NREL's Electricity Markets Investment Suite (EMIS)

Also called EMIS-AS (Agent-based Simulation)

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The Current EMIS Team

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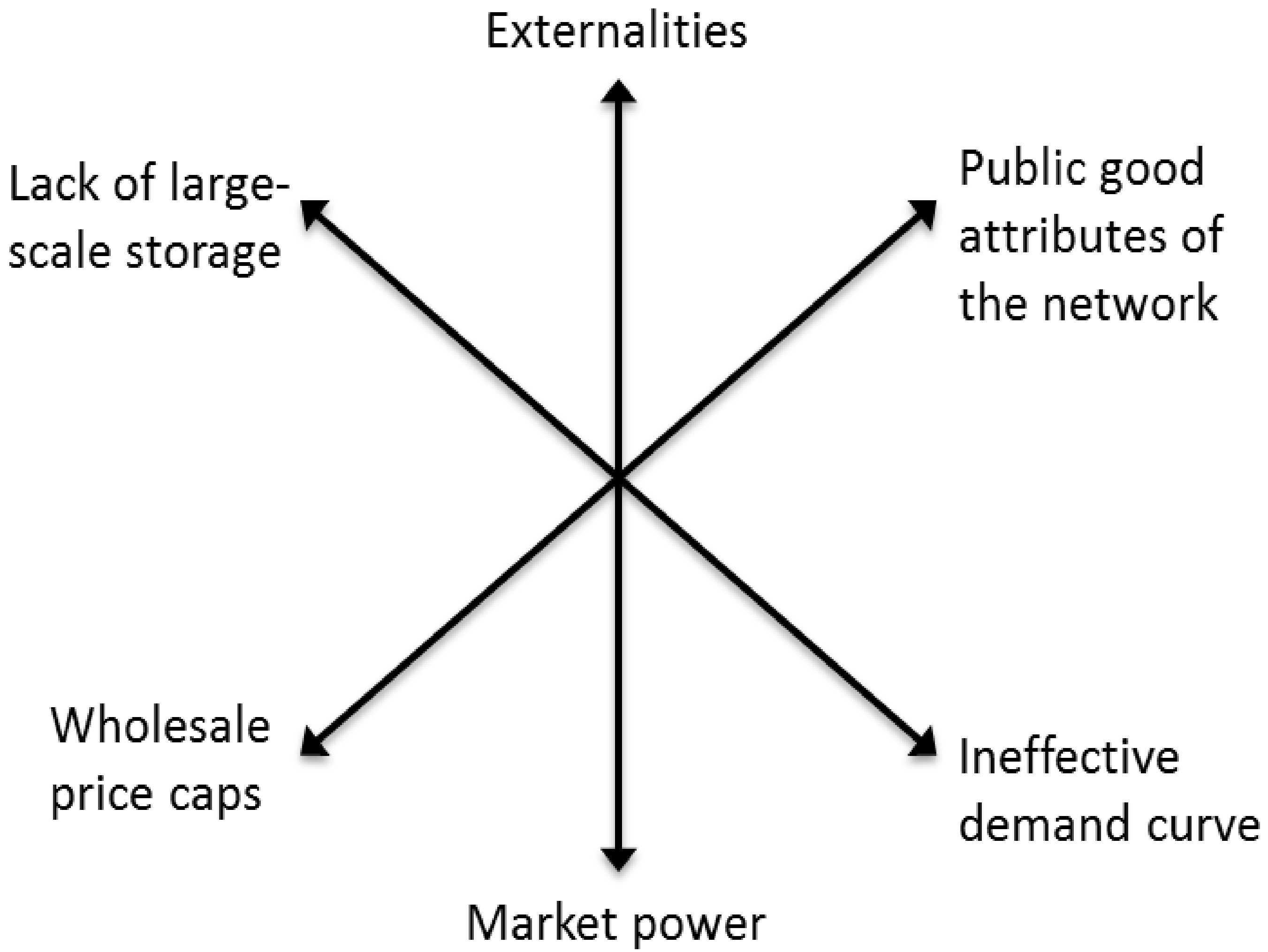
Why Should You Care About EMIS?

In the United States, Independent System Operators (ISOs) and Regional Transmission Organizations (RTOs) operate competitive wholesale electricity markets.

Today, these ISOs/RTOs collectively serve two-thirds of electricity consumers in the United States.

Source: ISO/RTO Council

Electricity Markets Are Unlike Any Other Market

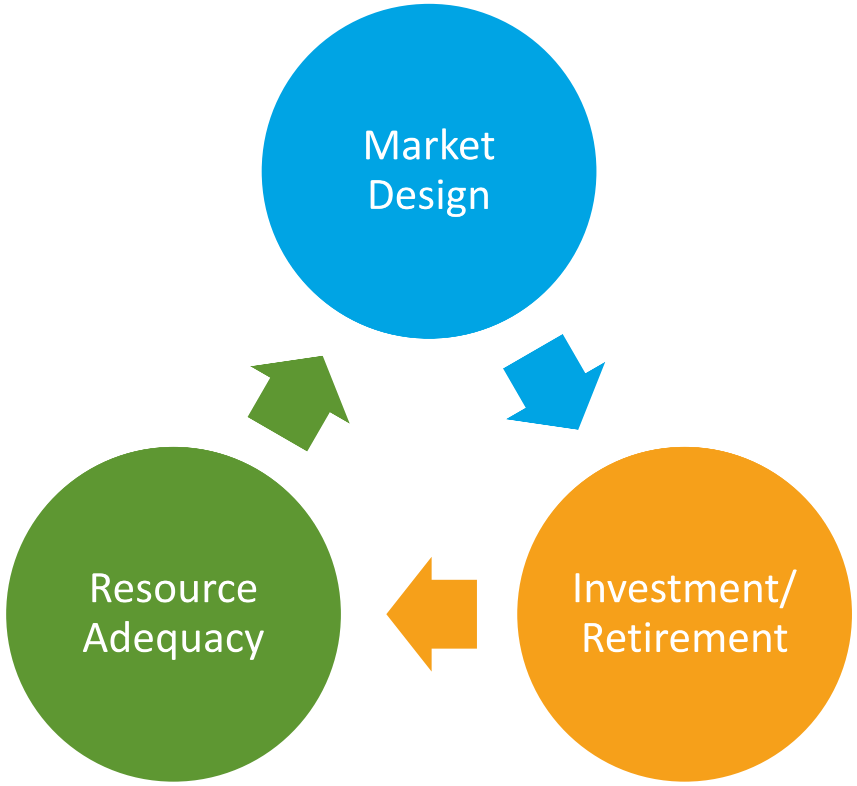


Source: [Marginal Cost Pricing in a World without Perfect Competition]

Core Challenge: Getting Prices Right

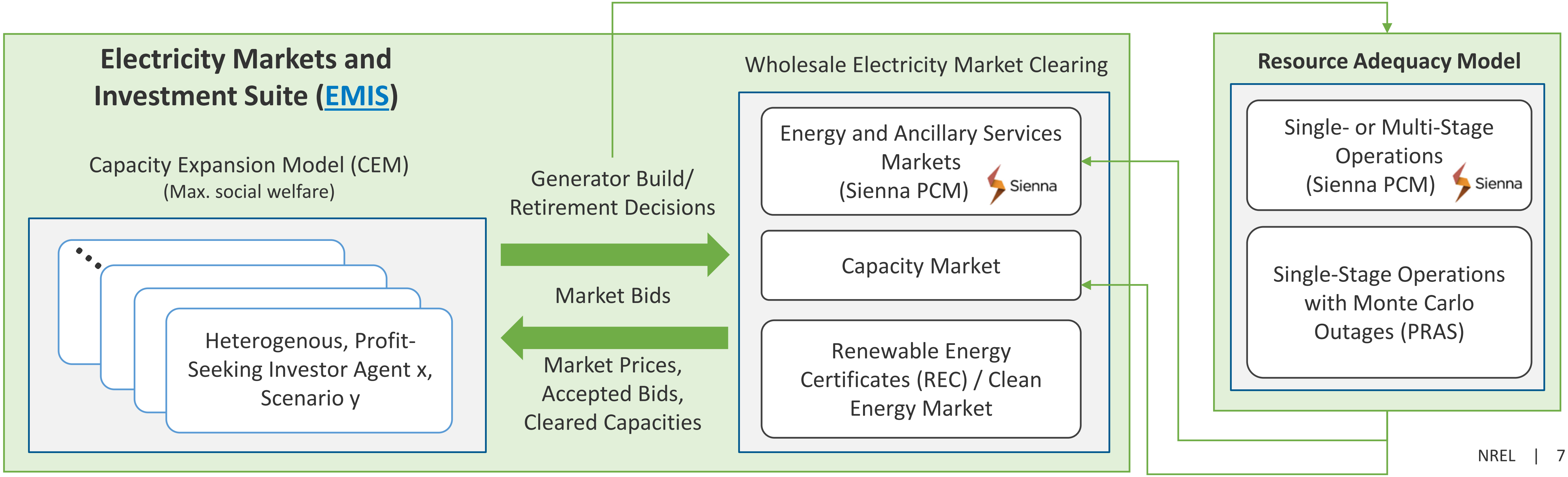
- Market prices and operational outcomes impact investment decisions, which in turn influence **resource adequacy (RA)**. This interaction is especially challenging under future economic, market, and system **uncertainty.**

- Traditional capacity expansion models inherently guarantee **cost recovery** and miss nuances of real-world investment processes, such as **imperfect information** and **investor risk attitudes**.



