Evaluating Long-Duration Energy Storage in Nova Scotia's Energy Transition: Advanced Modelling Insights

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2025 Atlantic Conference on Energy System Modelling

June 18, 2025

The Modelling Challenge

As Energy Systems Transform, How Must Our Models Evolve?

- **Renewable variability & grid dynamics:** increasing penetration of zero-marginal cost generation (and inverter-based resources) introduce challenges across planning, operating and market design dimensions

- **System shocks & uncertainty:** Extreme weather events, inter-annual variability, and fuel price shocks → require formal uncertainty analysis.

- **Cross-sector integration:** Energy demand is increasingly interconnected. Models ought to span power, transport, industry, etc., to reflect real-world operations and constraints.

- **Policy relevance & actionable insights:** Policymaking is moving fast – models are expected to directly inform targets, regulations, and investments.

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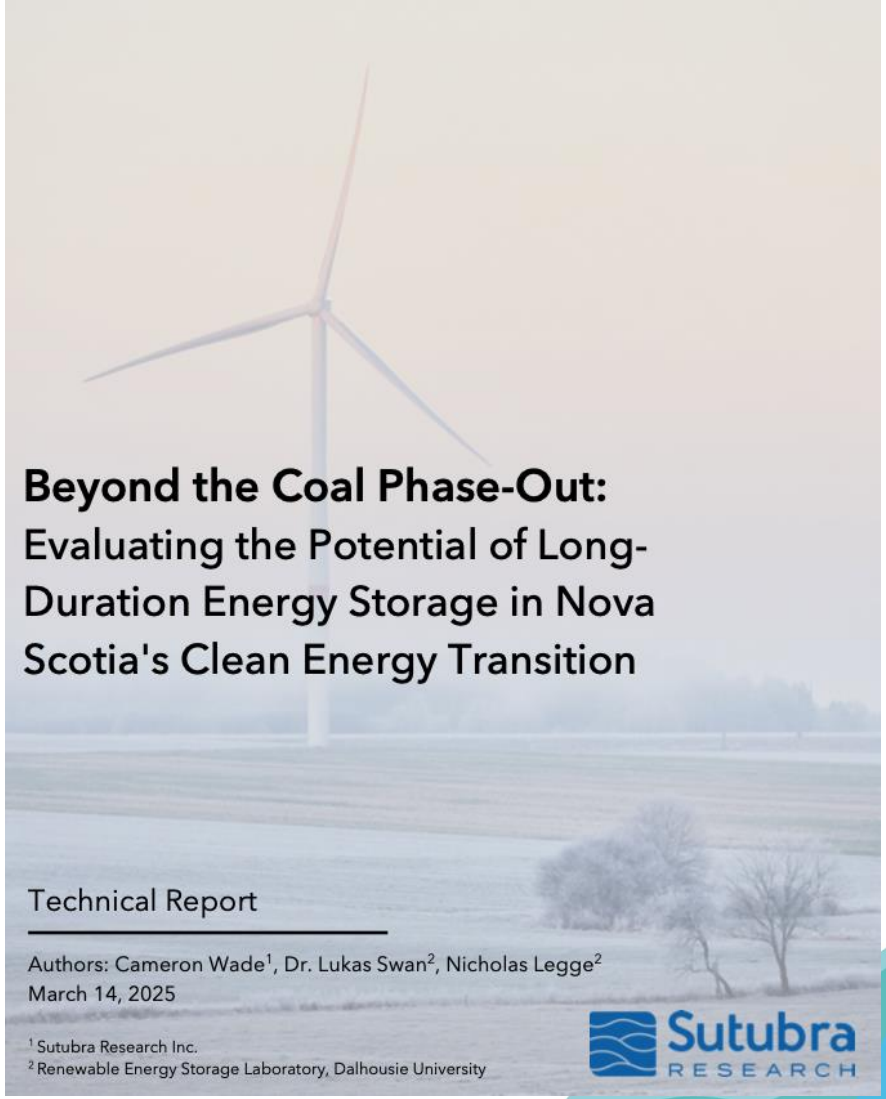
Nova Scotia's coal phase-out provides a great test case



Case Study Context

Nova Scotia's Energy Transition Challenge

Current System (2023):

- 31% Coal; 17% Natural Gas; 1% Oil
- 48% of *firm capacity* from coal generation
- Weakly connected to Eastern Interconnection
- World-class wind resource
- Wind curtailment already occurring during low-demand periods

Policy Drivers

- Federal coal phase-out by 2030
- Renewable electricity standard of 80% by 2030
- Federal carbon price framework (OBPS)

