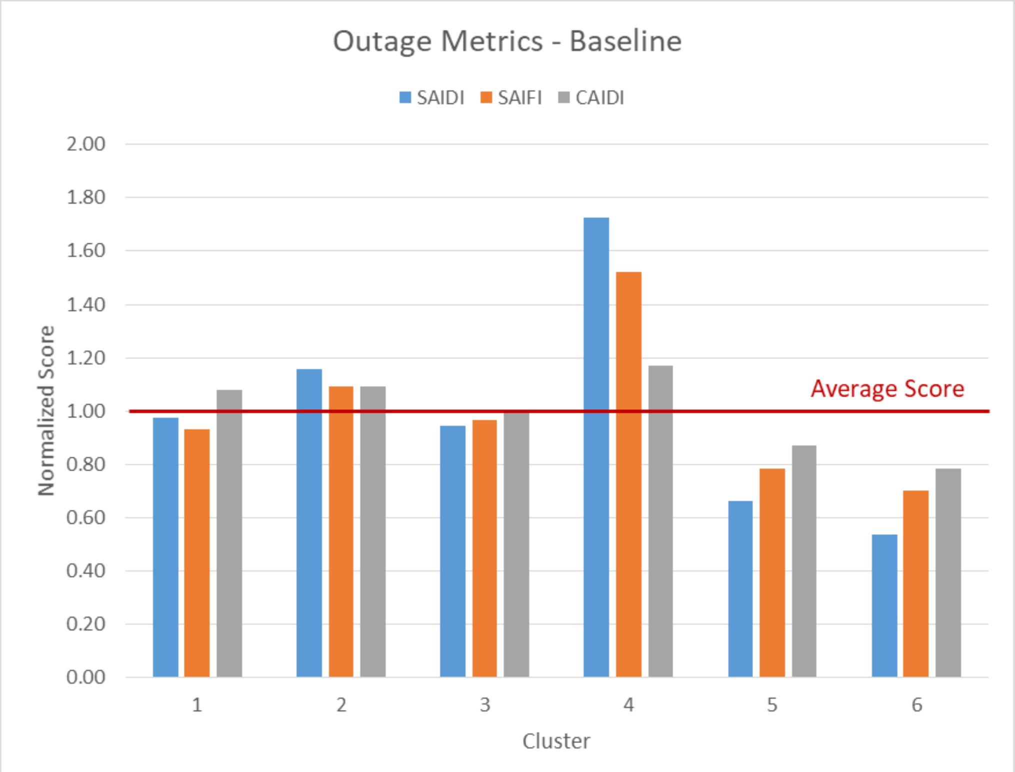
Available Storage Varies by Operating Mode

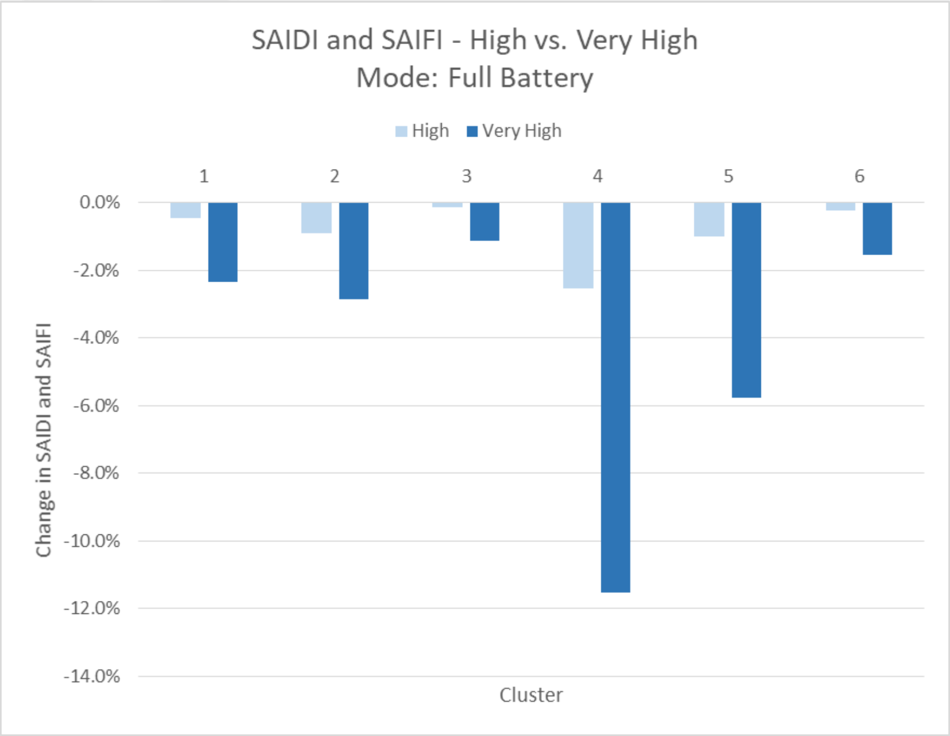
- Modes of operation:
  - Full: Battery only for outages – does not discharge otherwise
  - Half: Same as "Full" but with half of the capacity
  - Peak Times: Battery charges during off-peak times and discharges to offset on-peak
  - PV: Battery charges from PV system – net of on-site usage
  - Islanding: Similar to PV mode, but allows PV to continue operating during an outage