EMIS: A Fundamentally Different Modeling Approach

- Agent-based capacity expansion modeling with detailed representation of market design, as well as **imperfect information** and different **risk attitudes**, **technology preferences**, and **financing** parameters
- Capture interaction between **market design, investment, and RA**
- Integrated with NREL's Probabilistic Resource Adequacy Suite (PRAS) and Sienna tools



Modified from https://doi.org/10.1016/j.apenergy.2021.117908

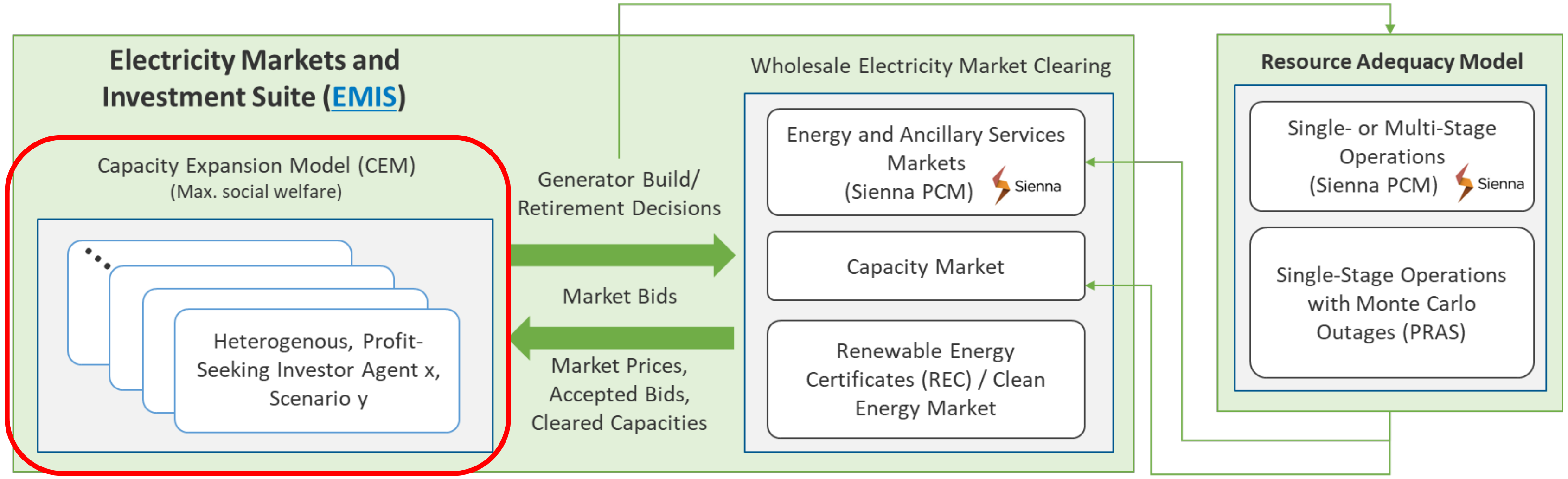
PCM = Production Cost Model (unit commitment and economic dispatch)

EMIS Can Answer Questions Relating to Market Design and RA Under Uncertainty

- What **market structures** are needed to incentivize for **investment** of the attributes needed to support **RA**?
- How robust are those market structures to **extreme weather** and/or climate change (with temperature-correlated outages)?
- How does **uncertainty** from other sources (load growth, policy, market design, fuel prices, etc.) impact **investment decisions**?

How Does EMIS Work?

Agent-Level Price Prediction and Investment



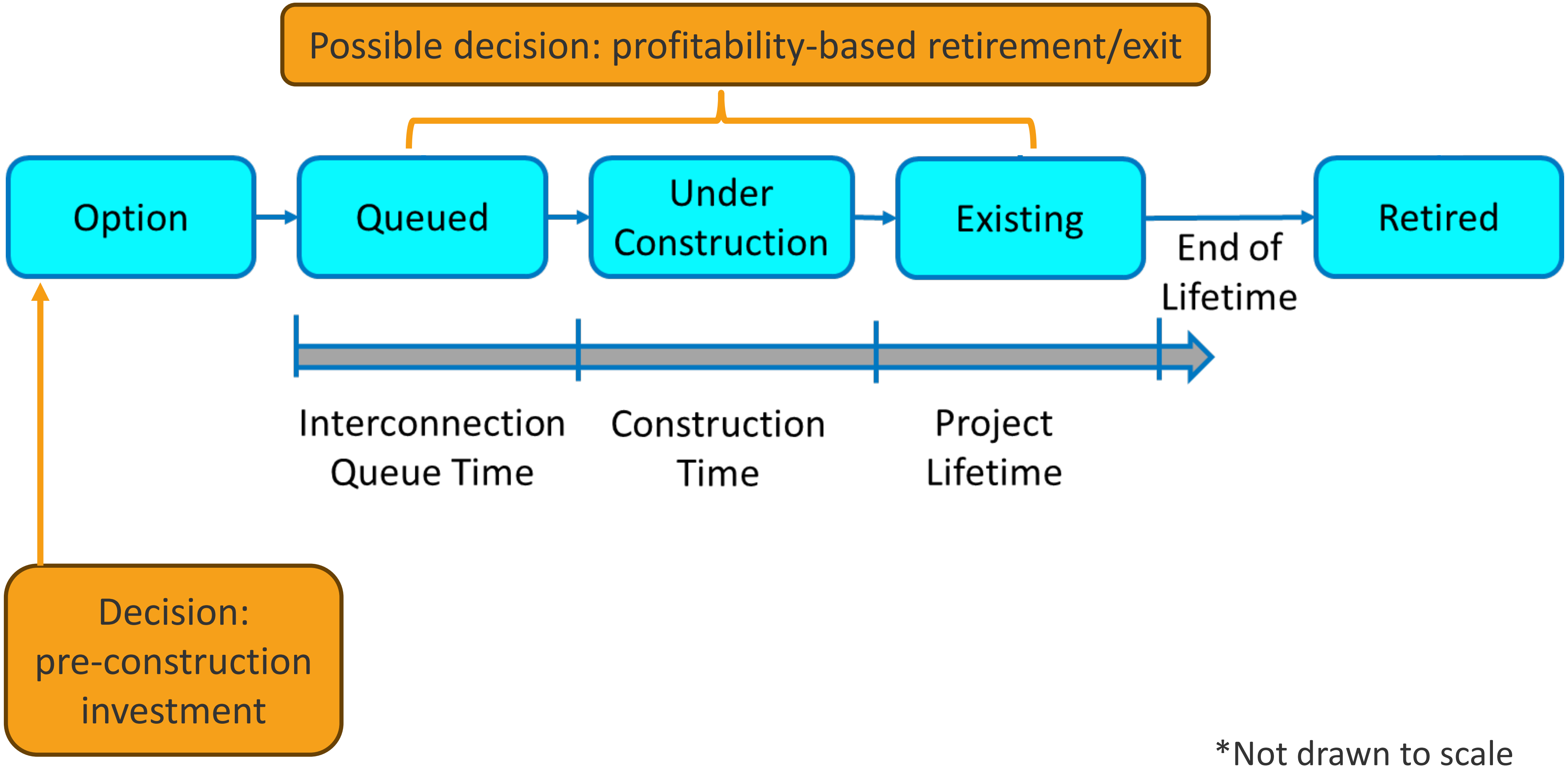
- Each investor agent uses a capacity expansion model (CEM) for predicting long-term wholesale electricity market prices (dual variables) and resource utilization.
- Each investor's CEM model considers their beliefs about the future (e.g., load growth, etc.) and is applied across multiple scenarios to capture uncertainty.
- Investment and retirement decisions are made based on expected utility, which is calculated from the prices, predicted resource utilization, financing parameters, and risk profiles across the scenarios.

EMIS Currently Includes Four Stylized Investor Agents

Name	Investment Technology Preference	Capital Cost Multiplier (increasing capital cost)	Perceived Riskiness (impacts discount rate)	Risk Preference (parameter in expected utility)
New Entrant	Wind, PV, Battery	High (1.143)	High (2.0%)	Very Risk Averse (1.0e-5)
IPP	Gas CC, Gas CT, RE-CT	Mid (1.105)	Mid (1.0%)	Very Risk Averse (1.0e-5)
C&I IPP	Wind, PV	Mid (1.105)	Low (0.5%)	Risk Averse (1.0e-6)
Large Utility	Gas CC, Gas CT, RE-CT, Wind, PV, Battery	Low (1.085)	None (0.0%)	Risk Averse (1.0e-6)

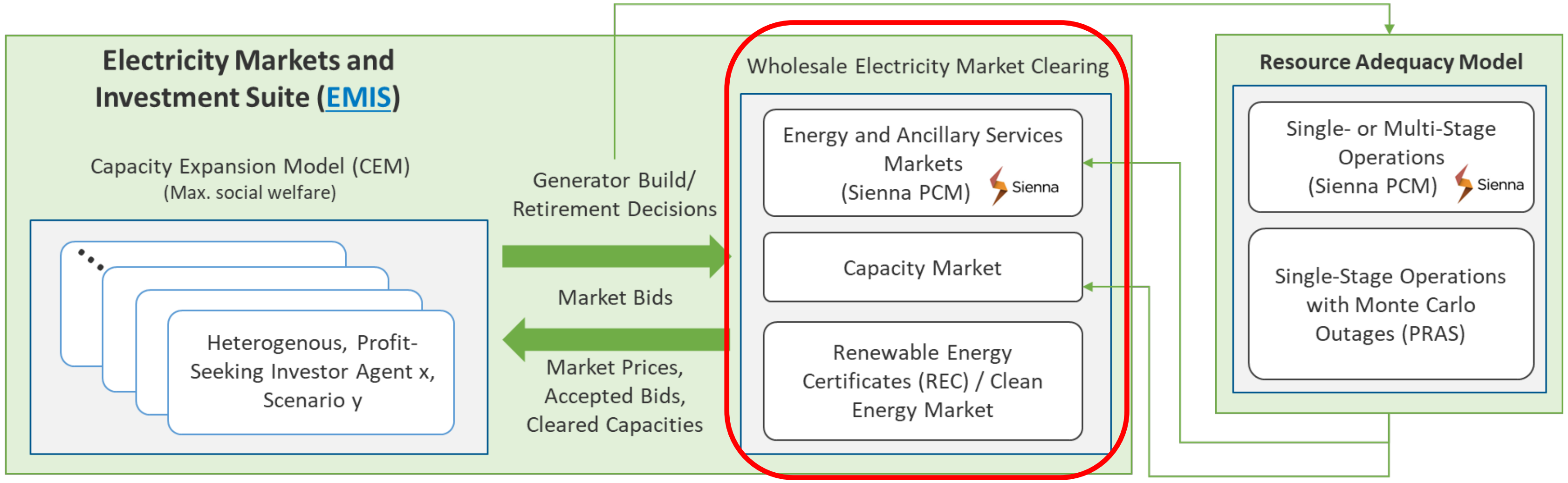
IPP: Independent Power Producer; C&I: Commercial and Industrial; PV: Photovoltaic;
CC: Combined Cycle turbine; CT: Combustion Turbine; RE-CT: Renewable Energy CT; WACC: Weighted Average Cost of Capital; p.a: per annum