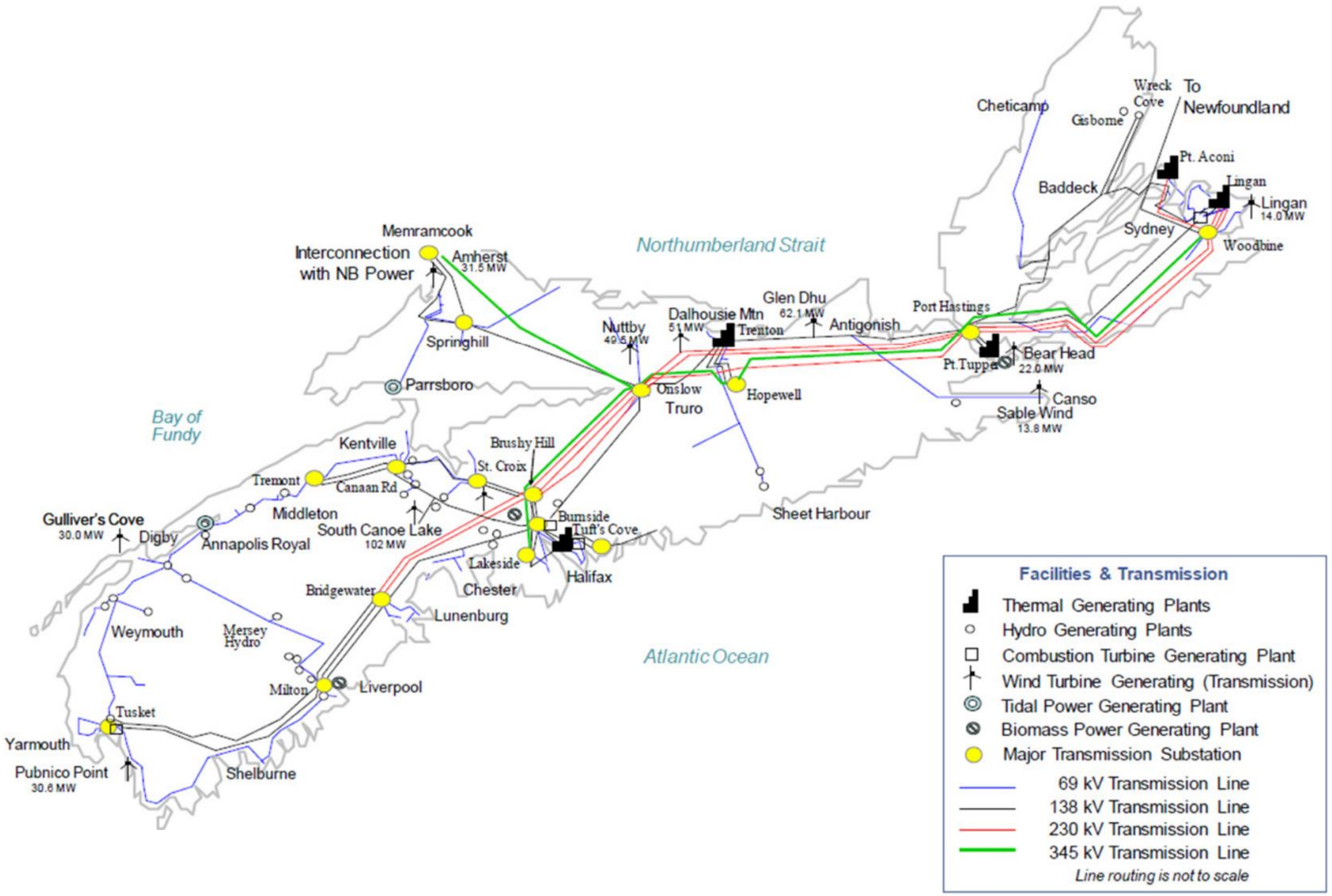
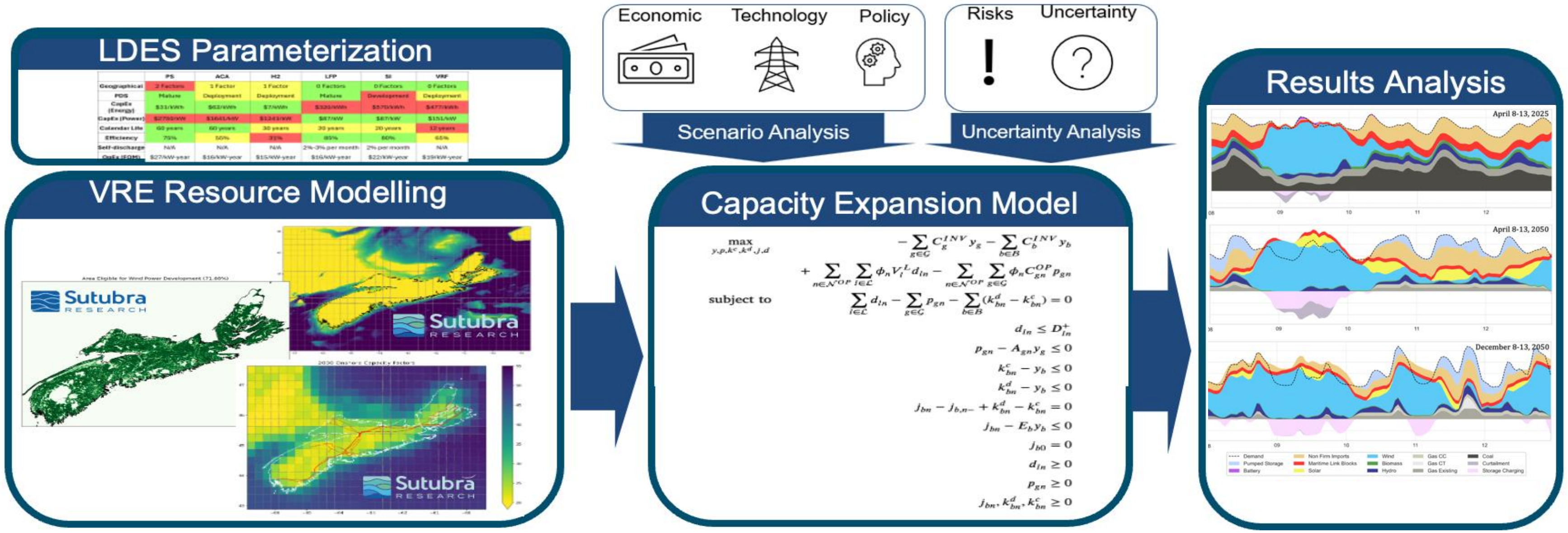


Image from Nova Scotia Power's 2024 Power 10-Year System Outlook

Research Question: Can long-duration energy storage enable deep decarbonization while maintaining reliability?

