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RESOLVE Model Overview

IRP Modeling Advisory Group

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Agenda

- Flexibility Planning Paradigm
- Key RESOLVE Features
  - Model overview
  - Candidate resources
  - Operational model
- Case Study: CAISO SB350 Analysis

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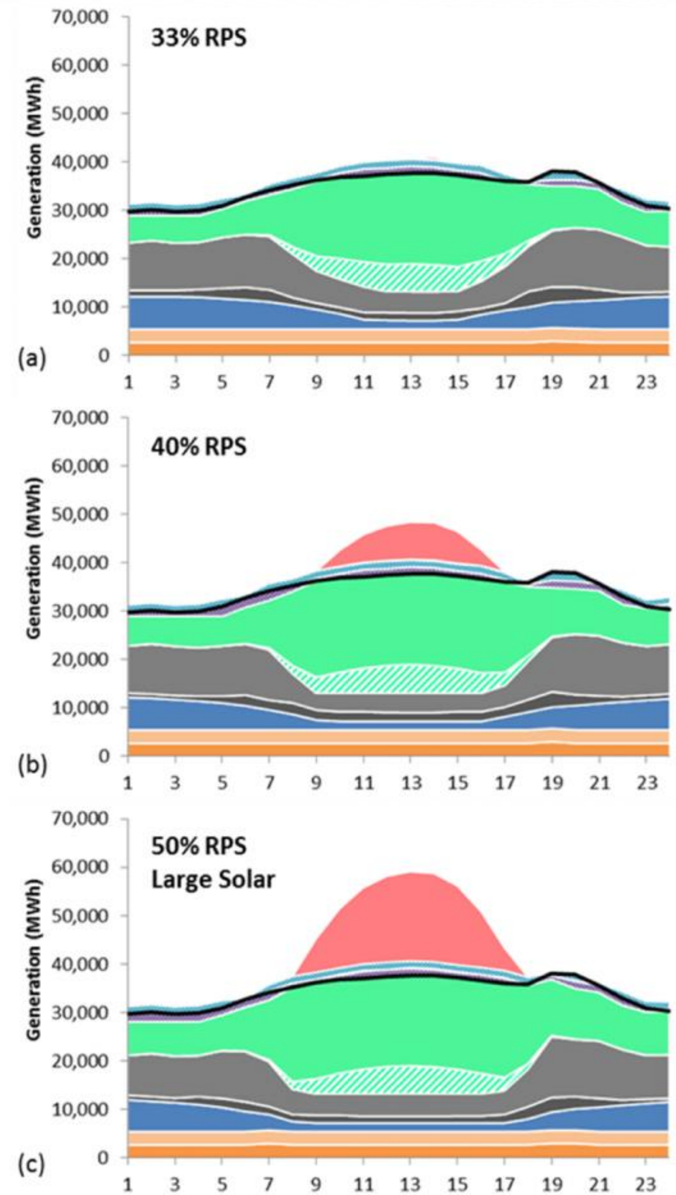
FLEXIBILITY PLANNING PARADIGM

Defining the New Planning Problem

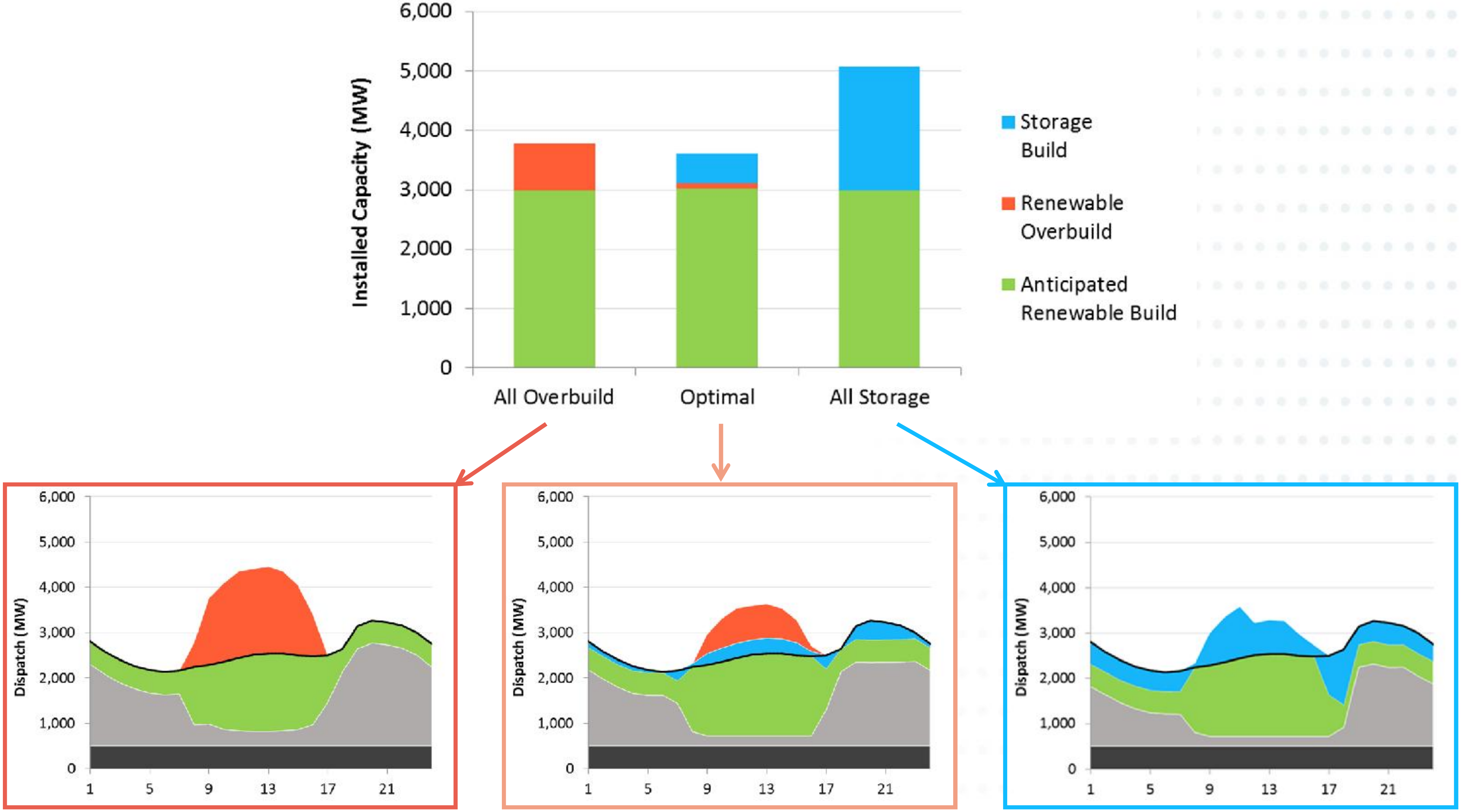
- Introduction of variable renewables has shifted the capacity planning paradigm
- The new planning problem consists of two related questions:
  1. How many MW of dispatchable resources are needed to (a) meet load, and (b) meet flexibility requirements on various time scales?
  2. What is the optimal mix of new resources, given the characteristics of the existing fleet of conventional and renewable resources?