EMIS Tracks Multiple Project Phases for Investment and Retirement



*Not drawn to scale

Wholesale Market Clearing

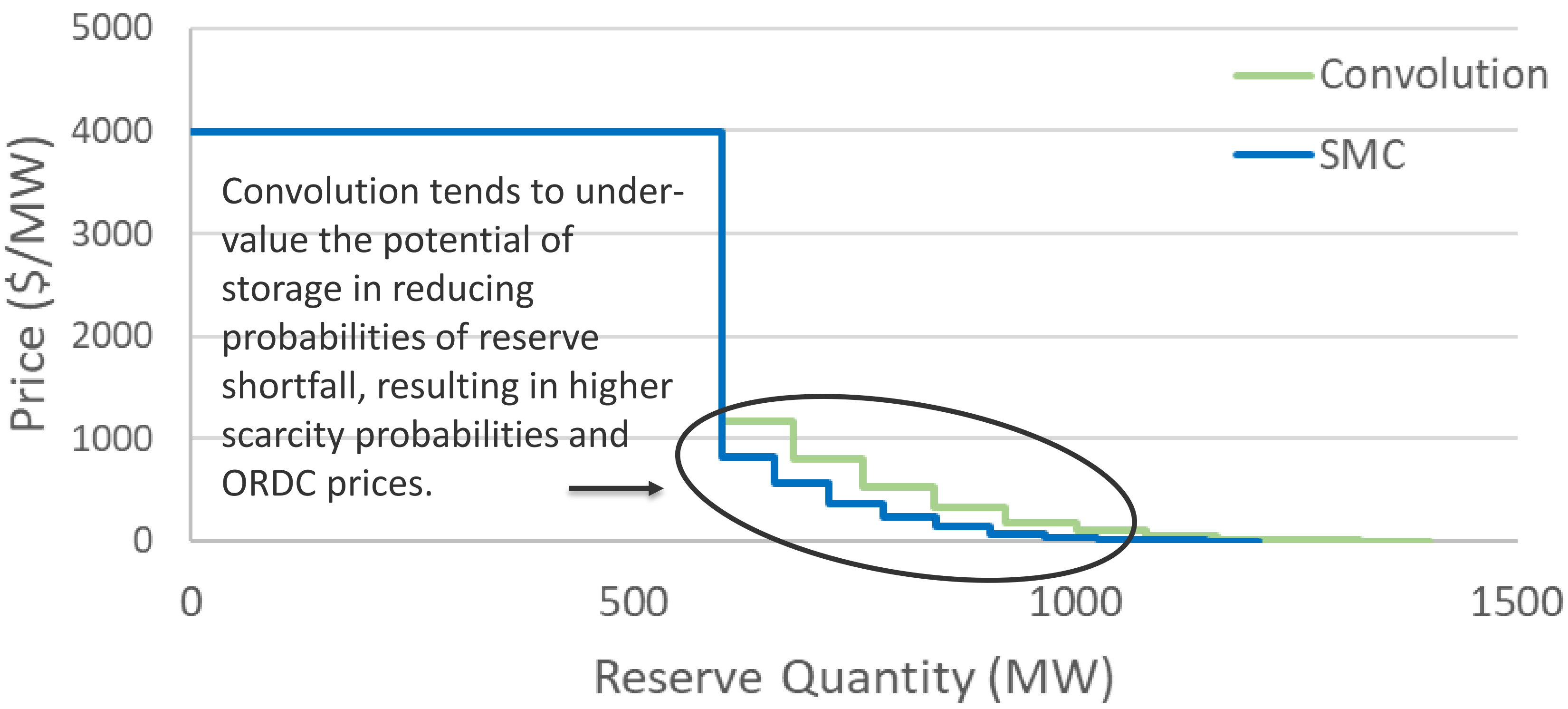


- Each market is cleared based on full set of agents' submitted bids.
- The set of market products and/or operational structures is customizable:
  - Forward capacity market
  - Operating reserves (e.g., reg up, reg down, flex up, flex down, primary, synchronous) with various scarcity pricing structures (e.g., single value, operating reserve demand curve [ORDC], etc.) and eligibility rules
  - Renewable/clean energy markets
  - Multi-day markets
  - Other

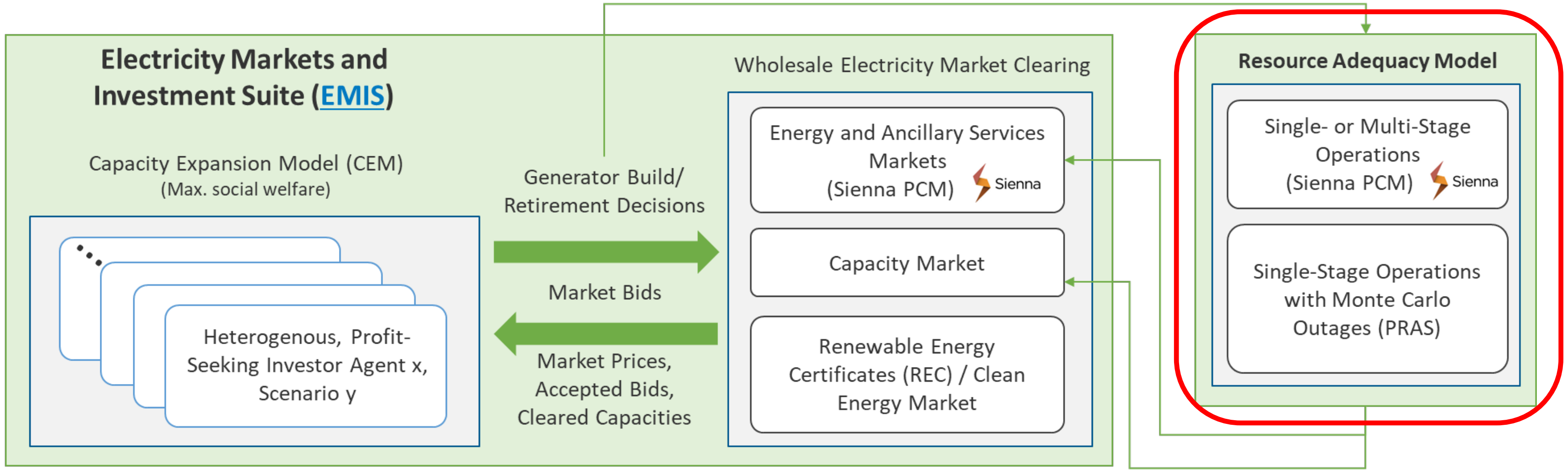
Recent Market Design Updates Have Strengthened the Linkage with RA

ORDCs are one example:

- **Sequential Monte Carlo (SMC):** RA-informed approach that calculates generator and storage resource unavailability profiles accounting for chronology factors
- **Convolution**: Original method that does not account for chronology



RA Check and Feedback



- RA is assessed at each investment interval and can also be feed back into the market design(s)
  - So far, we have focused on RA-adjusted capacity markets and ORDCs
- Many different RA model configurations are possible

See past Powered By webinars for more on PRAS (September 2024) and Sienna (June 2024)!

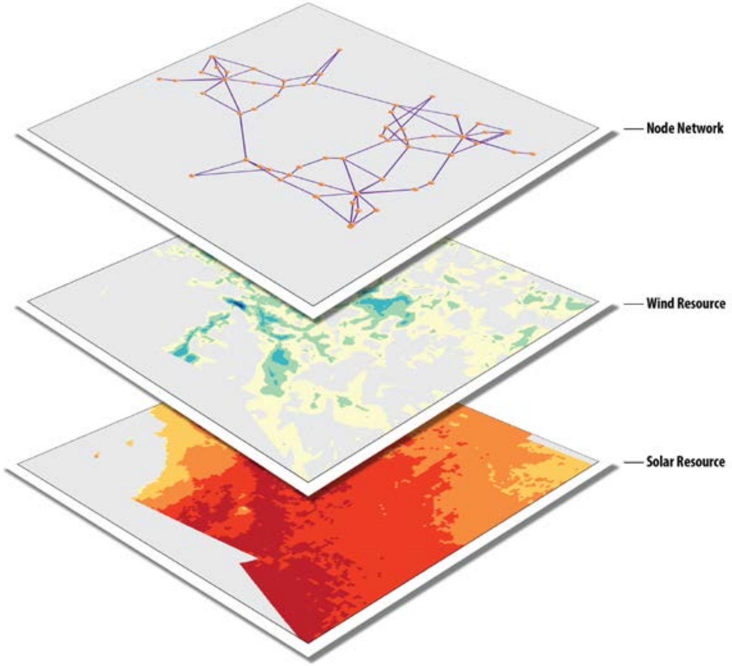
www.nrel.gov/grid/powered-by-webinar-series.html

EMIS Use Cases

Currently Applied to Two Stylized, Realistic Test Systems

RTS-GMLC

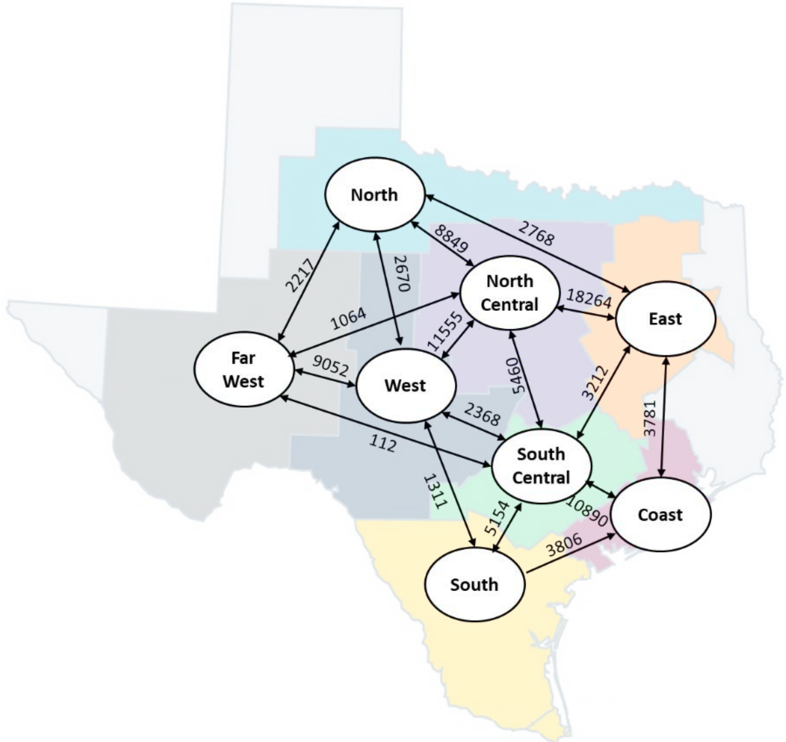
- 3 zones based loosely on portions of the SW U.S. (CA, NV, AZ)
- Initial system peak load ~8 GW



https://github.com/GridMod/RTS-GMLC

ERCOT-like test system

- 8 zones
- Initial system peak load ~76 GW



https://dx.doi.org/10.2139/ssrn.4896921

Published EMIS Analyses

- Impacts of investor heterogeneity, uncertainty, risk aversion, etc.

