Navigating Grid's Perfect Storm
Building a Reliable and Resilient Power System

Andy Sun
MIT Sloan School of Management
MIT Energy Initiative
December 10, 2025

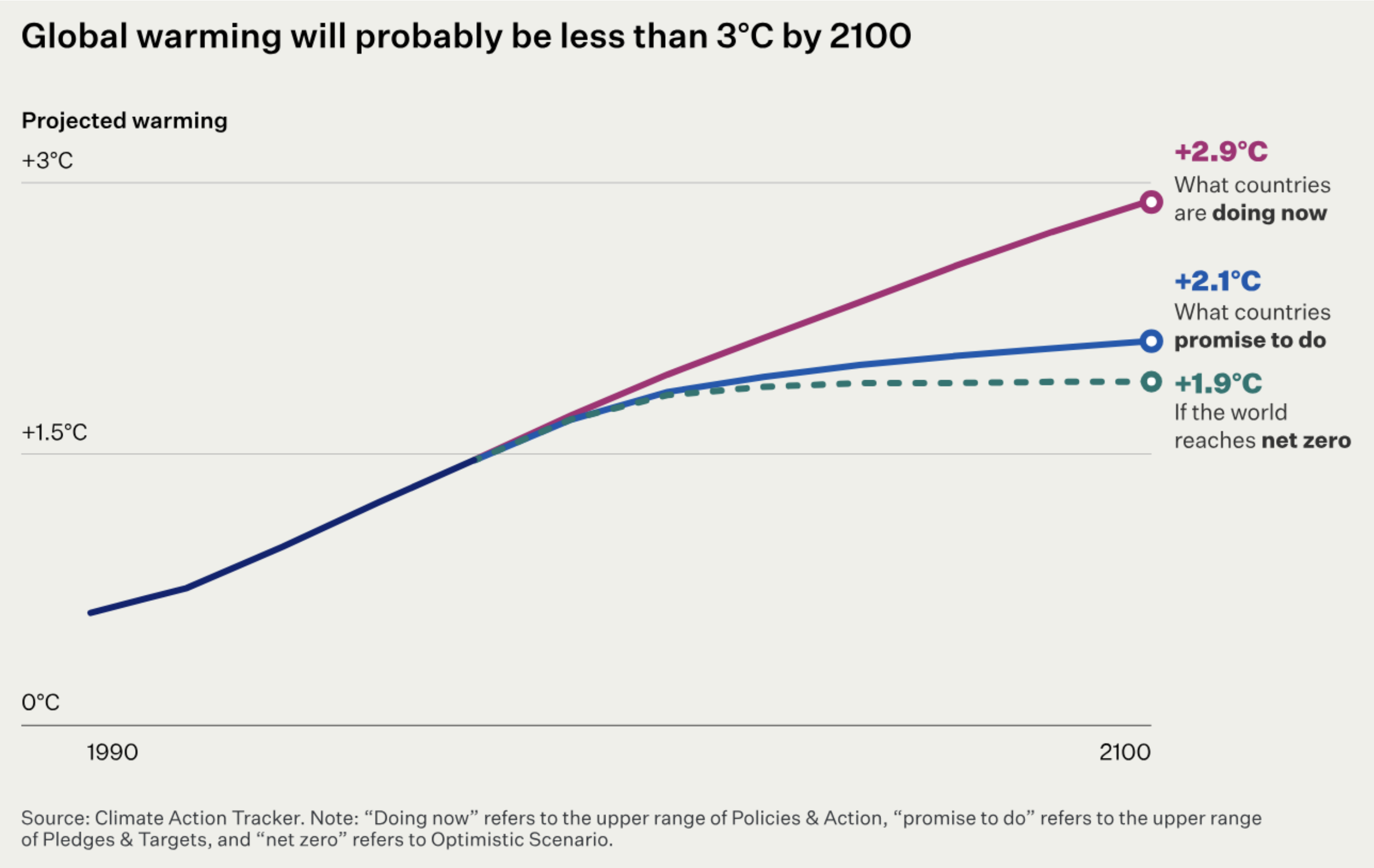
Presentation Agenda

1. Confluence of Fundamental Changes
2. Recalibrating Our Compass: Four Pillars
3. Deep Dive: Reliability
4. Deep Dive: Resiliency
5. Integrating Technology and Policy

Confluence of Fundamental Changes

Creation of the Perfect Storm

Global Warming: Trajectory & Near-Term Risk



Near-Term Forecast (2025-2029)

70%

Chance that the 5-year average warming will exceed 1.5°C.

(Up from 47% in last year's report)

Impact of Every Fraction of a Degree:

- More harmful heatwaves
- Extreme rainfall events
- Intense droughts
- Rising sea levels & melting ice

Visceral Threats: Extreme Weather Events

Climate change is a direct assault on physical infrastructure. Recent history provides stark examples.

Winter Storm Uri (2021)

Catastrophic gas/power failure in Texas.

(FERC, 2021)

Hurricane Maria (2017)

Complete grid collapse in Puerto Rico.

(GAO, 2018)

2024 Atlantic Season

Storms Milton & Helene caused outages for **8.4 million** homes and businesses.

Hurricane Ida (2021)

Most extensive outage in Louisiana history.

Italy (2023-24)

Floods in Emilia-Romagna (May '23, Nov '24) submerged infrastructure.

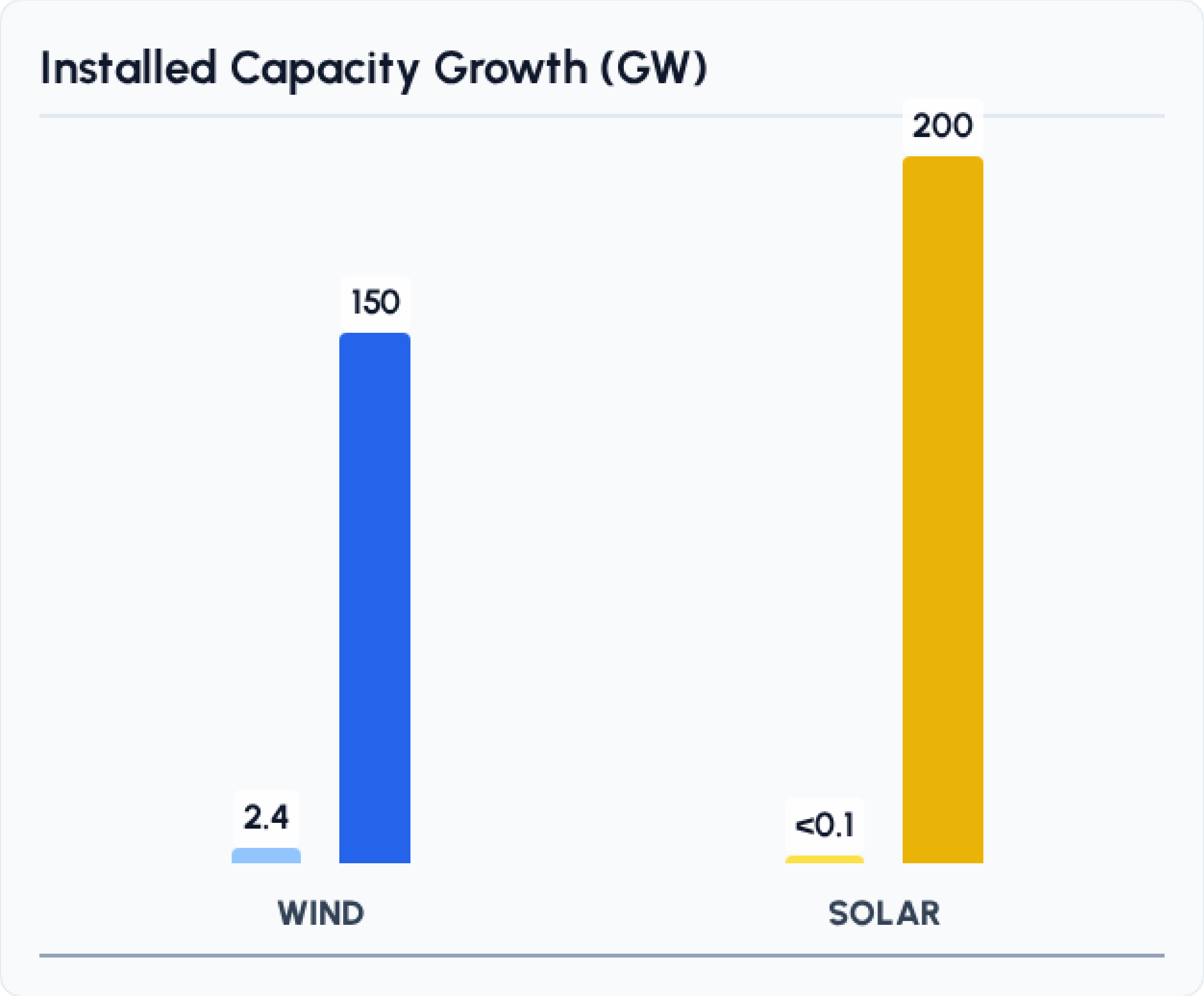
(Reuters, 2024a)