The Renewable Integration Challenge

- Primary drivers of renewable integration challenges at high penetrations:
  - Renewable oversupply during low load periods
  - Inflexible conventional generation
    - Must-run resources
    - Technical constraints on ramping, minimum stable levels, minimum up and down times
    - High costs associated with cycling
  - Small balancing areas or constrained interactions with neighboring regions
- Research has shifted to focus on grid integration solutions

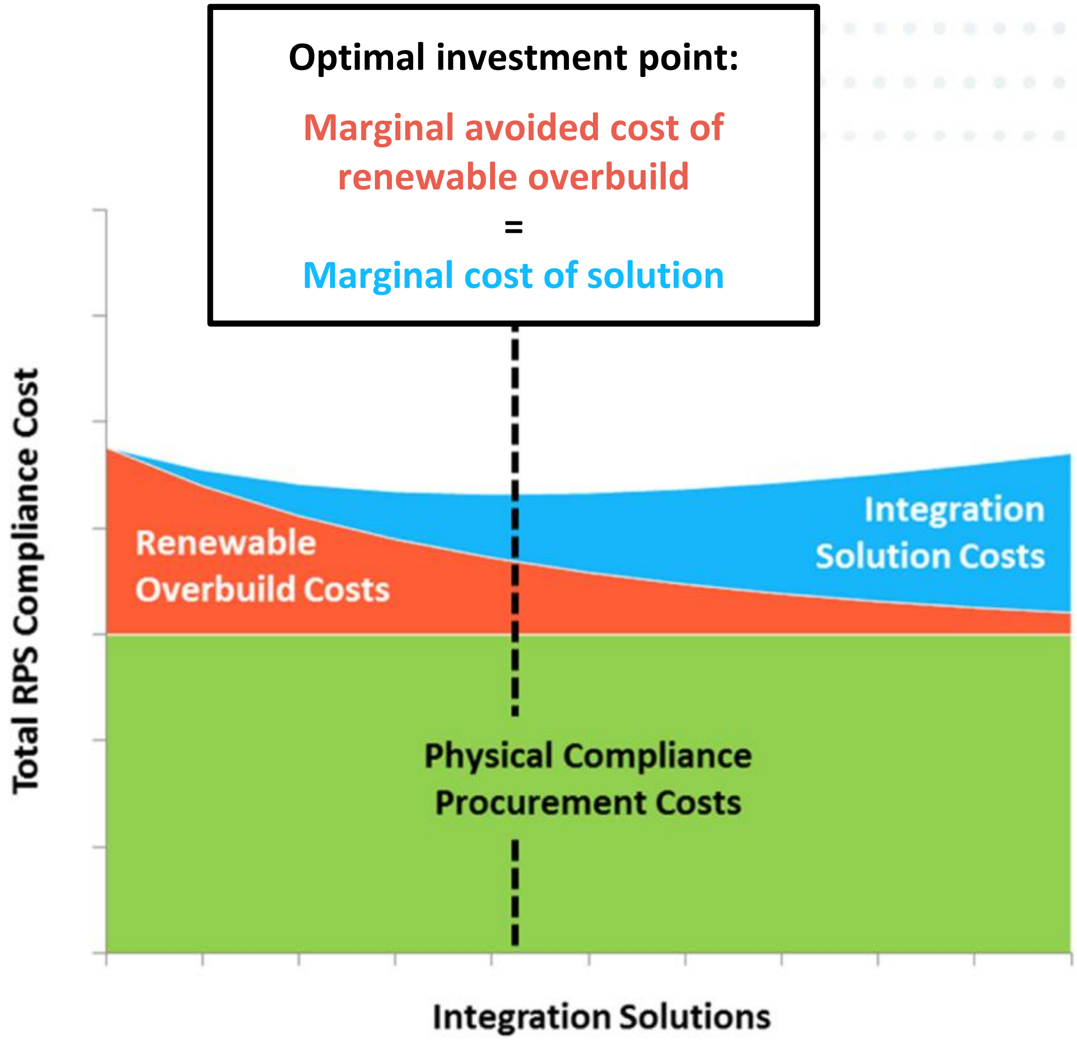


Optimal Solution Balances Non-Renewable Solutions with Overbuild



Identifying Optimal Investment in Solutions

- **Single solution case:**
  - The cost of the solution can be weighed against the avoided cost of overbuilding renewables for RPS compliance
- **Multiple solution case:**
  - Multidimensional optimization
  - Complex interactive effects
  - Requires sophisticated model that treats both operations and investment costs



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RESOLVE OVERVIEW

Overview of the RESOLVE Model

- RESOLVE is a capacity expansion model designed to identify optimal investments under high penetrations of renewable generation
  - Selects portfolio of solar, wind, geothermal, biomass, and small hydro to meet RPS & GHG constraints
  - Adds cost-effective integration solutions such as energy storage and flexible conventional resources, in combination with the renewable portfolio, to minimize total cost over the analysis period
- Resources are added to meet RPS target, overbuilding renewable portfolio if necessary
  - Renewables are curtailed if the output cannot be consumed in California or exported to neighboring systems due to oversupply or insufficient power system flexibility
  - Renewable contracts are treated as sunk costs and fully compensated for curtailed output
  - Resources added to portfolio if necessary to replace curtailed output; renewable curtailment implicitly valued at replacement cost, which increases geometrically with curtailment

RESOLVE Co-optimizes Investment and Operational Decisions

- RESOLVE allows portfolio optimization across a long time horizon (10-20 years)
  - Investments made in multiple periods
- Fixed costs capture capital, financing, and fixed O&M associated with new physical infrastructure
- Operational detail focuses on primary drivers of renewable integration challenges
- Optimization is constrained by many factors, including:
  - Hourly load
  - RPS target
  - Planning reserve margin*
  - GHG limit*

RESOLVE Objective Function

+ **Fixed Costs of New Resources**
  - Renewables
  - Energy storage
  - Demand response
  - Thermal

+ **Fixed Costs of New Transmission**

+ **System Operating Costs**
  - Variable O&M
  - Start costs
  - Fuel costs
  - Carbon