- Different wholesale market structures and products:
  - Energy-only
  - Capacity market
  - Clean Energy Certificates
  - Operating Reserve Demand Curves (ORDCs)
  - Inertia/FFR
  - Eligibility rules for operating reserves and capacity markets (e.g., Minimum Offer Pricing Rule [MOPR])
  - RA-informed ORDCs and capacity market demand curves
  - Multi-day markets

https://publications.anl.gov/anlpubs/2024/08/190452.pdf

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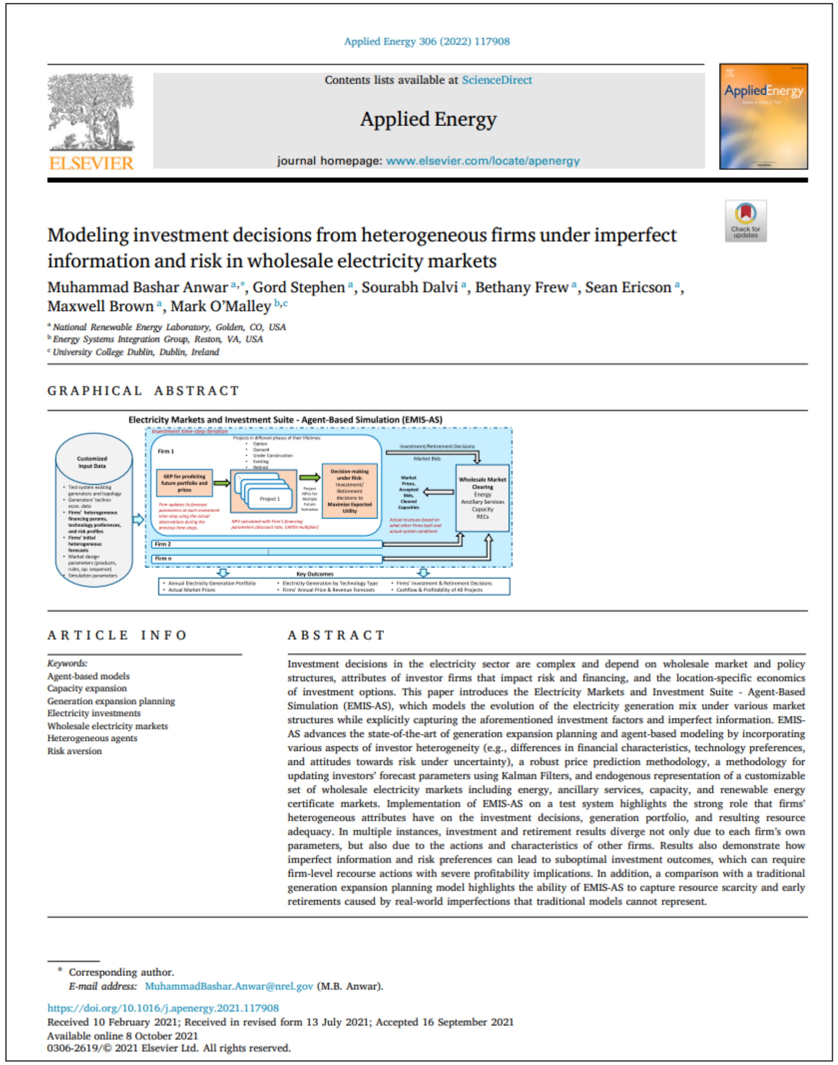
Explore Impacts of Investor Heterogeneity



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Modeling investment decisions from heterogeneous firms under imperfect information and risk in wholesale electricity markets

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GRAPHICAL ABSTRACT

Electricity Markets and Investment Suite - Agent-Based Simulation (EMIS-AS)

ARTICLE INFO

Keywords:
Agent-based models
Capacity expansion
Generation expansion planning
Electricity investments
Wholesale electricity markets
Heterogeneous agents
Risk aversion

ABSTRACT

Investment decisions in the electricity sector are complex and depend on wholesale market and policy structures, attributes of investor firms that impact risk and financing, and the location-specific economics of investment options. This paper introduces the Electricity Markets and Investment Suite - Agent-Based Simulation (EMIS-AS), which models the evolution of the electricity generation mix under various market structures while explicitly capturing the aforementioned investment factors and imperfect information. EMIS-AS advances the state-of-the-art of generation expansion planning and agent-based modeling by incorporating various aspects of investor heterogeneity (e.g., differences in financial characteristics, technology preferences, and attitudes towards risk under uncertainty), a robust price prediction methodology, a methodology for updating investors' forecast parameters using Kalman Filters, and endogenous representation of a customizable set of wholesale electricity markets including energy, ancillary services, capacity, and renewable energy certificate markets. Implementation of EMIS-AS on a test system highlights the strong role that firms' heterogeneous attributes have on the investment decisions, generation portfolio, and resulting resource adequacy. In multiple instances, investment and retirement results diverge not only due to each firm's own parameters, but also due to the actions and characteristics of other firms. Results also demonstrate how imperfect information and risk preferences can lead to suboptimal investment outcomes, which can require firm-level recourse actions with severe profitability implications. In addition, a comparison with a traditional generation expansion planning model highlights the ability of EMIS-AS to capture resource scarcity and early retirements caused by real-world imperfections that traditional models cannot represent.

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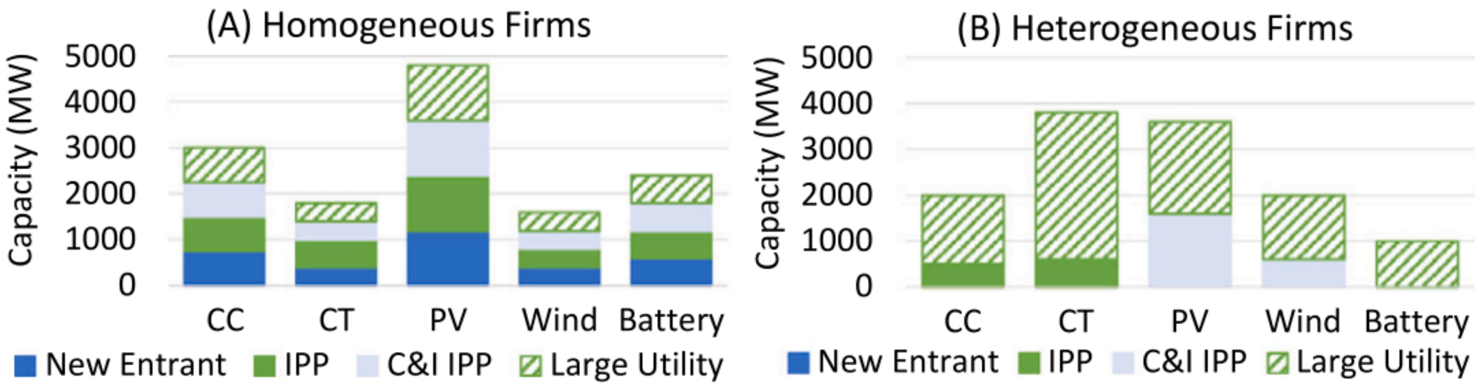

Compared to homogenous agents, heterogeneous agents build different quantities of new capacity (1) at the aggregate technology level, and (2) between agents, with the Large Utility taking the majority share due to favorable financing terms.

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Explore Different Products: Stylized Inertia/Fast Frequency Response

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The interaction of wholesale electricity market structures under futures with decarbonization policy goals: A complexity conundrum

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H I G H L I G H T S :

- We used EMIS-AS model to explore various market structures and clean energy targets.
- Energy-only markets can achieve same clean energy goals as capacity markets.
- ORDC scarcity pricing exhibits substitutional relationship with capacity markets.
- Even one well-designed market mechanism can achieve desired clean energy targets.
- Capacity/reserve eligibility rules for one technology or product can impact others.

A R T I C L E I N F O

Keywords:
Competitive wholesale electricity markets
Market design
Decarbonization
Capacity expansion modeling
Production cost modeling
Renewable energy

A B S T R A C T

Competitive wholesale electricity markets can help facilitate energy system decarbonization by incentivizing investments in clean energy technologies that meet evolving system needs. We explore market structure impacts on generator operations and deployment by risk-averse, heterogeneous investor firms using the Electricity Markets and Investment Suite – Agent-based Simulation (EMIS-AS) model. We apply clean energy targets of 45%–100% by 2035 considering energy, ancillary services, capacity, and clean energy credit products and pricing and eligibility rules. Results highlight a complexity conundrum, whereby finding the "right" market design to achieve decarbonization goals and avoid unintended consequences can be a highly-nuanced, non-incremental challenge. Carefully designed energy-only markets can achieve the same clean energy targets as capacity market structures but with different revenue and profitability outcomes. Operating reserve demand curve-based scarcity pricing can substitute capacity markets for similar deployment outcomes. Carbon pricing alone is most effective at achieving decarbonization levels at low clean energy targets, and clean energy credit markets and carbon pricing are substitutionary at high clean energy targets. Restricting technology participation in capacity and operating reserve markets can impact deployment and operations, even for nonrestricted technologies. Adding an inertia product with fast frequency response yields insufficient provision at high clean energy targets, but work is needed to understand frequency requirements and capabilities.

1. Introduction

The growing momentum behind power system decarbonization efforts—prompted by both policy goals and declining costs of clean energy technologies—has led to numerous studies on the technical challenges of such a transformation (e.g., [1–3]). In areas with competitive wholesale electricity markets, the market design structures and rules present additional challenges for ensuring efficient investment and operations of resources that can supply the necessary set of grid services across numerous timescales to support system reliability as the system evolves.

In the United States, wholesale electricity markets managed by independent system operators (ISOs) or regional transmission operators (RTOs) serve roughly two-thirds of the load [4]. The market design varies by each ISO/RTO. While which designs and products will be most effective in supporting the transition to a decarbonized power system is unclear, the general consensus is market design modifications are needed in every existing ISO/RTO area, both for the existing system and

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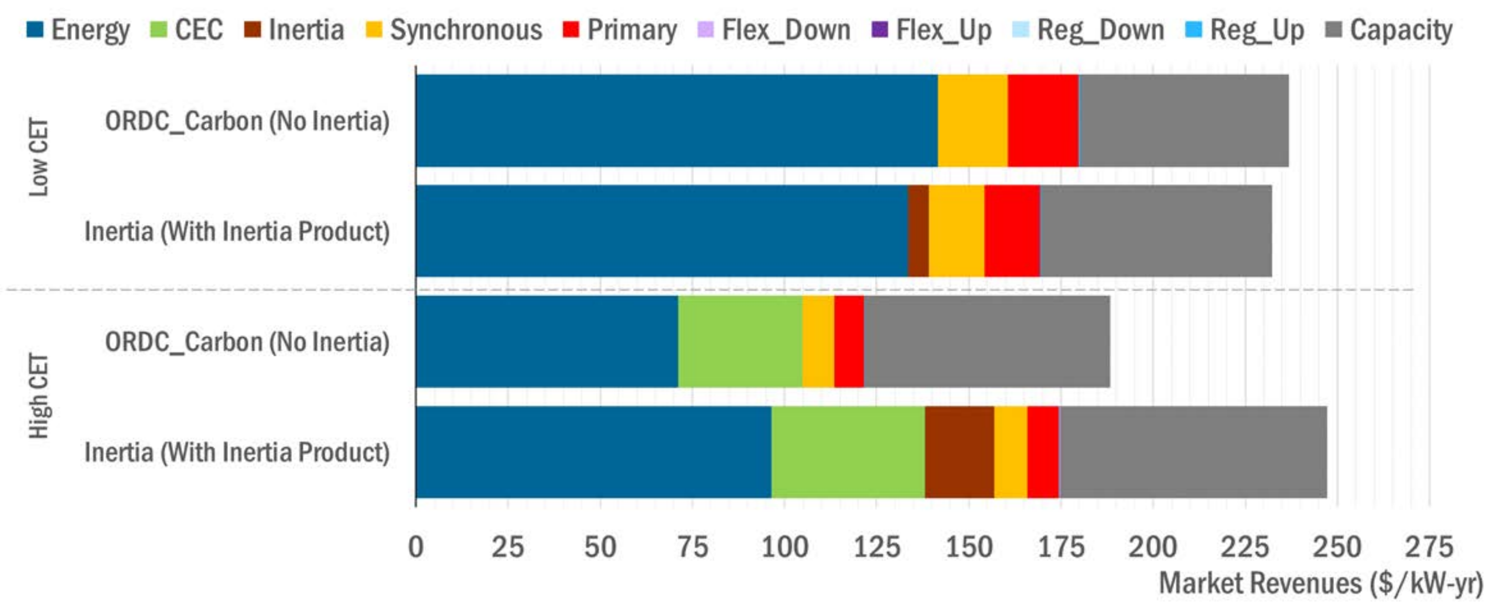
At high clean energy targets, adding an inertia-like product can favor technologies that support both the inertia requirement and clean energy target but also result in potentially redundant resource utilization.



