Energy+Environmental Economics

Study performed in partnership with Energy Futures Initiative

ENERGY FUTURES INITIATIVE

Electric Reliability under Deep Decarbonization in New England

Presentation at NEPOOL Meeting

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Draft/Preliminary Results

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Agenda

- Introduction
- Economy-Wide Decarbonization Results
- Electricity Resource Portfolios
- Illustration of 2050 Electricity Sector Reliability Challenge
- Key Findings

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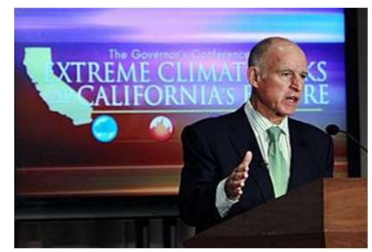
Introduction

E3 has worked with a wide range of clients to understand the challenges of deep carbon reductions and high renewable penetration

+ **United Nations Deep Decarbonization Pathways Project**

+ **California:**
  - Carbon Reduction Pathways studies
  - Landmark 2014 study of 50% RPS goal for PG&E, SDG&E, SCE, LADWP, SMUD, CAISO
  - 100% RPS studies for LADWP, SMUD, Calpine, The Nature Conservancy
  - Support for California CPUC IRP process



+ **Deep carbon reduction and 100% renewables planning in a diverse group of regions:**
  - **New York:** NYSERDA, NYPSC
  - **Hawaii:** HECO
  - **Canada:** Nova Scotia Power, Atlantic provinces
  - **Upper Midwest:** Xcel Energy
  - **Pacific NW & Desert SW:** numerous utilities
+ **Asset valuation and strategy support for resource developers in multiple jurisdictions**

About the Energy Futures Initiative (EFI)

EFI is a nonprofit clean energy think tank founded by former Secretary of Energy Ernest Moniz dedicated to harnessing the power of innovation to create clean energy jobs, grow economies, enhance national and global energy security, and address the imperatives of climate change.

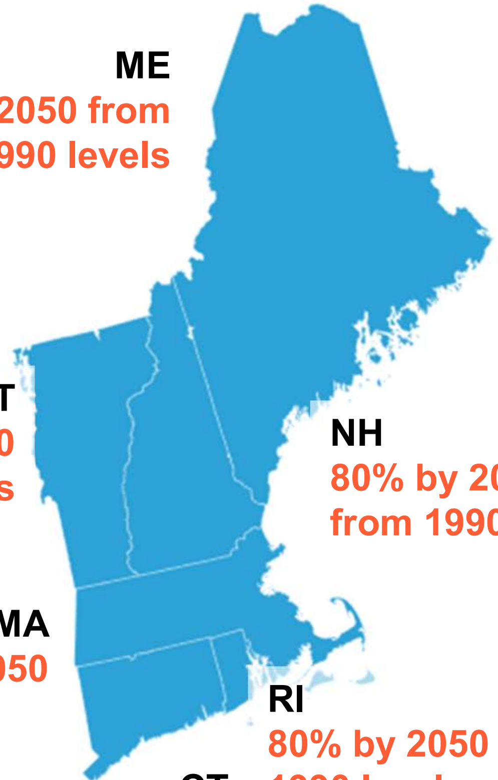
Some of EFI's work:

- **Optionality, Flexibility, and Innovation: Pathways to Deep Decarbonization in California (May 2019): Identified 33 pathways for California to meet its 2030 low-carbon energy goals, and outlined a California-specific innovation agenda for midcentury.**
- **Advancing the Landscape of Clean Energy Innovation (February 2019): Co-produced with IHS Market and sponsored by Breakthrough Energy, assesses energy technologies based on four criteria—technical merit, market viability, compatibility with other energy systems and consumer value.**
- **Clearing the Air: A Federal RD&D Initiative and Management Plan for Carbon Dioxide Removal Technologies (September 2019): Outlines a 10-year RD&D initiative to bring innovative CDR technologies to commercial readiness at a gigaton scale, at technology-specific cost targets, with minimal ecological impacts. Sponsored by the Linden Trust for Conservation and ClimateWorks.**
- **Regional Clean Energy Innovation (February 2020): Analyzes how state-level policy efforts to accelerate local clean energy technology innovation can complement federal activity on climate and energy while creating local economic development opportunities.**

Study Motivation

- **The six New England states are pursuing efforts aimed at increasing renewable energy generation and reducing carbon emissions**
  - Notable recent "net zero" mandate signed in Massachusetts
- **The electricity sector will play a key role by providing low-carbon energy to power the New England economy under economy-wide deep decarbonization**
  - Economy-wide decarbonization will require significant renewable build-out
  - Open questions remain around how much firm capacity is needed in the medium to long-term, and how substitutable renewable generation is for firm dispatchable capacity in "keeping the lights on"

Mid-Century Economy-wide GHG Emission Reduction Targets in New England



Key Study Questions

Study Question: How can New England provide affordable, reliable electric power under future scenarios that achieve net zero economy-wide greenhouse gas emissions by 2050?