Flexible Model Design Facilitates Scenario Analysis

- RESOLVE is designed to allow easy scenario analysis of a variety of uncertainties
- Assumptions on key uncertainties can be easily adjusted to allow analysis of future risks:
  - Future renewable costs
  - Future energy storage costs
  - Customer adoption of behind-the-meter PV
  - Export limits from California
  - Achievement of energy efficiency goals
  - Deployment of electric vehicles

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CANDIDATE RESOURCES IN RESOLVE

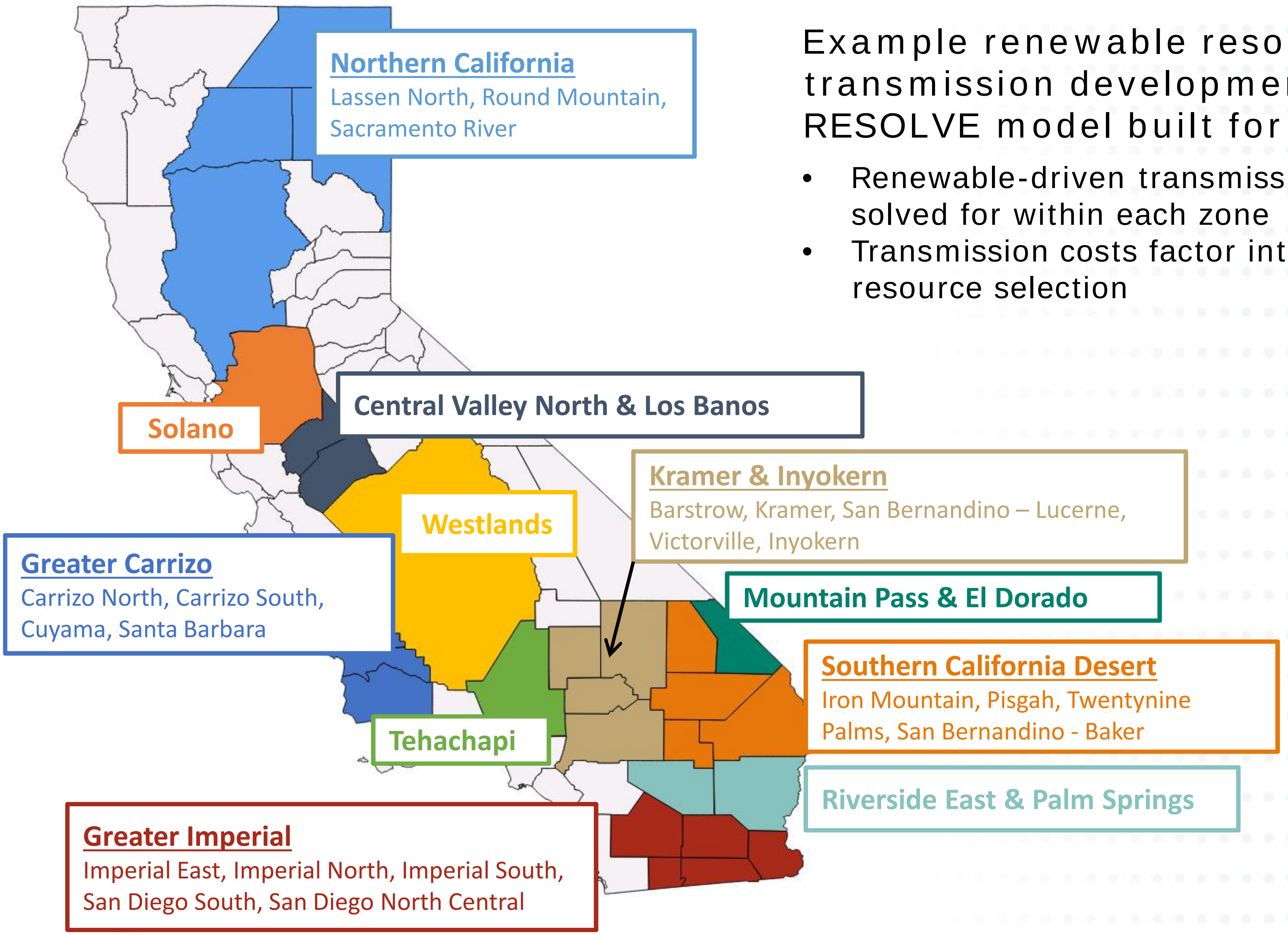
Candidate Resources Represented by Cost, Performance, and Potential

- Cost captures all fixed costs, including capital, interconnection, fixed O&M, financing, taxes for each resource
  - Cost assumptions can be adjusted through time to reflect changes in underlying technology costs
- Performance characteristics depend on type of resource:
  - Renewables: hourly profiles
  - Storage: round-trip efficiency, operating limits
  - Demand response: load impact
  - Thermal units: heat rates, operating costs, operating limits
- Potential reflects feasible or reasonable limits on resource development
  - Renewable potential limited by resource availability & quality in each CREZ

Inventory of Current Candidate Resources

Integration Solution	Examples of Available Options	Functionality
Energy Storage	• Batteries: 1-, 2-, 4-, or 8-hour • Pumped Storage: 12-hr, 24-hr	• Stores excess energy for dispatch in later hours • Contributes to meeting minimum generation and ramping constraints
Flexible Loads & Advanced Demand Response	• Flexible electric vehicle charging • Flexible water heaters • Flexible building thermal loads (eg. pre-cooling or pre-heating) • Flexible fuel production (electrolysis) • Other flexible loads	• Delays and dispatches electric loads based on balancing needs subject to service demand constraints • Can be scheduled based on seasonal/diurnal trends or dispatched dynamically
Conventional Demand Response	• LTPP modeled programs ($600/MWh and $1,000/MWh priced resources) • New demand response programs	• Provides capacity to avoid unserved energy
New Flexible Gas Plants	• Simple cycle gas turbines • Reciprocating engines • Flexible combined cycle gas turbines	• Dispatches economically based on heat rate, subject to ramping limitations • Contributes to meeting minimum generation and ramping constraints
Renewables	• Biofuels • Geothermal • Solar PV • Wind	• Dynamic downward dispatch (with cost penalty) of renewable resources to help balance load

Renewable Resources Linked to Transmission Zones



Example renewable resource and transmission development zones in RESOLVE model built for CAISO

- Renewable-driven transmission build solved for within each zone
- Transmission costs factor into optimal resource selection

