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Ducks on water: A public lecture by Prof. Amro Farid

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Ducks on Water: Lessons Learned from New England's System Operational Analysis and Renewable Energy Integration Studies

Prof. Amro M. Farid[1,2]

[1]- Stevens Institute of Technology
School of Systems and Enterprises
[2]- MIT Mechanical Engineering

LABORATORY FOR INTELLIGENT INTEGRATED NETWORKS OF ENGINEERING SYSTEMS
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http://amfarid.scripts.mit.edu

Invited Seminar
Melbourne Energy Institute
University of Melbourne
Melbourne, VIC, Australia
November 3, 2022

Presentation Abstract

The introduction of variable energy resources (VERs), like solar and wind, necessitates fundamental changes in the power grid's dynamic operation. This evolution is caused by several drivers including decarbonization, growing electricity demand, the deregulation of electricity markets, active end-user participation, and digital innovations in energy technologies. Furthermore, VER forecasts are uncertain and their profiles are intermittent; thus requiring greater quantities of operating reserves. In such a case, fast-ramping natural gas and hydro-electric power plants take on a prominent grid balancing role. At even higher levels of solar PV and wind generation, grid flexibility saturates and VER curtailment becomes the only remaining option for reliable grid balancing. To avoid this undesirable future, demand-side resources become a necessary path for energy system development. These resources are not just energy artifacts, but also exist within other engineering systems. Consequently, their integration gives rise to new multi-disciplinary challenges such as the energy-water nexus. This presentation seeks to share lessons learned from two system operational analysis and renewable energy integration studies conducted in cooperation with ISO New England. In the first, VER resources are increased in the coming decade to reveal a future of grid saturation and VER curtailment. The follow-on New England Energy-Water Nexus Study shows that coordinated energy-water resources can create a triple bottom-line synergy worth $70M/yr. The presentation concludes that a decarbonization agenda must evolve from power grid studies with electricity as a single energy carrier to multi-energy engineering systems studies that specifically coordinate multiple energy carriers through many layers of coordinated planning and operations management decisions.

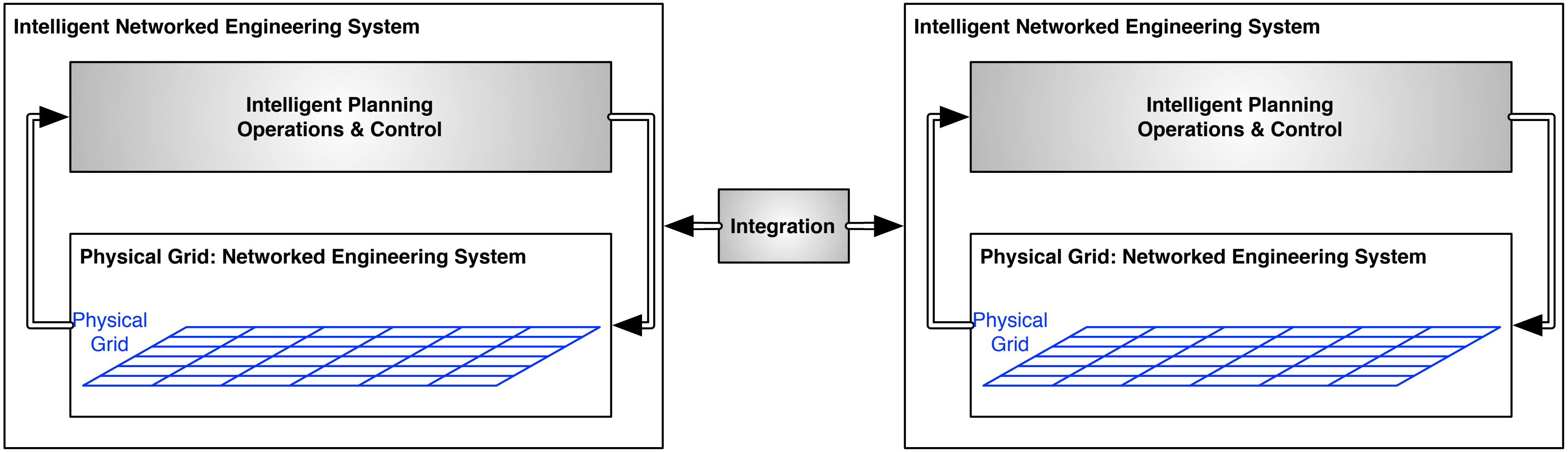
Professional Bio: Prof. Amro M. Farid

- Alexander Crombie Humphreys Chair Professor of Economics in Engineering at Stevens Institute of Technology School of Systems and Enterprises (2022)
- Fulbright Future Scholar – CSIRO Visiting Scientist (2022)
- Visiting Professor MIT Mechanical Engineering (2022)
- CEO/CTO of Engineering Systems Analytics LLC (since 2014)
- Chair of the IEEE Smart Cities R&D Committee
- Highly active and prolific researcher ~150 peer-review publications

- MIT Mechanical Engineering Sc.B. (2000) and Sc.M. (2002)
- Ph.D. at U. of Cambridge Institute for Manufacturing (2007)
- Air Liquide Environment and Greenhouse Gases Specialist (2007-2010)
- MIT MechE Visiting Scientist/Research Affiliate (since 2010)
- Assistant Professor of Engineering Systems & Management Masdar Institute (2010– 2015)
- Chair/Executive Committee of Council of Engineering Systems Universities (since 2014)
- Associate Professor of Engineering at Dartmouth (2015-2022)

LIINES Research Mission & Scope

The **LIINES** (Laboratory for Intelligent Integrated Networks of Engineering Systems) is devoted to enhancement of ***sustainability***, and ***resilience*** in ***intelligent multi-energy engineering systems***. We seek to develop an internationally recognized, ***locally relevant*** and industrially-facing program of research that engineers intelligent & integrated control, automation, and information technology systems that support the operations and planning of large-scale integrated energy systems. These activities encourage and facilitate technology policy that supports the achievement of energy, water, transportation & industrial policy objectives while eliminating barriers to sustainable and resilient automated solutions.



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LIINES Research Themes

Smart Power Grids

Energy-Water Nexus

Electrified Transportation Systems

Industrial Energy Management

Interdependent Smart City Infrastructures

- **Smart Power Grids**: As a full energy value chain including power generation, power transmission & distribution and building systems. Electricity currently accounts for ***29% of U.S. CO_2 emissions***.
- **Energy Water Nexus**: Focusing on points of interconnection including power generation, desalination, water pumping and building systems. Electricity currently accounts for ***49% of U.S. water withdrawals***.
- **Electrified Transportation Systems**: Focusing on electric vehicles as a point of interconnection. Transportation currently accounts for ***27% of U.S. CO_2 emissions***.
- **Industrial Energy Management**: Automated approaches to energy management industrial production & service delivery. Manufacturing currently accounts for ***21% of U.S. CO_2 emissions***.
- **Interdependent Smart City Infrastructure**: This research theme represents a concerted effort to generalize sustainability, resilience, to the emerging need for integrated smart cities. U.S. cities are home to ***62.7% of the population*** but comprise just ***3.5% of the land area***.

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Acknowledgements

DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA

NSF

DEPARTMENT OF DEFENSE · UNITED STATES OF AMERICA

ISTS
Institute for Security, Technology, & Society at Dartmouth College

MITSUBISHI HEAVY INDUSTRIES

ISO new england

EPRI ELECTRIC POWER RESEARCH INSTITUTE

The Arthur L. Irving Institute for Energy and Society

Presentation Outline

Goal: To share lessons learned from two system operational analysis and renewable energy integration studies conducted in cooperation with ISO New England

- **Drivers for the Evolution of the Electric Power Grid**
  - *The introduction of variable renewable energy resources necessitates fundamental changes in the power grid's dynamic operation*
- **Lessons from the ISO New England Renewable Energy Integration Study**
  - *At high levels of solar PV and wind generation, dispatchable demand-side resources become the only remaining option for a cost-effective, reliable, and sustainable grid*
- **Lessons from the New England Energy Water Nexus Study**
  - *The integration of water-energy resources creates several synergies: additional operating reserves, reduced water withdrawals and consumption, and reduced energy market production costs (~$70M).*
- **Looking Ahead to Intelligent Multi-Energy Engineering Systems**
  - *A decarbonization agenda must evolve from power grid studies with electricity as a single energy carrier to multi-energy engineering system studies that specifically coordinate multiple energy carriers through many layers of coordinated planning and operations management decisions.*

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Q: Can Business-As-Usual Persist?

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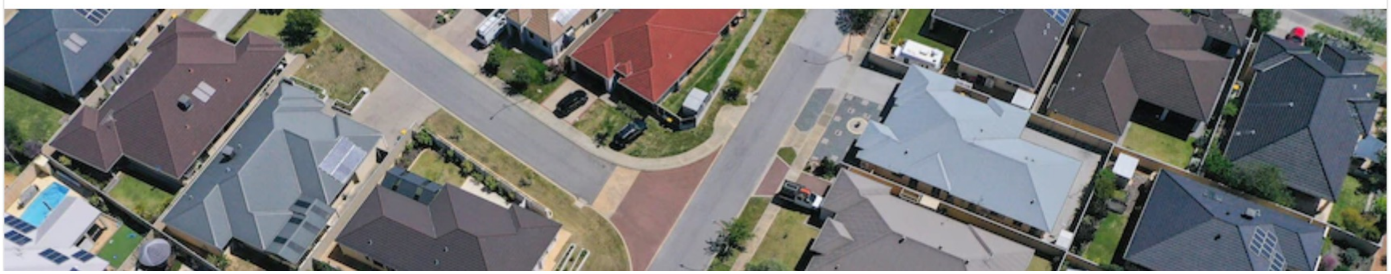
Australian Energy Market Operator suspends spot market for wholesale electricity to ensure reliability and avoid blackouts

By political reporter Melissa Clarke and Nicholas McElroy

Posted 21h ago, updated 18h ago



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Q: Can Business-As-Usual Persist?

Energy market suspended after chaos made it ‘impossible to operate’

By **Mike Foley**

Updated June 15, 2022 — 6.42pm, first published at 3.31pm

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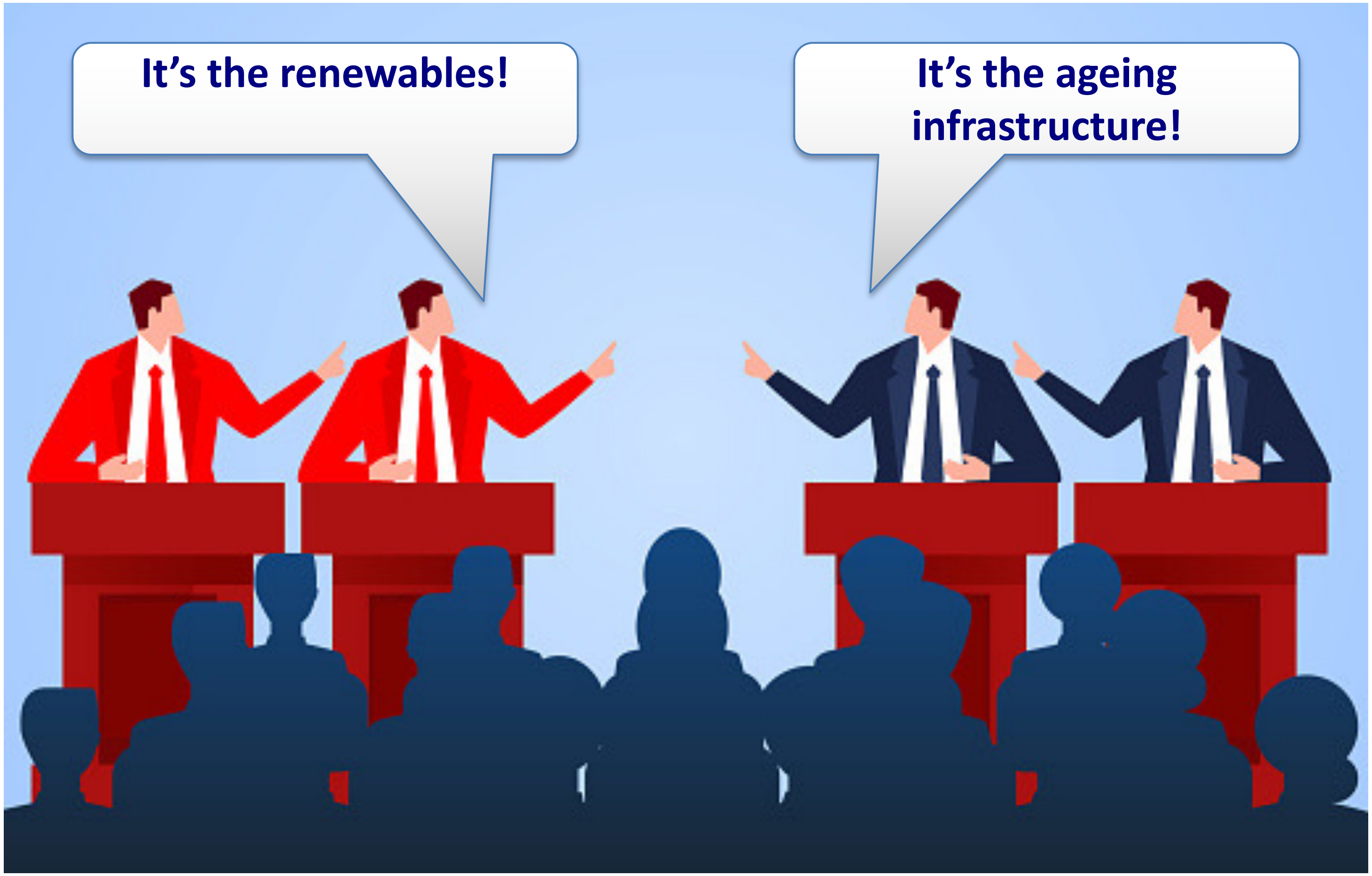
The Australian Energy Market Operator (AEMO) has made an unprecedented market intervention to suspend trading across the entire east coast electricity power network as it scrambles to restore calm to an increasingly volatile situation.

https://www.smh.com.au/politics/federal/energy-market-suspended-after-chaos-made-it-impossible-to-operate-20220615-p5atyk.html

Q: Can Business-As-Usual Persist? → A: No!



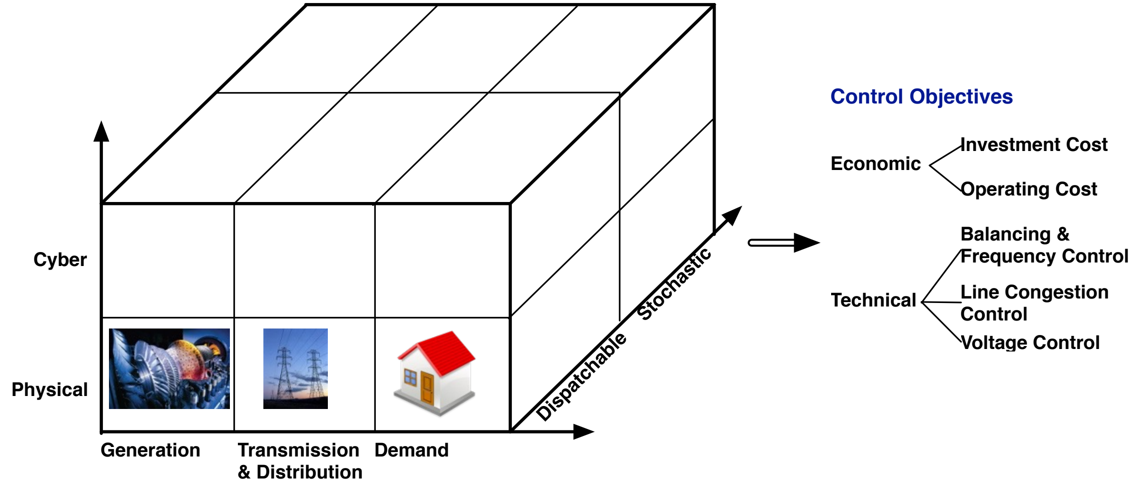
It stands to reason that if you can operate the grid well w/o the market but can't with the market, then you need to fix the market!

Drivers for the Evolution of the Electric Power Grid

Traditional power systems were built upon the assumption that generation was controlled by a few centralized generation facilities that were designed to serve fairly passive loads.