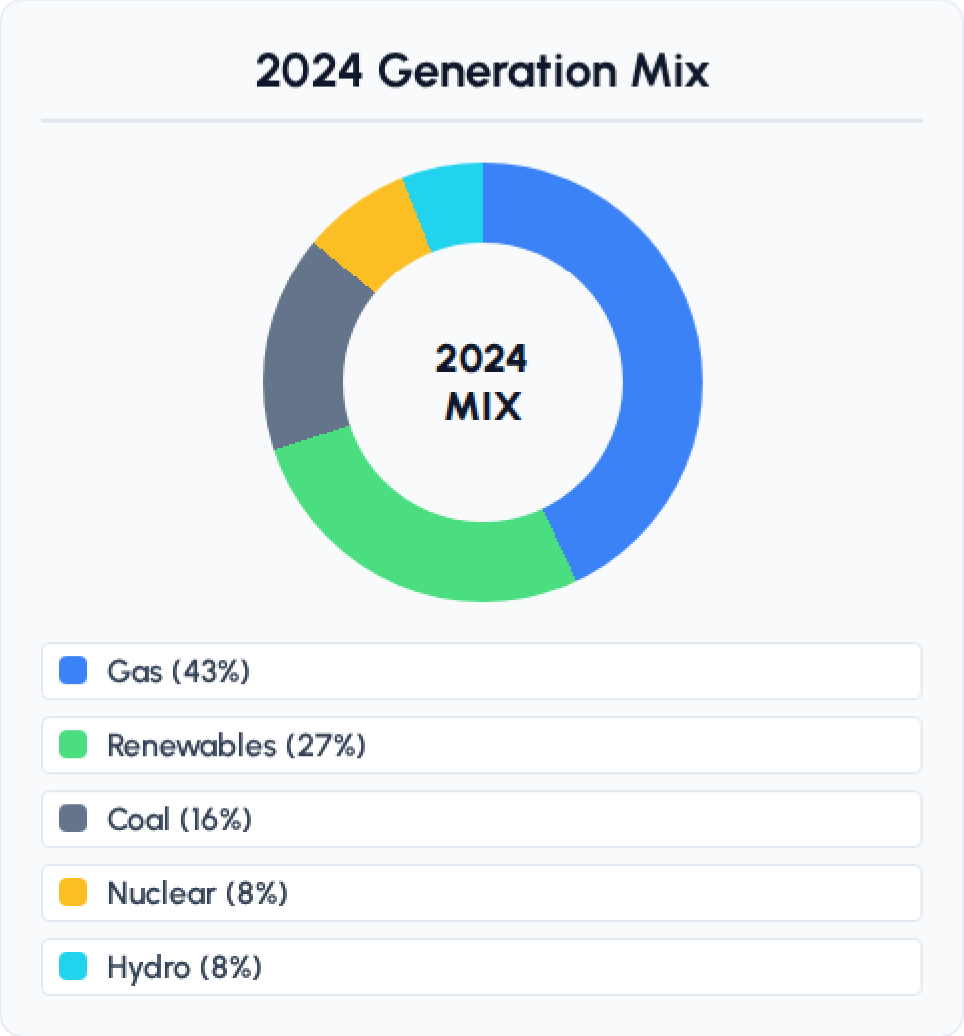
Brazil (2024)

Prolonged blackouts affecting millions due to heavy rain/winds.

(Reuters, 2024b)

Fast Growth: Generation Capacity in US (2000–2024)





The Storage Boom (2024): >30 GW

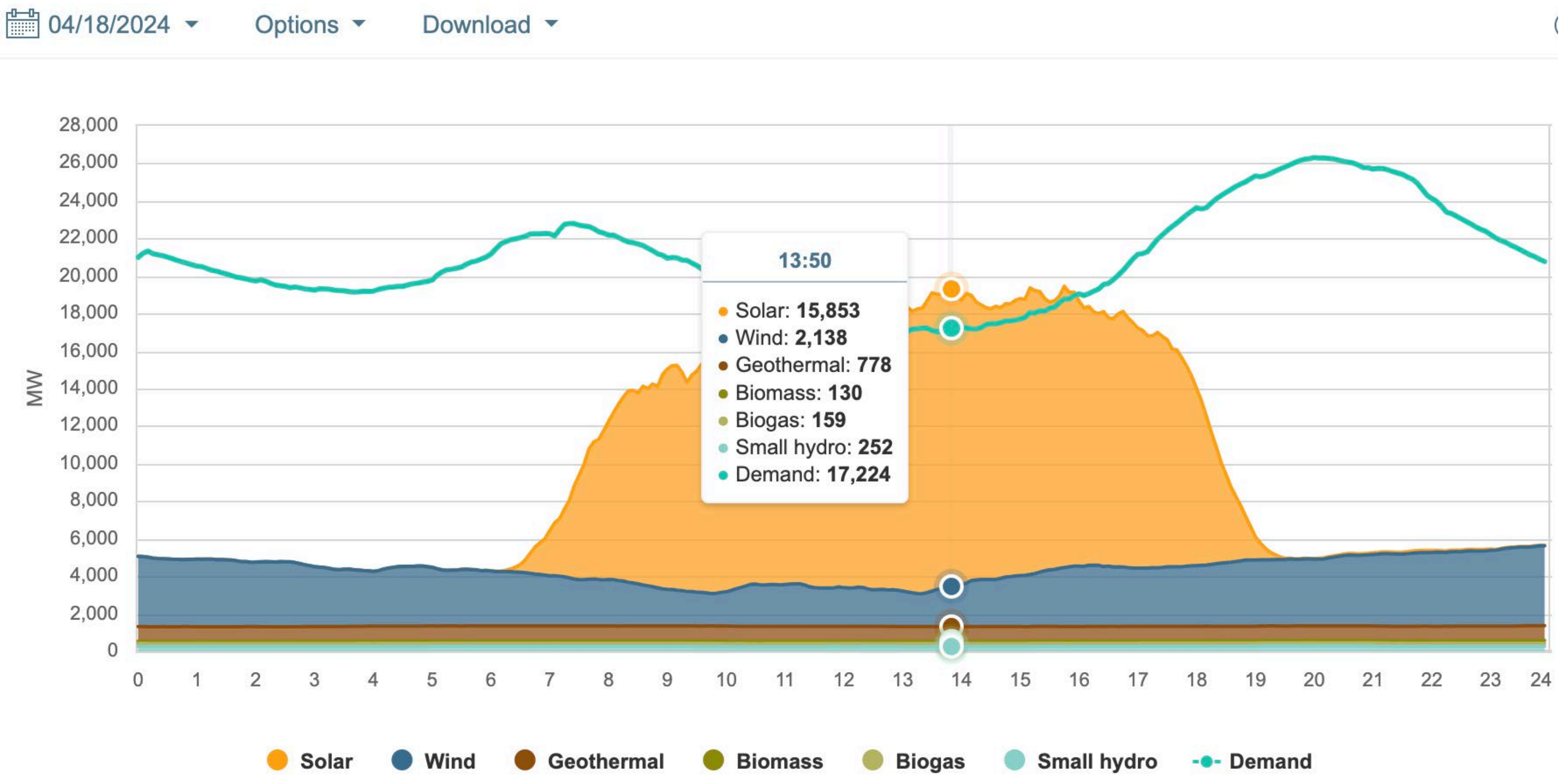
Projected 2030: >125 GW

California’s 100% Clean Electricity

California Grid Runs on 100% Renewable Energy for Over 9 Hours

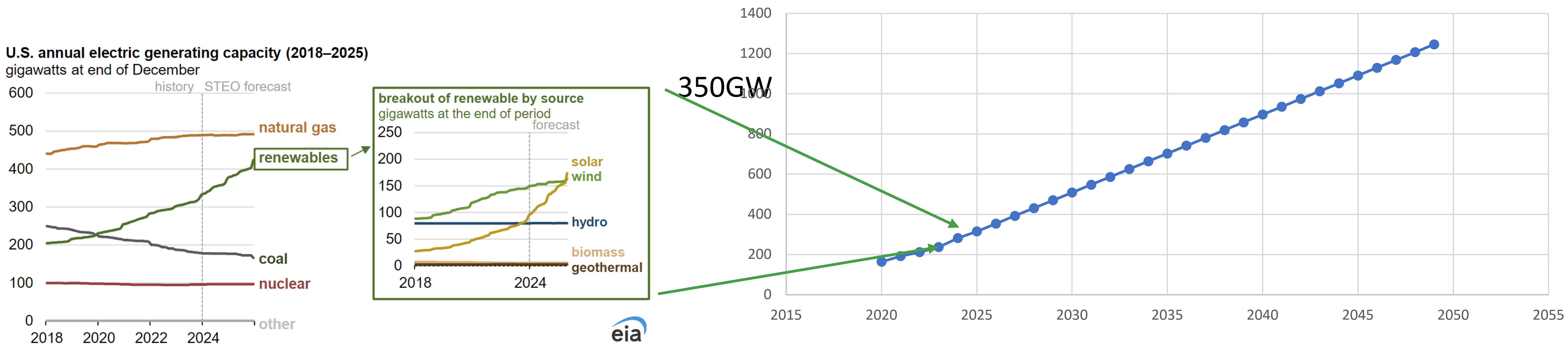
The state’s energy grid was entirely powered by clean energy for some portion of the day on 37 out of the last 45 days.