Corollary Questions:

- What **decarbonization technologies and strategies** are most likely to be successful in New England, given weather, policy, economics, etc.?
- How much must **electricity sector emissions** be reduced by 2050?
- How much **new electric load** will materialize due to electrification of end-uses in other sectors by 2050?
- What is the **optimal electricity resource mix** to meet's NE energy and resource adequacy needs through 2050 while achieving economy-wide GHG goals?
- What roles do various supply resources play in achieving **resource adequacy**?

Today's discussion focuses on the initial electricity sector resource portfolio results and reliability findings.

Study Approach is a Coordinated E3-EFI Effort

Modeling Steps

1. PATHWAYS
Economy-wide GHG Scenarios

New England PATHWAYS model develops scenarios for meeting 2050 economy-wide decarbonization goals (E3)

- Electric sector carbon budgets and electrification loads passed to RESOLVE

2. RESOLVE
Electricity Capacity Expansion

New England RESOLVE model develops least-cost resource portfolios to meet GHG targets (E3)

- Electricity resource portfolio passed to RECAP

3. RECAP
Electricity Resource Adequacy

New England RECAP model tests the resource adequacy of the portfolios (E3)

- Calculates Loss-of-Load Expectation

iteration

Parallel Research

Carbon Dioxide Removal Potential (EFI)

Innovation Portfolio (EFI) informed by rest of study

Study sponsored by Calpine Corp.

CALPINE®

Technical Advisory Group provided advice and feedback across the study components

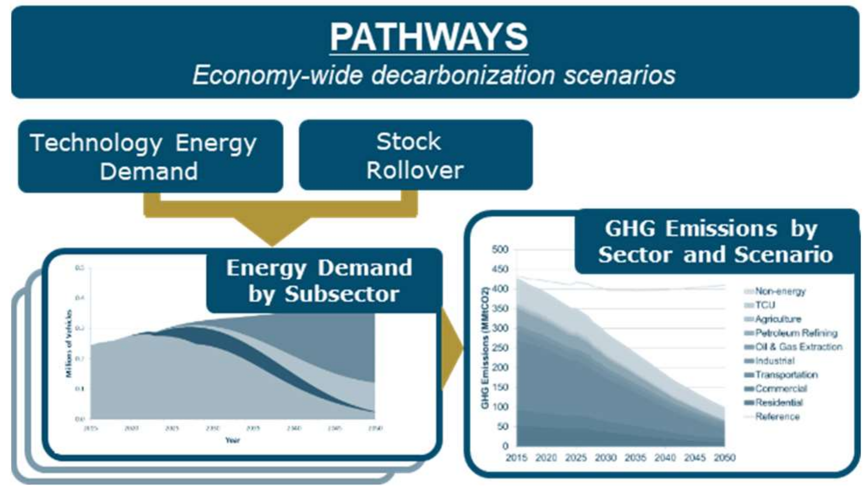
Preview: Key Study Findings

1. **Electricity demand will increase significantly in New England over the next three decades under all plausible low-carbon scenarios**
   - Electricity demand grows by 66 - 97 percent
2. **A significant quantity of renewable generation is selected in every case, particularly solar and offshore wind**
   - Land and transmission availability will likely be constraining factors
3. **The New England system requires 30-37 GW of thermal capacity through 2050 in all cases**
   - Thermal resources operated at increasingly low capacity factors over time
   - It is expected that some form of low-carbon fuel will be available to reduce the carbon intensity of this use
4. **Cases with broader sets of available solutions have lower costs and lower technology risks**
   - Firm, low-carbon technologies such as advanced nuclear, CCS or hydrogen could play a significant role
   - Increasing the availability of land-based wind and solar also reduces cost

Economy-Wide Decarbonization

Step 1: E3 PATHWAYS model used to identify economy decarbonization strategies

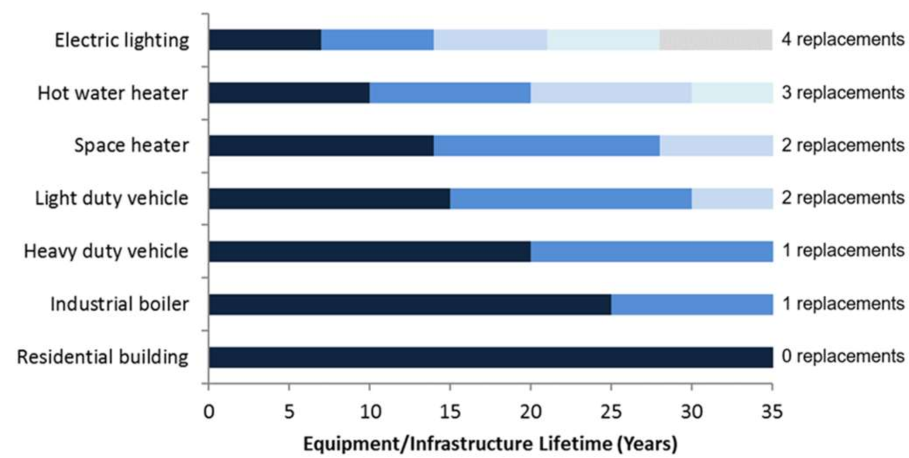
- **Economy-wide infrastructure-based GHG analysis**
  - Driven by user-defined scenarios (i.e., not an optimization)
  - Stock rollover captures “infrastructure inertia” reflecting lifetimes and vintages of buildings, vehicles, equipment