CET = clean energy target (Low = 45% by 2035, High = 100% by 2035)

Evaluate Investor-Level Profit

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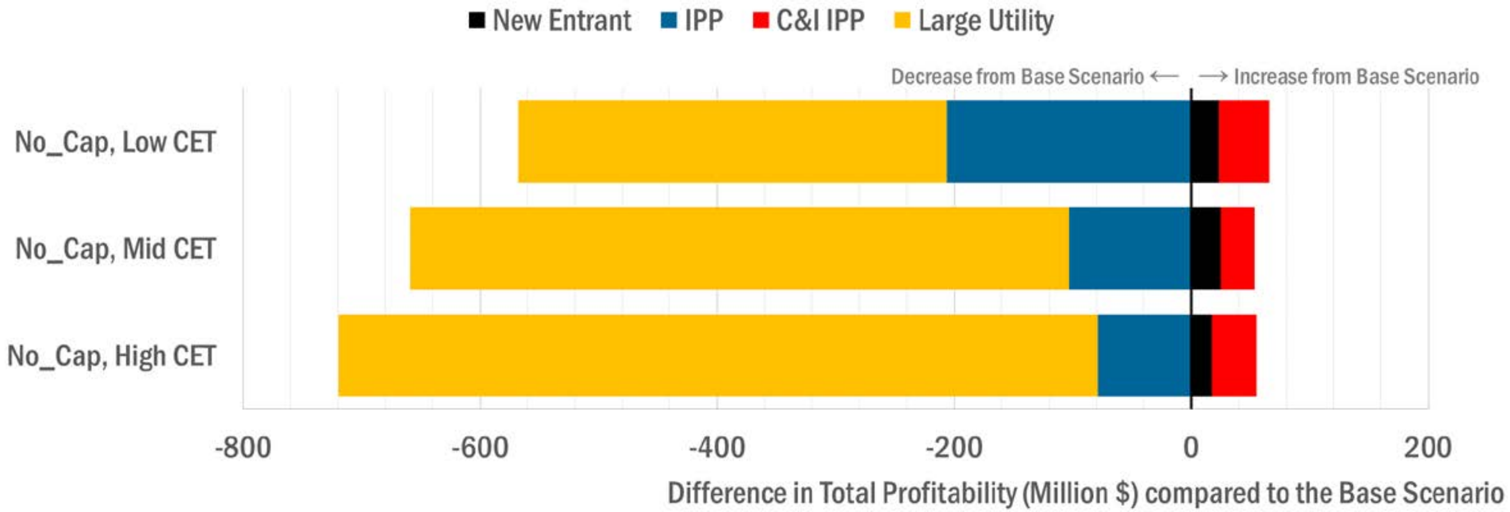
Without a capacity market (i.e., energy-only market):

- Firms that invest in thermal units (IPP and Large Utility) experience reductions in profitability
- New Entrant and C&I IPP (who only build clean energy) experience slight improvements in profitability, as they can more than recover lost capacity market revenues through higher clean energy market and energy market revenues



CET = clean energy target (Low = 45% by 2035, Mid = 75% by 2035, High = 100% by 2035)

Explore Impact of Eligibility Rules: Operating Reserves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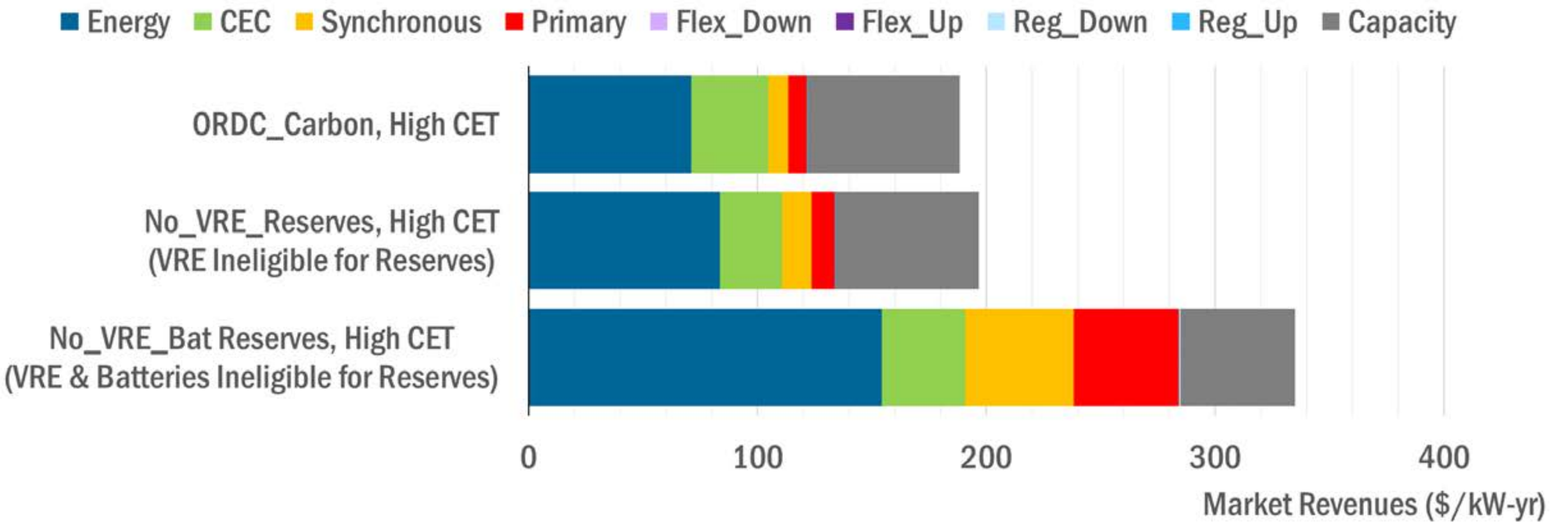
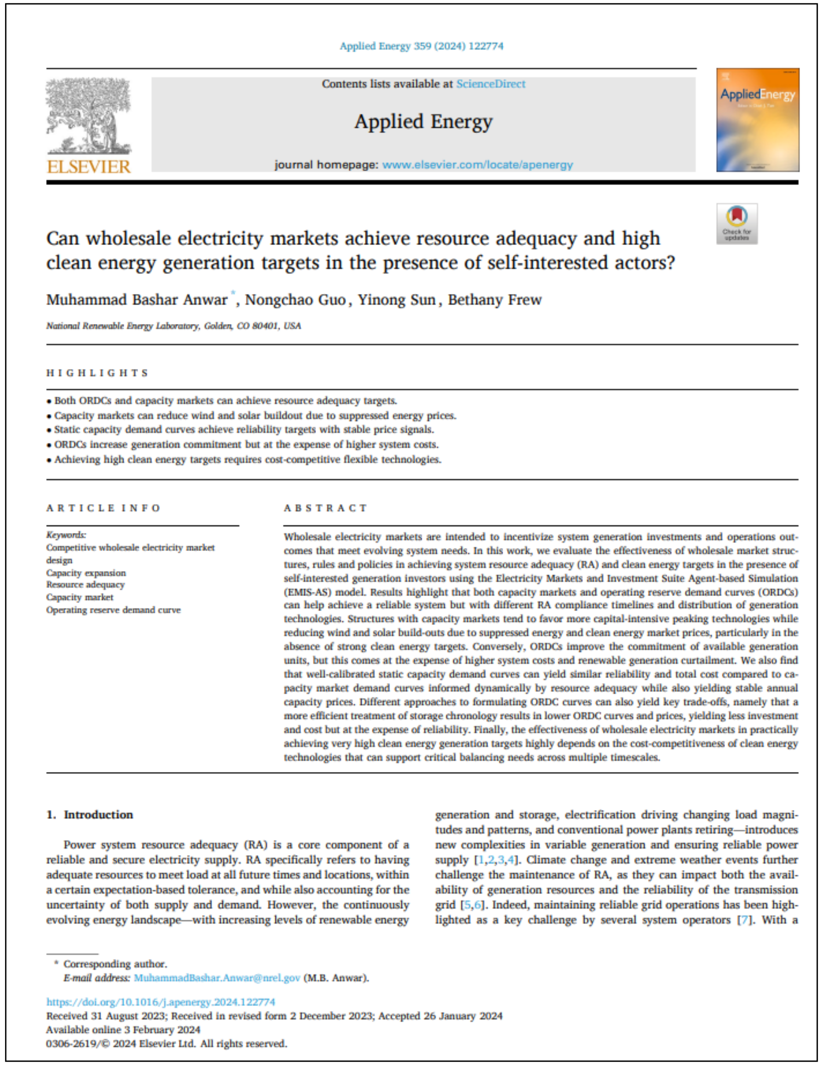
Market rules that restrict participation of clean energy resources for providing operating reserves can result in significant price (and revenue) differences.



VRE = variable renewable energy; CET = clean energy target (High = 100% by 2035)

Compare Market Designs Across Different Clean Energy Targets



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Can wholesale electricity markets achieve resource adequacy and high clean energy generation targets in the presence of self-interested actors?

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H I G H L I G H T S

- Both ORDCs and capacity markets can achieve resource adequacy targets.
- Capacity markets can reduce wind and solar buildout due to suppressed energy prices.
- Static capacity demand curves achieve reliability targets with stable price signals.
- ORDCs increase generation commitment but at the expense of higher system costs.
- Achieving high clean energy targets requires cost-competitive flexible technologies.