1 Minute Read
April 24, 2024, 12:00 PM PDT
By Diana Ionescu @aworkoffiction



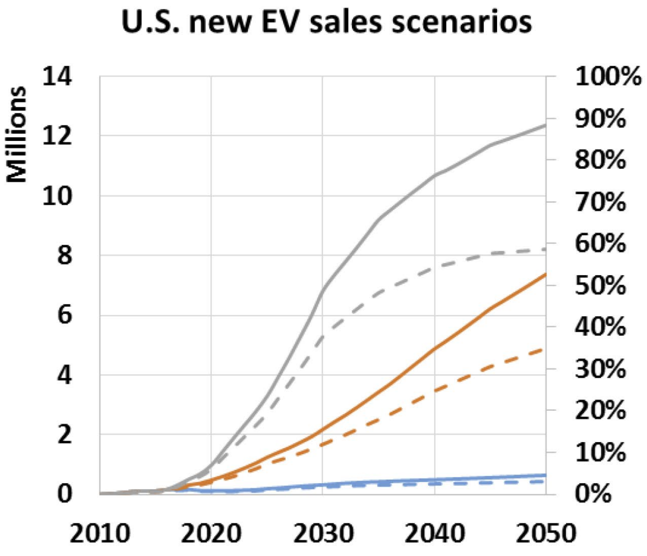
Electric Grid In Transition: Scaling Up Renewable

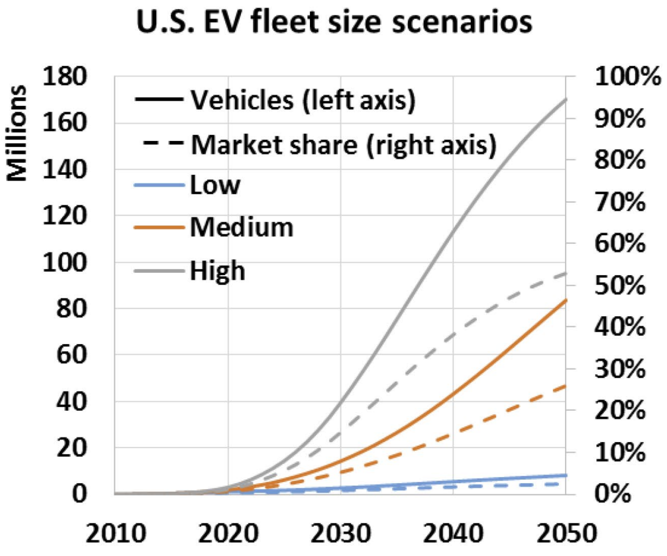
To Reach a **90% Renewable System across US**



"Electrify Everything": Transportation & AI

Electric Transportation



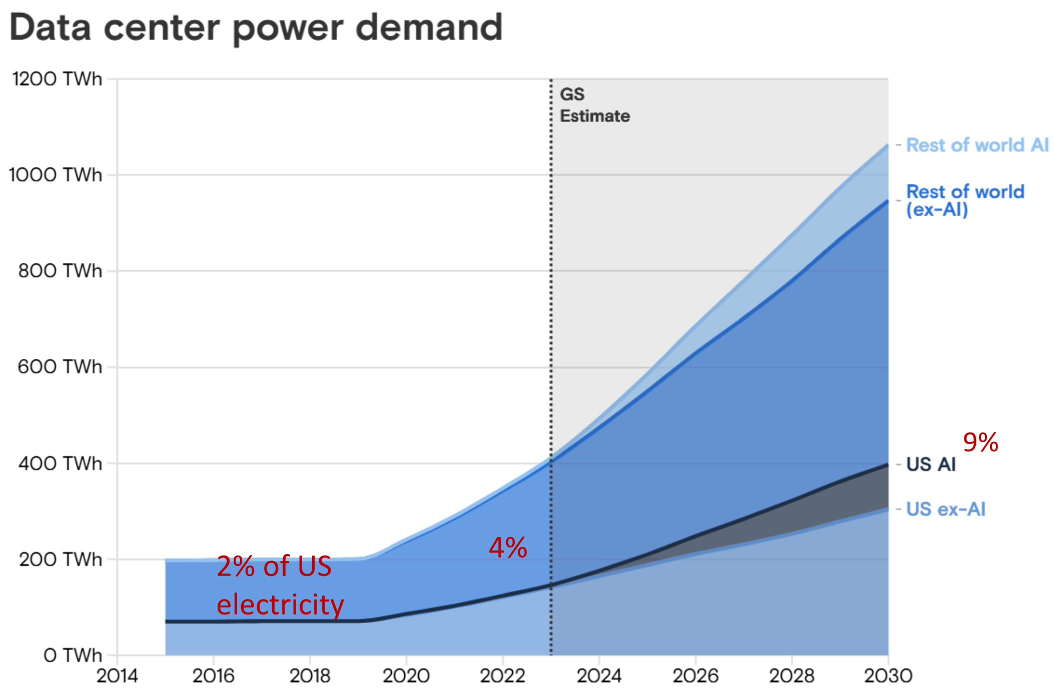


2030 EV sales
Low: 320k
Medium: 2.2 million
High: 6.8 million

2030 EV stock
Low: 3 million
Medium: 14 million
High: 40 million

Electric energy requirement: 1% - 3% of total generation by 2030

Artificial Intelligence = Energy



Electric energy requirement: 10% of total generation by 2030

The Surge: U.S. Data Center Power Demand

BloombergNEF Forecast (2035)

106 GW

Projected Demand

+36% Increase from previous April estimate.

Current Baseline (2024)

Operating Capacity ~25 GW

(Bloom Energy, 2024)

Growth Drivers

Scale is increasing rapidly:

- **150** significant projects announced in past year.
- **>25%** of new projects are larger than **500 MW**.

Geographic Shift: Diversifying beyond hubs (N. Virginia/Atlanta) to exurban regions in PA, Carolinas, Texas, and Midwest served by fiber trunks.

The Confluence: A Perfect Storm

Force 1: Intensifying Climate Risks

Physical Impacts on Infrastructure

- **Frequency:** "100-year" events becoming common.
- **Intensity:** Stronger hurricanes & heat domes.
- **Compound Hazards:** Simultaneous failure modes.

×

Force 2: Fundamental Grid Shifts

Supply Volatility & Load Surge

- **Renewables:** Variable supply, low inertia.
- **Load Growth:** Surge from AI & Electrification.
- **Complexity:** Intermittency, uncertainty, & steep ramps.

The Imperative

We must engineer a **Reliable and Resilient Grid** that can withstand the collision of these two fundamental changes.

Recalibrating Our Compass

Four Pillars

Core Concepts: The Four Pillars

Reliability

The ability to deliver electricity to all points of consumption, in desired amount, under **normal operating conditions**.

Resiliency

The ability to withstand and recover from high-impact, low-probability external hazards that push the system **beyond design limits**.

Flexibility

The capacity to quickly and cost-effectively respond to rapid and unpredictable changes in **net load** (supply/demand balance).

Efficiency

Maximizing **social welfare** by internalizing the full spectrum of costs (including outages and externalities) and benefits.

Defining Reliability: The Subway Analogy

Reliability is the **bedrock** of power systems. Think of it like a city's transit network:

Resource Adequacy

The Long Term: Do we have enough trains (generators) to carry everyone during rush hour?

System Security

The Real-Time: Can the system withstand a breakdown without a total collapse?

Power Quality

User Experience: Is the ride smooth? Maintaining voltage within strict tolerances.

Resiliency: A Paradigm Shift

Reliability (Traditional)

Focuses on preventing failures from causes **within** the system's design limits.

Resiliency (New Paradigm)

Focuses on performance when external hazards push the system **beyond** design limits.

- **Target:** "Black Swan" / HILP events.
- **Examples:** Major hurricanes, widespread wildfires, extreme cold snaps.

The Engineering Gap

The "N-1" Standard

Traditional planning assumes independent component failures. It uses probabilistic analysis of known risks.

The "N-k" Reality

Climate disasters cause widespread, **correlated failures** of many components simultaneously.

"Traditional frameworks are fundamentally ill-equipped for single events that cause massive, simultaneous infrastructure loss."

Flexibility: The New Critical Commodity

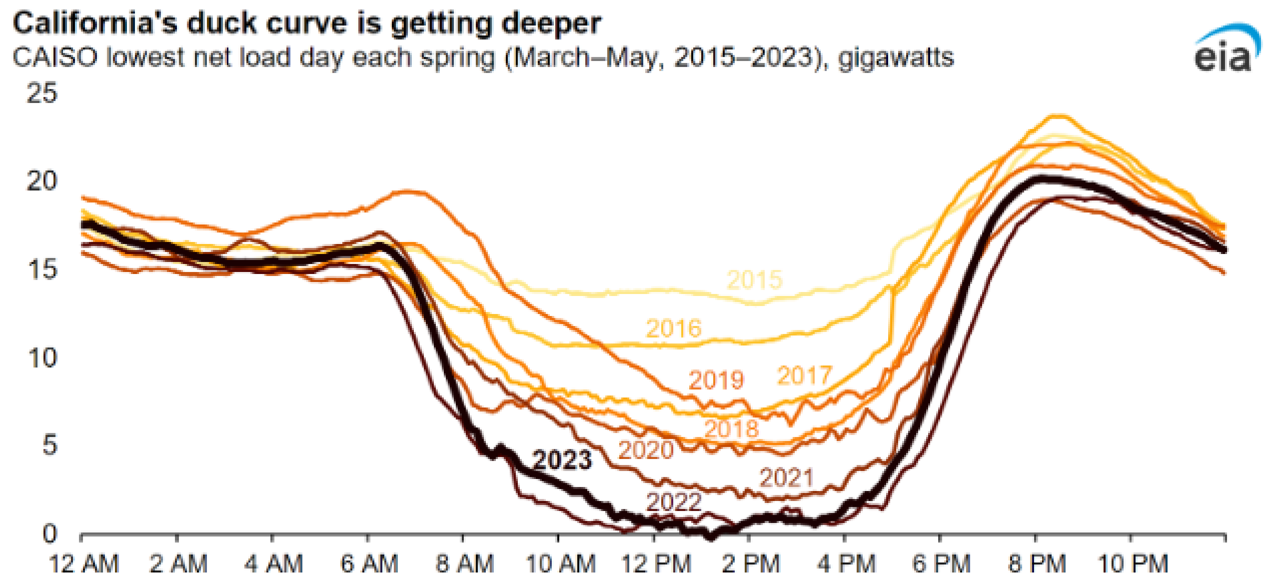
What is Flexibility?

The ability of the power system to ramp generation up or down rapidly to match the volatility of **Net Load.**

Flexible Resources

To fill the gaps left by solar/wind, we need:

- **Battery Storage:** Fast, accurate response.
- **Gas Peakers:** Sustained ramping capability.
- **Demand Response:** Shifting load off-peak.



Solar Generation

Midday solar floods the grid, pushing net load down. Traditional plants must ramp down or shut off.

The "Ramp" Challenge

Requirement: 13,000+ MW in < 3h.

Solution: Flexible Generation (Batteries/Peakers) must deploy instantly.

Efficiency: Multiple Objective Optimization

What is Efficiency?

Efficiency is maximizing social welfare while maintaining reliability.

Two Time Horizons

- **Operation (Short-term):** Dispatching the most efficient resources to meet demand while maintaining security.
- **Planning (Long-term):** Optimizing investment mix to meet future reliability standards at the lowest net cost.