Comprehensive Assessment Framework



1. Technology Screening and Evaluation:

- Comprehensive examination of promising LDES technologies
- Detailed technical assessment of performance, costs, **geographical constraints**
- Comparative analysis establishing relative strengths and limitations

2. Spatially-Explicit Renewable Resource Modelling:

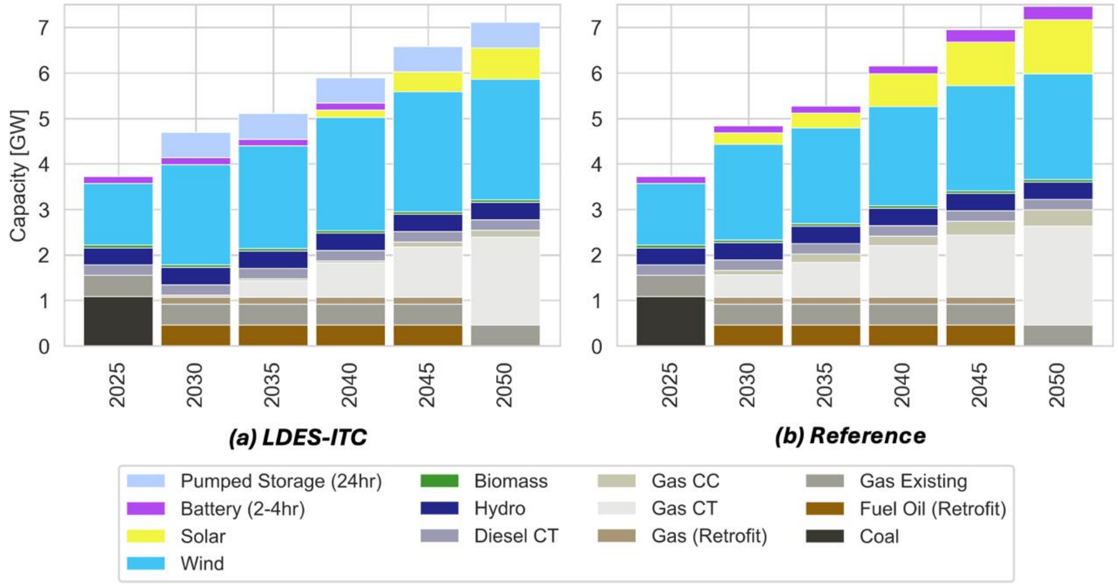
- ERA-5 reanalysis weather data (0.25° resolution)
- Site-specific turbine specs and interconnection costs
- Land-use and siting constraints

3. Capacity Expansion Modelling:

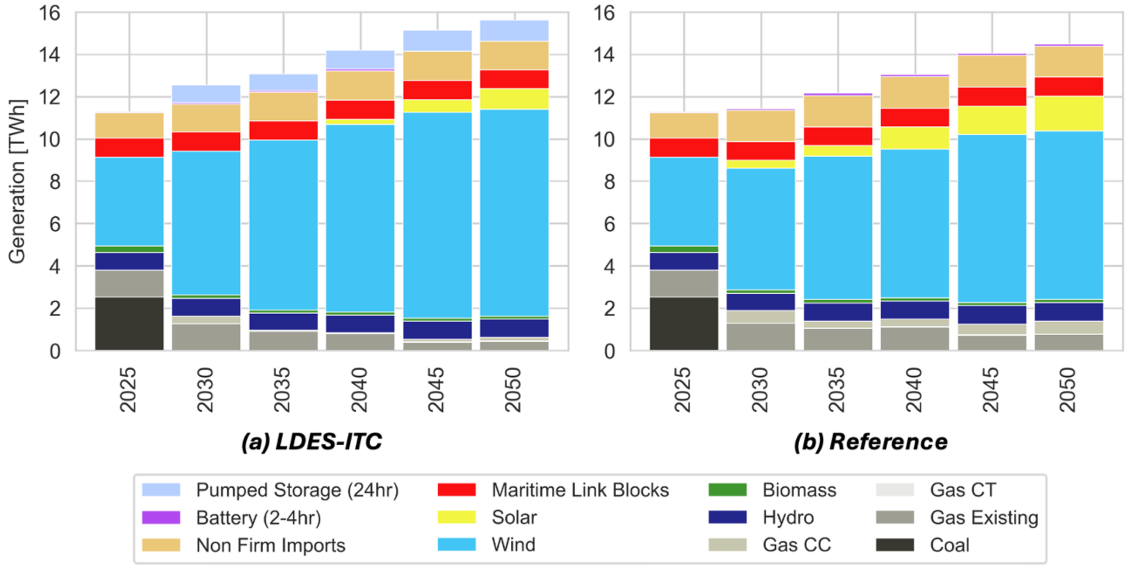
- *Full chronological detail (8,760 hours/year)*
  - ***Necessary to evaluate the operation and economics of LDES***
- 2025-2050 in five-year increments
- Zonal treatment (6)
- Co-optimization of generation, storage and transmission
- Include policy sensitivities (ITCs, CER)
- Rich treatment of existing resources and policies (e.g., hydro operations and renewable integration constraints)