A R T I C L E I N F O

Keywords:
Competitive wholesale electricity market design
Capacity expansion
Resource adequacy
Capacity market
Operating reserve demand curve

A B S T R A C T

Wholesale electricity markets are intended to incentivize system generation investments and operations outcomes that meet evolving system needs. In this work, we evaluate the effectiveness of wholesale market structures, rules and policies in achieving system resource adequacy (RA) and clean energy targets in the presence of self-interested generation investors using the Electricity Markets and Investment Suite Agent-based Simulation (EMIS-AS) model. Results highlight that both capacity markets and operating reserve demand curves (ORDCs) can help achieve a reliable system but with different RA compliance timelines and distribution of generation technologies. Structures with capacity markets tend to favor more capital-intensive peaking technologies while reducing wind and solar build-outs due to suppressed energy and clean energy market prices, particularly in the absence of strong clean energy targets. Conversely, ORDCs improve the commitment of available generation units, but this comes at the expense of higher system costs and renewable generation curtailment. We also find that well-calibrated static capacity demand curves can yield similar reliability and total cost compared to capacity market demand curves informed dynamically by resource adequacy while also yielding stable annual capacity prices. Different approaches to formulating ORDC curves can also yield key trade-offs, namely that a more efficient treatment of storage chronology results in lower ORDC curves and prices, yielding less investment and cost but at the expense of reliability. Finally, the effectiveness of wholesale electricity markets in practically achieving very high clean energy generation targets highly depends on the cost-competitiveness of clean energy technologies that can support critical balancing needs across multiple timescales.

1. Introduction

Power system resource adequacy (RA) is a core component of a reliable and secure electricity supply. RA specifically refers to having adequate resources to meet load at all future times and locations, within a certain expectation-based tolerance, and while also accounting for the uncertainty of both supply and demand. However, the continuously evolving energy landscape—with increasing levels of renewable energy generation and storage, electrification driving changing load magnitudes and patterns, and conventional power plants retiring—introduces new complexities in variable generation and ensuring reliable power supply [1,2,3,4]. Climate change and extreme weather events further challenge the maintenance of RA, as they can impact both the availability of generation resources and the reliability of the transmission grid [5,6]. Indeed, maintaining reliable grid operations has been highlighted as a key challenge by several system operators [7]. With a

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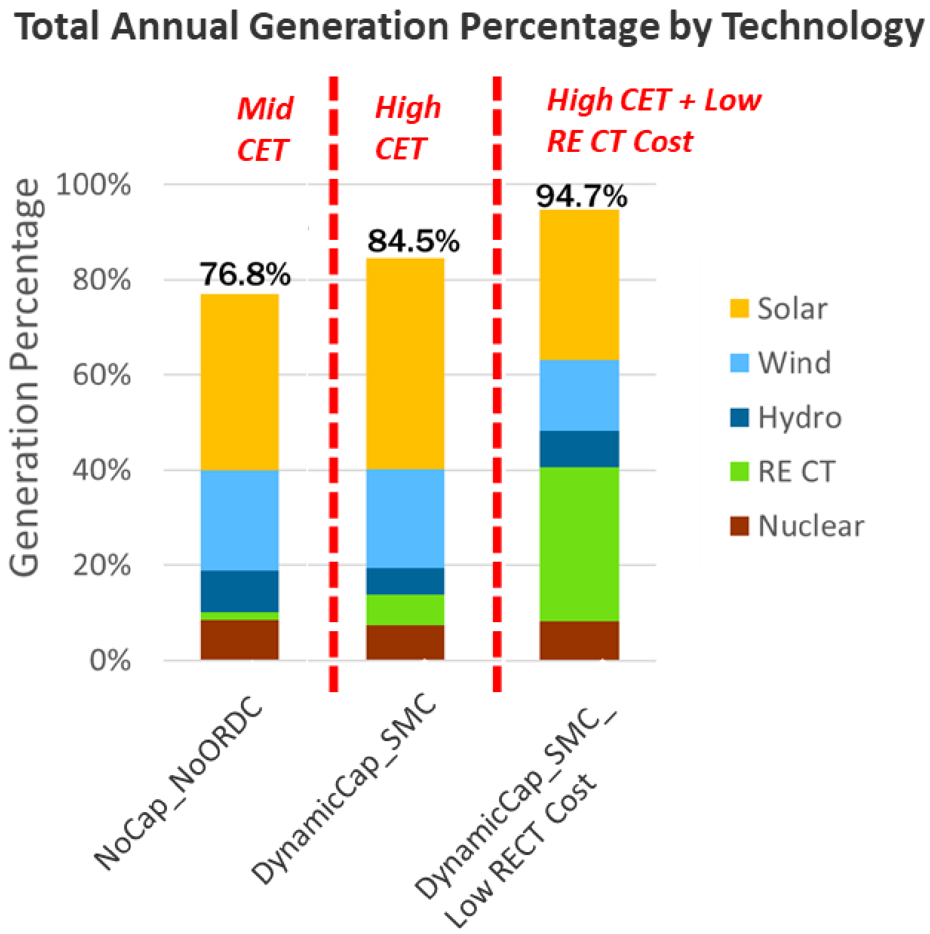
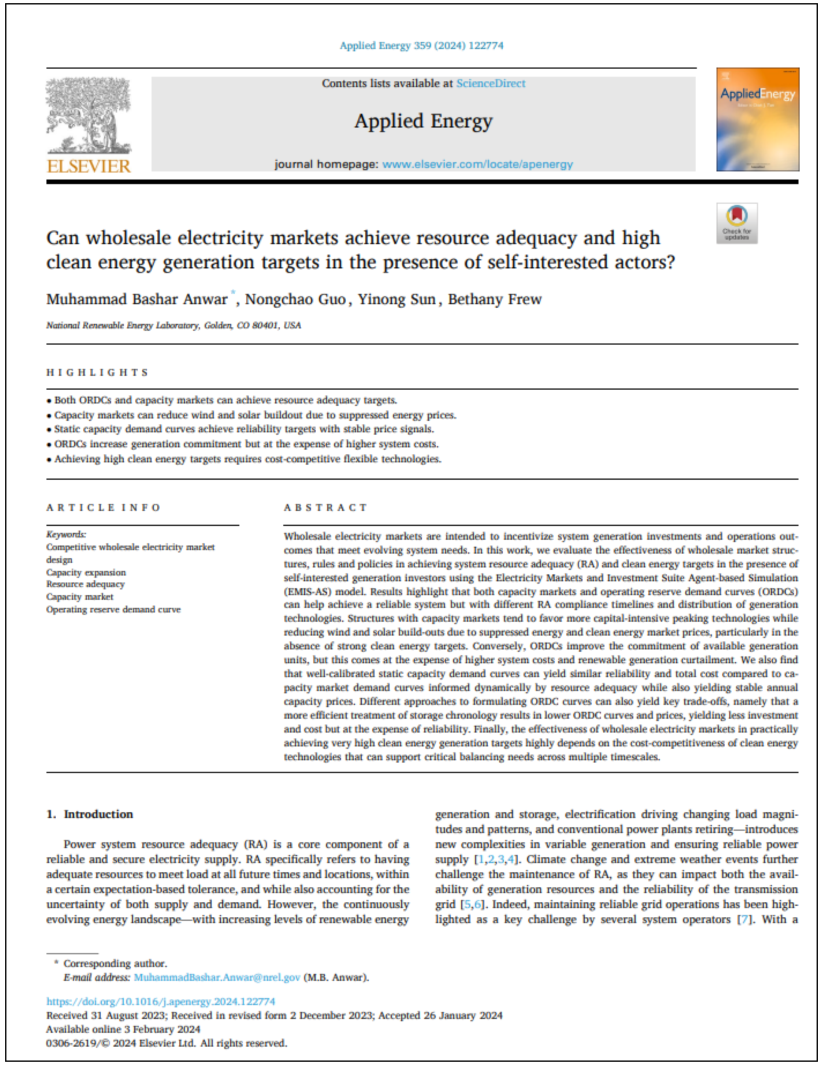
Achieving very high clean energy generation targets depends on the cost-competitiveness of clean energy technologies that can support balancing needs across multiple timescales.



CET = clean energy target (Mid = 75% by 2035, High = 100% by 2035); RE CT = renewable combustion turbine (CT), which is proxy for generic flexible CT generator that is fueled by a range of potential renewable fuels

Compare Different RA Mechanisms: RA Impacts



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Can wholesale electricity markets achieve resource adequacy and high clean energy generation targets in the presence of self-interested actors?

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HIGHLIGHTS

- Both ORDCs and capacity markets can achieve resource adequacy targets.
- Capacity markets can reduce wind and solar buildout due to suppressed energy prices.
- Static capacity demand curves achieve reliability targets with stable price signals.
- ORDCs increase generation commitment but at the expense of higher system costs.
- Achieving high clean energy targets requires cost-competitive flexible technologies.

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ABSTRACT

Wholesale electricity markets are intended to incentivize system generation investments and operations outcomes that meet evolving system needs. In this work, we evaluate the effectiveness of wholesale market structures, rules and policies in achieving system resource adequacy (RA) and clean energy targets in the presence of self-interested generation investors using the Electricity Markets and Investment Suite Agent-based Simulation (EMIS-AS) model. Results highlight that both capacity markets and operating reserve demand curves (ORDCs) can help achieve a reliable system but with different RA compliance timelines and distribution of generation technologies. Structures with capacity markets tend to favor more capital-intensive peaking technologies while reducing wind and solar build-outs due to suppressed energy and clean energy market prices, particularly in the absence of strong clean energy targets. Conversely, ORDCs improve the commitment of available generation units, but this comes at the expense of higher system costs and renewable generation curtailment. We also find that well-calibrated static capacity demand curves can yield similar reliability and total cost compared to capacity market demand curves informed dynamically by resource adequacy while also yielding stable annual capacity prices. Different approaches to formulating ORDC curves can also yield key trade-offs, namely that a more efficient treatment of storage chronology results in lower ORDC curves and prices, yielding less investment and cost but at the expense of reliability. Finally, the effectiveness of wholesale electricity markets in practically achieving very high clean energy generation targets highly depends on the cost-competitiveness of clean energy technologies that can support critical balancing needs across multiple timescales.