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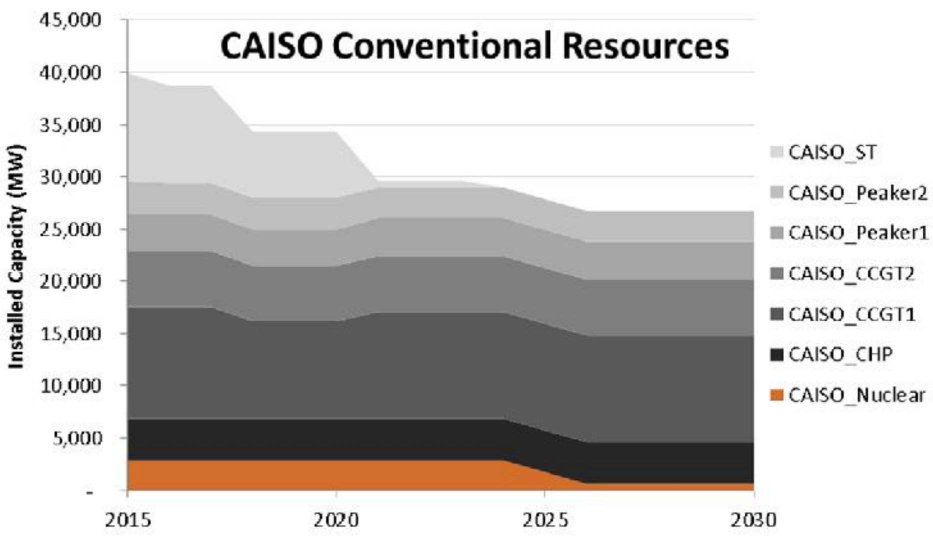
OPERATIONAL MODELING IN RESOLVE

RESOLVE's Operational Model

- Linear hourly dispatch model
- Zonal WECC representation with transmission constraints
- Smart sampling of historical load, wind, solar, and hydro conditions
- Detailed representation of flexibility reserves

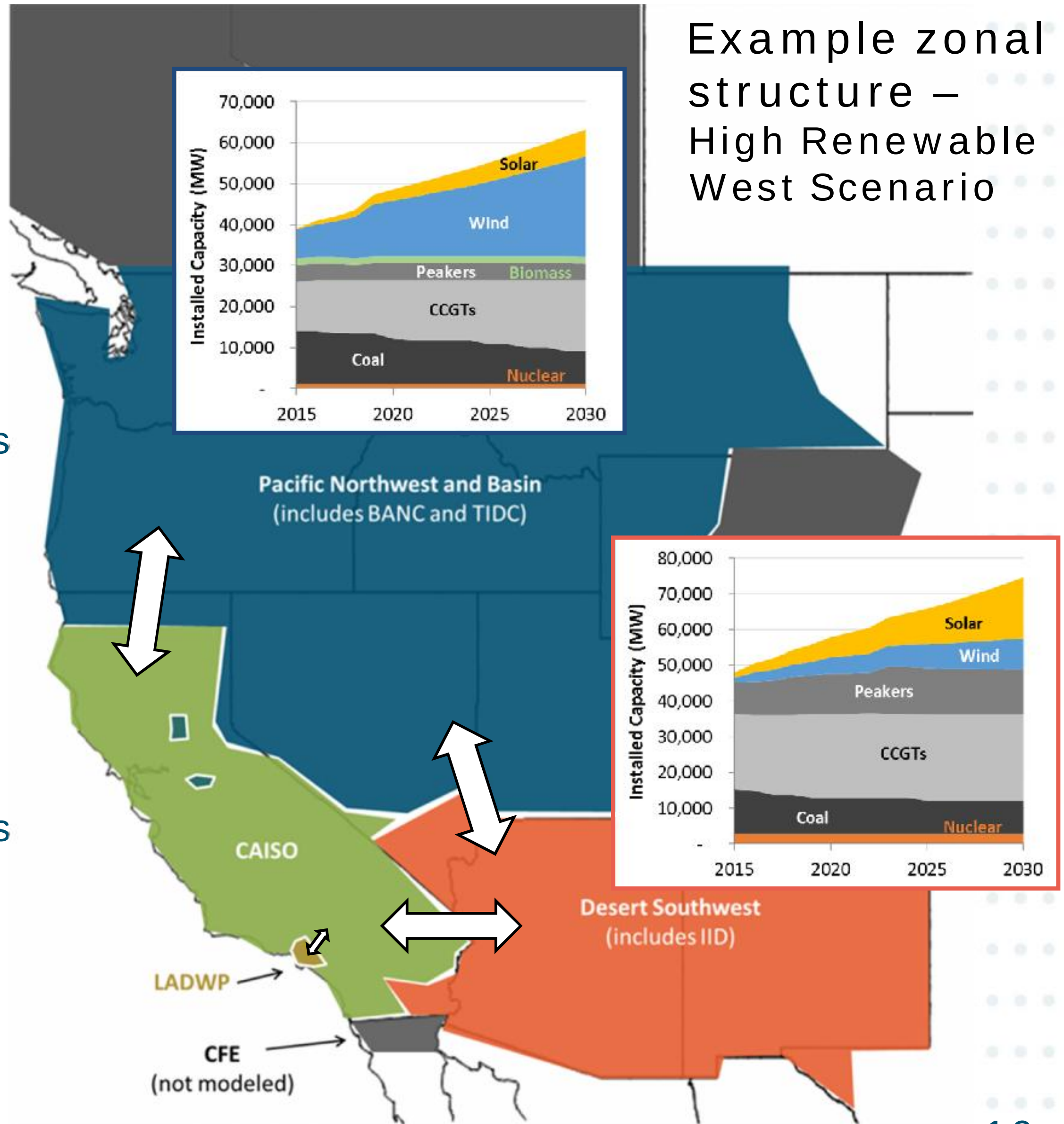
Overview of Operational Model

- RESOLVE uses an hourly operational model to simulate the economics of system operations, accounting for:
  - Hourly profiles for load, wind, and solar resources
  - Daily hydro energy budgets
  - Operating constraints on thermal generators and storage resources
  - Flexibility reserve requirements
- Rather than modeling each generator individually, RESOLVE groups similar plants together to model different classes of thermal generation
  - CAISO existing thermal fleet represented by seven categories of generation