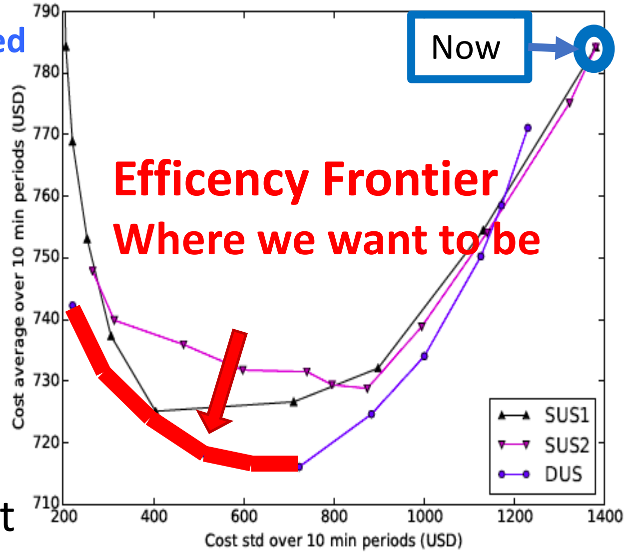
Real-time Social Welfare Maximization (ISO Control Room)

Current system can be improved
In both cost and reliability

Reliability

Achieving both

System cost



Recalibrating Our Compass: 4 Distinct Attributes

Reliability

Definition: The ability to deliver electricity to all points of consumption under normal stochastic operating conditions.

- Resource Adequacy (Long-term)
- System Security (Short-term/Real-time)
- Power Quality (Voltage/Frequency tolerances)

Resiliency

Definition: The ability to perform when external hazards push the system *beyond* design limits.

- "Black Swan" / high impact low probability events
- Strategies: Prepare → Bending without breaking → Intelligent restoration.

Flexibility

Definition: The capacity to quickly and cost-effectively respond to rapid, unpredictable changes in net load.

- Driven by variable renewables ("Duck Curve")
- Requires fast-ramping resources (batteries, peakers)

Efficiency

Definition: Maximizing social welfare by internalizing the full spectrum of costs and benefits.

- Reliability is a core economic value, not a luxury
- Multi-objective: Achieving both efficient costs and reliability

Deep Dive: Long-Term Planning

Market Mechanisms for Resource Adequacy and New Challenges

Securing Resource Adequacy

Integrated Resource Planning

Vertically Integrated Regions:

Utilities perform long-term planning (15–20 year horizon) to guide capital-intensive transmission and generation investments.

ISO/TSO Interconnection Studies

Deregulated Regions (ISOs/TSOs):

Decentralized investment decisions

Centralized transmission studies and some capacity markets.

Market Signals: The Supply-Demand Crunch

PJM Interconnection (USA)

Auction Year: 2026/2027

Clearing Price: Hit Regulatory Cap

Price Increase: +22% vs. Prior Year

Driver: Forecasted peak load surge from data centers & electrification vs. tight supply.

Single Electricity Market (Ireland)

Auction Type: T-4 (Year 2028/29)

Clearing Price: €149,960 / MW-year

Policy Change: Gas Plant Price Cap Lifted

Driver: Acute demand growth from data centers requiring urgent investment signals.

Ensuring Performance: Two Approaches

PJM: Capacity Performance

Philosophy Administrative Penalty ("The Stick")

Trigger Physical Emergency
Performance Assessment Intervals (PAI)

Must-Offer Strict daily bid obligation into Day-Ahead Market

Consequence Massive fines for under-delivery during emergencies

Focus: Punishing non-performance during critical physical grid stress.

VS

Europe: Reliability Options

Philosophy Financial Hedge ("The Option")

Trigger Economic Scarcity: Spot Price > Strike Price

Must-Offer Explicit bid rules (MGP/MSD) + Economic necessity

Consequence Difference Payment: Must pay back (Spot - Strike) if not running

Focus: Mitigating market power & forcing generation during high prices.

Future Capacity Market Design: Storage Challenge

"Snapshot" Models Fail

- **Static Curves:** Traditional markets assume Hour *t* is independent of Hour *t+1*.
- **Reality:** Storage fundamentally *couples* time. Charging now creates capacity later.

Demand curves for individual hours become invalid.

Multi-period stochastic optimization for capacity market clearing with storage, renewables, and fuel constraints: Ongoing collaboration with ISO-NE.

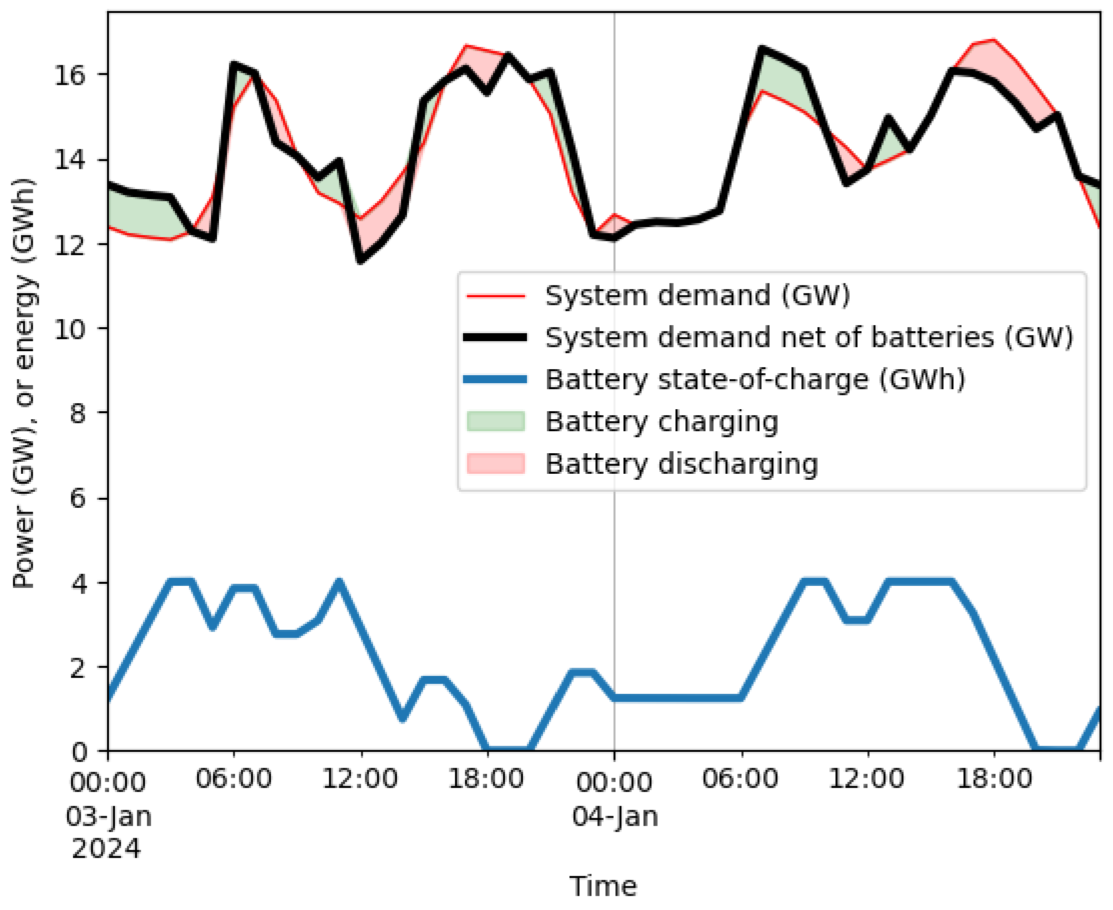


Figure: *4-hour duration Battery SOC vs System Load (T. Lee).*

CANOPI: A New Planning Tool

Contingency-Aware Nodal Optimal Power Investment

Continental-Wide Generation/Transmission Co-Planning

Continental-Wide Planning

Can we do it?

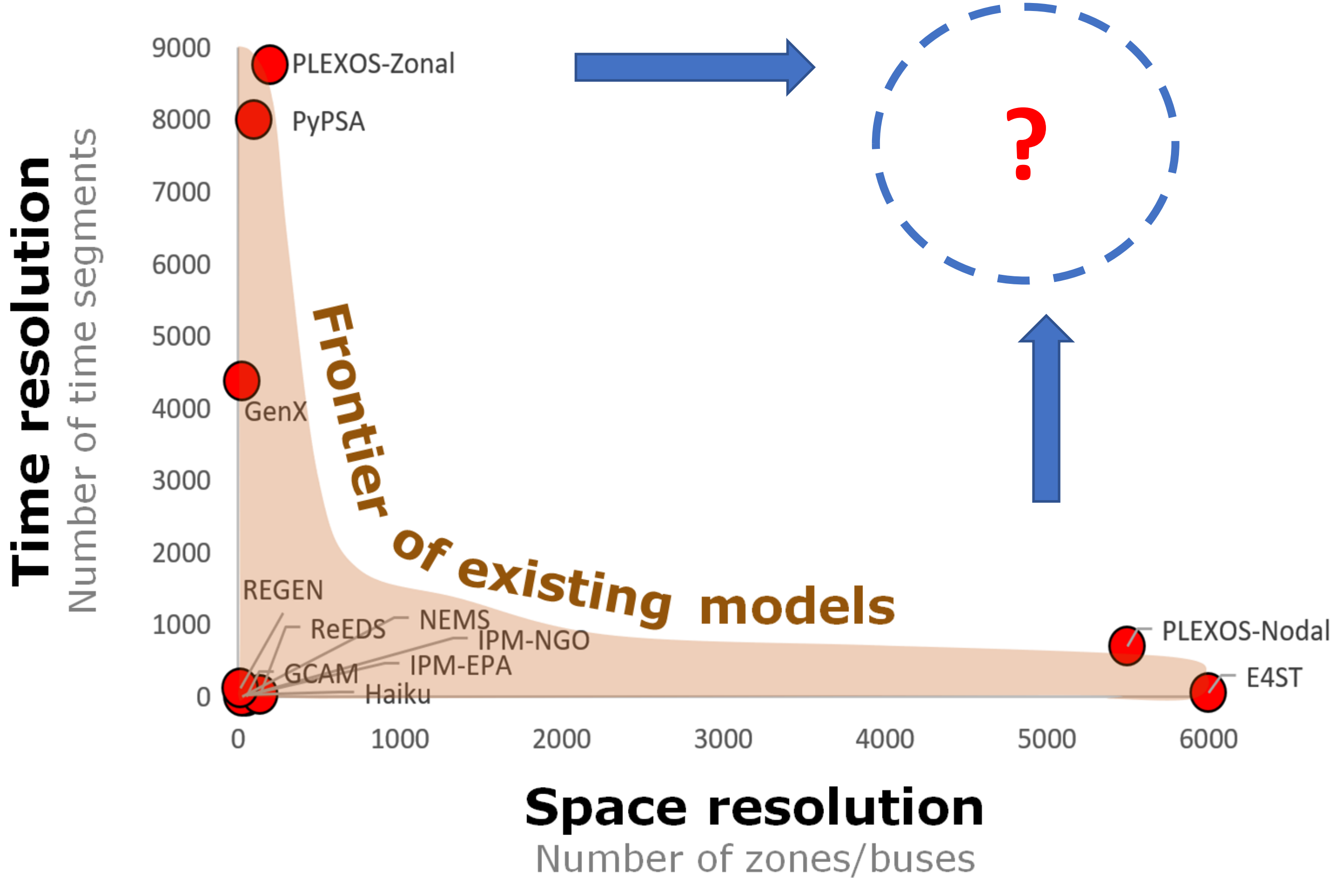
- Policy
- "Soft" technology: Computation