Several drivers have emerged to challenge this assumption:

- Decarbonization
- Disruptive electricity demand
- Deregulation of electricity markets with active end-user participation
- Digital innovations in energy technologies (eIoT)



We need holistic techniques that integrate multiple layers of control and simultaneously manage technical and economic objectives.

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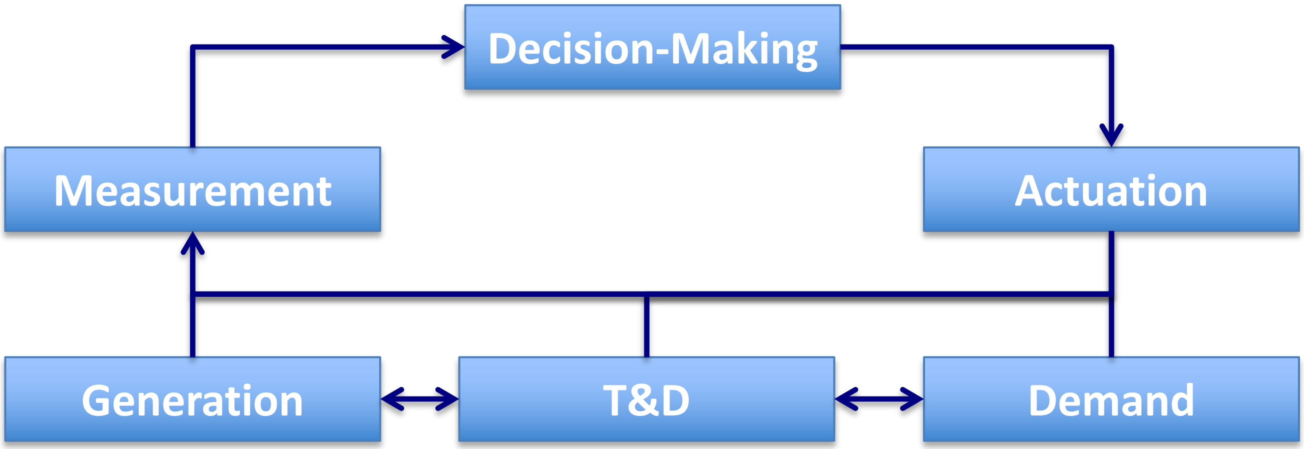
Towards The Future of the Electric Grid



"Opportunities for improving the functioning and reliability of the grid arise from technological developments in sensing, communications, control, and power electronics. These technologies can enhance efficiency and reliability, increase capacity utilization, enable more rapid response to remediate contingencies, and increase flexibility in controlling power flows on transmission lines. ***If properly deployed and accompanied by appropriate policies***, they can deal effectively with some of the challenges described above. They can facilitate the integration of large volumes of renewable and distributed generation, provide greater visibility of the instantaneous state of the grid, and make possible the engagement of demand as a resource". (MIT Future of the Electric Grid Study 2011)

The electric power grid evolves to a more intelligent, responsive, and dynamic system that propels the sustainable energy transition.

The Emergence of Variable Renewable Energy (VRE)

Past:

Generation/Supply	Load/Demand
Thermal Units: Few, Well-Controlled, Dispatchable, In Steady-State	Conventional Loads: Slow Moving, Highly Predictable, Always Served

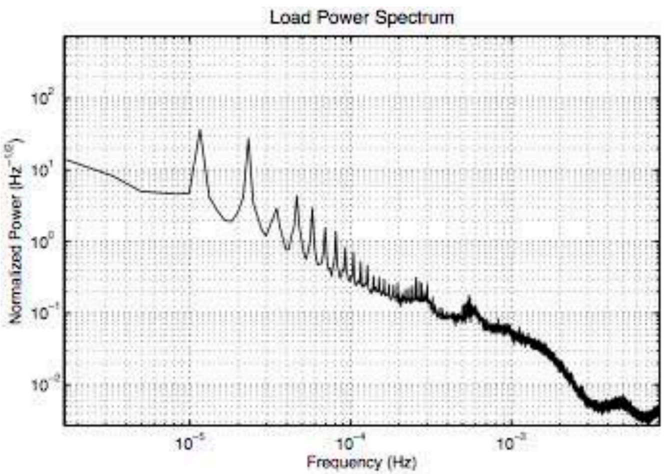
Future:

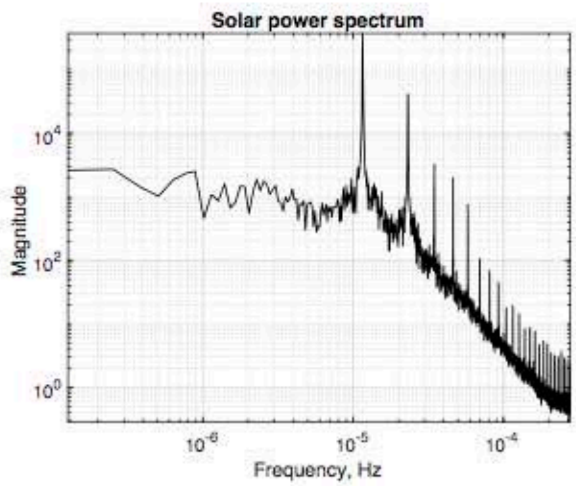
	Generation/Supply	Load/Demand
Well-Controlled & Dispatchable	Thermal Units: (Potential erosion of capacity factor) ↓	Demand Side Resources (Requires new control & market design) ↑
Stochastic/ Forecasted	Solar & Wind Generation: (Can cause unmanaged grid imbalances) ↑	Conventional Loads: (Growing & Needs Curtailment) ↓

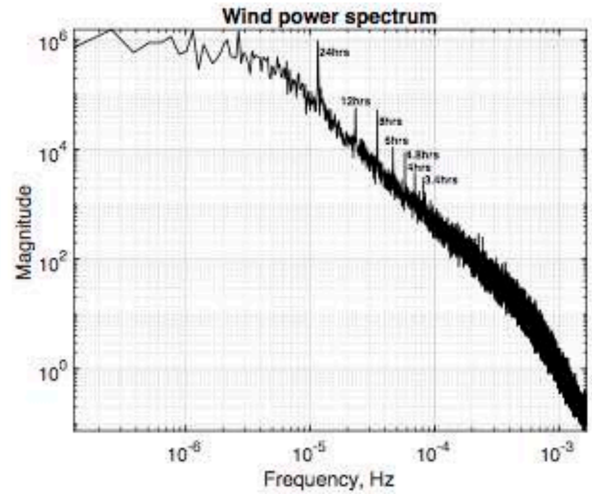
Fundamental Shift: From resource-stocks to resource flows

The emergence of VRE necessitates active demand side resources.

The Multi-Timescale Nature of Variable Renewable Energy

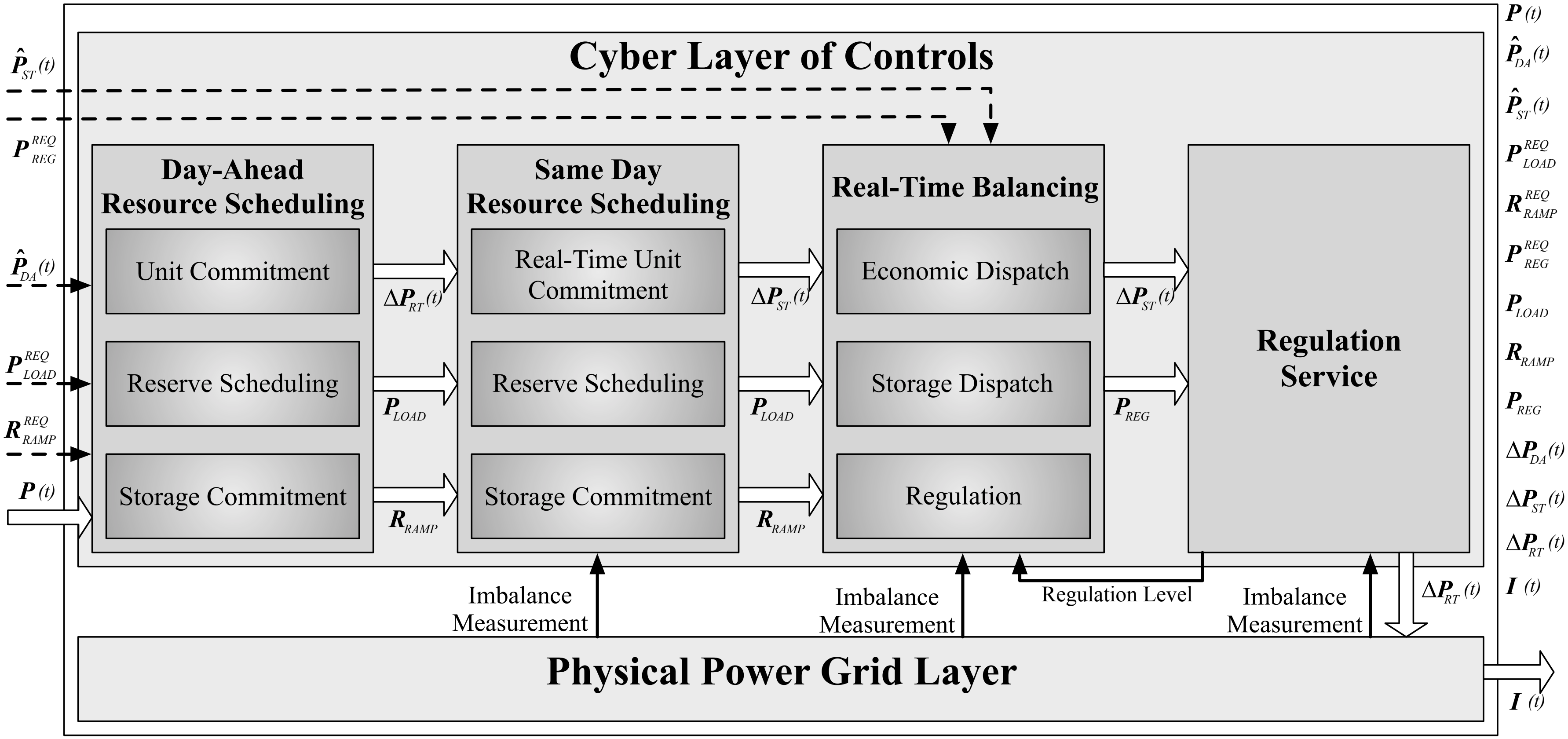






The emergence of VRE necessitates a multi-timescale assessment.

Electric Power Enterprise Control System Simulation (EPECS)



EPECS Simulation has been used to study techno-economic system performance in the presence of variable renewable energy resources.

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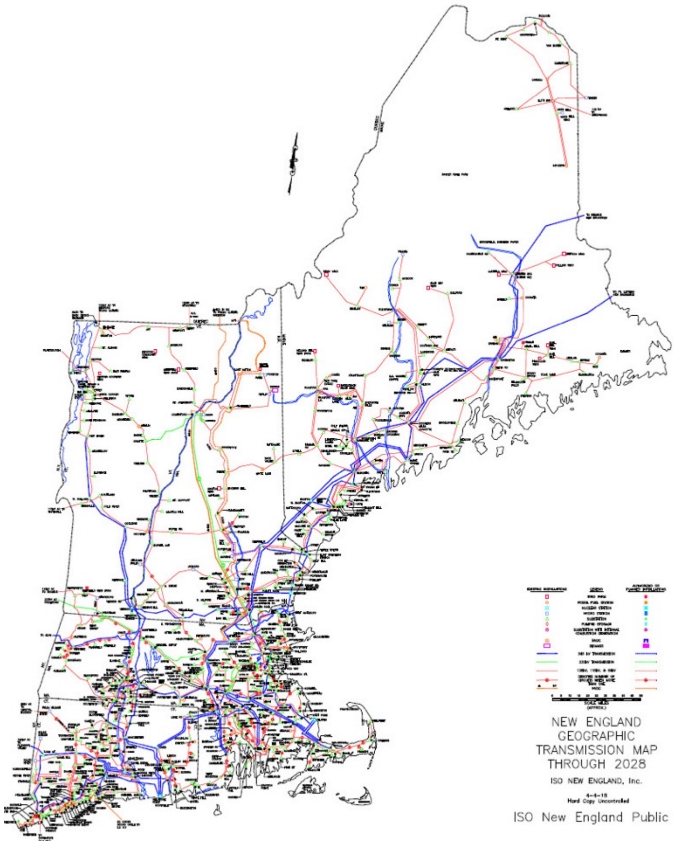
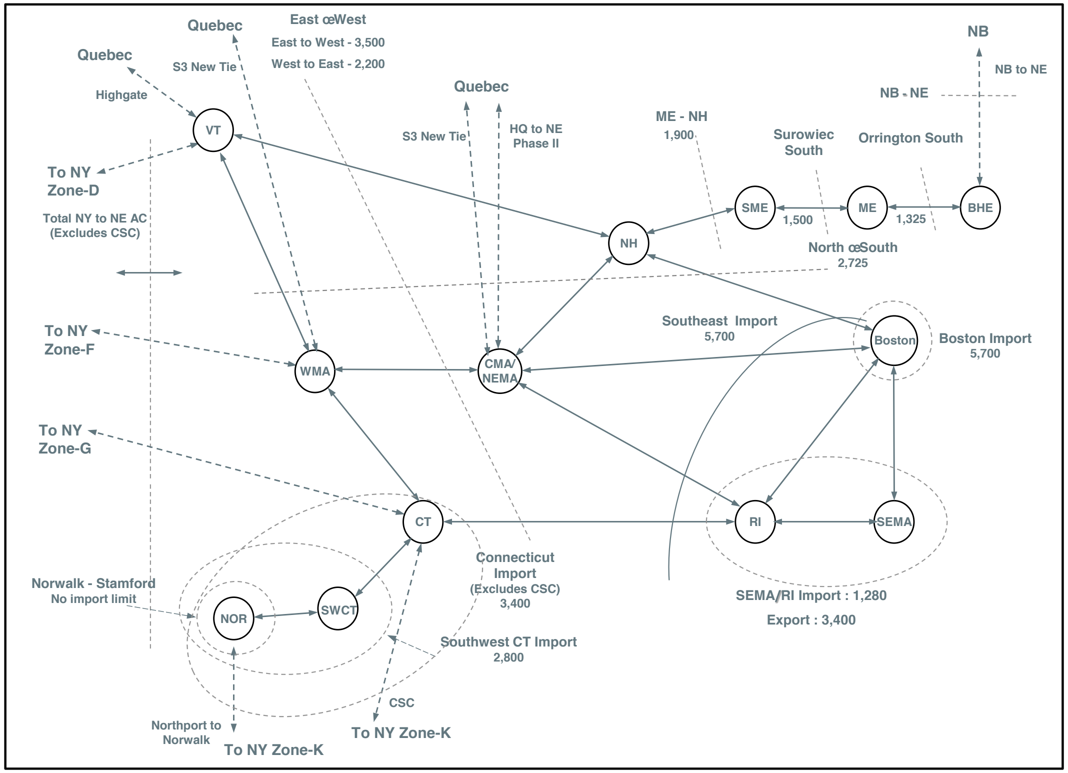
The ISO New England Transmission System





ISO-NE Stakeholders chose a “Pipe and Bubble” representation of transmission.