Interactions with Other Regions

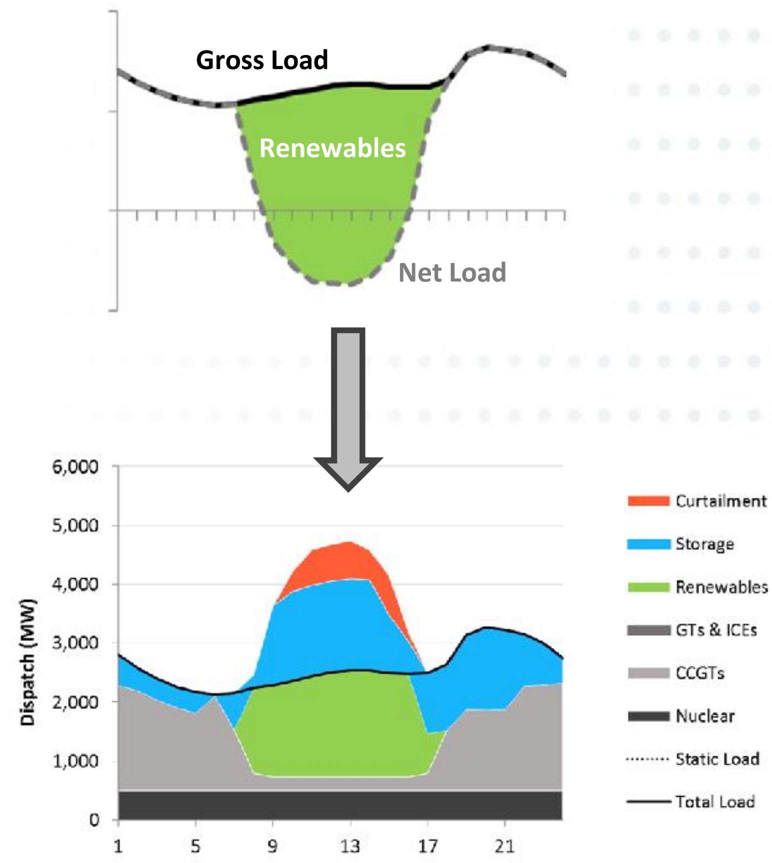
- Main zone:
  - Optimal investment decisions
  - Detailed treatment of operating reserves
- Other zones:
  - Exogenous resource assumptions and loads by scenario
- Flows may be impacted by:
  - Min and max intertie flow constraints
  - Min and max simultaneous flow constraints for groups of interties
  - Ramping constraints on interties
  - Hurdle rates



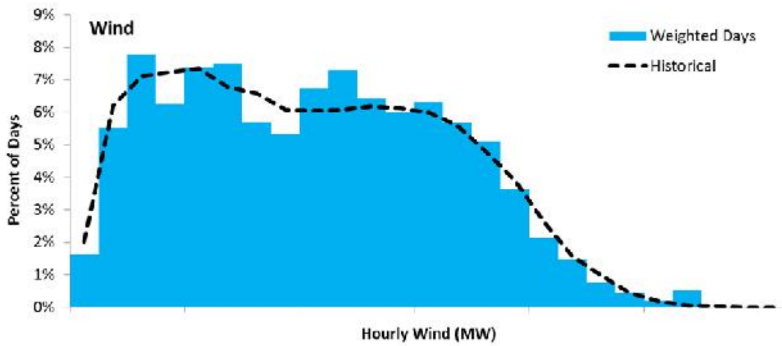
Hourly Model Brings Operational Challenges into Investment Decisions

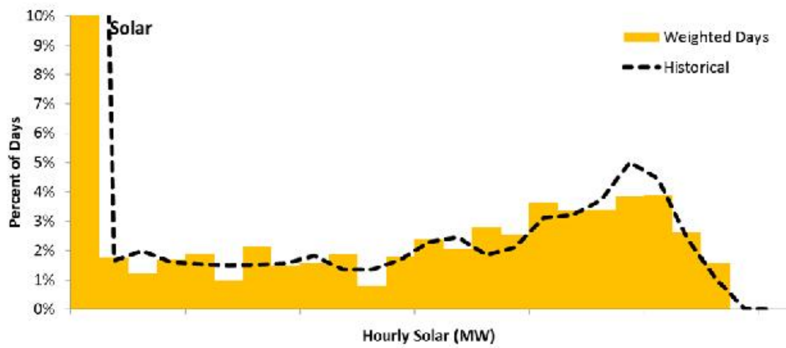
- For each year in the simulation, a subset of days are selected and weighted to reflect long-run distributions of:
  - Daily load, wind, and solar
  - Monthly hydro availability
- Operations modeled using linear dispatch formulation
  - Upward and downward operating reserve constraints
  - Parameterization of subhourly renewable curtailment due to downward reserve shortfalls

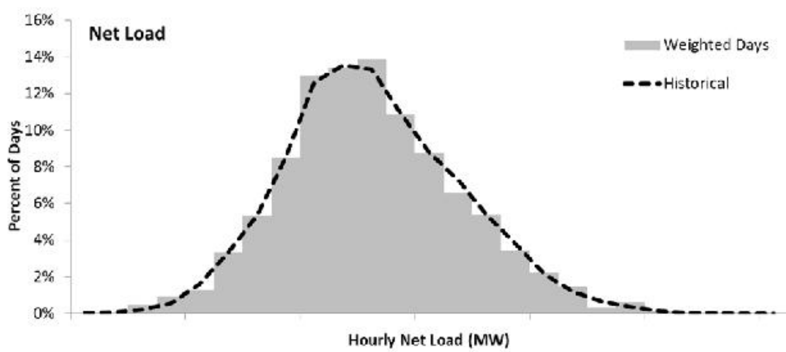
Captures operational impacts of renewable integration challenges



Sampling of Days Captures Long-Run Expectation of Net Load Distribution







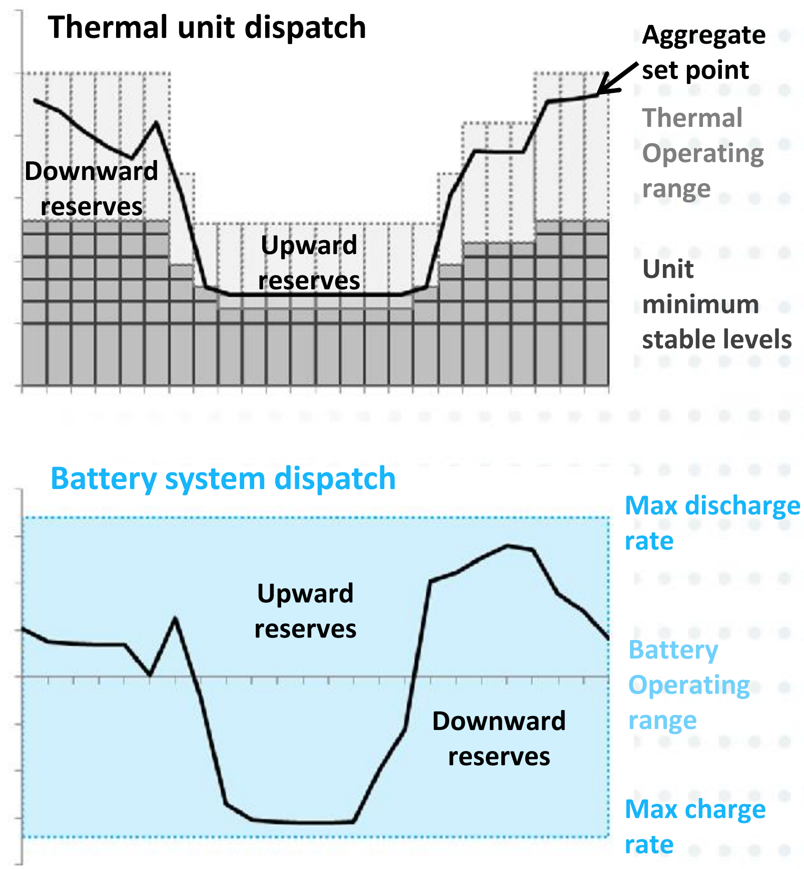
+ For each year in the analysis horizon, RESOLVE models operations for 37 independent days