Benefits:

"Gold Standard"

High spatial and temporal resolution

- Better valuation of grid assets
- Better handling of uncertain scenarios



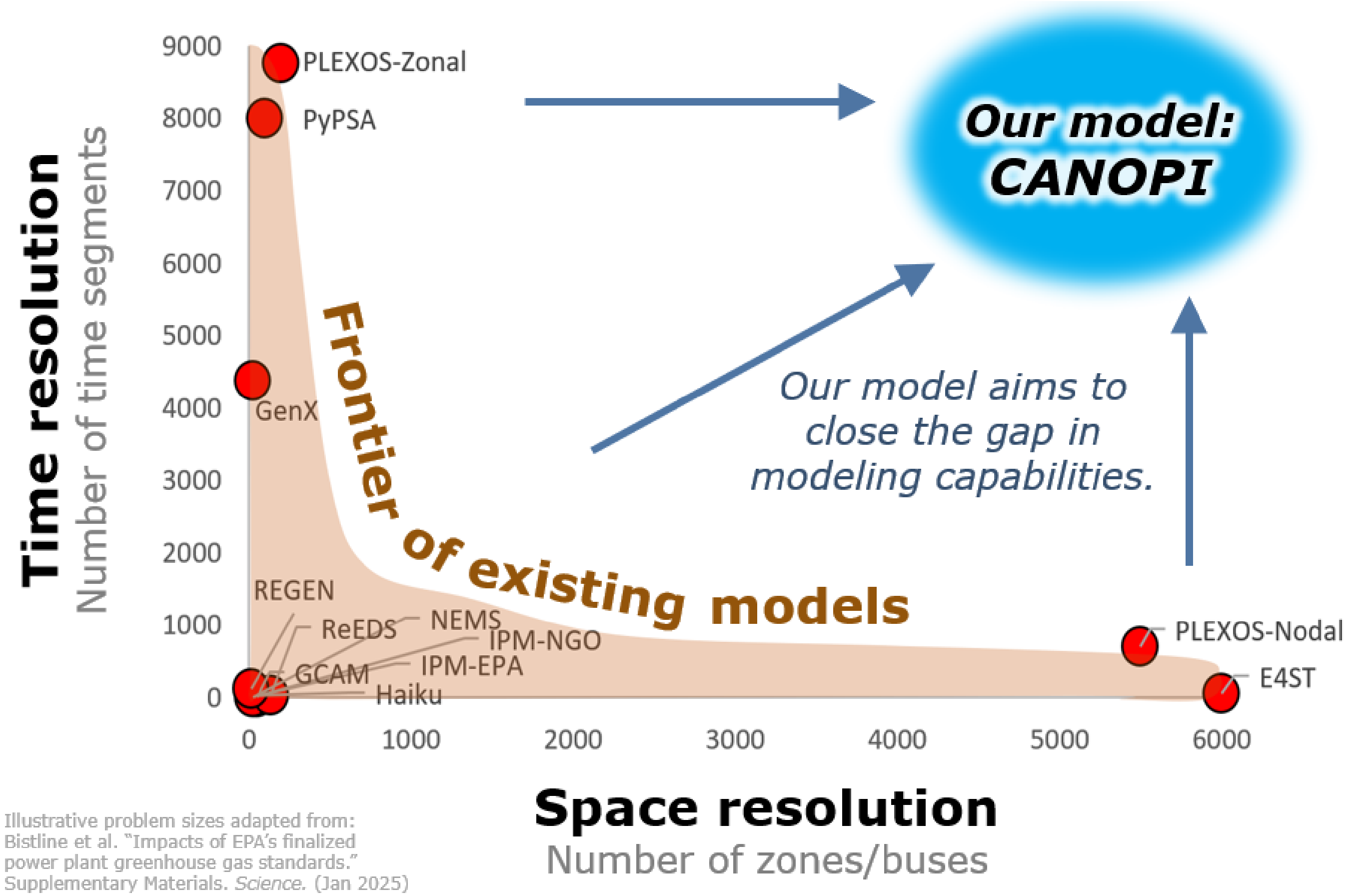
Continental-Wide Generation/Transmission Co-Planning

Continental-Wide Planning

Can we do it?
- Policy
- “Soft” technology: Computation

Benefits:
“Gold Standard”

High spatial and temporal resolution
- Better valuation of grid assets
- Better handling of uncertain scenarios