Results - Impact of Batteries to Customer-Perceived Outage Metrics

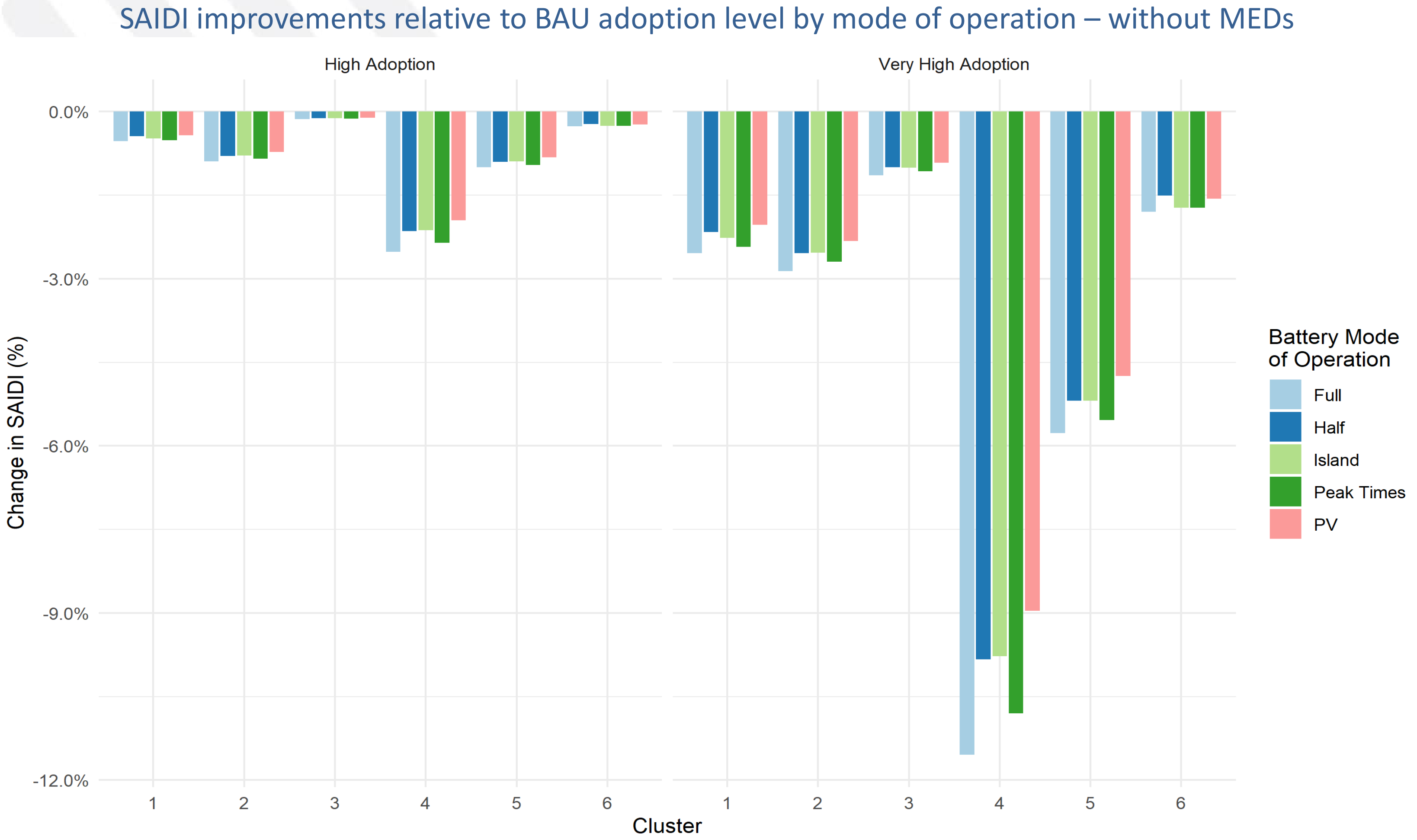
- Cluster 4 has higher SAIFI, SAIDI, CAIDI, while Clusters 5 and 6 are generally lower
- SAIDI and SAIFI improve most for Clusters 4 and 5, driven by residential adoption assumptions
  - No substantial changes to CAIDI