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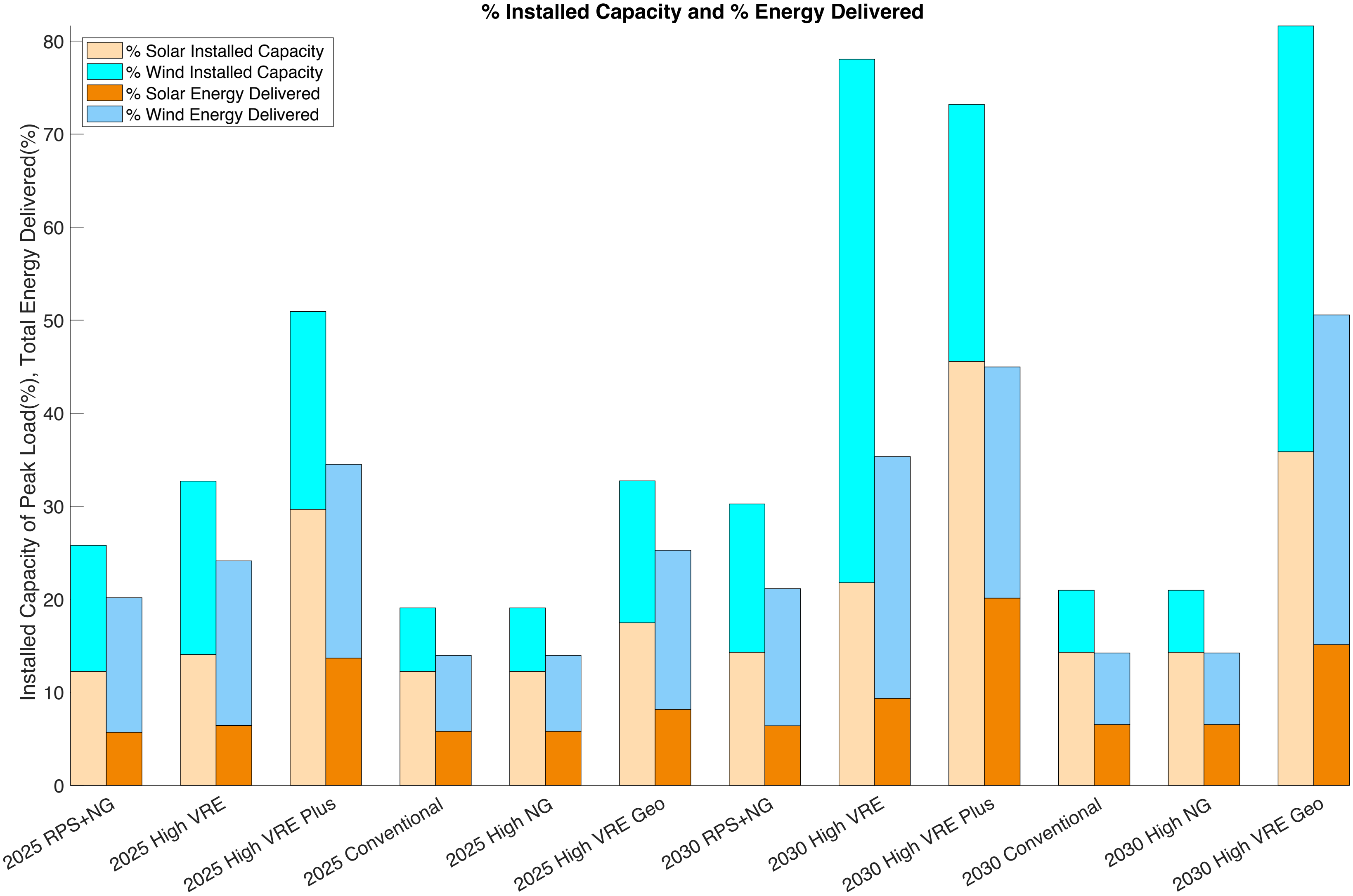
The ISO New England Renewable Energy Study Scenarios



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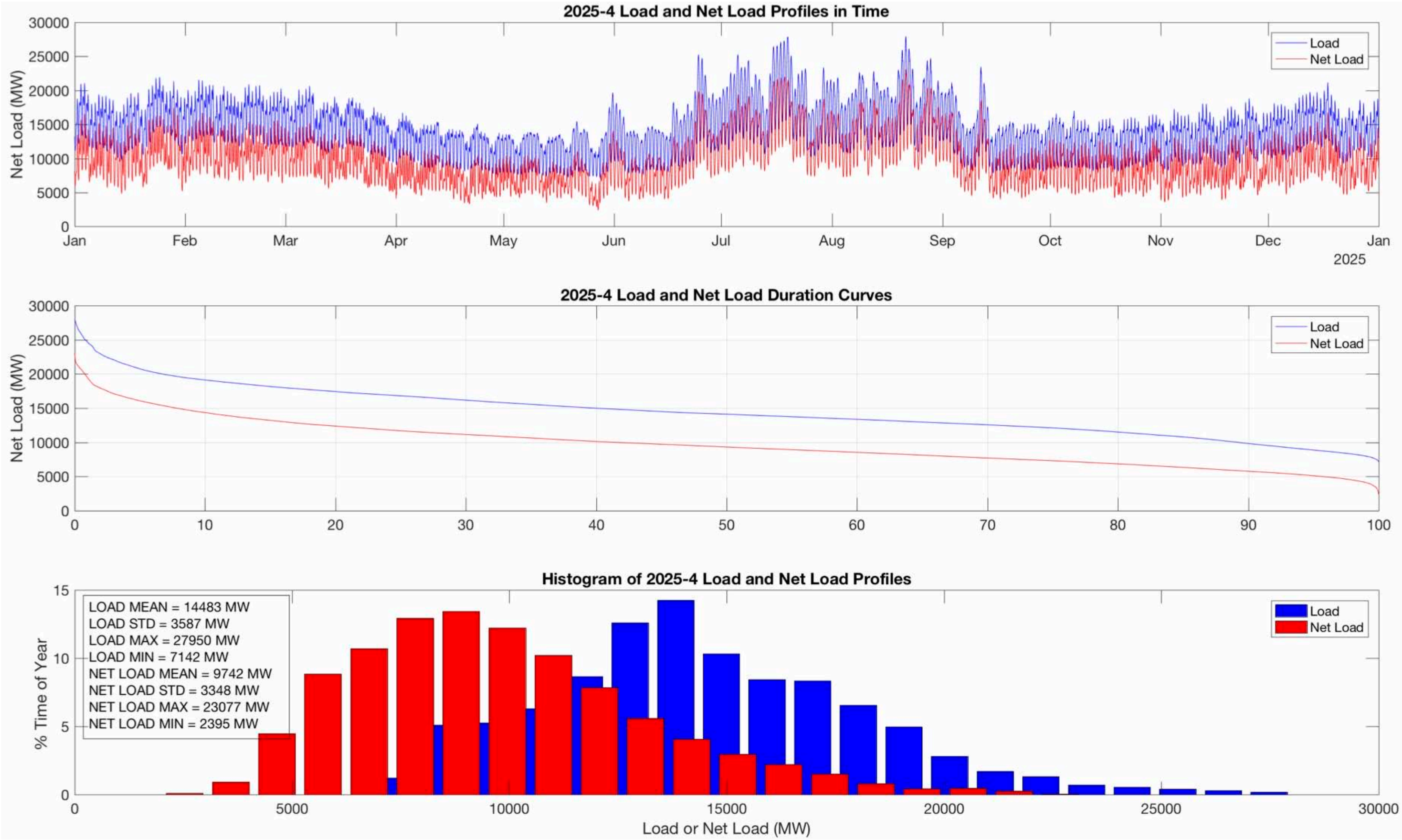
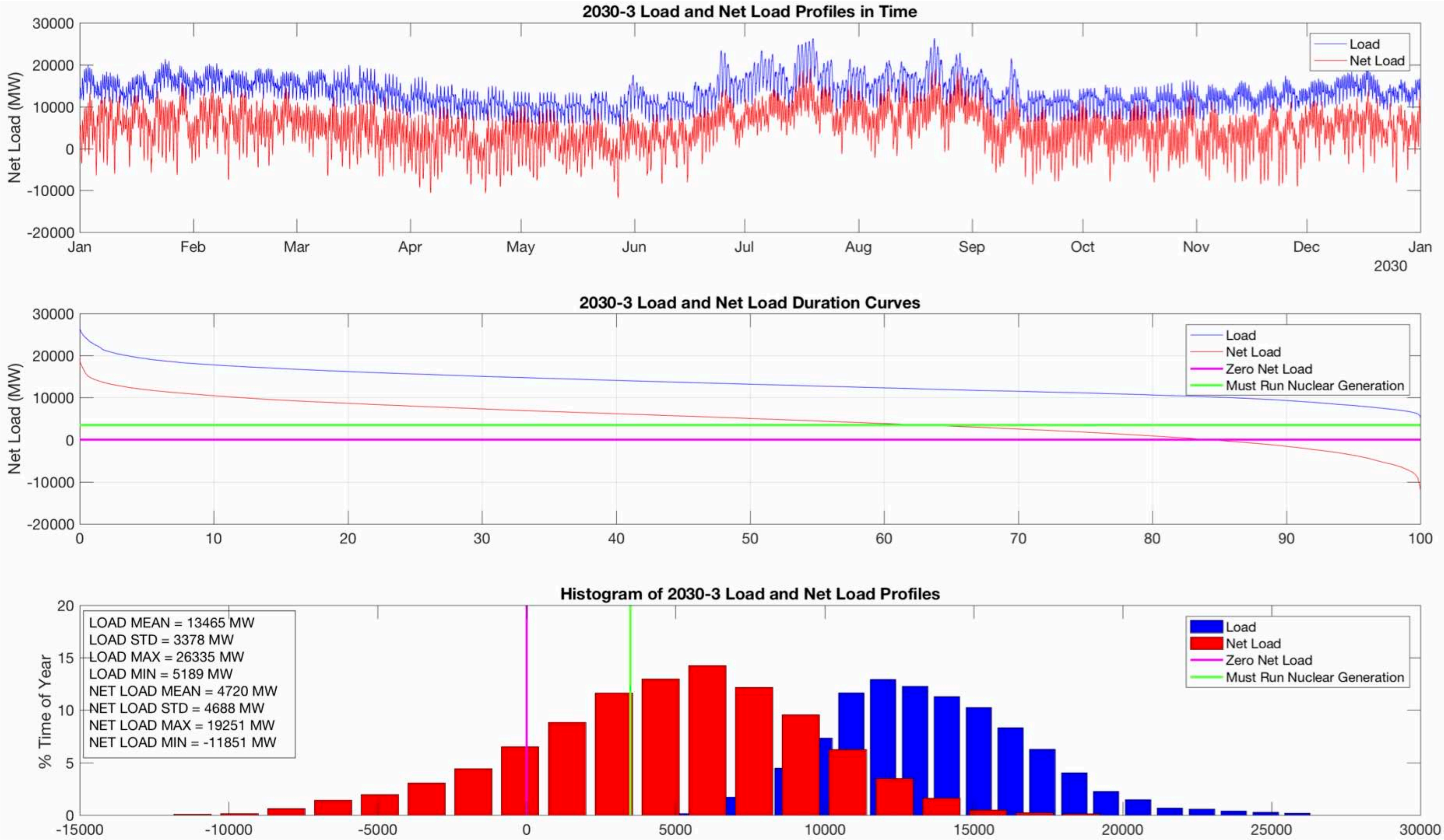
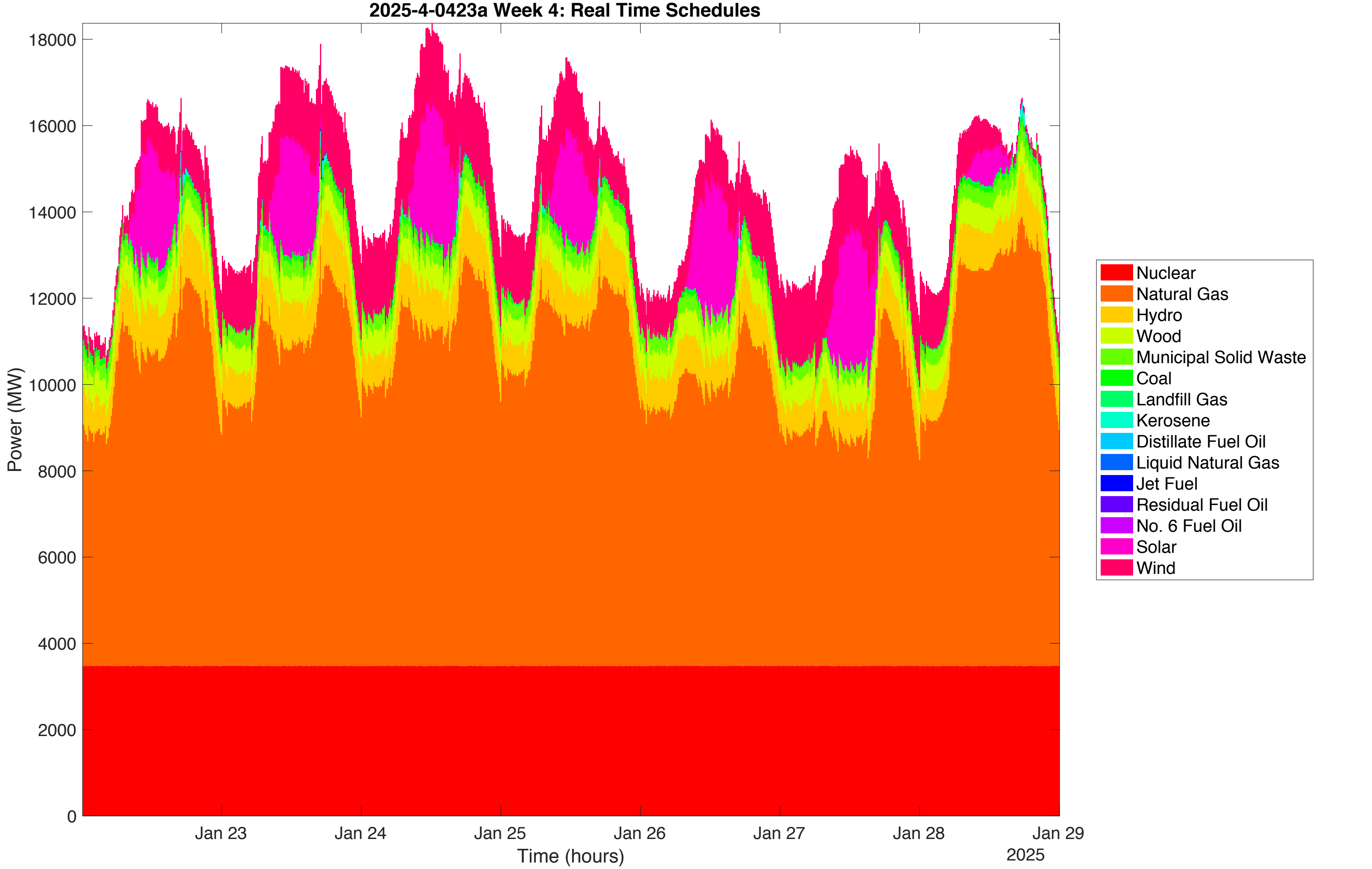
Net Load: 2025 Conventional Scenario