+ Results of 37 days weighted to approximate long-run distributions of:
  - Hourly load
  - Hourly solar
  - Hourly wind
  - Hourly net load
  - Daily hydro energy
  - Monthly hydro energy
  - Monthly renewable capacity factors by site

Modeling Flexibility Reserves

- At high renewable penetrations, operations become increasingly constrained by the need to meet flexibility reserve requirements (or "load following")
- This, in turn, becomes an important driver of the value of investments in flexible resources
  - Renewables assumed to contribute to meeting downward flexibility reserves through subhourly curtailment
  - Integration solutions that can also provide downward reserves offer a benefit through reductions in curtailment

Simulates economic dispatch on each day subject to technical operating constraints



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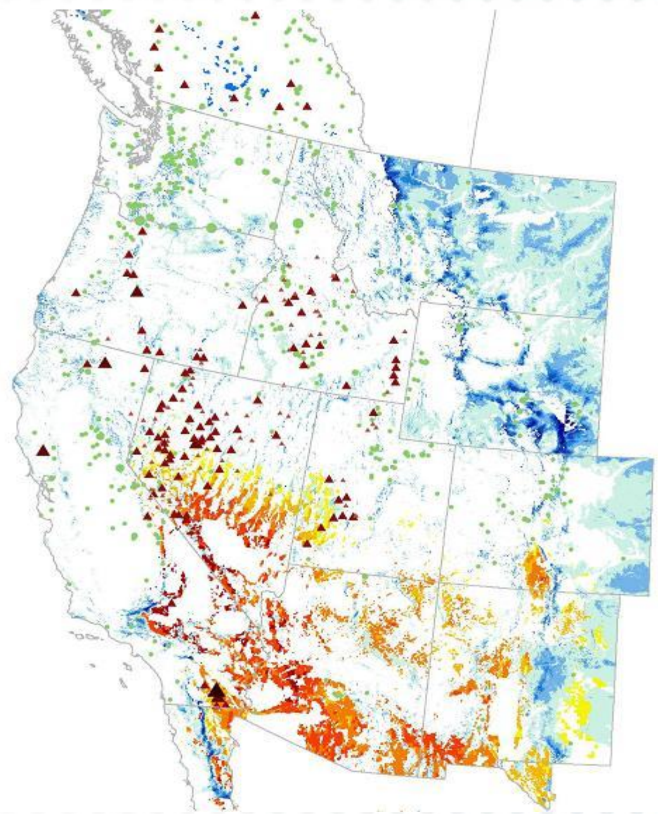
CASE STUDY: CAISO SB350 STUDY PORTFOLIO RESULTS

SB350 Study: Impact of a Regional Market on Renewable Procurement

Two major effects are tested in RESOLVE:

1. Effect of regional operations
   - Increased access to latent flexible capacity across a broad, diverse region
   - Increased ability to export surplus energy
   - Could result in changes to least-cost portfolio
2. Effect of regional transmission tariff
   - Reduces wheeling costs across the region
   - Provides a mechanism for needed new transmission infrastructure to be studied and approved for inclusion in rates
   - Provides access to high-quality wind in the Rockies and solar in the Southwest