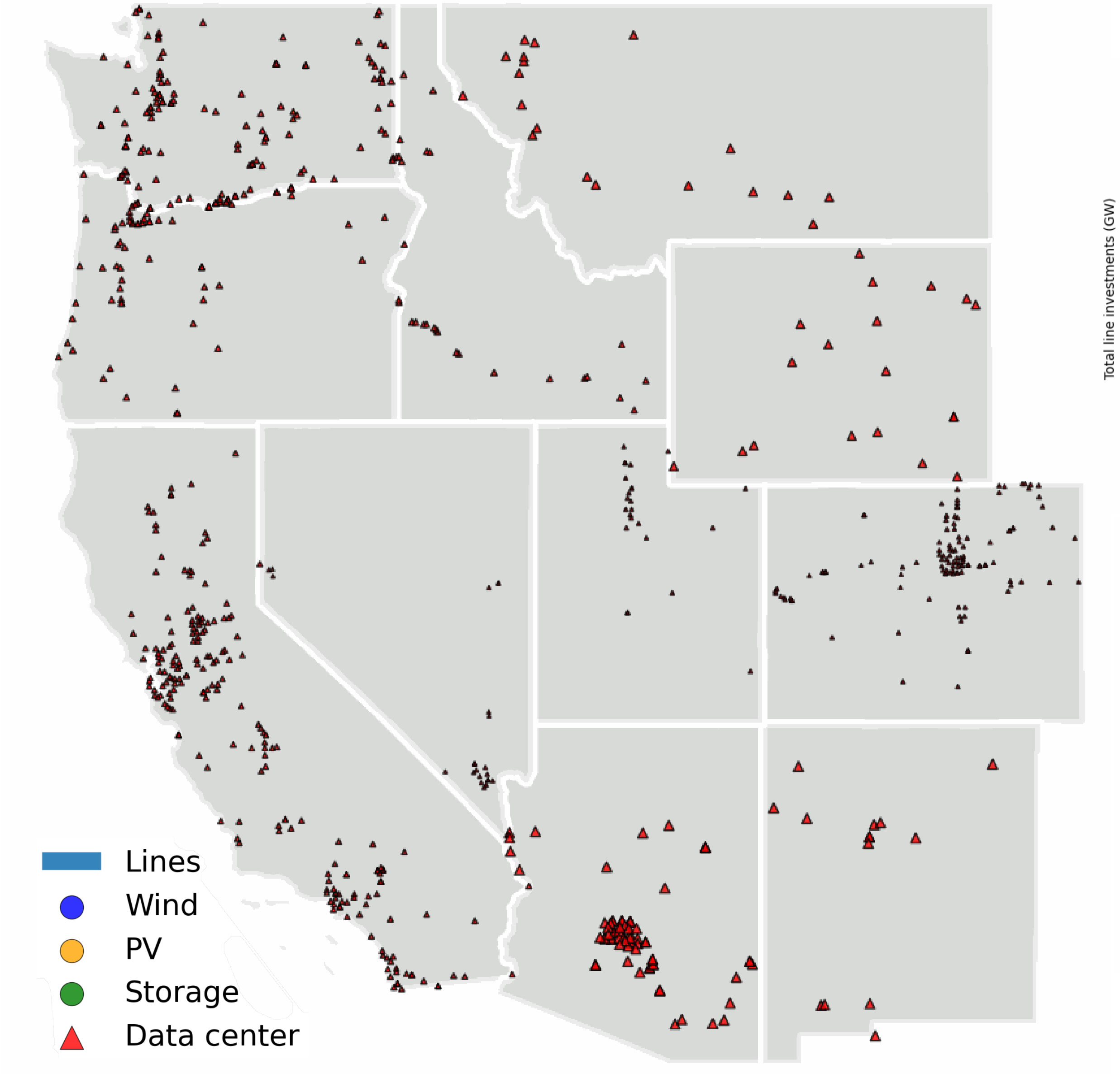


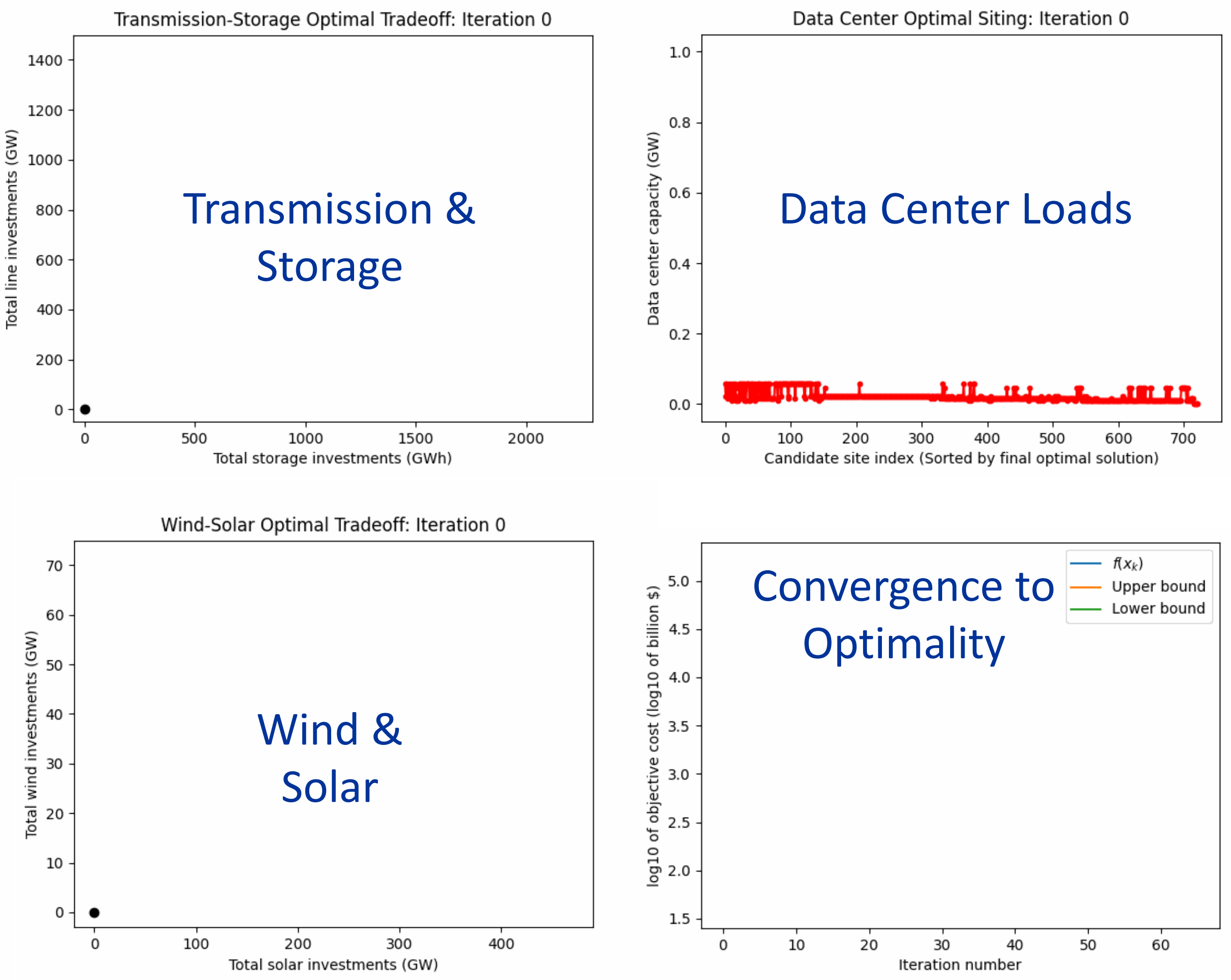
Illustrative problem sizes adapted from: Bistline et al. “Impacts of EPA’s finalized power plant greenhouse gas standards.” Supplementary Materials. *Science.* (Jan 2025)

Video Animation Demo:

CANOPI (**C**ontingency-**A**ware **No**dal **P**ower **I**nvestments)

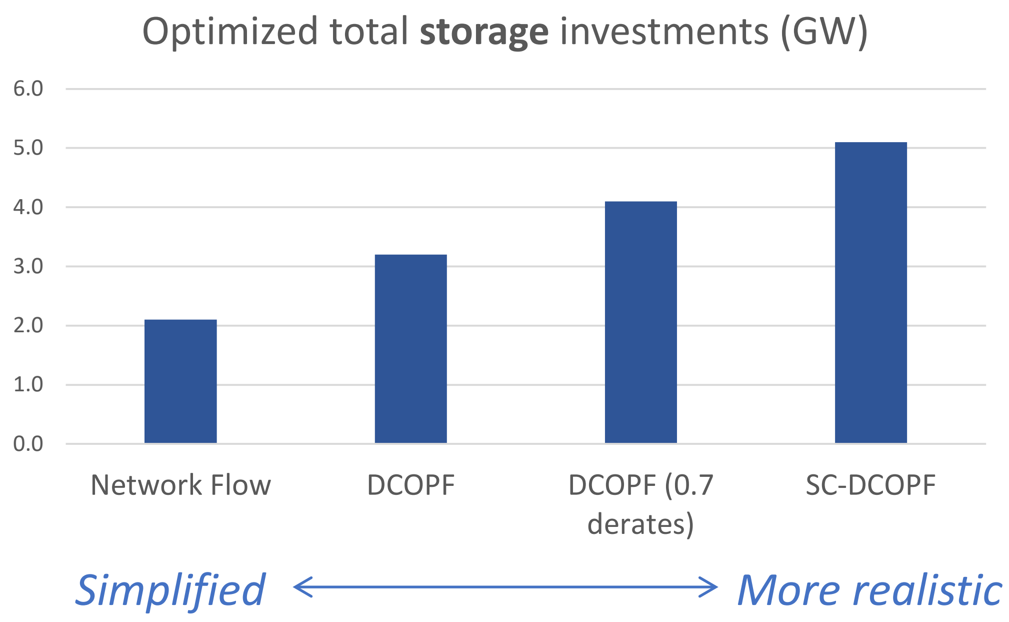
Co-Optimized Nodal Capacity Expansion with 8760-Hourly Resolution

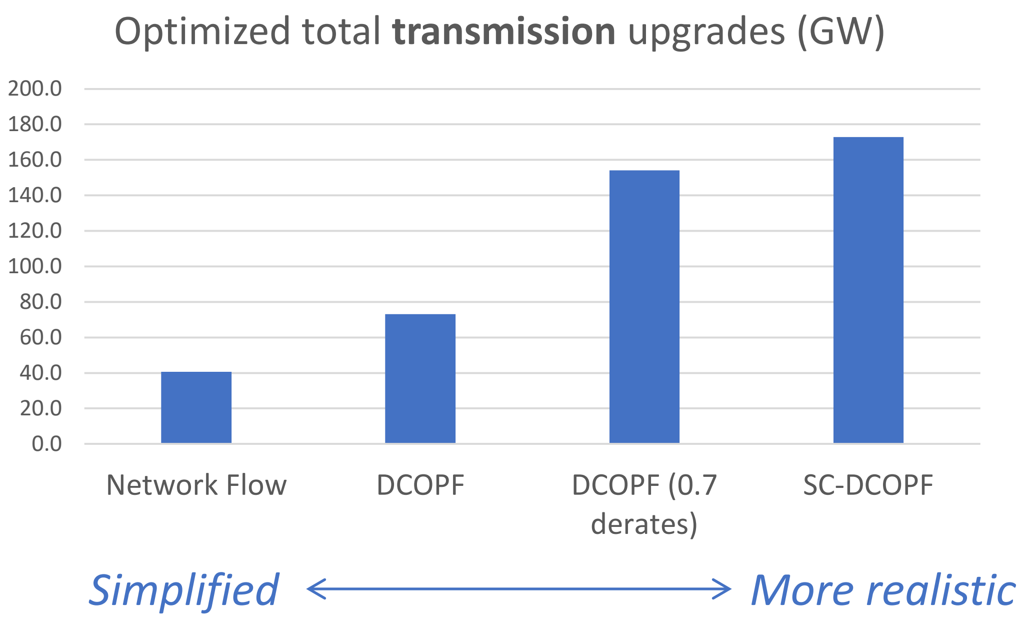




Why do we need CANOPI?

Part 1: Impact of grid physics on grid investments

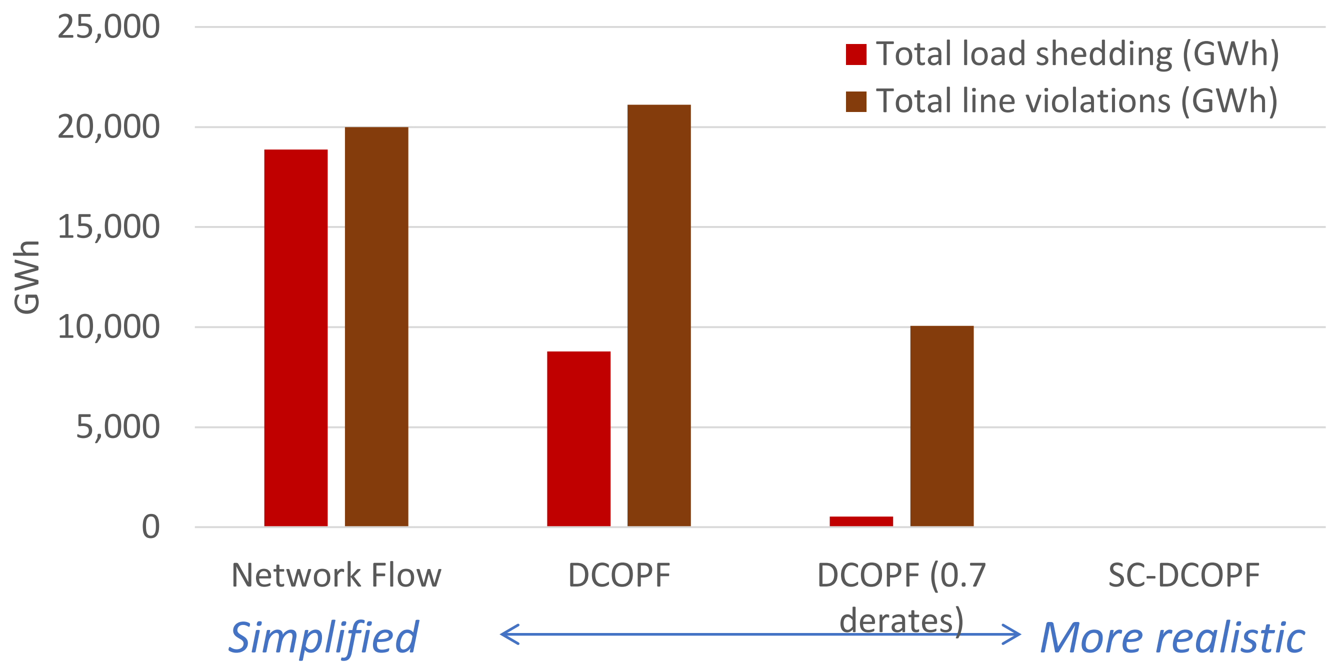




- Simplified models can **underinvest** in critical grid technologies, which exhibit strong locational and network values

Why do we need CANOPI?