Net Load: 2030 High VREs Plus Scenario



Real-Time Energy Market Dispatch: 2025 Conventional



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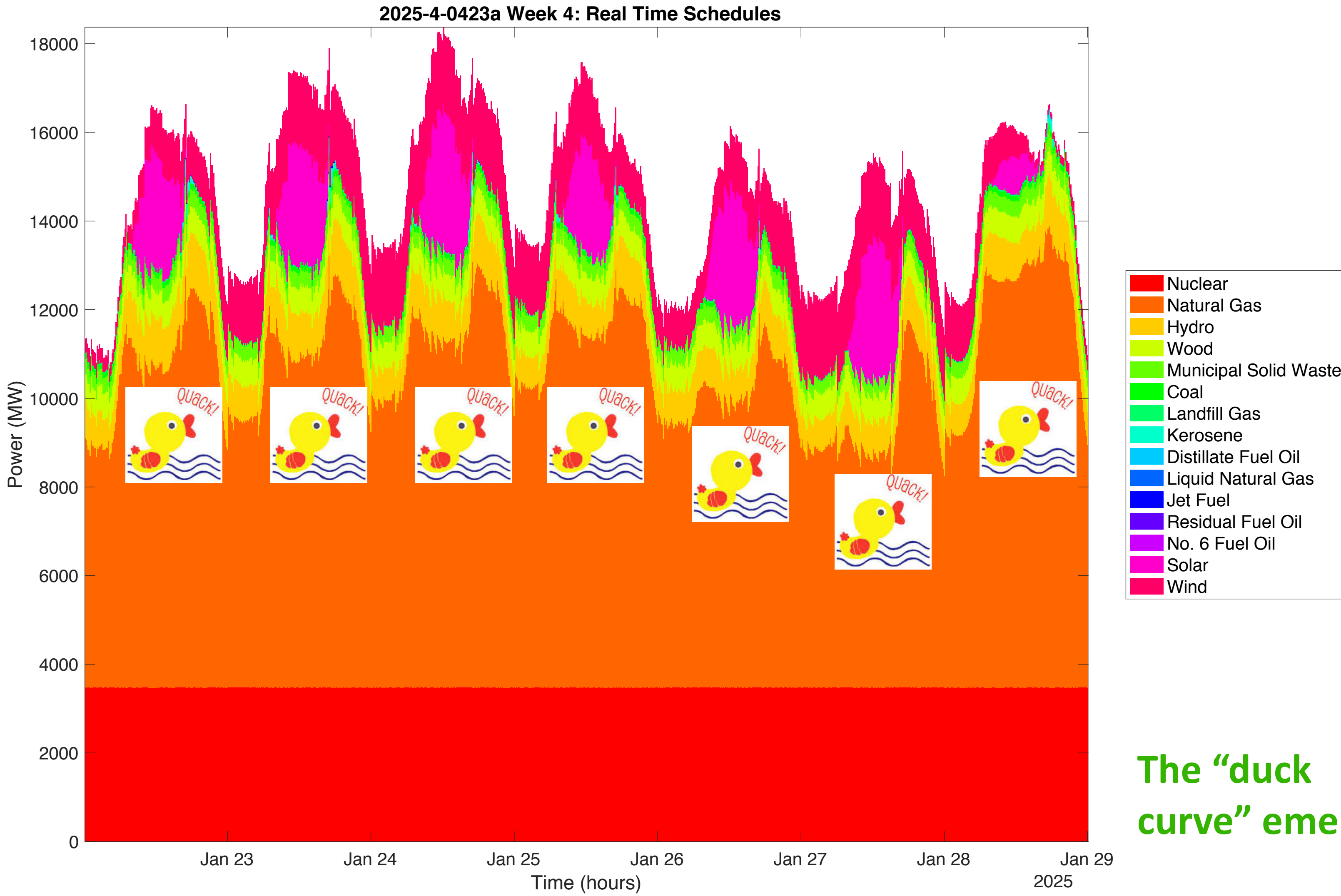
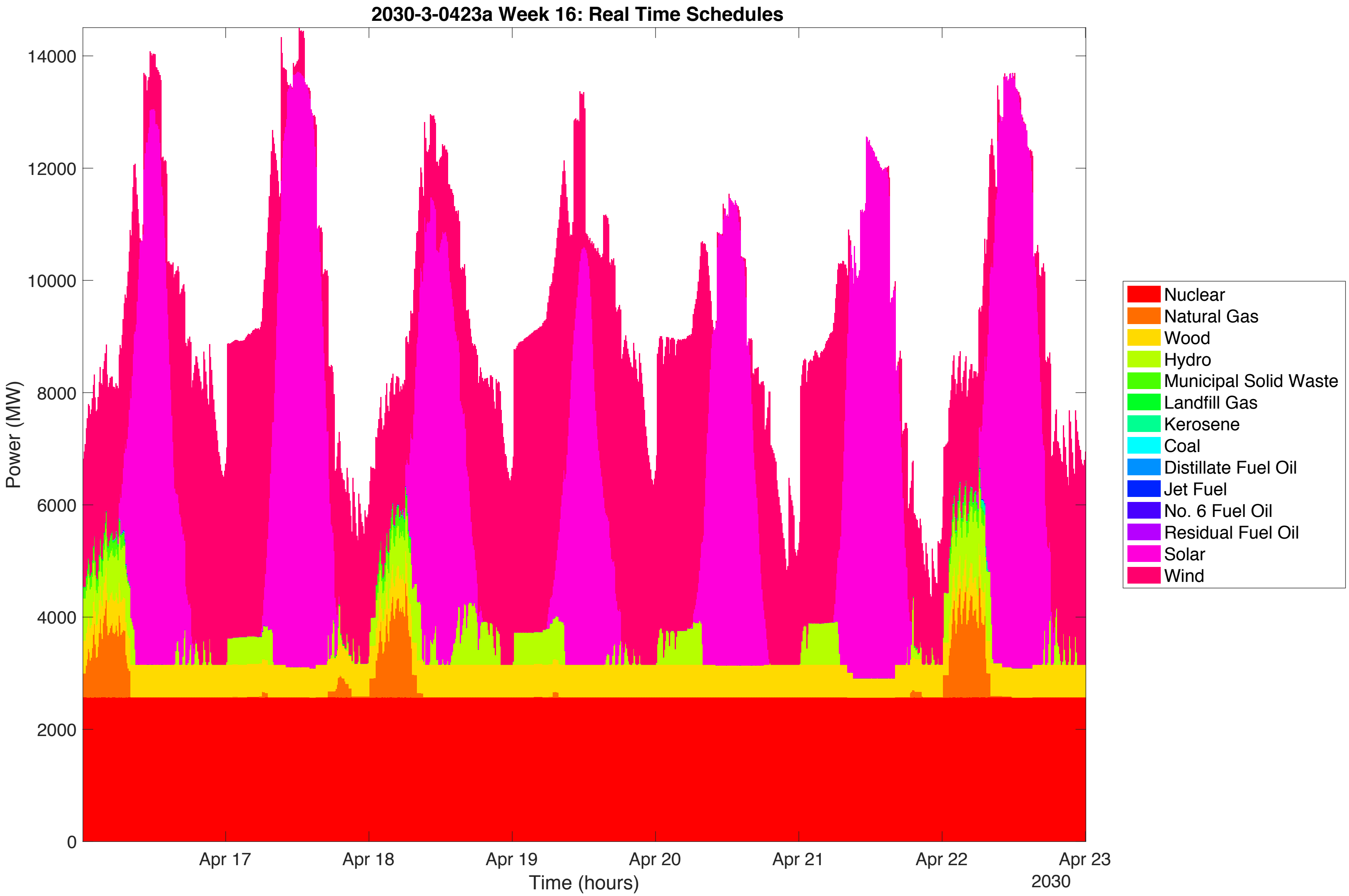
Real-Time Energy Market Dispatch: 2025 Conventional



The "duck curve" emerges!

Real-Time Energy Market Dispatch: 2030 High VREs Plus



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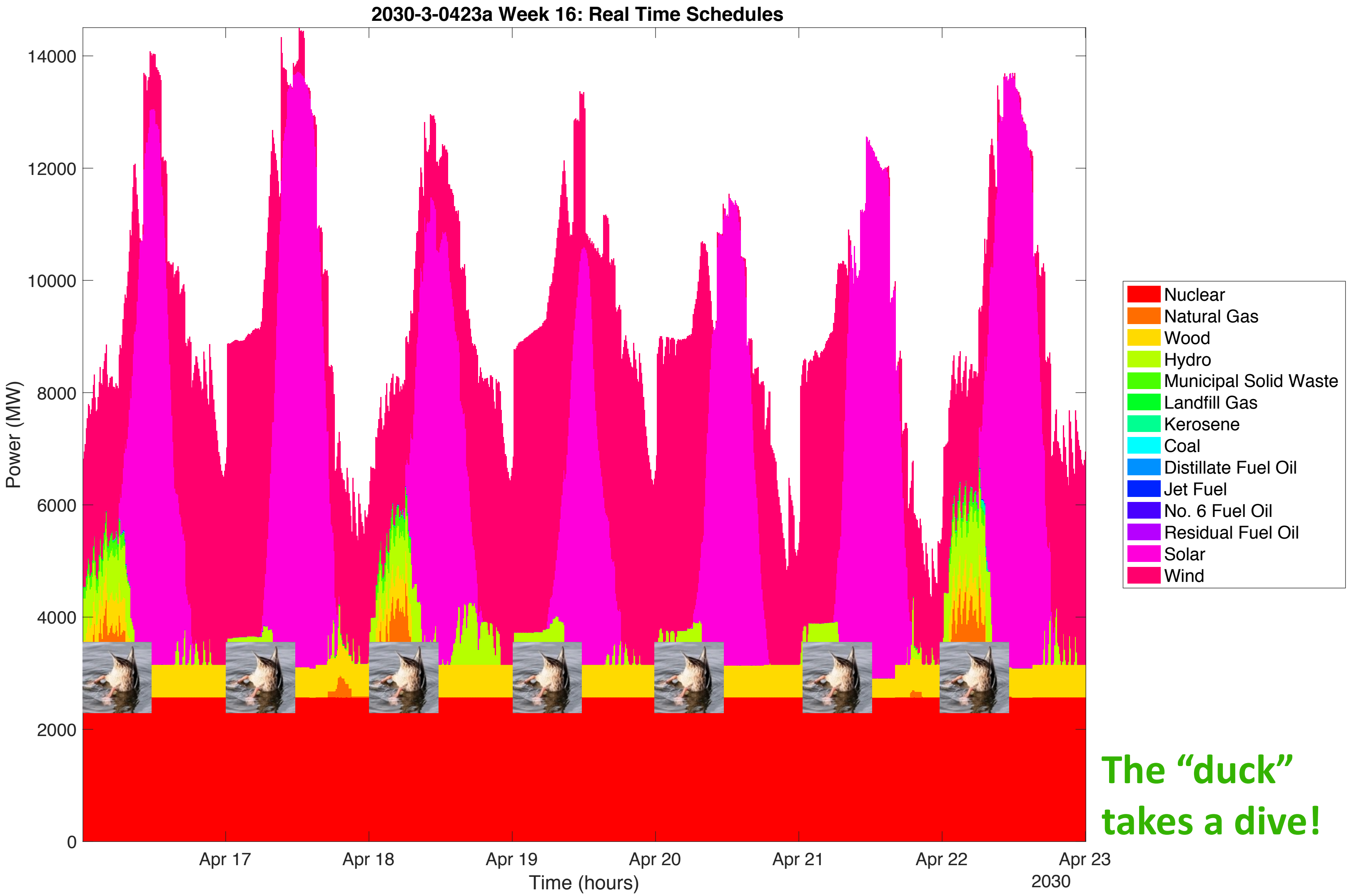
Real-Time Energy Market Dispatch: 2030 High VREs Plus



The "duck" takes a dive!

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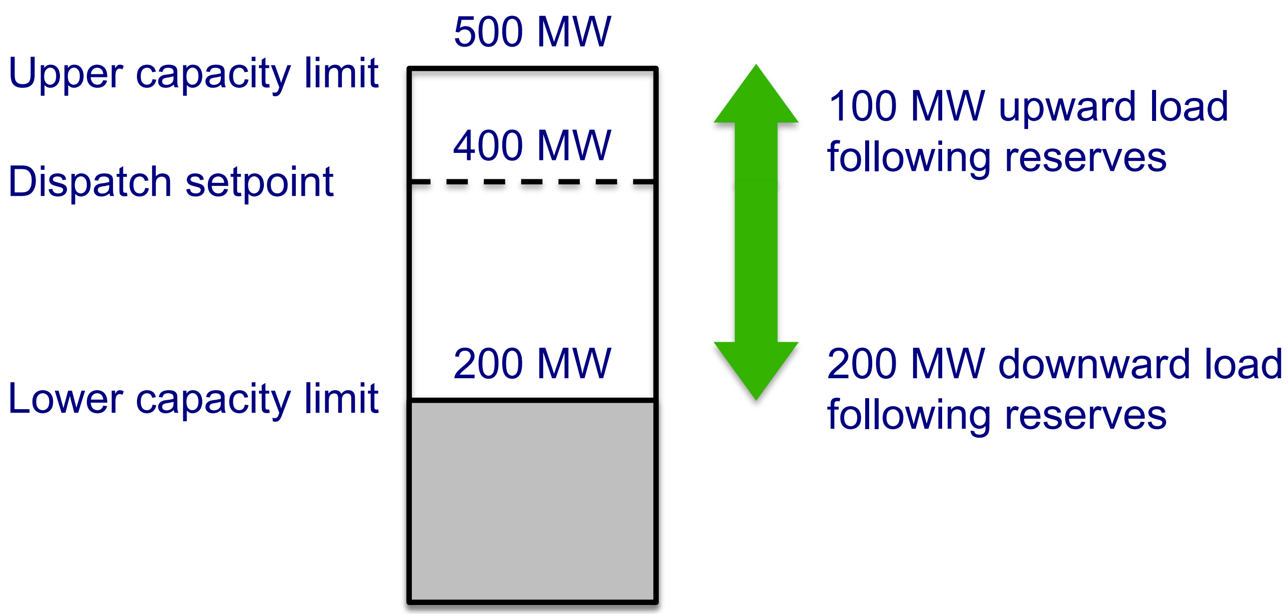
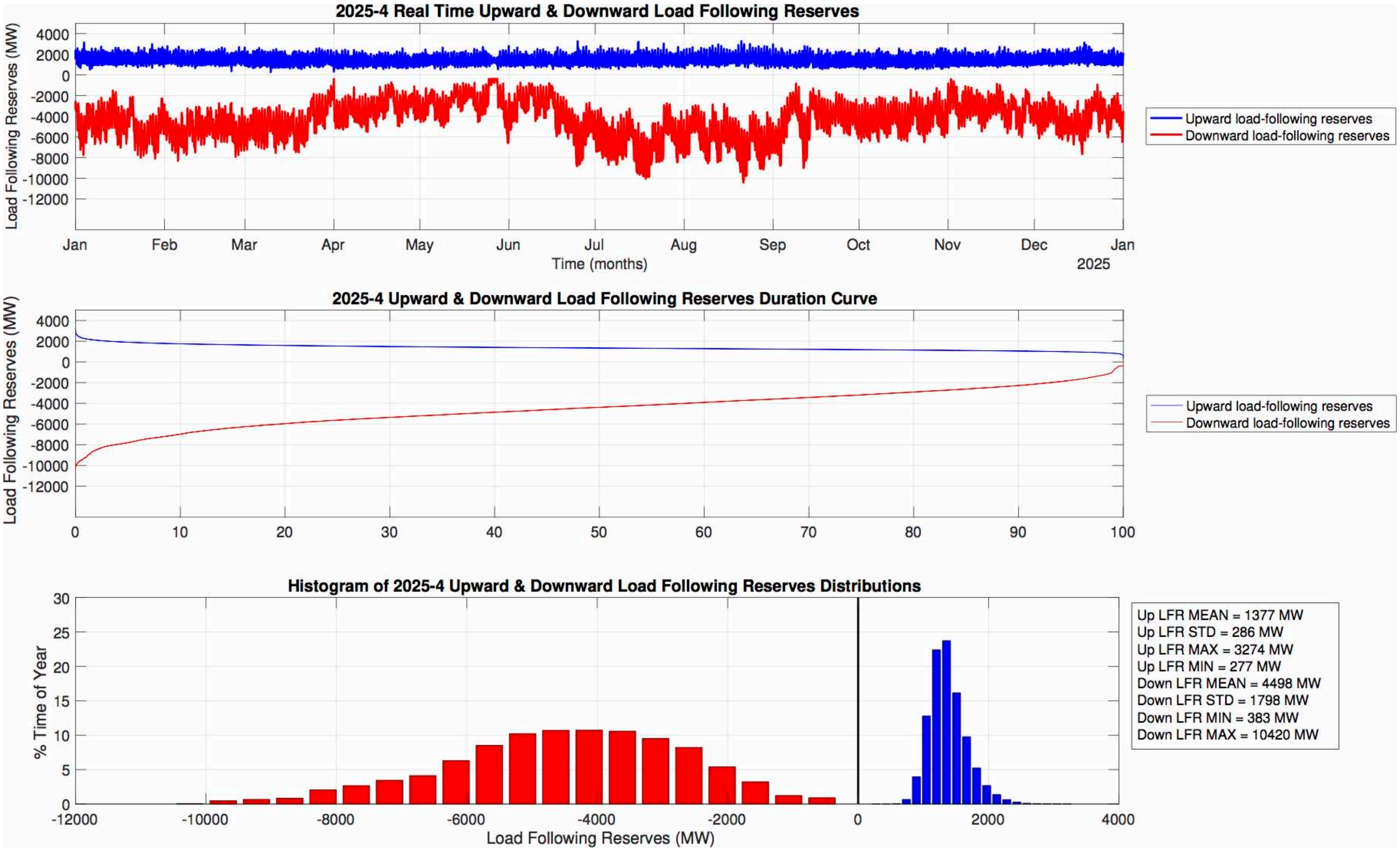
Load Following Reserves

The quantity of load following reserves is equal to the excess capacity of the aggregate generation fleet to move up or down. (i.e. economic surplus, ”head-room”, “leg-room”)



Load following reserves, as a physical quantity, assists in responding to net load variability and uncertainty.