Deployment Results: Resource Mix

Capacity Mix



Generation Mix



LDES Transforms System Resource Mix

- 560 MW/ 13,440 MWh of LDES deployed by 2030
- 1,200+ MW of additional wind capacity by 2050
- 84.4% renewable share achieved in 2030 (vs 80% target)
- Removes the need for new fossil-fuel baseload generation
- 55% reduction in natural gas use (2030 onwards)

LDES unlocks – and *firms up* – our world-class wind resource. It is found to be cost-optimal across all modelled scenarios.

Deployment Results: Infrastructure Siting

Two Pumped Hydro Sites Selected as Cost-Optimal

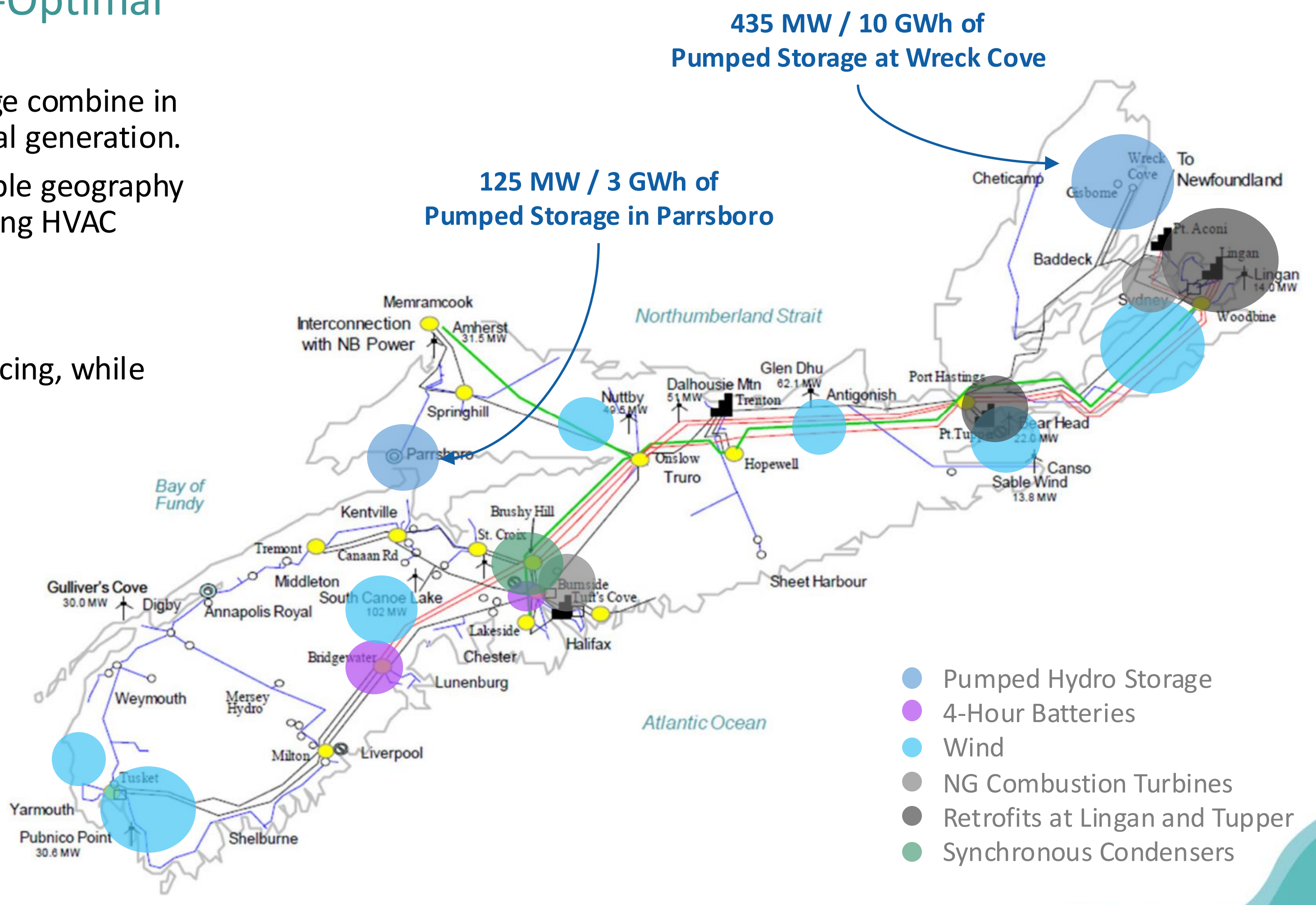
- **New realities in Cape Breton:** Wind and Pumped Storage combine in Cape Breton to replace much of what was lost in thermal generation.
  - This takes advantage of its windy coastline, favourable geography and existing infrastructure in Wreck Cove, and existing HVAC transmission lines to the mainland.

- **Storage synergy:** 4-hour batteries provide diurnal balancing, while LDES cycles at multi-day frequency.