1. Introduction

Power system resource adequacy (RA) is a core component of a reliable and secure electricity supply. RA specifically refers to having adequate resources to meet load at all future times and locations, within a certain expectation-based tolerance, and while also accounting for the uncertainty of both supply and demand. However, the continuously evolving energy landscape—with increasing levels of renewable energy generation and storage, electrification driving changing load magnitudes and patterns, and conventional power plants retiring—introduces new complexities in variable generation and ensuring reliable power supply [1,2,3,4]. Climate change and extreme weather events further challenge the maintenance of RA, as they can impact both the availability of generation resources and the reliability of the transmission grid [5,6]. Indeed, maintaining reliable grid operations has been highlighted as a key challenge by several system operators [7]. With a

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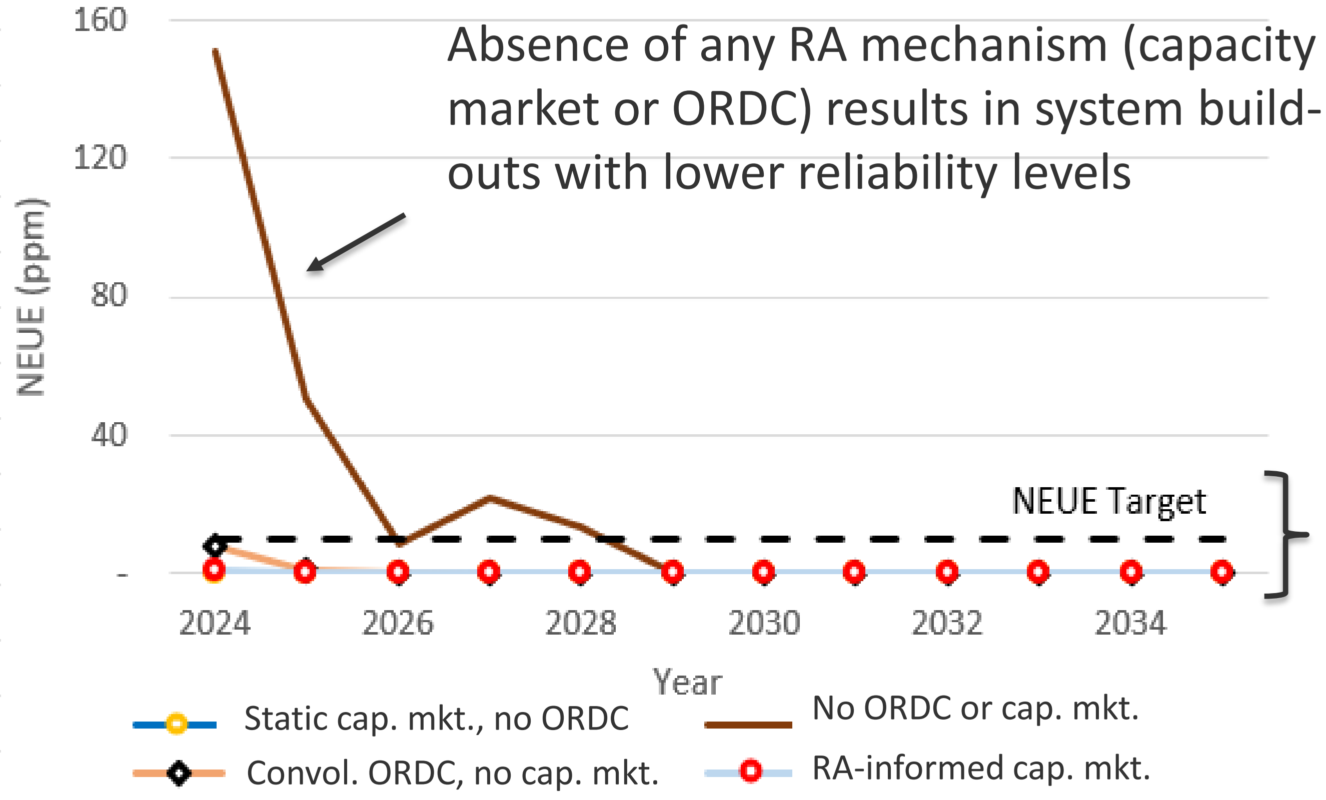
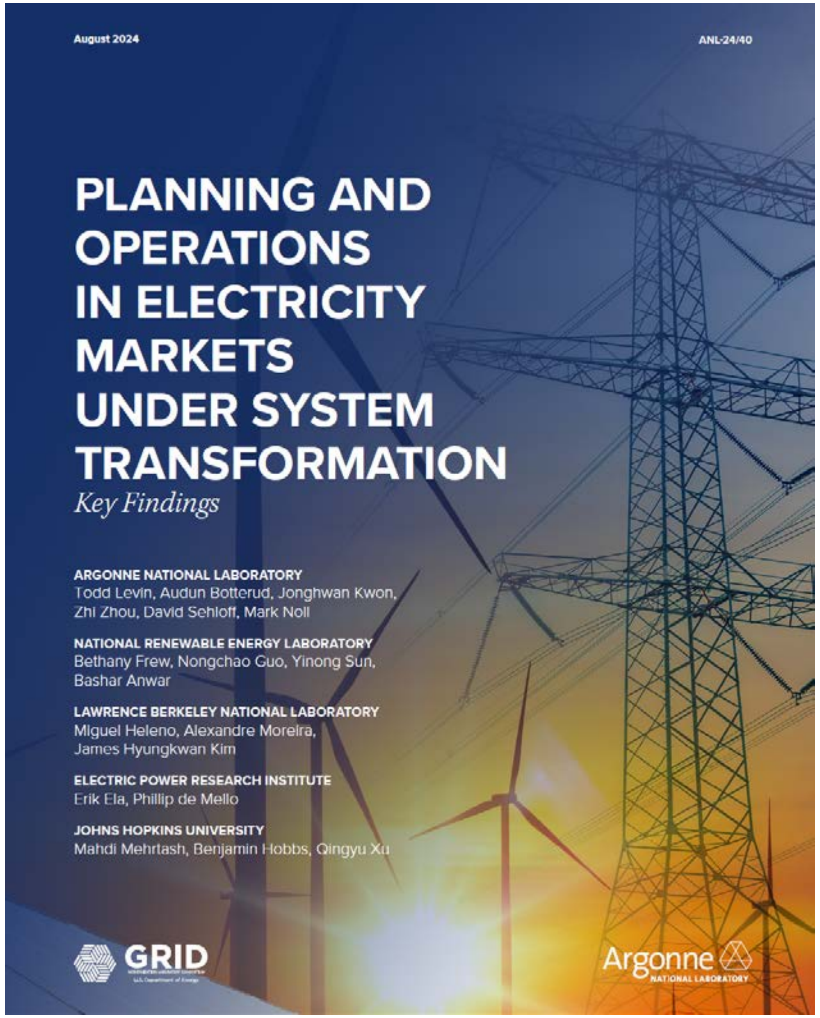


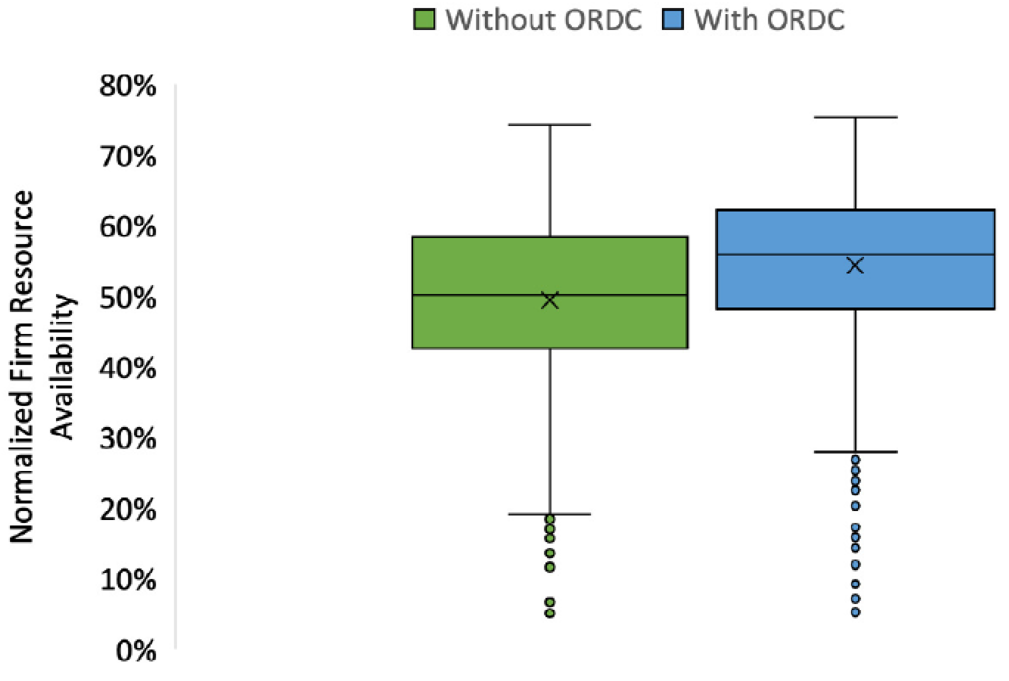
Capacity markets and ORDC can both achieve RA target

NEUE = normalized expected unserved energy

Compare Different RA Mechanisms: Operational Impacts



Compared to a capacity market alone, an ORDC alone may more effectively incentivize capacity availability by efficiently committing resources in the day-ahead market to be available in real-time operations.



Availability is based on the real-time capacity from day-ahead commitment outcomes of all generation resources excluding hydropower, wind, solar, and battery, and it includes hours when locational marginal prices are more than $1,000/MWh