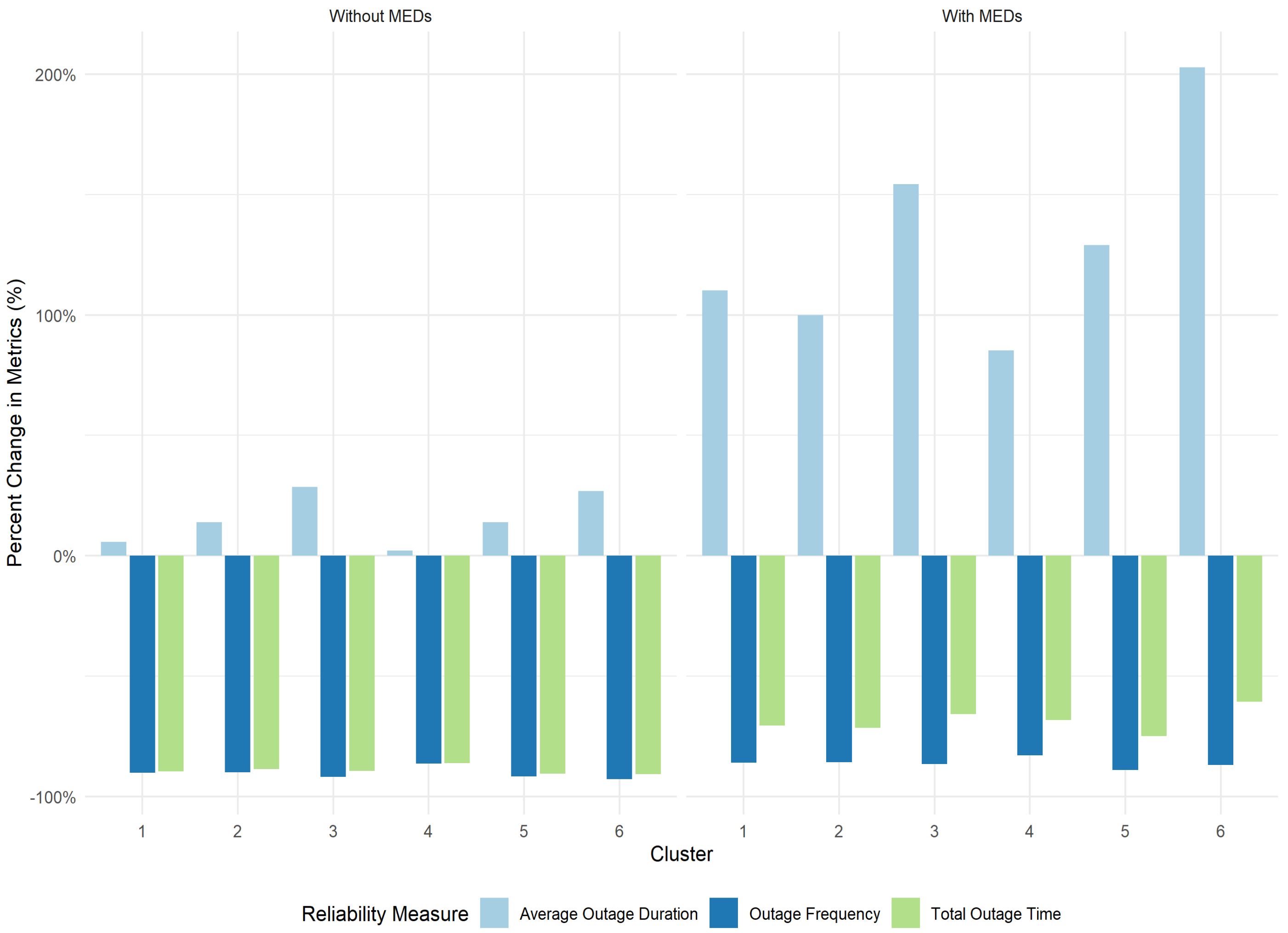
Reductions in Customer-Perceived SAIDI (and SAIFI) by Scenario and Battery Mode

- SAIDI and SAIFI reductions show similar magnitude for different modes of operation:
  - A mode of operation that offsets peak usage will have similar impact on system-wide outage metrics as full battery
  - Half-capacity batteries (6/10 kWh for Res/Com) mitigate outages almost as effectively as full capacity batteries