Load Following Reserves: 2025 Conventional Scenario



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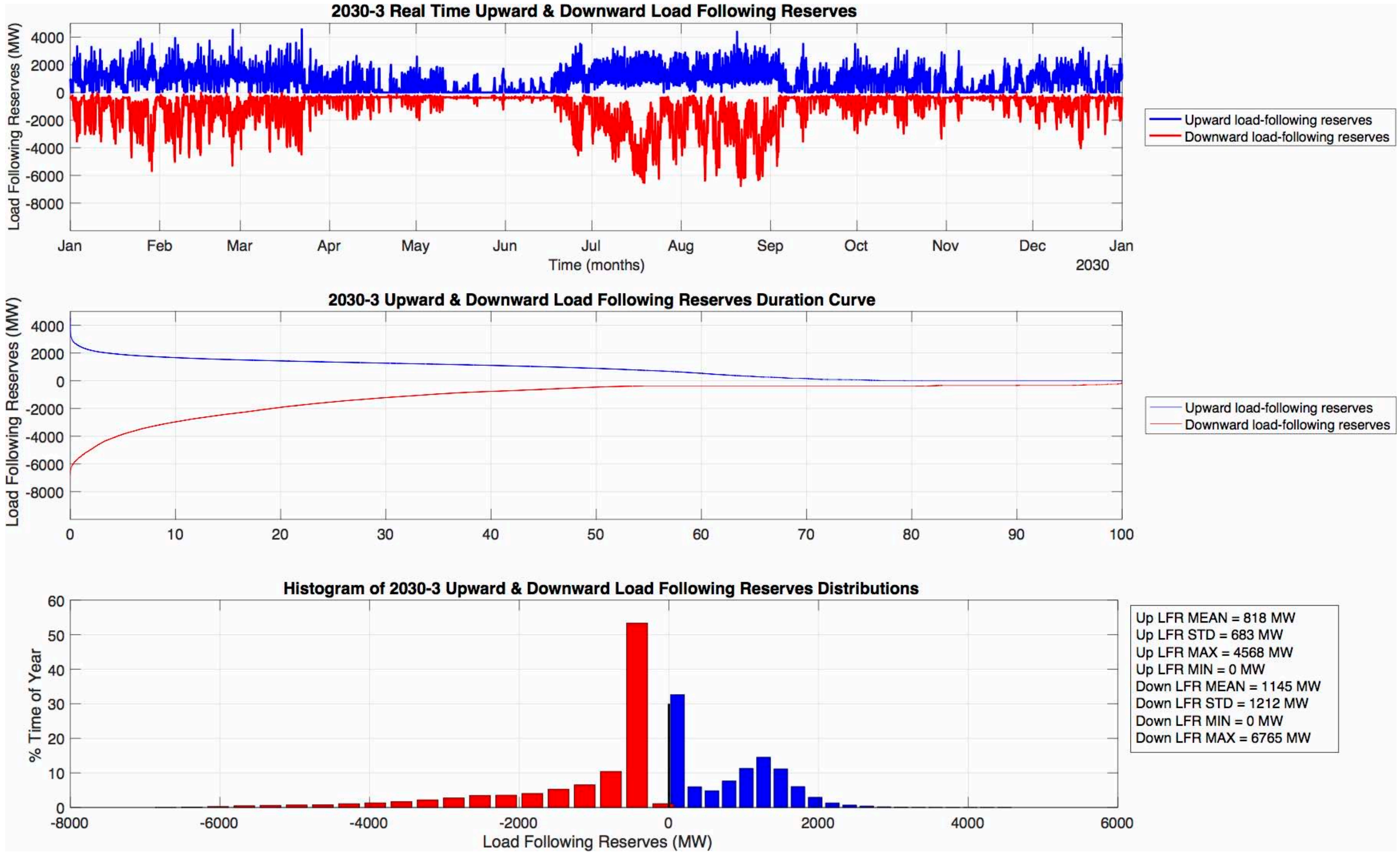
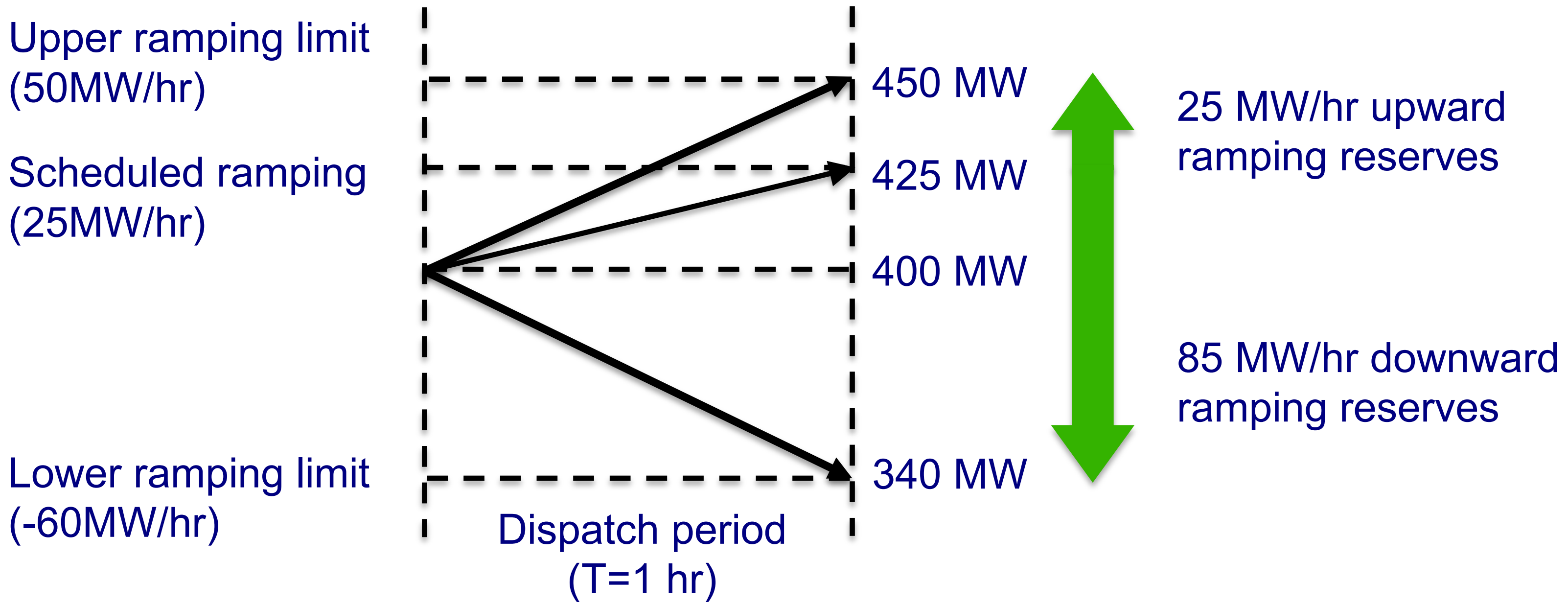
Load Following Reserves: 2030 High VREs Plus Scenario



In Spring & Autumn, the ability to track low net load conditions is constrained.

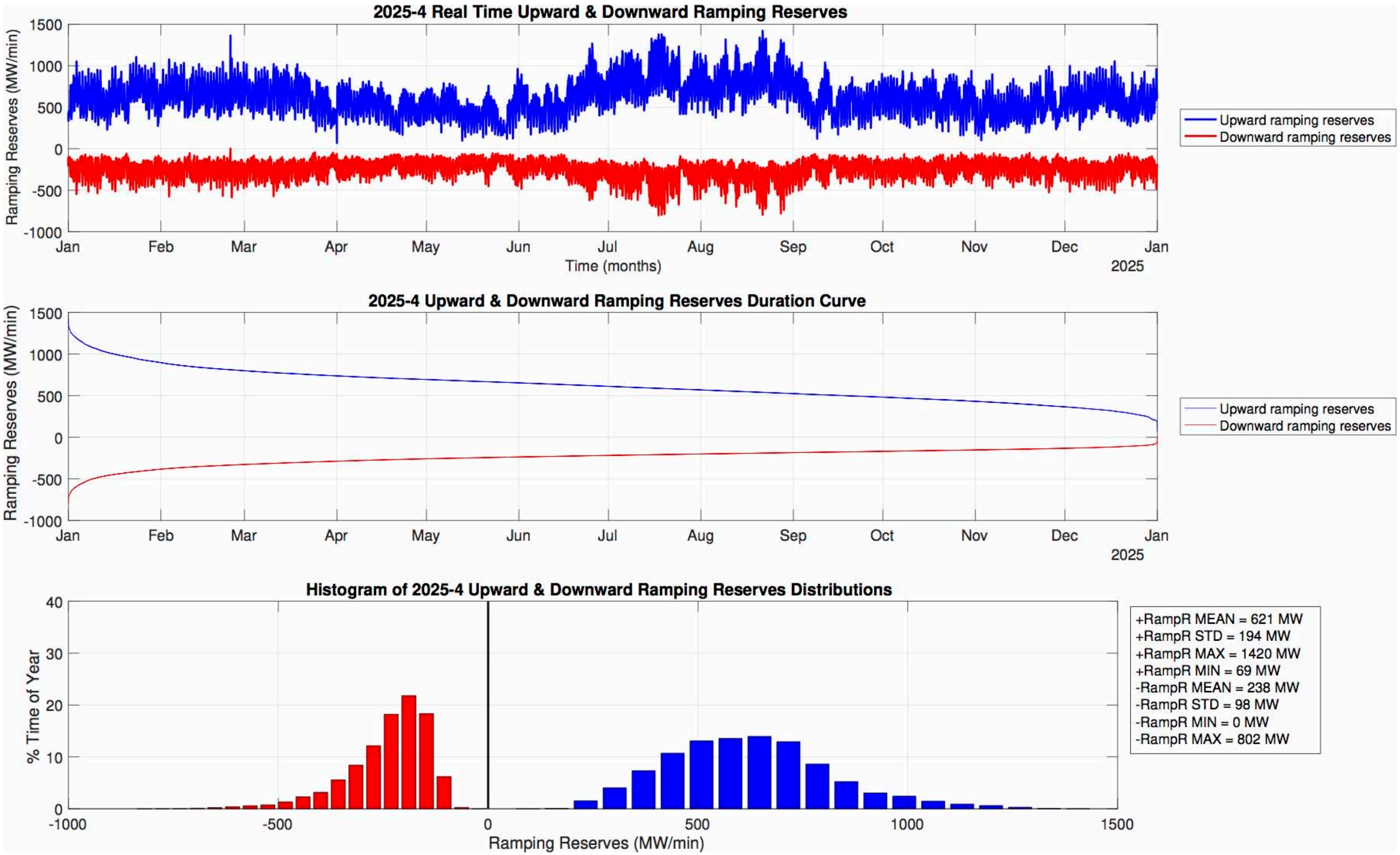
Ramping Reserves

The quantity of ramping reserves is equal to the excess ramping capability of the aggregate generation fleet to move up or down in time.



Ramping reserves, as a physical quantity, assists in responding to net load variability and uncertainty.

Ramping Reserves: 2025 Conventional Scenario



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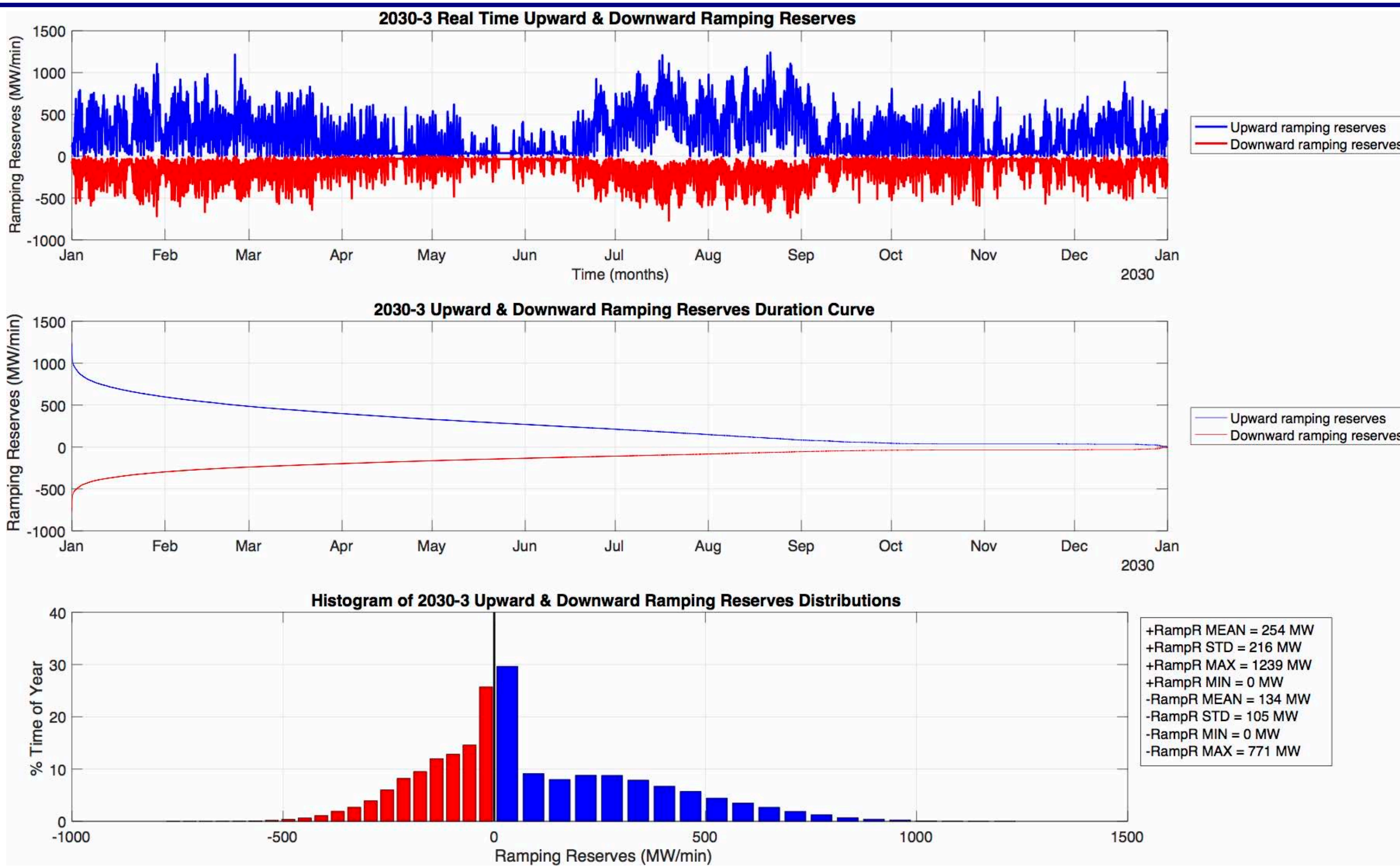
Ramping Reserves: 2030 High VREs Plus Scenario



In Spring & Autumn, the ability to track low net load conditions is constrained.