- **Spatial Smoothing:** New wind sites are selected to maximize total system value. The optimization model selects sites from Yarmouth to Eastern Cape Breton to take advantage of shifting weather patterns and *spatial smoothing.*

  Wind site selection often relies on:
  - Resource strength
  - Correlation with load and other must-take gen
  - Proximity to HVAC network

High spatial and temporal resolution are required!



Cumulative Capacity Additions (2030)

System map taken from Nova Scotia Power's 2024 Power 10-Year System Outlook

Operational Value: System Dispatch with LDES

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Energy Arbitrage:

- Absorbs excess renewable generation during high-output periods
- Discharges during low renewable output and high demand
- Bridges multi-day weather patterns that shorter-duration batteries cannot address

Does Not Remove the Need for Peaker Plants:

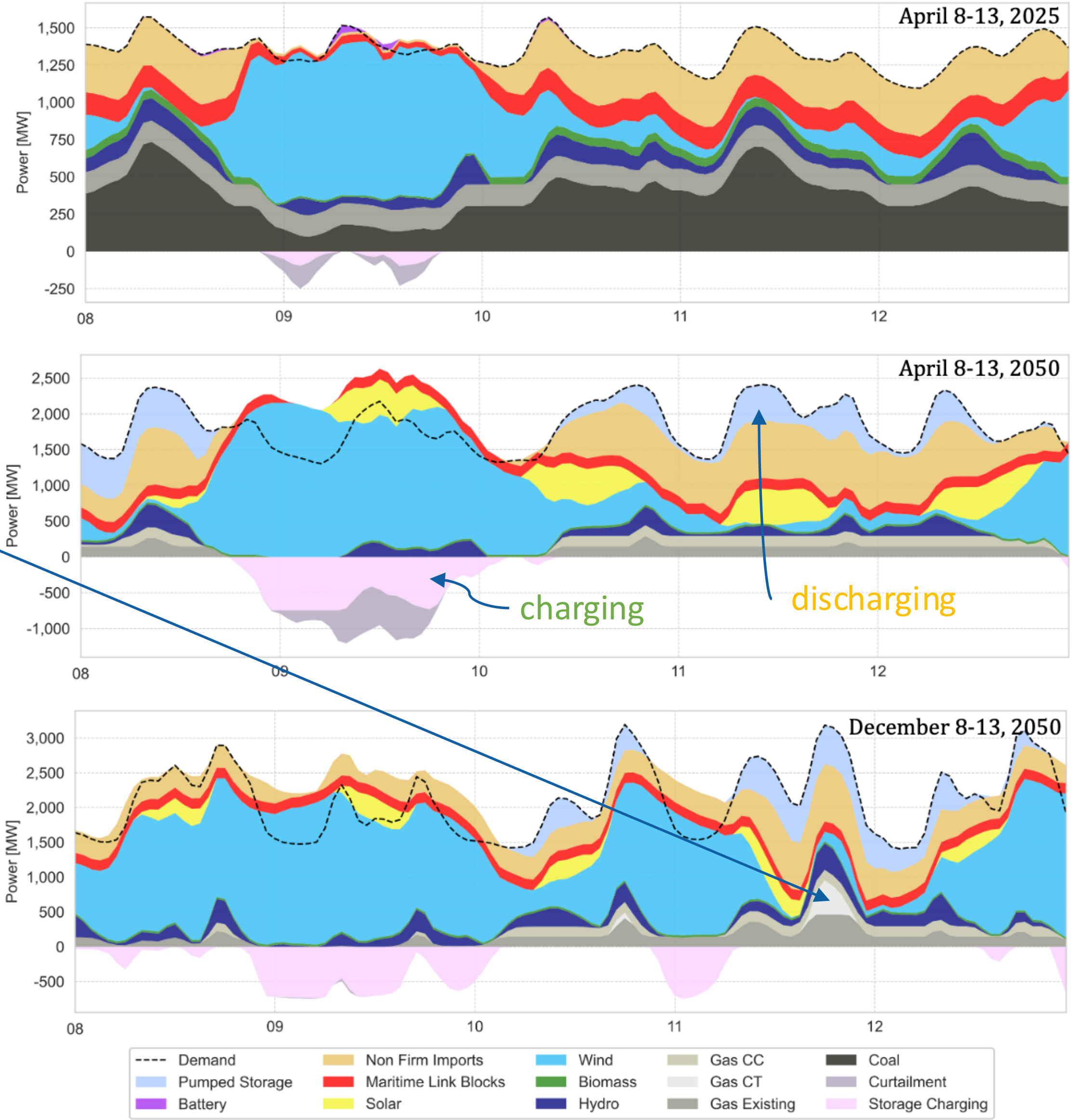
- It remains cost effective to maintain existing thermal fleet, and to add new peaking generation.
- These assets run at considerably lower capacity factors – firing at critical times and maintaining system reliability