Part 2: Impact of grid physics on grid reliability



- Simplified models' **underinvestment** can significantly **degrade reliability** through load shedding and transmission line thermal violations, once evaluated on a realistic simulation

Why do we need CANOPI?

Part 3: Impact of grid physics on *estimated* system costs

Simplified ⟷ *More realistic*

Grid physics representation	Network Flow	DCOPF	DCOPF (0.7 derates)	SC-DCOPF
Annualized total system cost *($ billion / year)* Estimated by the ***model itself***	17.9	18.1	18.9	18.7
Cost delta vs. SC-DCOPF *($ million / year)*	-811	-578	+141	0
Cost delta %	**-4.3%**	**-3.2%**	**+1.1%**	**0.0%**

- Simplified models (Network Flow, DCOPF) **underestimate** true system costs, when compared to an investment model with realistic constraints
- Heuristic models (0.7 line derating) can be overly restrictive and **overestimate** system costs

Why do we need CANOPI?

Part 4: Impact of grid physics on *evaluated* system costs

Simplified ⟷ *More realistic*

Grid physics representation	**Network Flow**	**DCOPF**	**DCOPF (0.7 derates)**	**SC-DCOPF**
Annualized total system cost *($ billion / year)* Evaluated by a ***realistic simulation***	247.3	148.6	44.5	18.6
Cost delta vs. SC-DCOPF *($ billion / year)*	+228.7	+130.0	+25.9	0
Cost multiplier	**13.3x**	**8.0x**	**2.4x**	**1x**

- Simplified models can incur significant “unexpected” system costs, once evaluated on a realistic operational simulation. This effect is driven by load shedding and line violations.

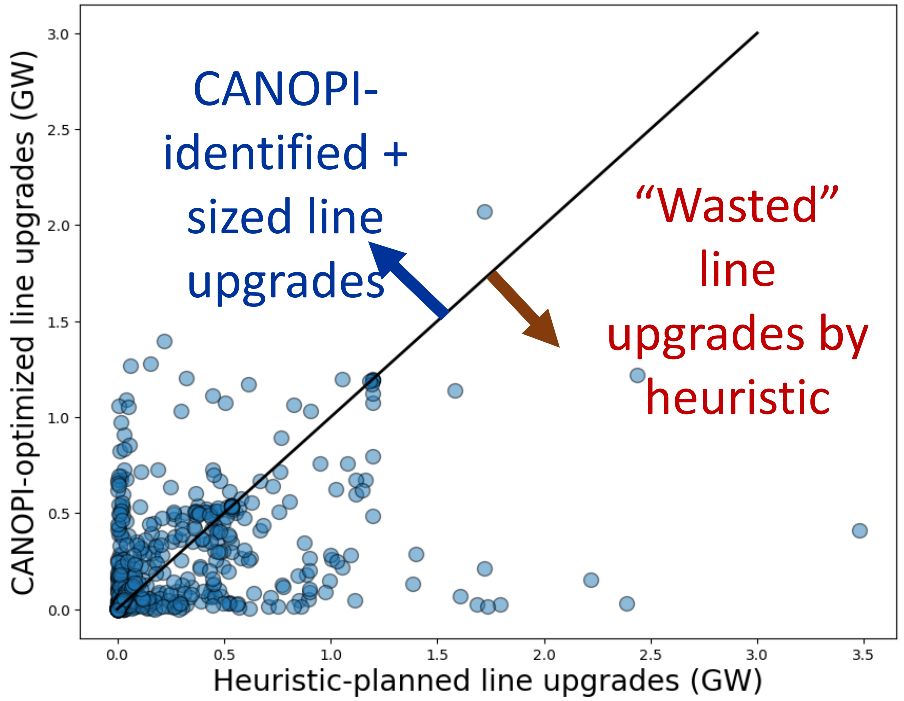
Take-Aways

- Contingency-aware planning results in siting decisions with ***fewer transmission upgrades*** and ***superior operational performance + reliability***, translating to ~$11bn savings over 20 years and 88% less load shedding.
- Heuristic method underinvests in critical lines while overinvesting in redundant lines.

Experiment Results

Metric	CANOPI Improvement vs. Heuristic Model
Line upgrades	**13%** lower (**$2 billion**)
Operating cost	**15%** lower (**$9 billion**) over 20 years
Emissions	**4%** lower
Load shedding	**88%** lower
Line overloads	**606%** lower