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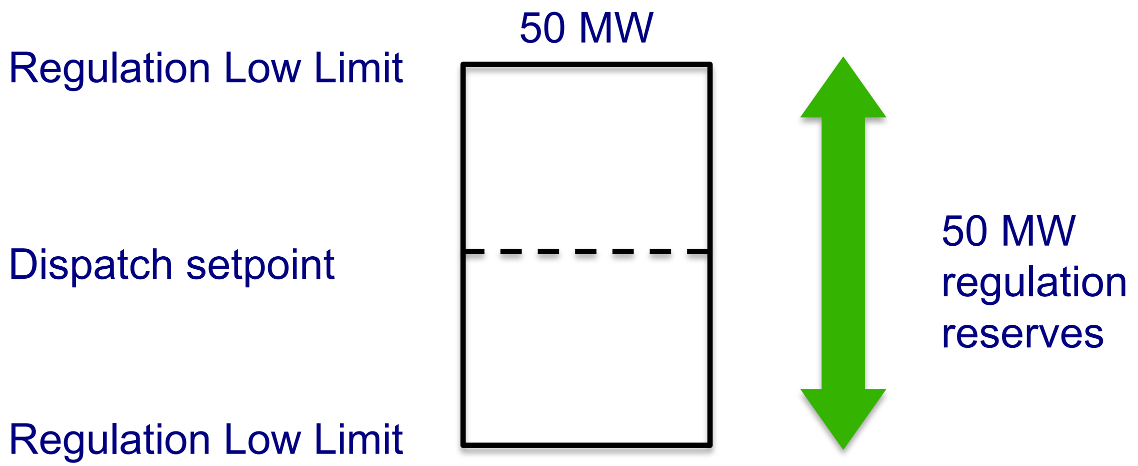
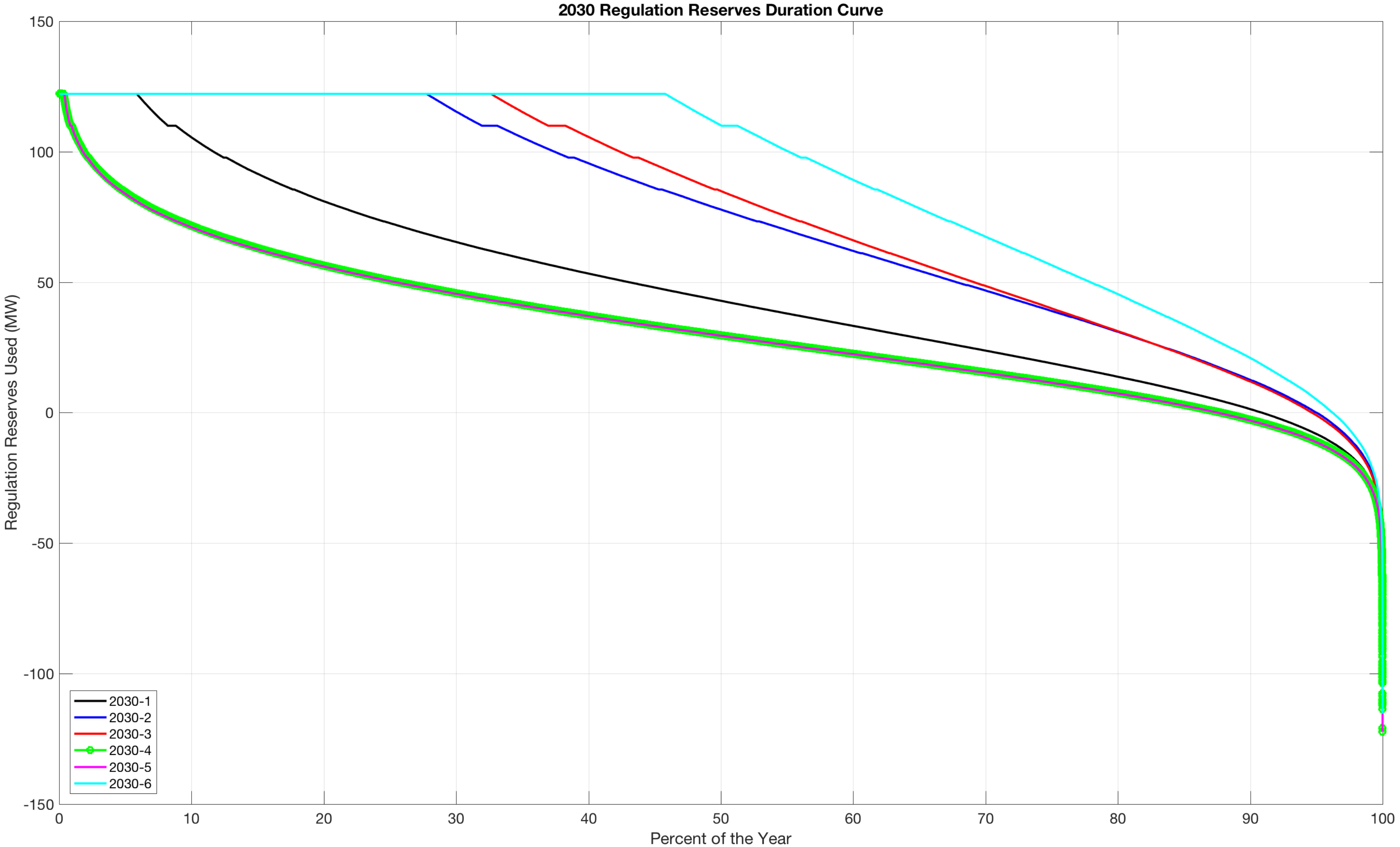
Regulation Reserves

The quantity of regulation reserves is equal to the excess real-time feedback control capability of the aggregate generation fleet to move up or down in time.



Regulation reserves, as a physical quantity and market product, assists in responding to net load variability and uncertainty.

Regulation Reserves: 2030 Scenarios



Relative to the conventional scenarios, high VREs saturate regulation reserves.

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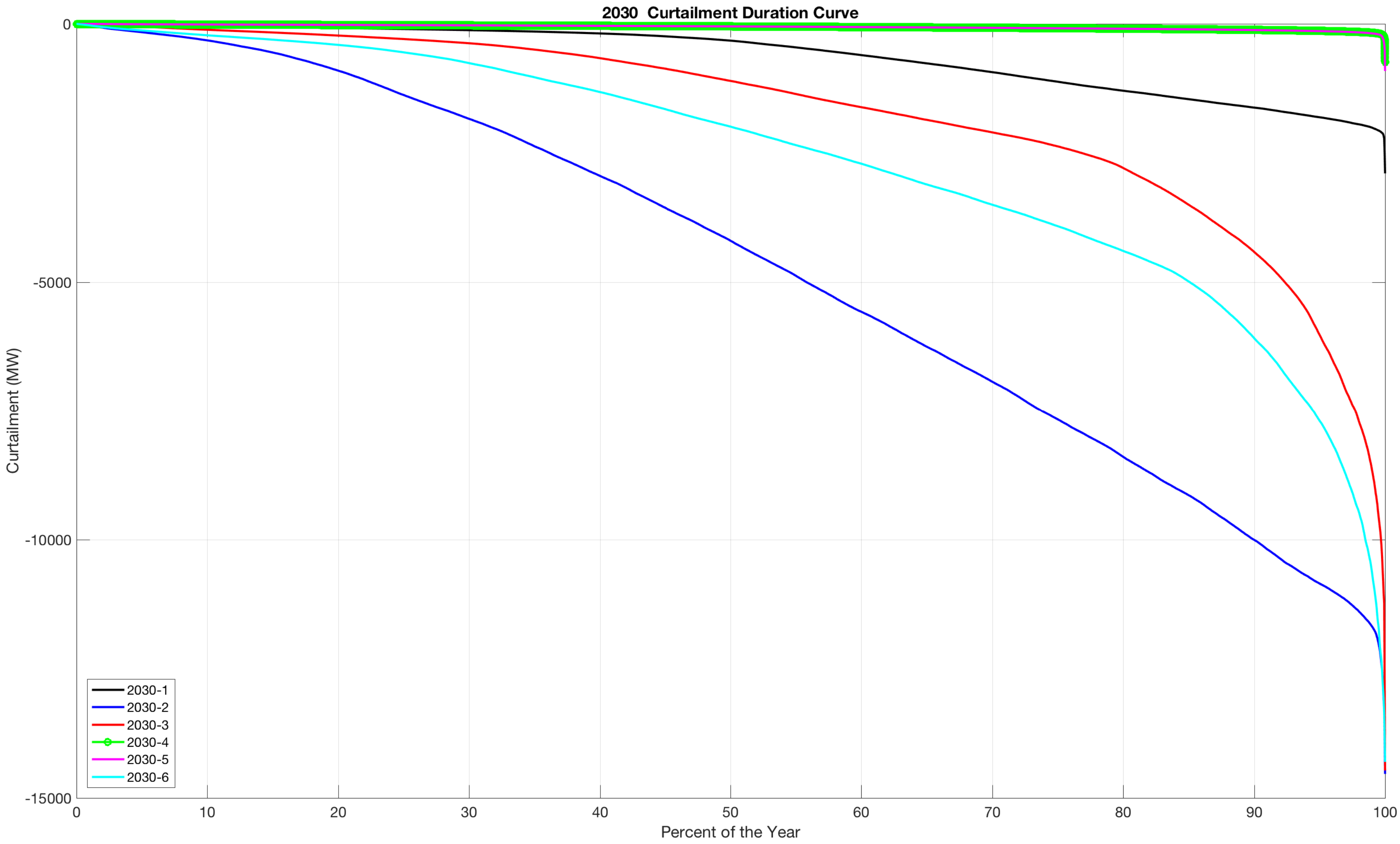
VRE Curtailment: 2030 Scenarios



Relative to the conventional scenarios, high VREs require significant curtailment.

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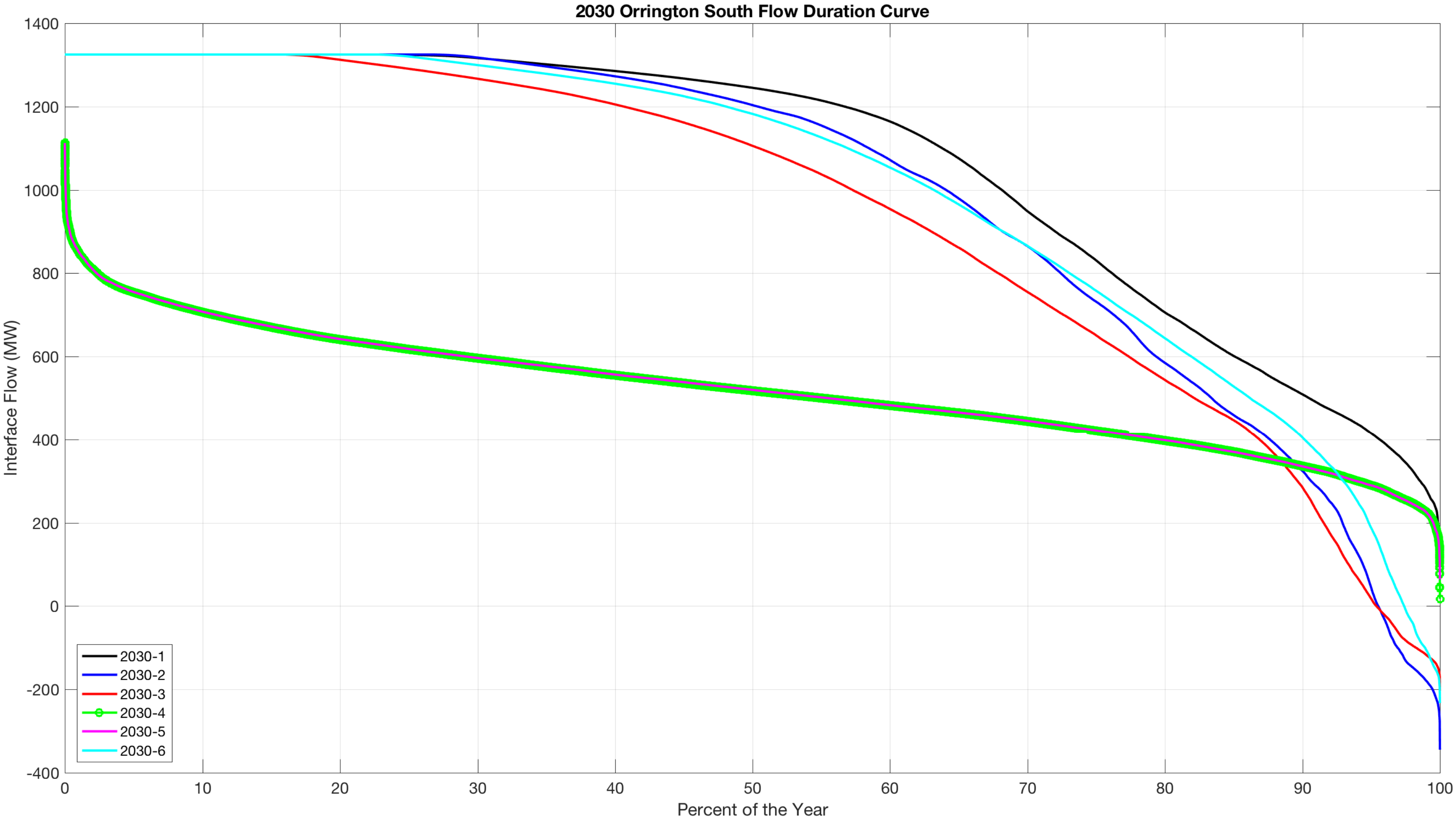
Interface Congestion: 2030 Scenarios



Relative to the conventional cases, high VREs cause North-South Congestion.

ISO-NE VRE Integration Study: Key Findings

- **Commitment Decisions**: The unit commitment of dispatchable resources and their associated quantities of committed load following and ramping reserves has a ***complex, non-linear*** dependence on the amount of VREs and the load profile statistics that is ***difficult to predict***.
- **Load Following Reserves**: For the scenarios with a significant penetration of VREs, the system may require additional amounts of ***upward load following*** reserves (*as a function of time*) to effectively mitigate imbalances and maintain reliable operations.
- **Ramping Reserves**: For the scenarios with a significant penetration of VREs, the system ***entirely exhausts*** upward and downward ramping capability.

Business-as-usual power system operations and control will do for now….

… but market and policy innovations can lead to vastly improved outcomes.

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ISO-NE VRE Integration Study: Key Findings

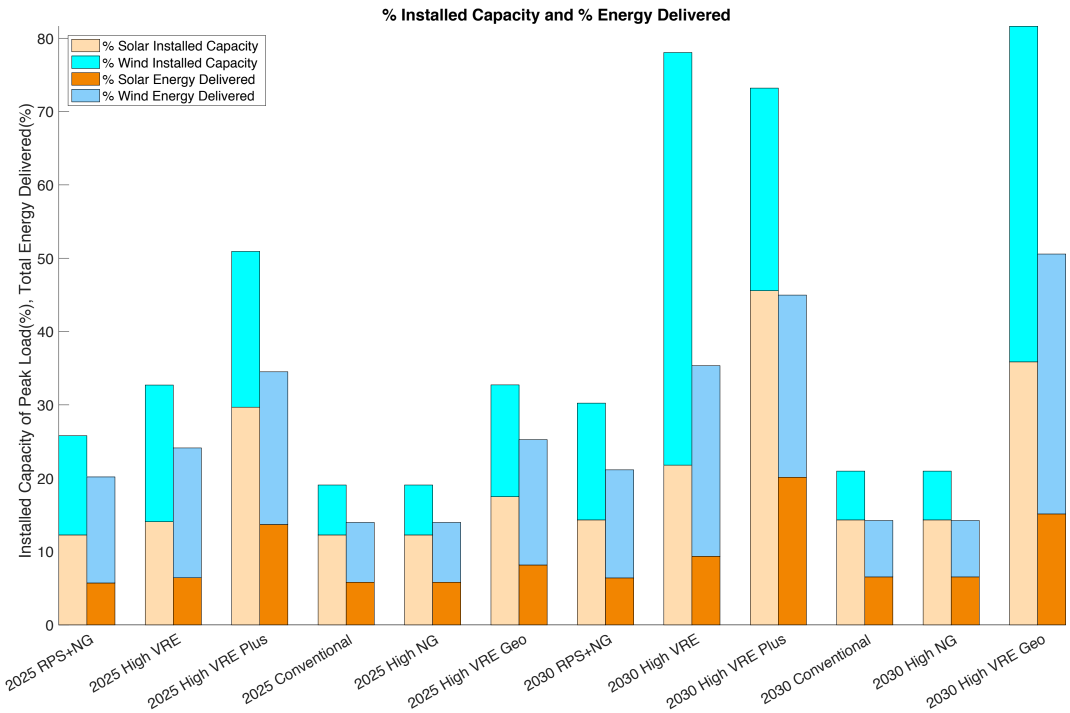
- **Curtailment**: The curtailment of VREs becomes an integral part of balancing performance; in part to complement operating reserves and in part to mitigate the topological limitations of the system. (***Up to 14.5GW and 41% of TWh***)
- **Congestion**: The integration of significant amounts of VREs increases the potential of congestion on several key interfaces (e.g. Orrington-South)
- **Regulation Reserves**: For the scenarios with a significant penetration of VREs, the system experiences heavy saturation of regulation reserves. More are needed.
- **Balancing Performance**: The scenarios with significant penetration of VREs have significantly degraded balancing performance.

Business-as-usual power system operations and control will do for now….