Outage Impacts for Battery Owners

- 80-90% reduction in outage frequency and total outage time
  - Consistent across clusters
- Average duration increases, likely because shorter outages were mitigated
  - Highest increases in Clusters 3 and 6



Results - Resilience

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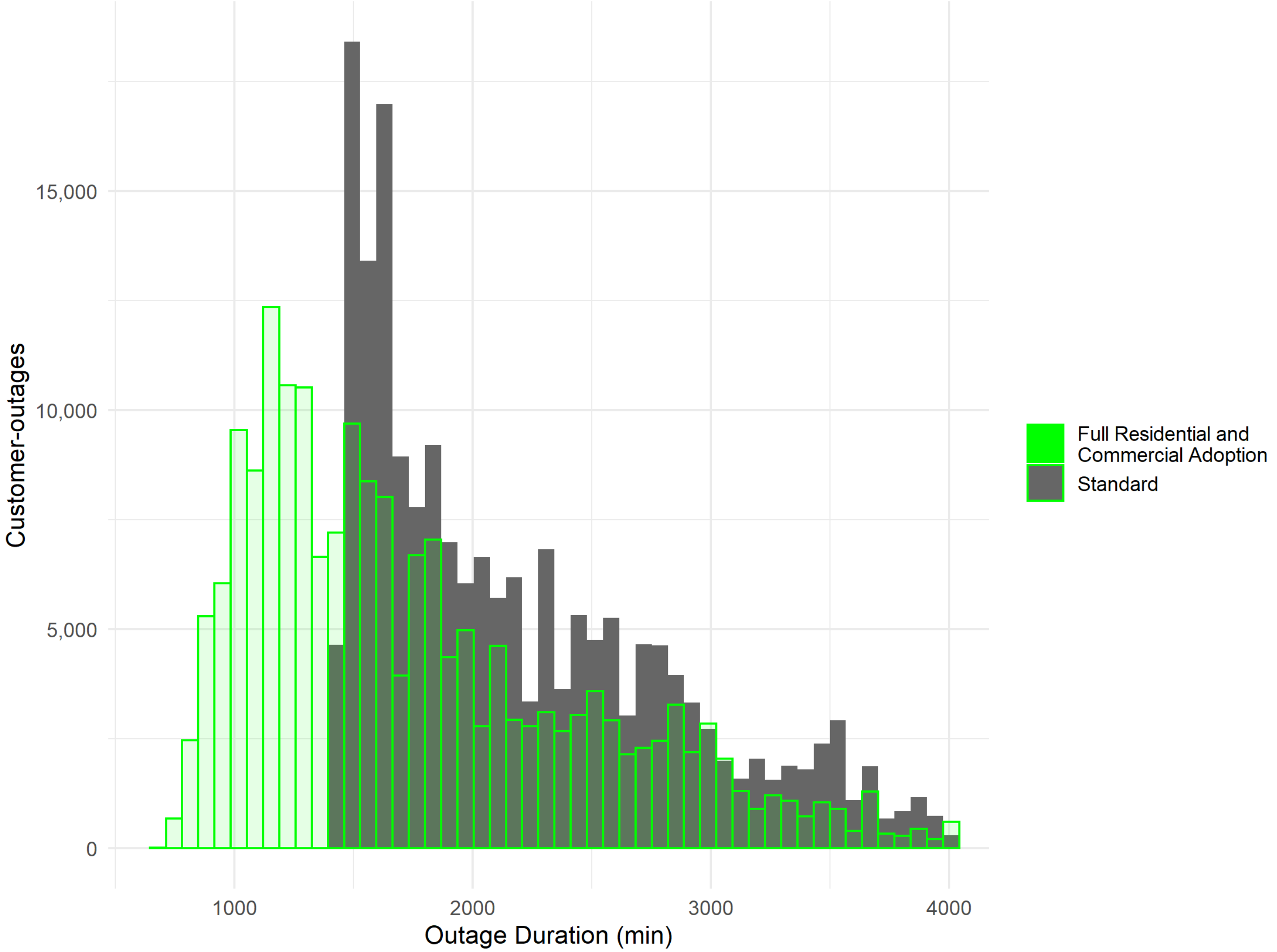
- Use a simplified metric of outages lasting more than 24 hours
- Widespread battery adoption for all res/com customers still leaves about 60% of long-term outages unmitigated
- Again, this assumes no conservation or DR strategies



Resilience impact of Very High level of battery storage adoption