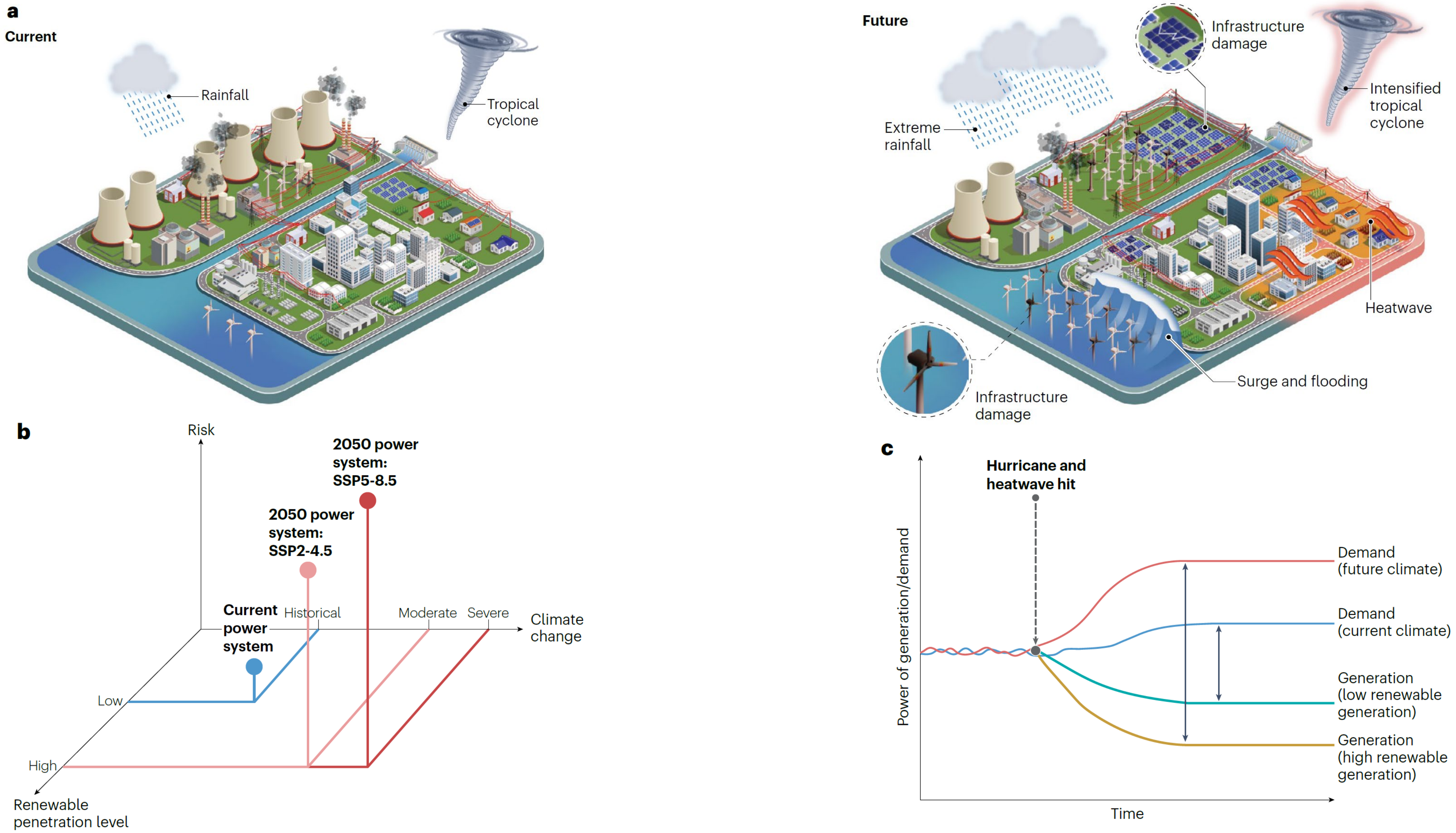
Planning Results Comparison



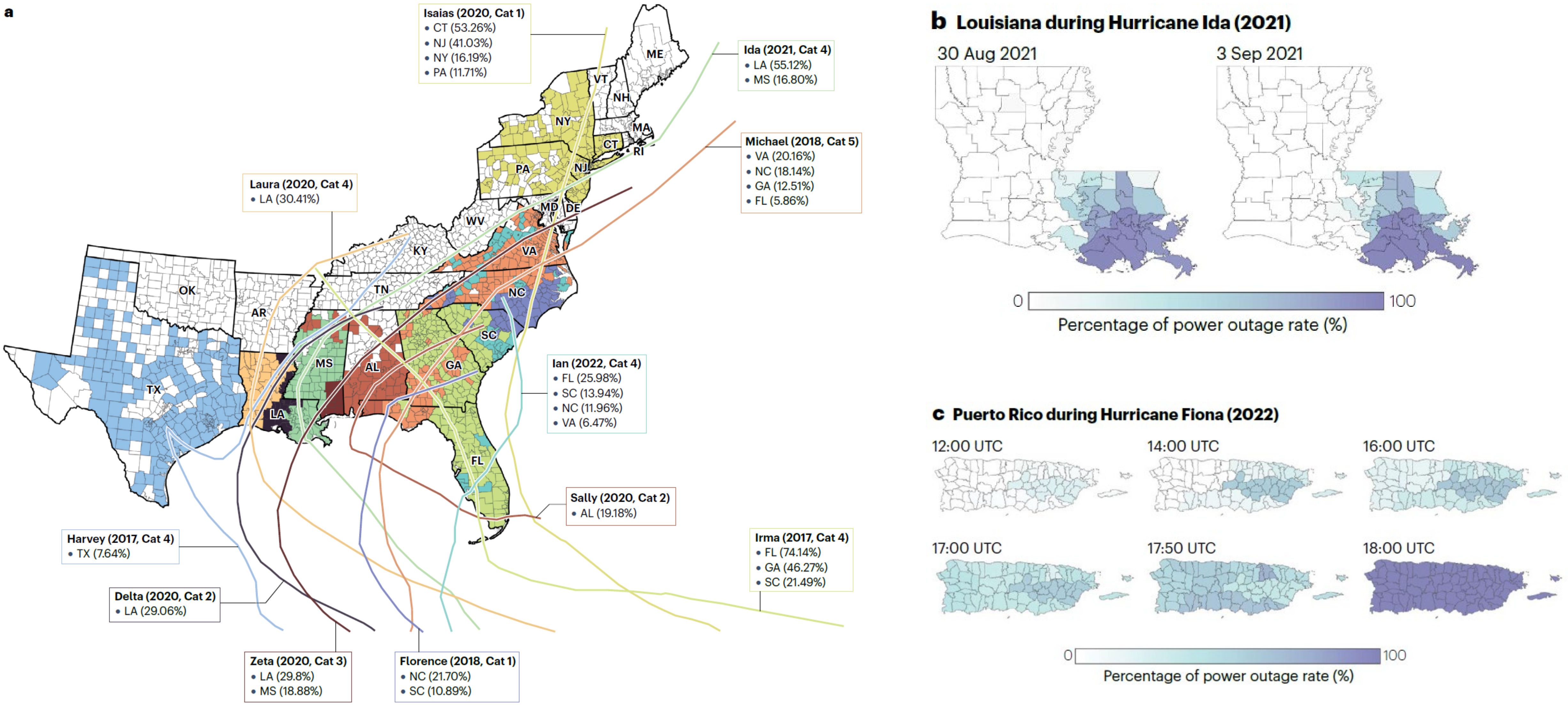
Deep Dive: Resiliency

Superimposed Risks Exacerbate Vulnerabilities

Superimposed Risks for Future Renewable System



Cyclone-Induced Power Outages in US 2017-2022



Climate-Renewable Challenges

Maintaining grid balance is becoming exponentially harder due to the convergence of three factors:

1. Intensified Heatwaves

Impact: Stresses the *steady-state* (hourly/daily) supply-demand balance.

Example: Texas 2023 saw repeated record-breaking peak demand under sustained heat.

2. Tropical Cyclones

Impact: Primary cause of catastrophic blackouts; threatens *dynamic stability*.

The Multiplier Effect

High Renewable Penetration:

The challenges of maintaining both steady-state balance (during heatwaves) and dynamic stability (during cyclones) are **exacerbated** in grids with high levels of variable renewable energy (VRE).

> Climate extremes stress the physics of a grid already in transition.

Transmission Grid Vulnerability

The "Power-Law" Distribution

Analysis of N. American grids (1984-2006) reveals:

Large blackouts occur with much higher probability

than predicted by standard exponential statistics.

(Hines et al., 2009)

Data Scope: Blackouts affecting >50,000 customers or >300 MW.

Network Topology

The grid relies on **critical hubs** (major plants & substations), making it inherently vulnerable to targeted disruptions attacking these central nodes.

(Albert et al., 2000)

Cascading Failures

Physics of loop flows & local protection schemes cause domino effects. Loss of one key element forces power to reroute, overloading adjacent lines.

(NASEM, 2017)

Distribution Grid Vulnerability

The "20-80" Scaling Law

20% of failures cause 80-90% of disruptions.

Cause: Hierarchical radial design. Failures in one primary feeder cascade to all downstream customers.

"Severe weather does not cause, but rather exacerbates, existing vulnerabilities."

(Ji et al., 2016)

The "30-60" Recovery Pattern

30% of small loads account for 60% of downtime.

The "Long Tail" Cause:

- Operational prioritization restores large customer groups first.
- Remote/severely damaged areas are left for last.
- Chronic underinvestment in proactive resilience (grid hardening, batteries).

(Executive Office of the President, 2013; Ji et al., 2016)

Renewables: The Shift to Distributed Resilience

The energy transition offers a unique opportunity to shift from centralized vulnerability to **distributed resilience**.

Microgrids: Topological Flexibility

- **Steady State:** Foster bidirectional power flow and local energy autonomy.
- **Climate Extremes:** Proactively islanding prevents failure propagation (cascading outages).

Success Stories

California (Wildfires)

Microgrids offer a safer, more economical alternative to "Public Safety Power Shutoffs" (PSPS) for preventing wildfire ignition.

Puerto Rico (PREPA)

Transforming the grid into independent, islandable clusters to survive hurricanes.

Technology: Grid-Forming Inverters

The Paradigm Shift

Current: Grid-Following

Passive current sources. Rely on Phase-Locked Loops (PLL) to track existing grid voltage/frequency.

Future: Grid-Forming

Active voltage sources. Use Power Synchronization Loops to *create* voltage/frequency references.

Capabilities

- **Virtual Inertia:** Emulating rotating mass via control software.
- **Black Start:** Can restart a dead grid without external power.
- **Island Stability:** Critical for stable microgrid operation.

Limitations

- **Fault Current:** Power electronics have low thermal limits (cannot sustain high short-circuit current).
- **Latency:** Virtual inertia is control-driven, not physical.

Distributed Energy Storage Systems (DESS)

Critical Resilience Asset

Standout Attribute: Inherent potential to be distributed. Offers high spatiotemporal flexibility.

Spectrum: Batteries, Power-to-Gas (Hydrogen), Power-to-Heat.

Crisis Response

- **During Event:** Maintains fast frequency balance in islanded microgrids.
- **Post-Event:** Vital for powering fragmented/sectionalized grid islands during recovery.
- **Emerging Concept:** Portable Energy Storage (Truck-mounted batteries) to bypass damaged transmission lines.

Integrated Solution

The Planning Gap: Costs of Simplification

The Old Way

Reliance on simplified models (single "zones", representative hours) underestimates the need for transmission and generation capacity.

Chile: Transmission Lag

~20% Solar/Wind Curtailed (2024)

North-South transmission bottlenecks trapped resource-rich generation.

(Ember, 2025)

Brazil: Curtailment Crisis

20 TWh Annual Waste (Est. 2025)

Rapid renewable expansion without upgrades discourages investment.

(Rystad Energy, 2025; Fitch Ratings, 2025)

The New Frontier: Advanced Planning/Operation

Nodal Transmission Planning

- **Contingency-Aware:** Modeling individual buses/nodes using HPC.
- **Granularity:** Analyzing thousands of hours across multiple weather years.

(Lee and Sun, 2025; Conejo et al., 2010)

Stochastic & Risk-Aware

Replacing deterministic "predict-then-prescribe" forecasts with probabilistic planning robust to future scenarios.

Operationalizing Philosophy

ISO New England (USA)

Implemented market rules based on an **adaptive robust optimization model**.

- Manages uncertainty of intermittent resources.
- Concrete step toward deploying advanced math in real-world operations.

(Bertsimas, Litvinov, & Sun, 2013; Sun and Conejo, 2022)

Proactive Distribution Planning

The local grid—the nexus of DERs and EV charging—can no longer be planned reactively.

Global Regulatory Mandates

United States (NY, CA, MA, ...)

"Reforming the Energy Vision" (REV), "Distribution Resources Plan" (DRP), and GMAC require long-term DER forecasting.

(NY DPS, 2016; CPUC, 2015; GMAC 2025)

European Union

"Clean Energy for all Europeans" package legally requires DSOs to plan for future needs.

Markets & Policy: The Primary Drivers

The Regulatory Bridge

Coherent frameworks define what gets incentivized. They are the essential bridge between theoretical innovation and real-world deployment.

- Distribution modernization.
- Ancillary services design (valuing inertia).
- Integration of storage technologies.

Italian MACSE

Mechanism: Energy-storage-focused capacity auction (October 2025).

10 GWh

Battery Capacity Procured

Significance: Demonstrates how specific policy mechanisms successfully drive investment in critical flexibility assets.

The Innovation Cycle: Technology & Policy

Advanced "Soft" Technologies

- **Planning:** Nodal Stochastic Optimization
- **Operation:** Robust Distributed Control
- **Forecasting:** AI & Machine Learning

ENABLE

Tech creates new capabilities (e.g. visibility, flexibility)

Policy creates value & directives

INCENTIVIZE

Policies & Markets

- **Incentives:** Capacity Remuneration
- **Regulation:** Performance-Based Rates
- **Design:** Ancillary Services for Inertia

THANK YOU!