… but market and policy innovations can lead to vastly improved outcomes.

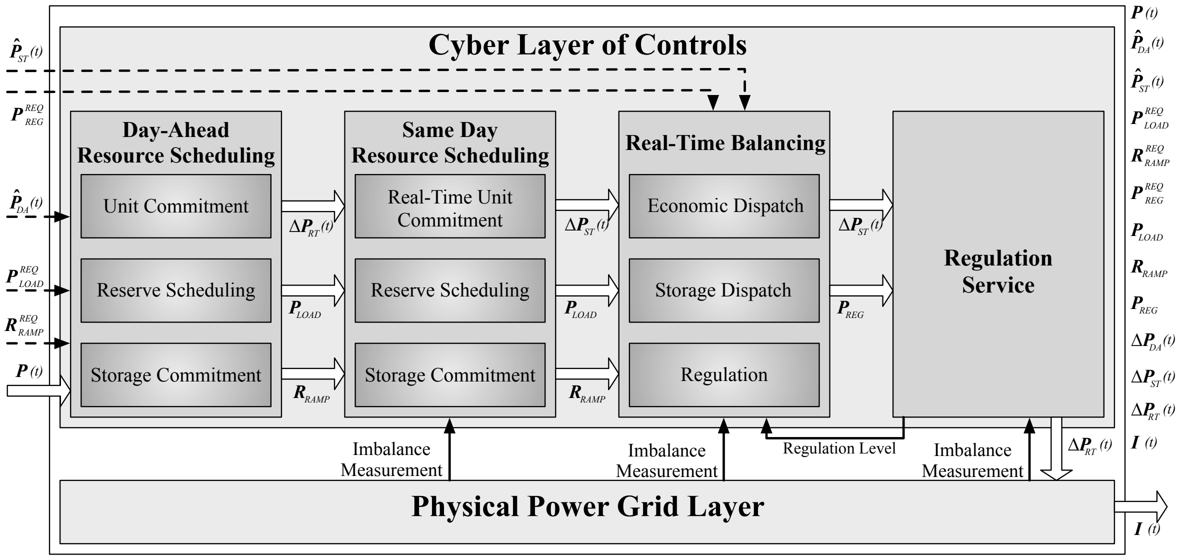
ISO-NE VRE Integration Study: Final Insights

- Expand transmission capacity
- Treat curtailment as a type of operating reserve
- Procure more regulation reserves from a diversity of energy resources
- Coordinate the scheduled maintenance of nuclear power generation
- Expand the role of energy storage and demand side resources



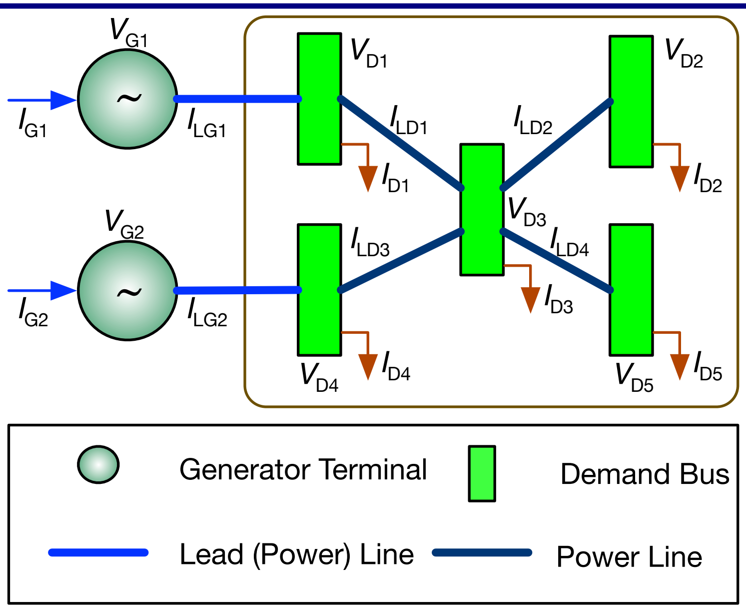
…or face a future where renewables never realize their promise…

Electric Power Enterprise Control System Simulation (EPECS)



Engineering Systems Analytics LLC has licensed the EPECS Software to ISO New England as the default tool for their stakeholder-driven planning processes.

Globally Optimal Solution of AC Optimal Power Flow



- Formulated in 1962, it minimizes generation costs subject to grid reliability constraints.
- Extensive literature, but globally optimal solution elusive. ***Worth $6-19B/yr in USA***.
- Directly supports sustainable energy transition through application to distribution systems, demand-side resources, and “beyond-the kWh” grid services.
- Supports integration with multiple infrastructures

Farid, Amro M. “A Profit-Maximizing Security-Constrained IV-AC Optimal Power Flow Model & Global Solution” IEEE Access, v.10, p. 2842-2859, 2021.

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  - *The integration of water-energy resources creates several synergies: additional operating reserves, reduced water withdrawals and consumption, and reduced energy market production costs (~$70M).*
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  - *A decarbonization agenda must evolve from power grid studies with electricity as a single energy carrier to multi-energy engineering system studies that specifically coordinate multiple energy carriers through many layers of coordinated planning and operations management decisions.*

The Emergence of Variable Renewable Energy (VRE)

Past:

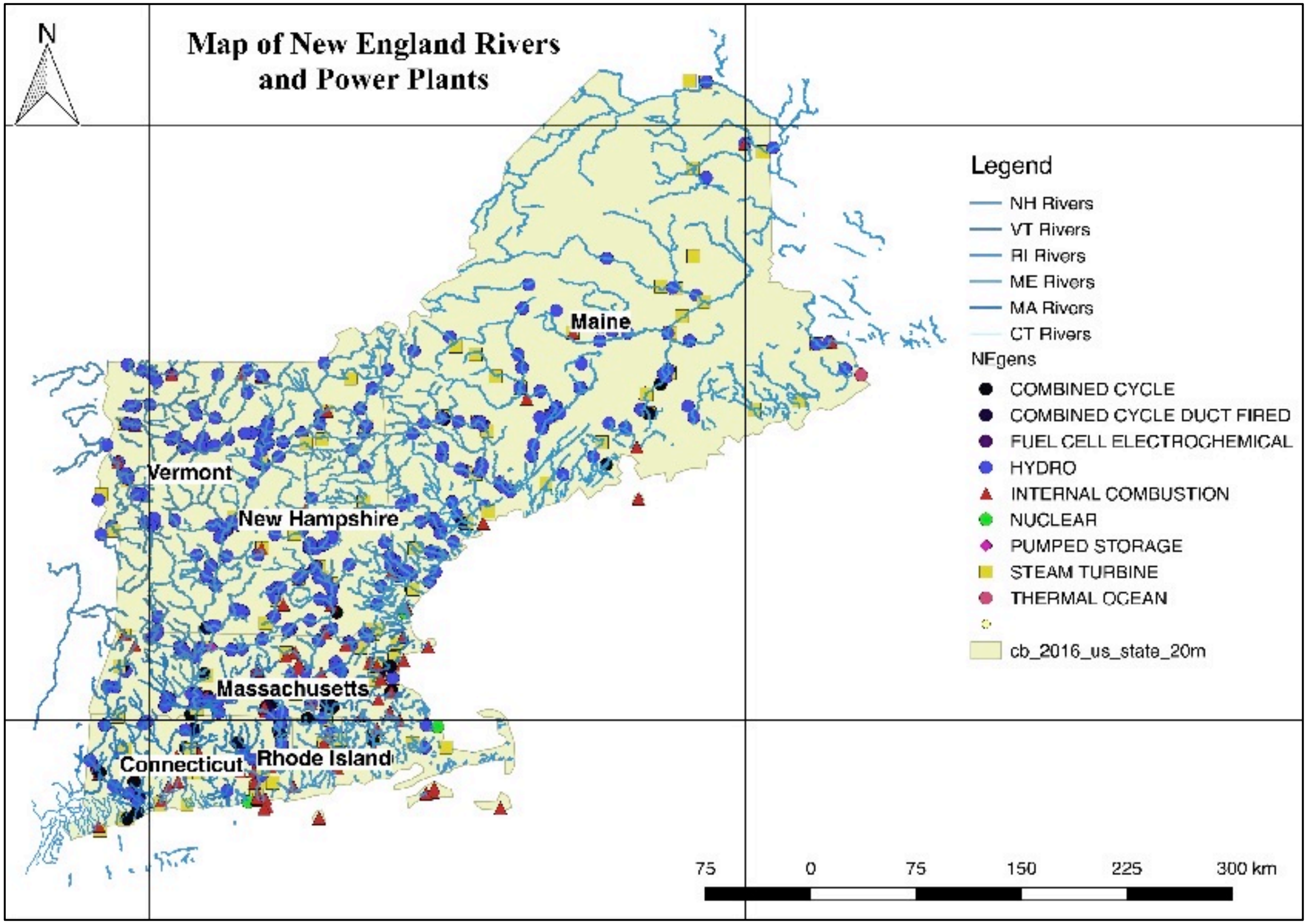
Generation/Supply	Load/Demand
Thermal Units: Few, Well-Controlled, Dispatchable, In Steady-State	Conventional Loads: Slow Moving, Highly Predictable, Always Served

Future:

	Generation/Supply	Load/Demand
Well-Controlled & Dispatchable	Thermal Units: (Potential erosion of capacity factor) ↓	Demand Side Resources (Requires new control & market design) ↑
Stochastic/ Forecasted	Solar & Wind Generation: (Can cause unmanaged grid imbalances) ↑	Conventional Loads: (Growing & Needs Curtailment) ↓

Fundamental Shift: From resource-stocks to resource flows
The emergence of VRE necessitates active demand side resources.

New England Power Plants and Rivers

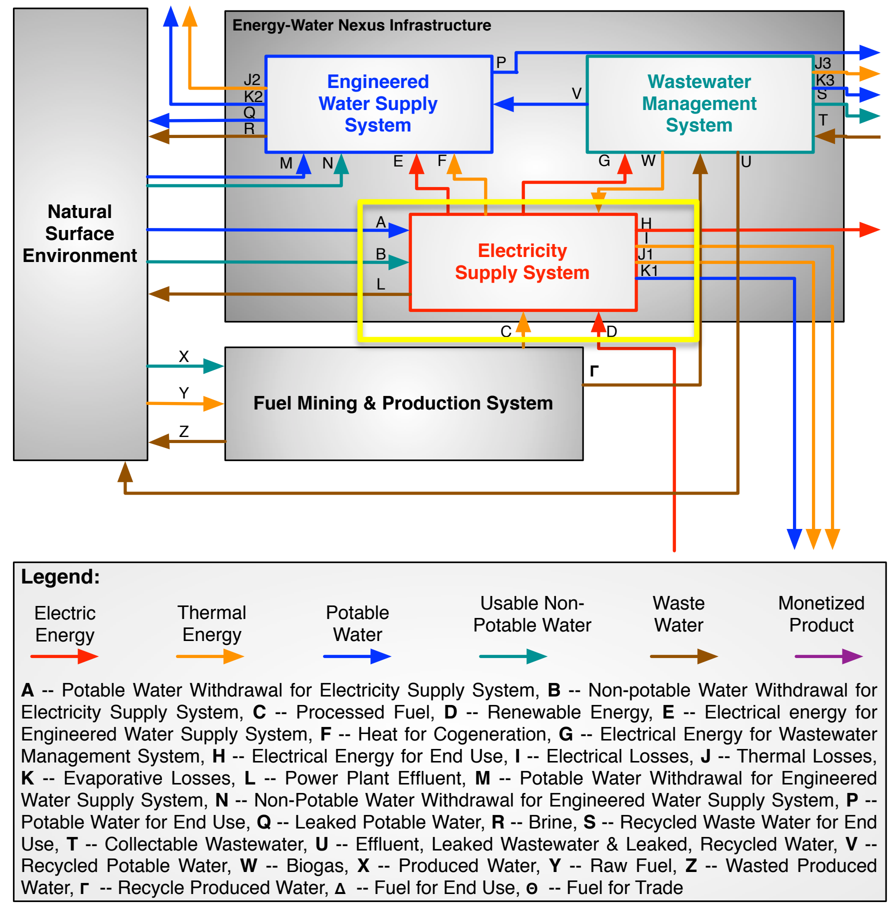


Most power plants are located near a water source. This indicates the strong coupling between the water supply and energy supply systems.

System-Level View of the Energy-Water Nexus

- Important to capture all the physical flows between the three physical infrastructures & the natural surface environment
- In the ISO-NE model, each water utility fits inside a "bubble" → full hydraulic modeling does not provide additional insight.
- Sufficient to capture all interfaces w/ electric supply system and impose aggregate energy constraints

EPECS will be enhanced to provide values for these flows.



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Flexible Water-Energy Resources Scenarios

	2040-RPS+NG	2040 High VRE	2040 High VRE Plus	2040 Conventional	2040-5 High NG	2040-6 High VRE Geo
Hydro Run-of-River & Pond	1854MW (6.21%)	1788MW (5.99%)	1646MW (7.10%)	1782MW (5.97%)	1798MW (5.99%)	1784MW (5.97%)
Pumped Storage	1758MW (6.15%)	1758MW (6.15%)	1758MW (6.15%)	1758MW (6.15%)	1758MW (6.15%)	1758MW (6.15%)
Water Load	565MW (1.89%)	565MW (1.89%)	565MW (2.44%)	565MW (1.89%)	565MW (1.89%)	565MW (1.89%)
System Peak Load	28594 MW	28594 MW	22103MW	28594MW	28594 MW	28594 MW

- Flexible water resources have load shedding (rather than shifting) capability
- Run-of-river & pond-hydro is curtailable at $4.5/MWh (as in ISO-NE study)
- Demand side resources are incentivized at $50/MWh (as in ISO-NE study)
- Flexible water resources are assumed to contribute to operating reserves.
- 709.7GWh of pumped storage is treated as dispatchable throughout the study.

We extended the energy mix to 2040 and used the EPECS to measure the effects of dispatchable vs non-dispatchable water-energy resources.