Curtailment Cut in Half

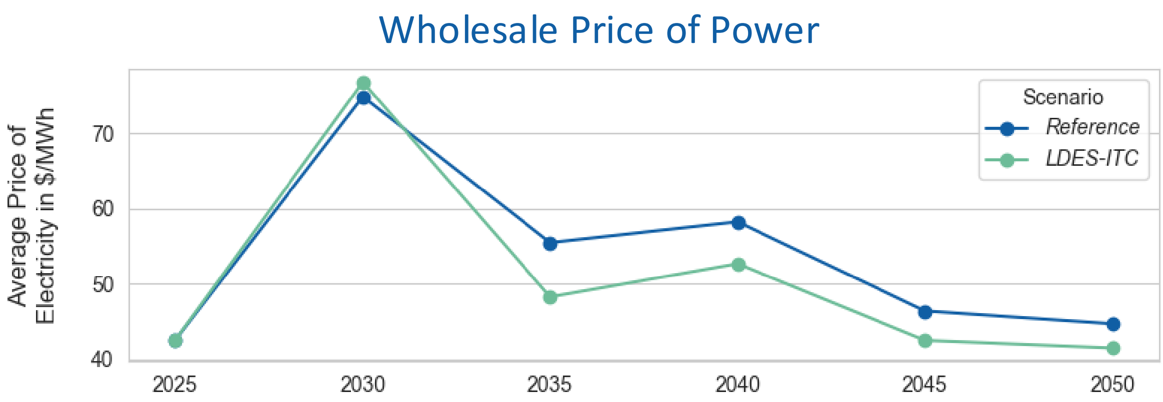
- Renewable integration constraints (in addition to transmission constraints) result in continued, albeit drastically reduced, curtailment levels.
- Curtailment levels effectively cut in half

Scenario		2025	2030	2035	2040	2045	2050
LDES-ITC	Generation (GWh)	4,197	6,801	8,028	9,066	10,223	10,576
	Curtailment (GWh)	227	1,461	474	680	571	572
	Curtailment Fraction	5.4%	21.5%	5.9%	7.5%	5.6%	5.4%
Reference	Generation (GWh)	4,197	6,077	7,170	7,931	9,059	9,376
	Curtailment (GWh)	226	2,059	1,047	1,145	938	958
	Curtailment Fraction	5.4%	33.9%	14.6%	14.4%	10.4%	10.2%

Dispatch Over Sample Weeks



Economic and Environmental Benefits



Total system cost reductions:

- LDES results in a 5.8% reduction in total system cost
- Translates to tens of millions in annual savings across the provincial grid

Wholesale price impacts:

- LDES reduces and stabilizes wholesale electricity prices after 2030
- **By 2035, average wholesale prices are reduced by 15%**
- Reduced price volatility and fewer scarcity events
- Provides hedge against fuel price volatility and environmental policy uncertainty

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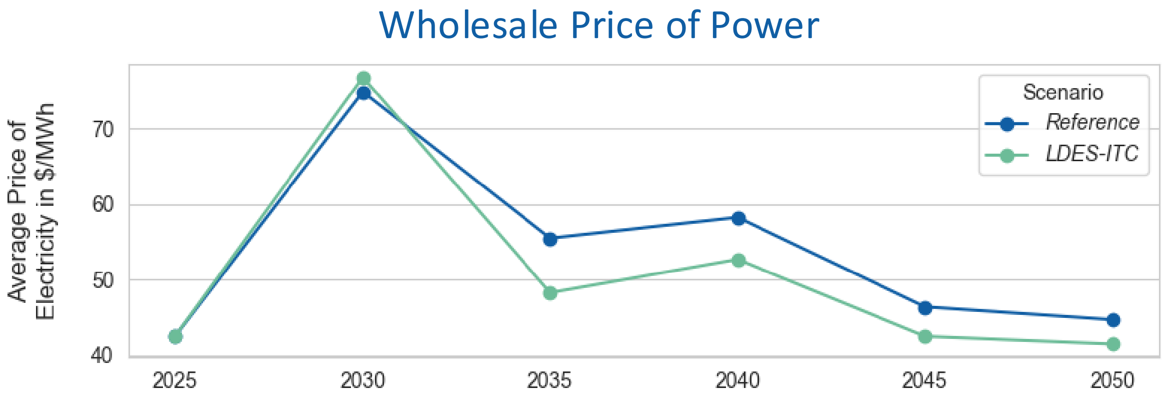

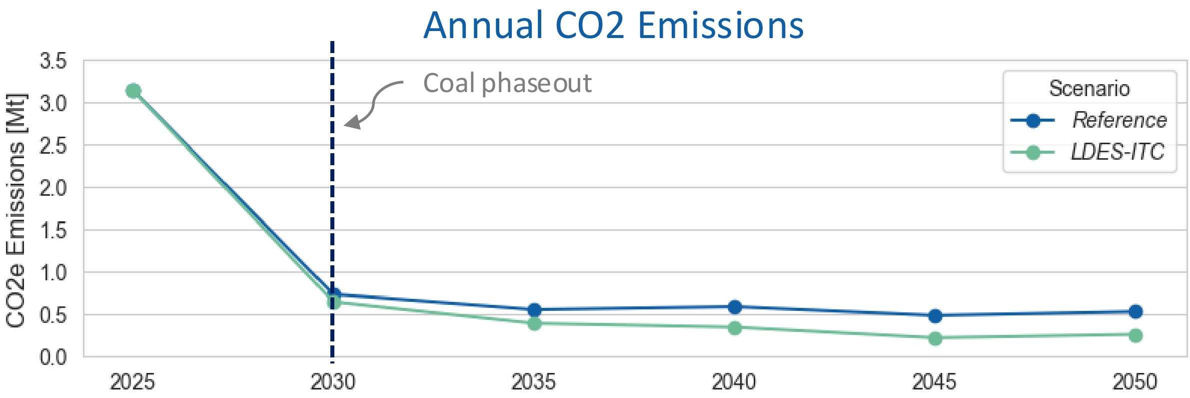

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Direct emissions impacts:

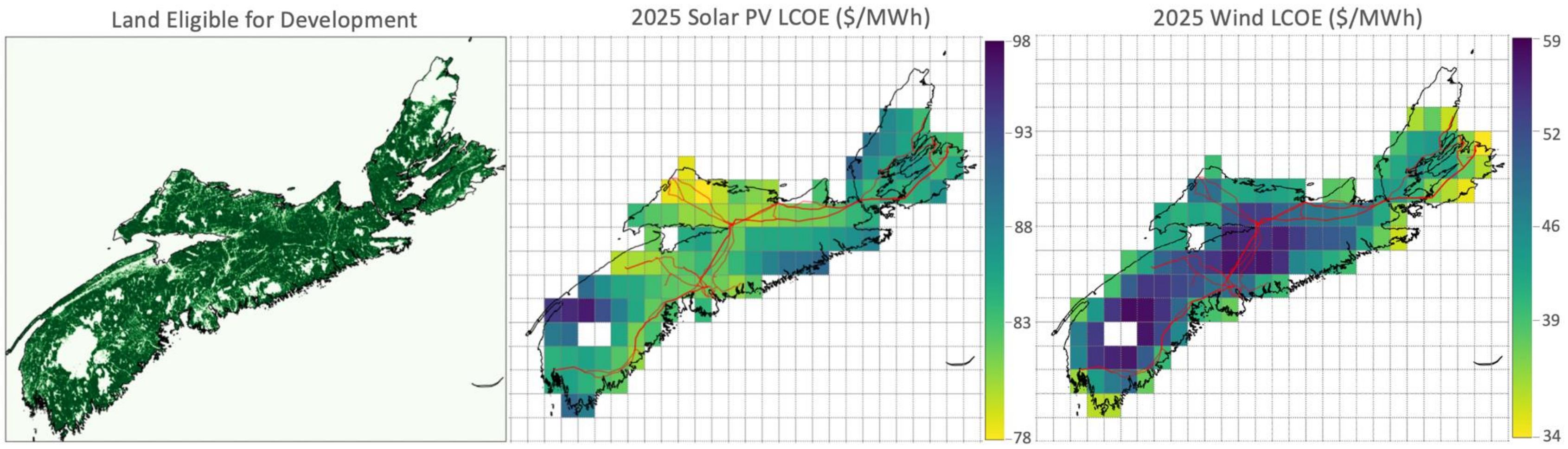
- 55% reduction in post-2030 carbon emissions
- Enables pathway to exceed 80% renewable target cost-effectively

Long-term climate strategy implications:

- Provides viable path to near-net-zero electricity
- Creates foundation for deeper economy-wide decarbonization

Wrapping Up: A Modelling Scorecard

- **Renewable variability & grid dynamics**
  - Spatially explicit treatment of candidate wind, solar, and storage sites.
  - Hourly resolution to resolve system variability.
  - Incorporation of renewable integration constraints (thanks Chris & team!)



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  - Myopic modelling framework to introduce policy & price uncertainties
  - Scenario analysis to understand robustness to policy pathways (CER, ITC, OBPS)
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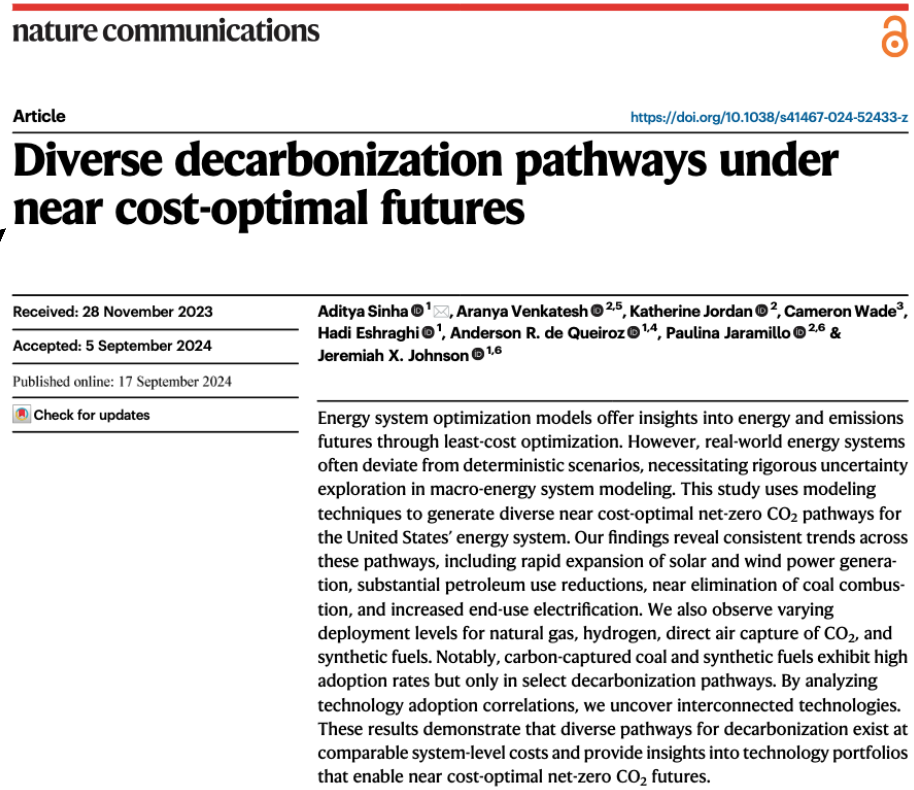
nature communications