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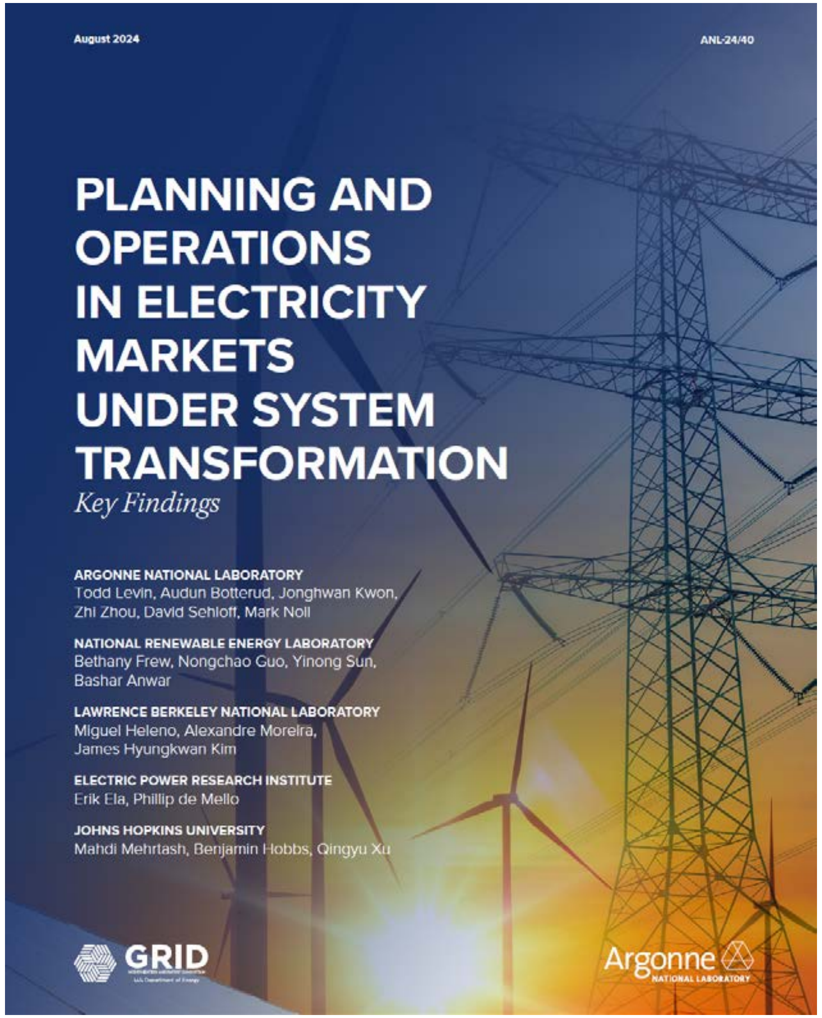
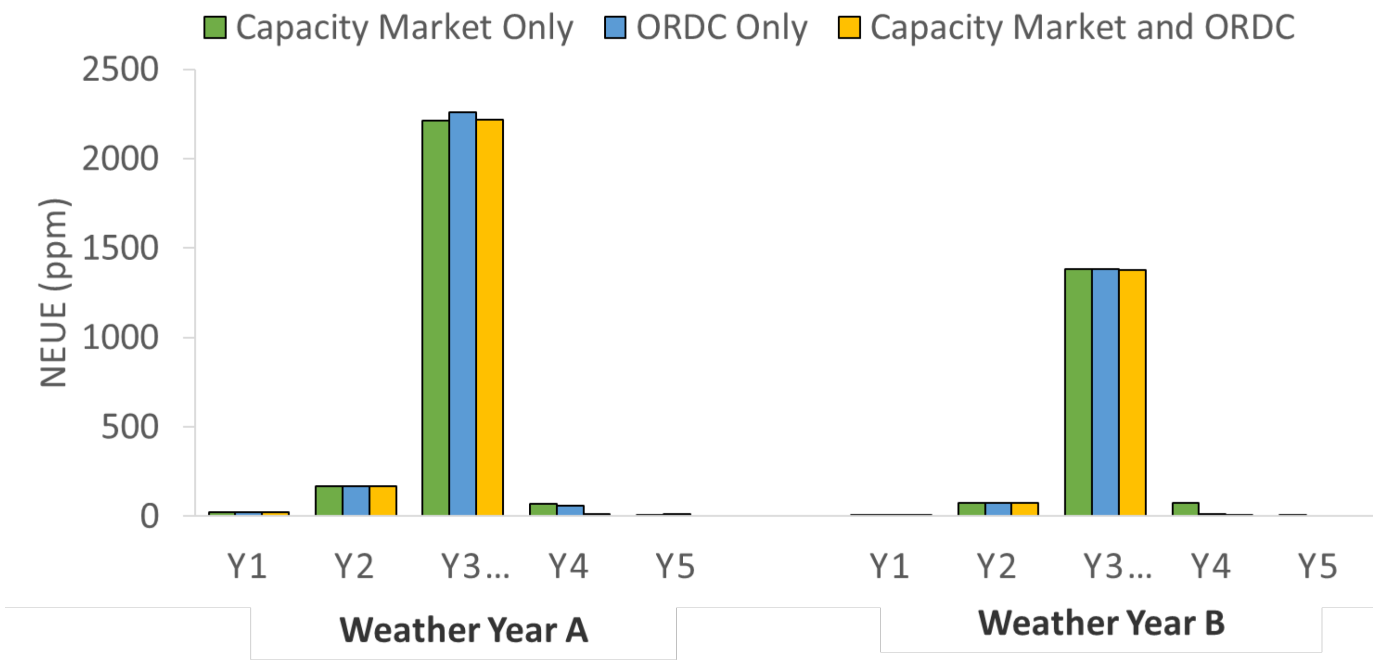
Evaluate the Impact of Different Weather Years on RA and Market Design





RA differences are greater between weather years than between market mechanisms.

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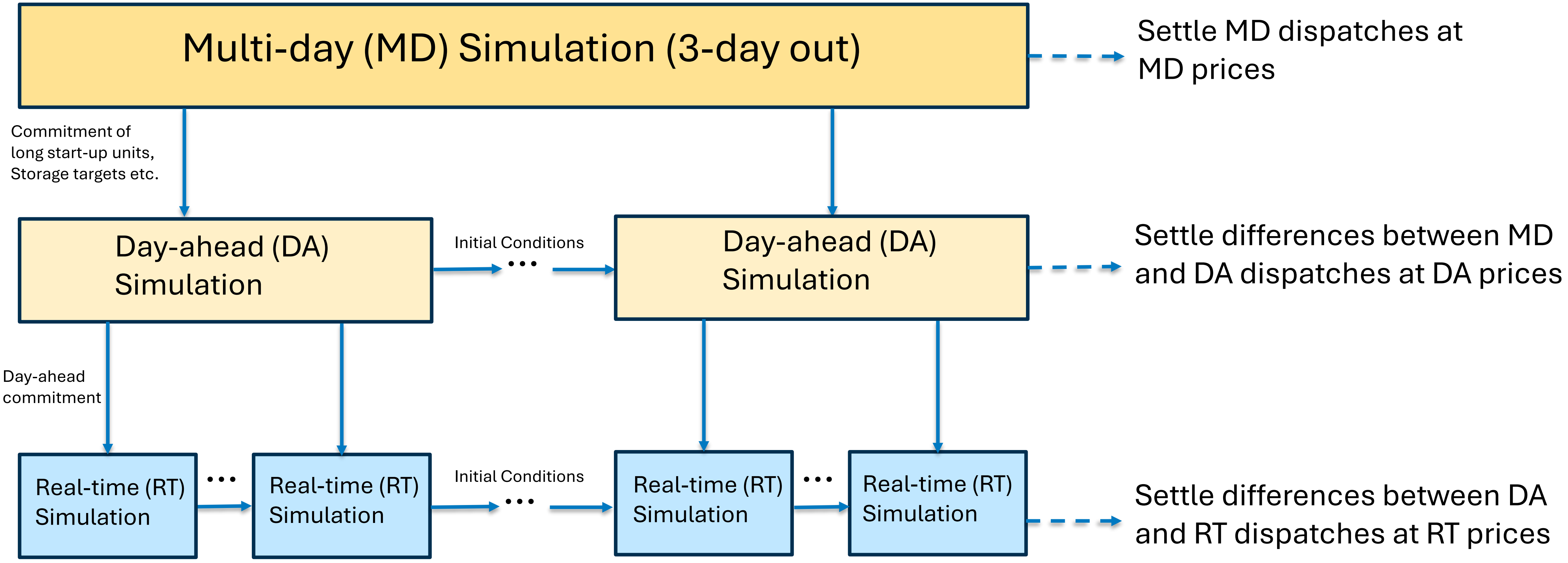
Current Work: Multi-Day Market



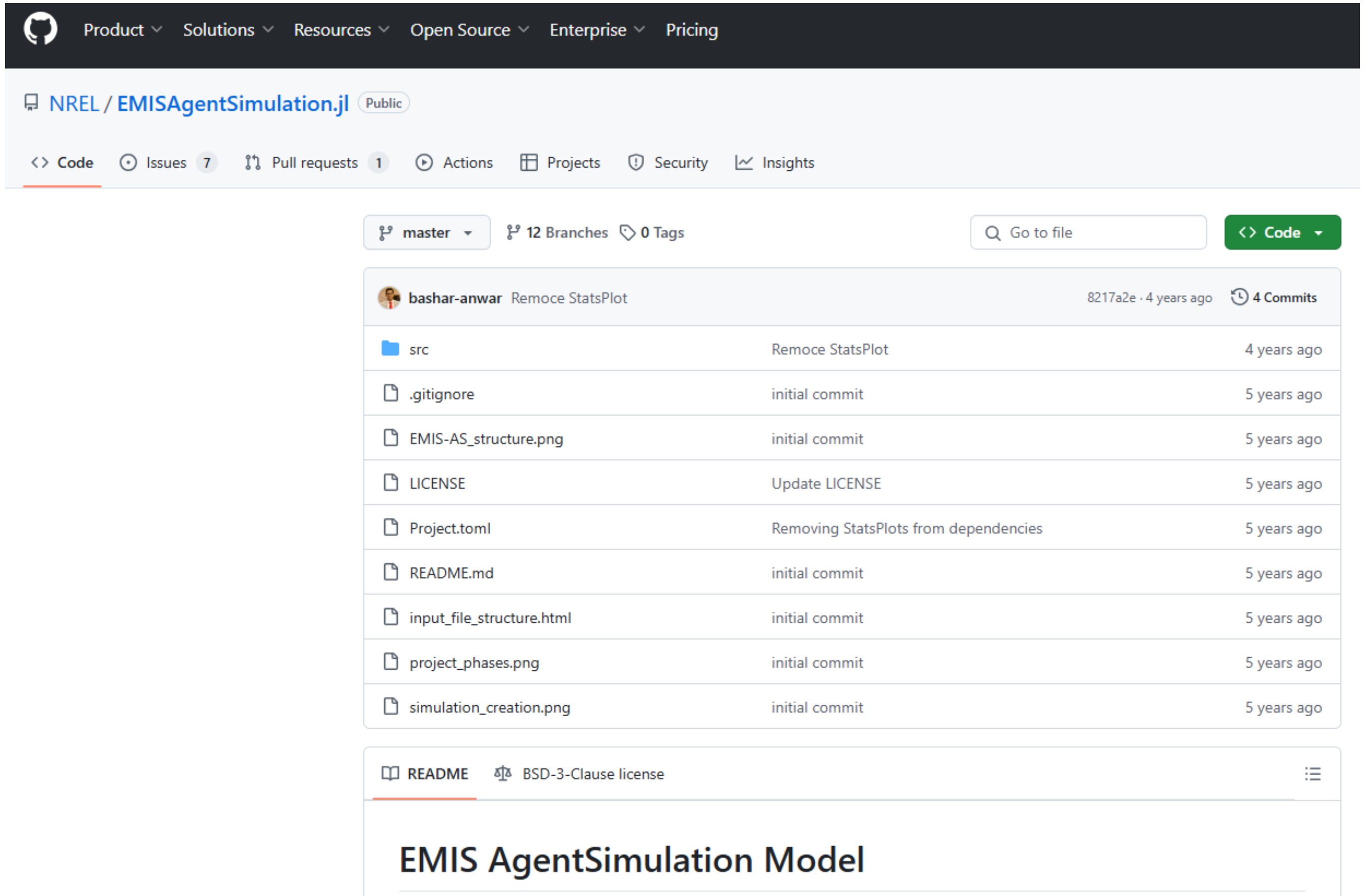
Stay tuned for future results!

How To Access EMIS

EMIS Is Open Source!

Only the application to the modified RTS-GMLC dataset (and not ERCOT) is currently available. We recommend starting with the “sa_analysis” branch, which corresponds to the Anwar et al. (2024) publication. We hope to make more data/versions available in the future.

https://github.com/NREL/EMISAgentSimulation.jl



Read more on the EMIS website:

https://www.nrel.gov/grid/emis.html

Questions?

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