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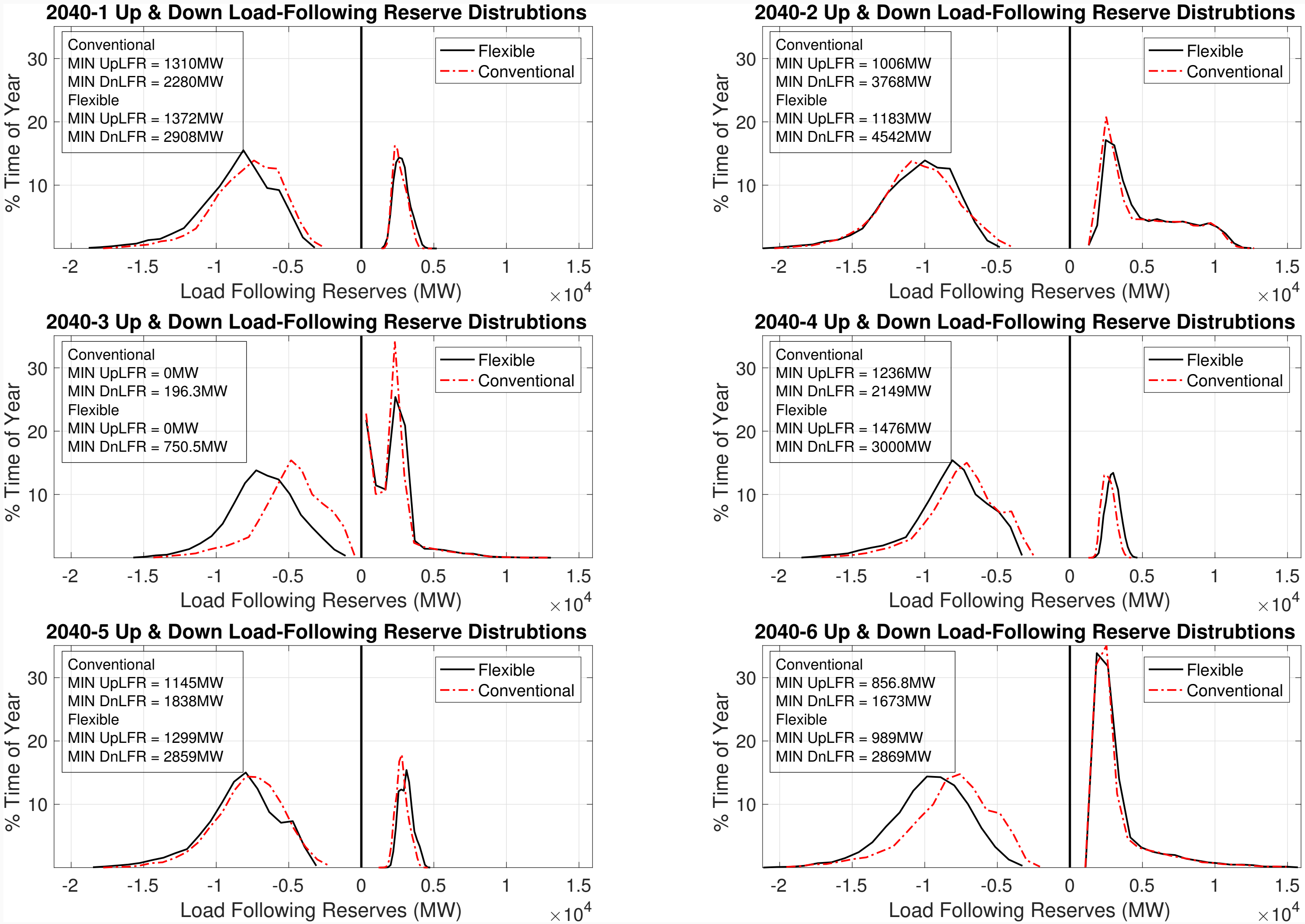
Balanced Sustainability Scorecard

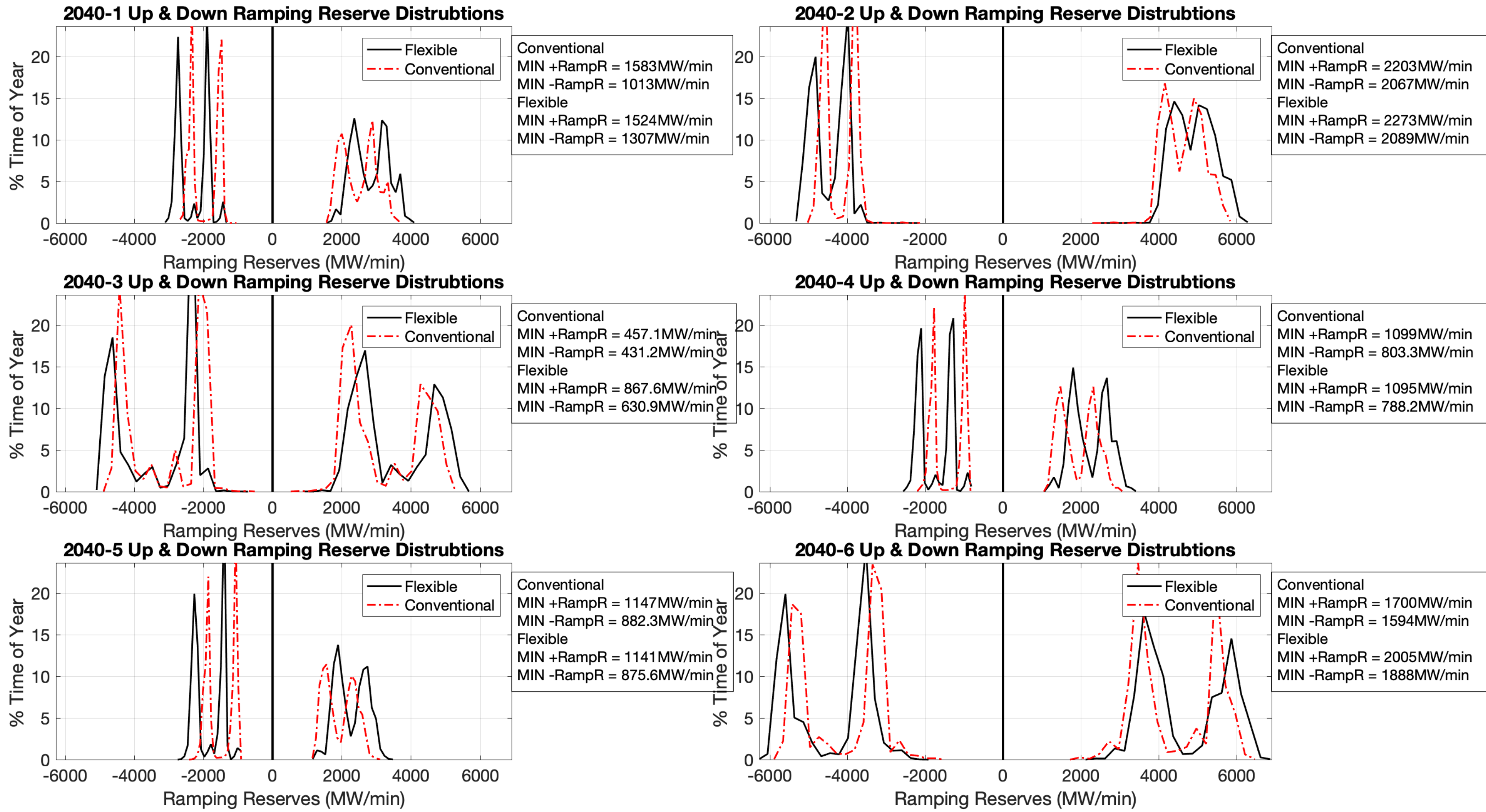
Table 15: The range of **improvements** caused by coordinated flexible operation of the energy-water nexus.

Balancing Performance	
Average Load Following Reserves	1.24–12.66%
Average Ramping Reserves	5.28–18.35%
Percent Time Curtailed	2.67–10.90%
Percent Time Exhausted Regulation Reserves	0%
Std. Dev. of Imbalances	3.874–6.484%
Environmental Performance	
Total Water Withdrawals	0.65–25.58%
Total Water Consumption	1.03–5.30%
Total CO_2 Emissions	2.10–3.46%
Economic Performance	
Total Day-Ahead Energy Market Production Cost	29.30–68.09M$
Total Real-Time Energy Market Production Cost	19.58–70.83M$

Load Following Reserves: Flexible vs Conventional 2040



Ramping Reserves: Flexible vs Conventional 2040



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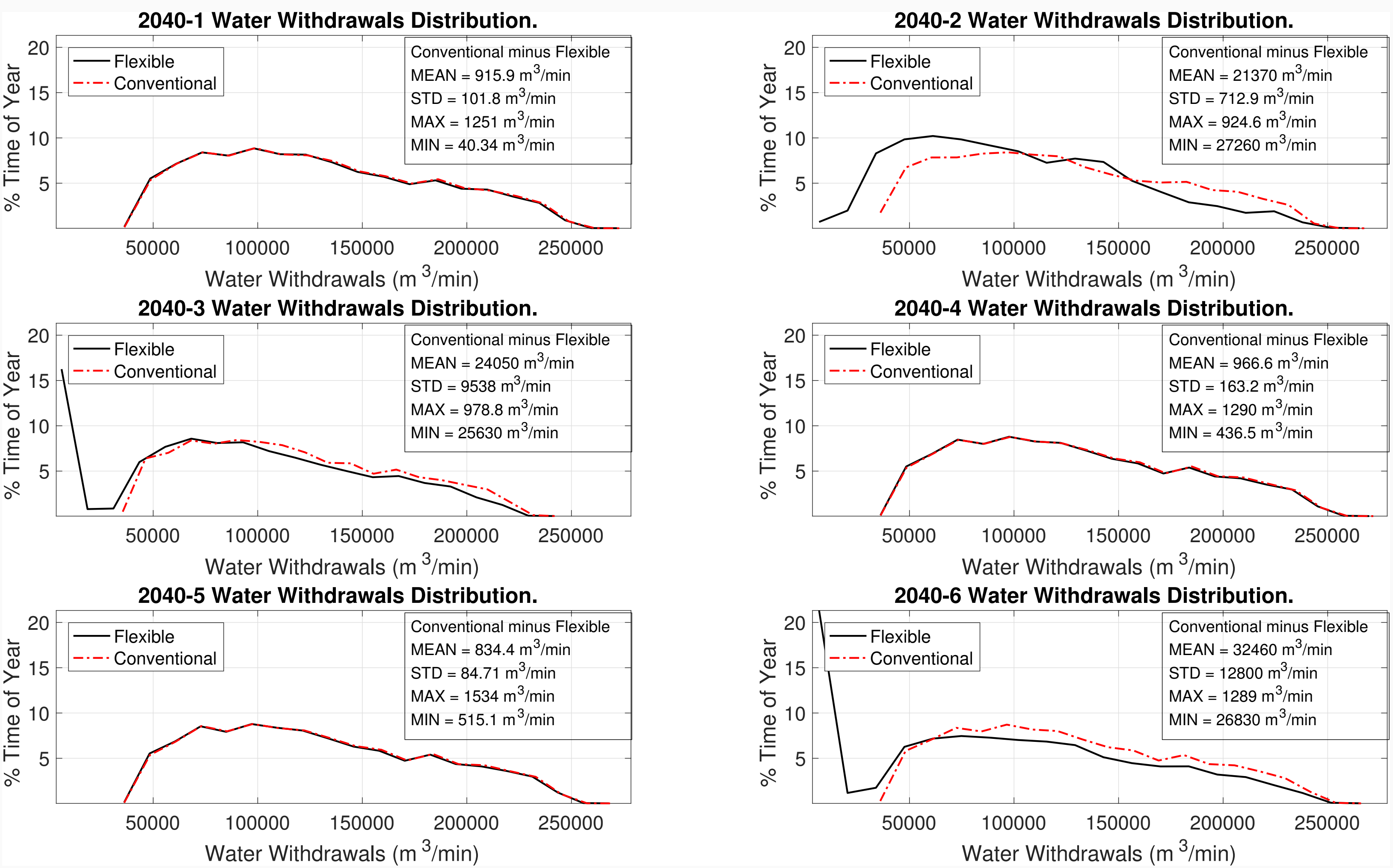
Water Withdrawals: Conventional vs Flexible 2040



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Presentation Outline

Goal: To share lessons learned from two system operational analysis and renewable energy integration studies conducted in cooperation with ISO New England

- **Drivers for the Evolution of the Electric Power Grid**
  - *The introduction of variable renewable energy resources necessitates fundamental changes in the power grid's dynamic operation*
- **Lessons from the ISO New England Renewable Energy Integration Study**
  - *At high levels of solar PV and wind generation, dispatchable demand-side resources become the only remaining option for a cost-effective, reliable, and sustainable grid*
- ***Lessons from the New England Energy Water Nexus Study***
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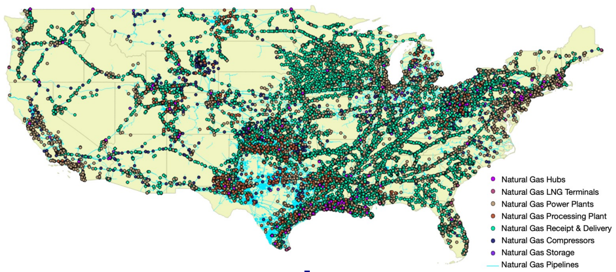
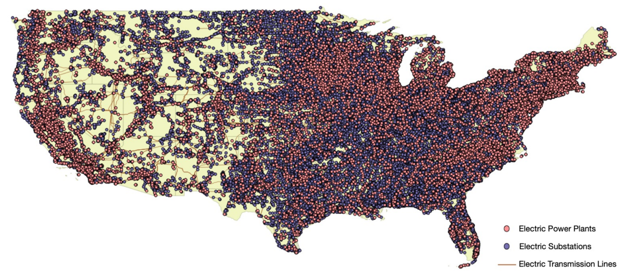
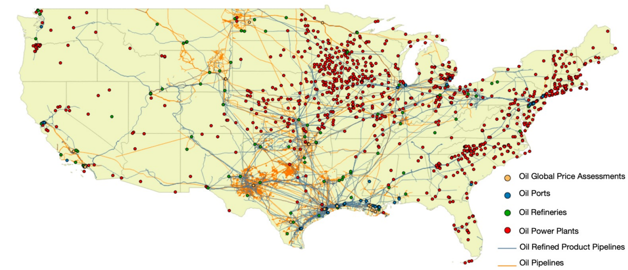
The American Multi-Modal Energy System Model

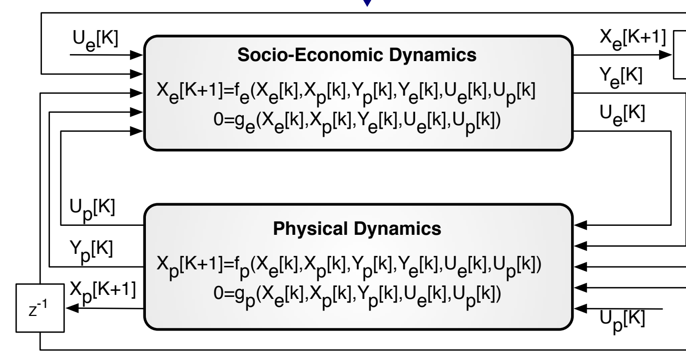






Research Objective: To develop an ***open-access,*** socio-technical, hetero-functional graph model of the entire American Multi-Modal Energy System using physically-informed machine learning

Future Directions: Systematic Study of the AMES' sustainability and resilience as it goes through the sustainable energy transition



∴Renewable energy integration → Deep Decarbonization → Securing Social & Environmental Well-Being

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Thank You

Ducks on Water: Lessons Learned from New England's System Operational Analysis and Renewable Energy Integration Studies

Prof. Amro M. Farid[1,2]

[1]- Stevens Institute of Technology
School of Systems and Enterprises
[2]- MIT Mechanical Engineering

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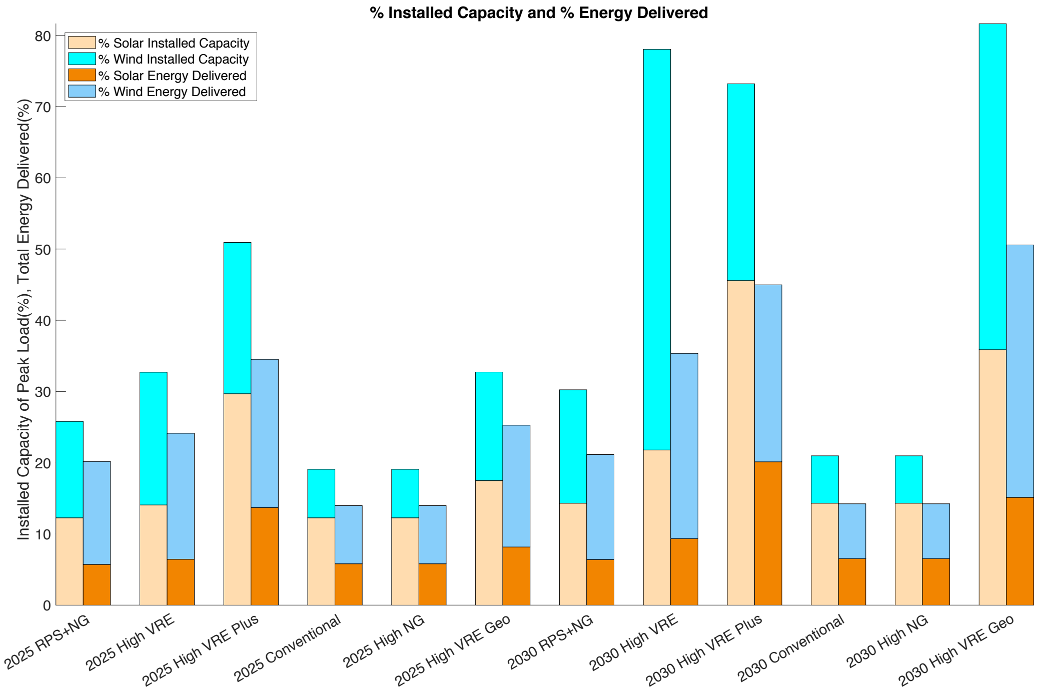
http://amfarid.scripts.mit.edu

Invited Seminar
Monash Energy Institute
Monash University
Clayton, VIC, Australia
October 19, 2022

Thank You



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Invited Seminar
Melbourne Energy Institute
University of Melbourne
Melbourne, VIC, Australia
November 3, 2022

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