Renewable Resource Potential in the West



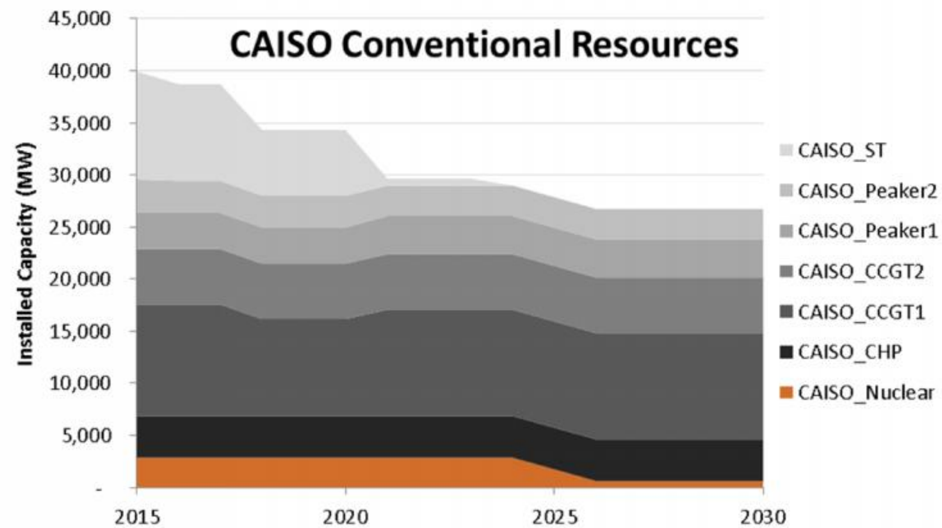
Source: NREL

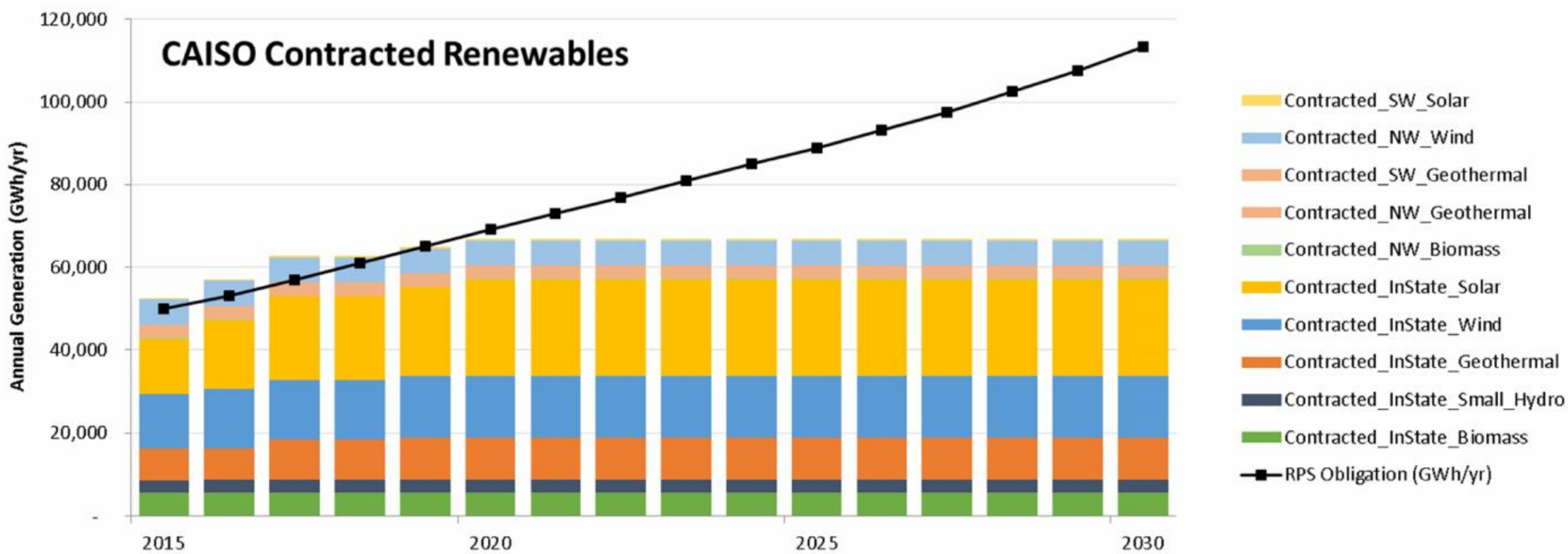
Three Scenarios Studied

1. Current Practice Scenario
   - Renewable energy procurement is largely from in-state resources, with 5,000 MW of out-of-state resources available over existing transmission
   - No regional market to help reduce curtailment
2. Regional market operations with 'Current Practice' renewable energy procurement policies
   - Assumes no increase in availability of out-of-state resources, but transmission wheeling charges are de-pancaked
   - Curtailment of renewables is reduced through better integration
3. Regional market and renewable energy procurement
   - Like Scenario 2, but with additional high-quality wind resources made available, requiring new transmission facilitated by the regional entity

Existing & Contracted Resources

- Conventional resources based on 2014 LTPP Thermal Stack
- Existing and Contracted Resources are from the RPS Calculator
- Resources outside of CAISO in the rest of the West are from the 2024 Common Case
- 14.6 GW of BTM rooftop PV by 2030





Sources for Data Inputs

- Renewable resources
  - RPS Calculator (CA resources), TEPPC Common Case (WECC resources), NREL Wind Toolkit (hourly wind profiles), Solar Prospector (hourly solar profiles), hydro dispatch (CAISO)
- Load shapes
  - CAISO (CA base load shapes), TEPPC Common Case (WECC load shapes), PATHWAYS scenarios (impacts of EE, electrification & flexible loads)
- Zonal topology
  - WECC Path Rating Catalog, WECC historical path flow data
  - Transfer capability between LADWP, TIDC, BANC and CAISO provided by CAISO
- Renewable integration solutions
  - Literature review & synthesis of industry reports – assumptions are under development

Total Incremental Resources for California (in GWh)

- Model selects a diverse portfolio of in-state solar and out-of-state wind across all cases

	Scenario 1a	Sensitivity 1b	Scenario 2	Scenario 3
CAISO simultaneous export limit	2,000	8,000	8,000	8,000
Procurement	Current practice	Current practice	Current practice	WECC-wide
Operations	CAISO	CAISO	WECC-wide	WECC-wide
Portfolio Composition (GWh)				
California Solar	21,482	23,483	22,147	9,827
California Wind	8,480	8,480	5,596	5,596
California Geothermal	3,942	3,942	3,942	3,942
Northwest Wind, Existing Transmission	4,056	1,253	1,574	891
Northwest Wind RECs	2,803	0	2,803	0
Utah Wind, Existing Transmission	1,693	1,693	1,693	1,177
Wyoming Wind, Existing Transmission	1,708	1,708	1,708	1,708
Wyoming Wind, New Transmission	0	0	0	8,037
Southwest Solar, Existing Transmission	0	809	1,489	1,489
Southwest Solar RECs	2,978	2,978	2,978	2,978
New Mexico Wind, Existing Transmission	3,416	3,416	3,416	3,416
New Mexico Wind, New Transmission	0	0	0	7,905
Total CA Resources	33,904	35,905	31,685	19,365
Total Out-of-State Resources	16,654	11,857	15,661	27,601
Total Renewable Resources	**50,558**	**47,762**	**47,346**	**46,966**
Curtailment (IOUs only, GWh)	4,818	2,022	1,606	1,226
Curtailment (% of available RPS energy)	4.5%	2.0%	1.6%	1.2%

- Curtailment is significantly reduced under regional operations

Scenario 1: Incremental Resources for California

	Scenario 1a	Sensitivity 1b	Scenario 2	Scenario 3
CAISO simultaneous export limit	2,000	8,000	8,000	8,000
Procurement	Current practice	Current practice	Current practice	WECC-wide
Operations	CAISO	CAISO	WECC-wide	WECC-wide
Portfolio Composition (MW)				
California Solar	**7,601**	**8,279**	7,804	3,440
California Wind	**3,000**	**3,000**	1,000	1,000
California Geothermal	**500**	**500**	[illegible]	[illegible]
Northwest Wind, Existing Transmission	**1,447**	**447**	[illegible]	[illegible]
Northwest Wind RECs	**1,000**	**0**	[illegible]	[illegible]
Utah Wind, Existing Transmission	**604**	**604**	[illegible]	[illegible]
Wyoming Wind, Existing Transmission	**500**	**500**	[illegible]	[illegible]
Wyoming Wind, New Transmission	**0**	**0**	0	1,995
Southwest Solar, Existing Transmission	0	272	500	500
Southwest Solar RECs	1,000	1,000	1,000	1,000
New Mexico Wind, Existing Transmission	1,000	1,000	1,000	1,000
New Mexico Wind, New Transmission	0	0	0	1,962
Total CA Resources	11,101	11,779	10,204	5,840
Total Out-of-State Resources	5,551	3,823	5,166	7,694
Total Renewable Resources	**16,652**	**15,602**	**15,370**	**13,534**
Energy Storage (MW)	**972**	**500**	500	500

- **Under higher export capability, in-state solar displaces out-of-state wind due to reduced curtailment**

- **Additional battery storage selected in Scenario 1a**

Scenario 2: Incremental Resources for California

- **Ability to export reduces curtailment; procurement of both in-state and out-of-state wind is avoided**