Article

https://doi.org/10.1038/s41467-024-52433-z

Diverse decarbonization pathways under near cost-optimal futures

Received: 28 November 2023

Accepted: 5 September 2024

Published online: 17 September 2024

Check for updates

Aditya Sinha[1], Aranya Venkatesh[2,5], Katherine Jordan[2], Cameron Wade[3], Hadi Eshraghi[1], Anderson R. de Queiroz[1,4], Paulina Jaramillo[2,6] & Jeremiah X. Johnson[1,6]

Energy system optimization models offer insights into energy and emissions futures through least-cost optimization. However, real-world energy systems often deviate from deterministic scenarios, necessitating rigorous uncertainty exploration in macro-energy system modeling. This study uses modeling techniques to generate diverse near cost-optimal net-zero CO_2 pathways for the United States' energy system. Our findings reveal consistent trends across these pathways, including rapid expansion of solar and wind power generation, substantial petroleum use reductions, near elimination of coal combustion, and increased end-use electrification. We also observe varying deployment levels for natural gas, hydrogen, direct air capture of CO_2, and synthetic fuels. Notably, carbon-captured coal and synthetic fuels exhibit high adoption rates but only in select decarbonization pathways. By analyzing technology adoption correlations, we uncover interconnected technologies. These results demonstrate that diverse pathways for decarbonization exist at comparable system-level costs and provide insights into technology portfolios that enable near cost-optimal net-zero CO_2 futures.

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  - Load forecasts include new load shapes from end-use electrification and new industrial loads (electrolysis) (thanks Chris & team!)
  - Modelling the power sector at hourly resolution precludes broad sector-coupling. Trade-offs!

ENVIRONMENTAL RESEARCH
ENERGY

PAPER

Marginal abatement costs for greenhouse gas emissions in the United States using an energy systems approach

Michael Blackhurst[1], Aranya Venkatesh[1], Aditya Sinha[2], Katherine Jordan[1], Nicholas Z Muller[1,3,4], Cameron Wade[5], Jeremiah X Johnson[2,*] and Paulina Jaramillo[1]

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Keywords: marginal abatement cost, decarbonization, energy system optimization

Supplementary material for this article is available online

Abstract

Deep decarbonization requires fundamental changes in meeting energy service demands, with some efforts increasing overall costs. Examining abatement measures in isolation, however, fails to capture their interactive effects within the energy system. Here we show the abatement costs of decarbonization in the United States using an energy system optimization model to capture technological interactions, multi-decadal path dependence, and endogenous end-use technology selection. Energy-system-wide net-zero CO_2-eq emissions are achieved in 2050 at a cost under \$400 per tonne CO_2-eq, led by emissions reductions in power generation, end-use electrification of ground transportation, space heating, and some industrial applications. Differences in mitigation costs and CO_2 geological storage potential lead to regional heterogeneities in mitigation rates and residual emissions. The marginal abatement cost curves show that additional decarbonization comes at higher incremental costs, this cost penalty decreases over time, and substantially greater abatement occurs in future time periods at the same abatement cost.

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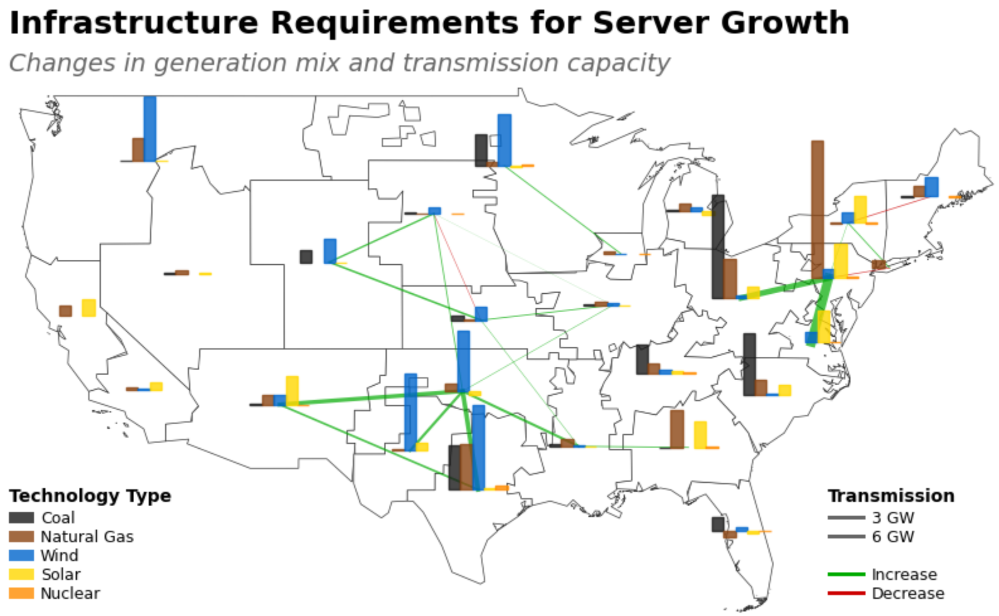

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