	Scenario 1a	Sensitivity 1b	Scenario 2	Scenario 3
CAISO simultaneous export limit	2,000	8,000	8,000	8,000
Procurement	Current practice	Current practice	Current practice	WECC-wide
Operations	CAISO	CAISO	WECC-wide	WECC-wide
Portfolio Composition (MW)				
California Solar	**7,601**	8,279	**7,804**	3,440
California Wind	**3,000**	3,000	**1,900**	1,900
California Geothermal	**500**	500	**500**	500
Northwest Wind, Existing Transmission	**1,447**	447	**562**	318
Northwest Wind RECs	**1,000**	0	**1,000**	0
Utah Wind, Existing Transmission	604	604	604	420
Wyoming Wind, Existing Transmission	500	500	500	500
Wyoming Wind, New Transmission	0	0	0	1,995
Southwest Solar, Existing Transmission	0	272	500	500
Southwest Solar RECs	1,000	1,000	1,000	1,000
New Mexico Wind, Existing Transmission	1,000	1,000	1,000	1,000
New Mexico Wind, New Transmission	0	0	0	1,962
Total CA Resources	11,101	11,779	10,204	5,840
Total Out-of-State Resources	5,551	3,823	5,166	7,694
Total Renewable Resources	16,652	15,602	15,370	13,534
Energy Storage (MW)	972	500	500	500

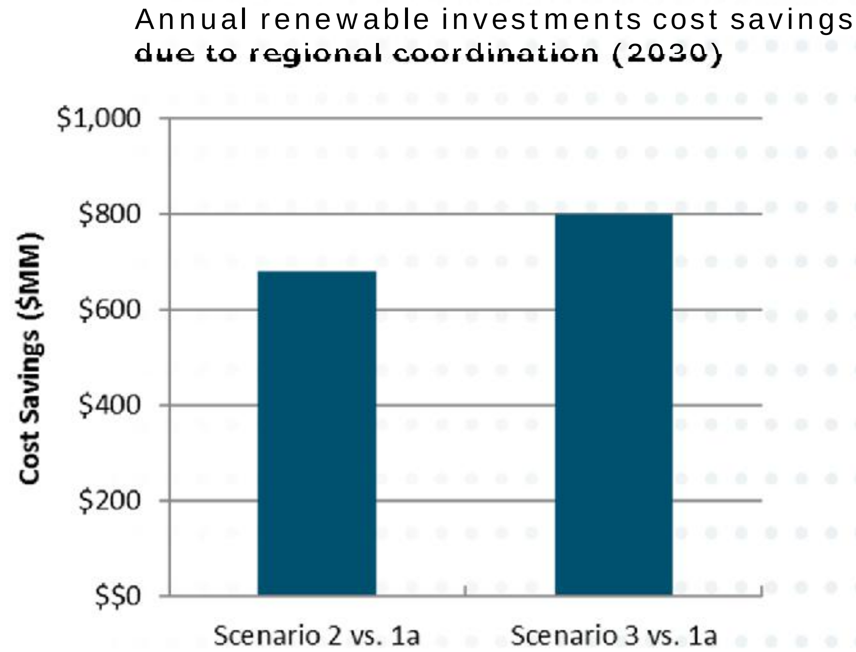
Scenario 3: Incremental Resources for California

	Scenario 1a	Sensitivity 1b	Scenario 2	Scenario 3
CAISO simultaneous export limit	2,000	8,000	8,000	8,000
Procurement	Current practice	Current practice	Current practice	WECC-wide
Operations	CAISO	CAISO	WECC-wide	WECC-wide
Portfolio Composition (MW)				
California Solar	**7,601**	8,279	7,804	**3,440**
California Wind	**3,000**	3,000	1,900	**1,900**
California Geothermal	**500**	[illegible]	[illegible]	**500**
Northwest Wind, Existing Transmission	**1,447**	[illegible]	[illegible]	**318**
Northwest Wind RECs	**1,000**	[illegible]	[illegible]	**0**
Utah Wind, Existing Transmission	**604**	[illegible]	[illegible]	**420**
Wyoming Wind, Existing Transmission	**500**	[illegible]	[illegible]	**500**
Wyoming Wind, New Transmission	**0**	0	0	**1,995**
Southwest Solar, Existing Transmission	**0**	272	500	**500**
Southwest Solar RECs	**1,000**	1,000	1,000	**1,000**
New Mexico Wind, Existing Transmission	**1,000**	1,000	1,000	**1,000**
New Mexico Wind, New Transmission	**0**	0	0	**1,962**
Total CA Resources	11,101	11,779	10,204	5,840
Total Out-of-State Resources	5,551	3,823	5,166	7,694
Total Renewable Resources	16,652	15,602	15,370	13,534
Energy Storage (MW)	972	500	500	500

WY and NM wind displace California solar and lower-quality NW wind

Cost Results

+ Annual renewable procurement cost savings in 2030: $680-$799 million
  - Fixed costs only; variable cost differences accounted for in PSO analysis
  - Modest savings assumed for non-CAISO BAs



	Scenario 1a	Scenario 2	Scenario 3
Fixed Costs ($MM) - CAISO	$2,578	$1,934	$1,840
Fixed Costs ($MM) – non-CAISO BAs	$714	$678	$652
Total California Fixed Costs ($MM)	**$3,291**	**$2,612**	**$2,492**
Fixed Costs Relative to Scenario 1a		**-$680**	**-$799**

Summary of Results with Sensitivity Analysis

- Annual savings from regional integration range from $391 million to $1.004 billion per year under 50% RPS
  - High flexible loads and high energy efficiency reduce savings
  - Low Portfolio diversity, high rooftop PV, and higher RPS increase savings
  - High out-of-state availability has limited effect on savings

Cost Savings from regional coordination ($MM)	Scenario 2 vs. 1a	Scenario 3 vs. 1a
Base assumptions	$680	$799
A. High coordination under bilateral markets	$391	$511
B. High energy efficiency	$576	$692
C. High flexible loads	$495	$616
D. Low portfolio diversity	$895	$1,004
E. High rooftop PV	$838	$944
F. High out-of-state resource availability	$578	$661
G. Low cost solar	$510	$647
H. 55% RPS	$1,164	$1,341

NEXT STEPS & QUESTIONS

Evolution of RESOLVE Model

- Current DR Potential study funded by LBNL has allowed E3 to integrate logic to model advanced demand response resources
- Additional model development tasks planned within IRP scope:
  - Implementation of GHG constraint
  - Refinement of planning reserve margin constraint
  - Addition of ELCC logic for wind and solar
  - Refinement of demand-side modeling

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Thank You!

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