E3 modeled two economy-wide scenarios to reflect a range of load implications

- **High Electrification:** Relies heavily on electrification to decarbonize end-uses, given assumption of somewhat more limited market development of advanced low carbon fuels
- **High Fuels:** Large-scale market development of advanced biofuels and hydrogen result in somewhat lower electrification rates and greater reliance on low-carbon fuels

Illustrative PATHWAYS Lifetimes



Assumptions regarding key decarbonization measures in 2050

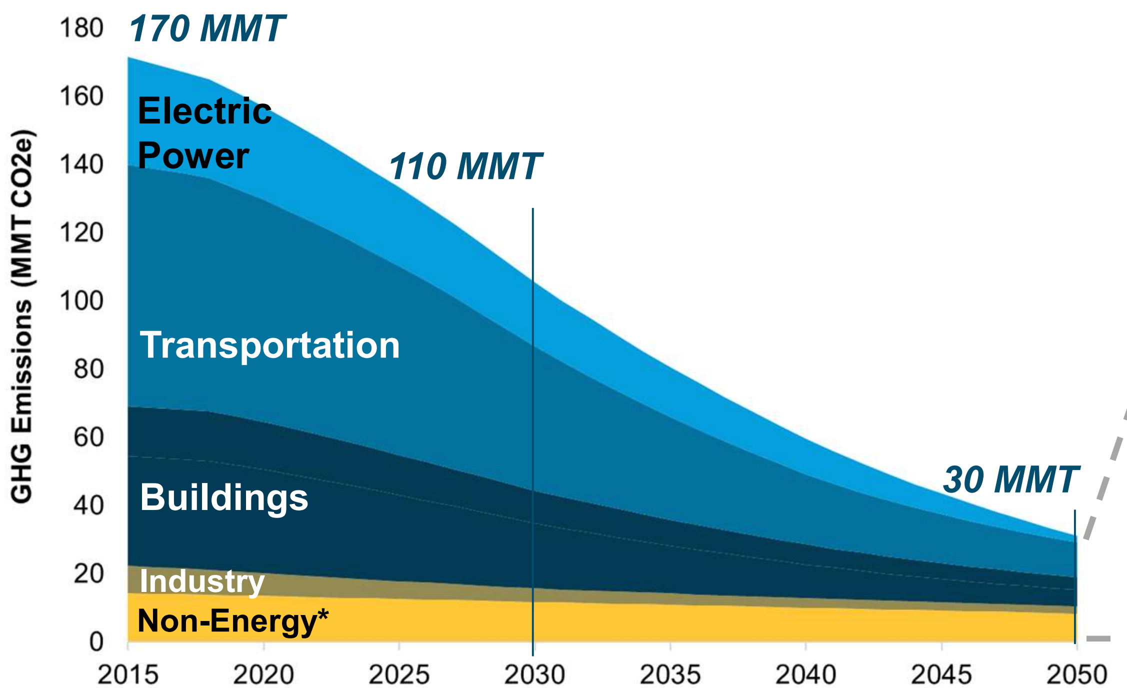
- **Both scenarios assume deeply decarbonized electric grid (90-100% zero-carbon generation scenarios)**
- **Both scenarios also include significant energy efficiency, including technological improvements resulting in efficiency gains, switching to high efficiency appliances, energy reductions due to behavioral conservation, and smart transportation growth.**

Sector	Key 2050 Measure	High Electrification	High Fuels
Buildings	Building efficiency	**100%** Energy Star + Grade Appliances **60%** of buildings have efficient shells	
	Building energy consumption	**About 80%** electricity, based on 80% of building space heating stock being heat pumps	**About 60%** electricity, based on 52% of building space heating stock being heat pumps; **13%** low carbon fuels (hydrogen and RNG).
Transportation	Light-duty vehicles and efficiency	**100%** sales are battery electric or plug-in hybrid electric **7%** reduction in VMT	
	Medium and heavy-duty vehicles	**90%** MDV sales are electric; **10%** sales hydrogen FC **50%** HDV sales are electric, and **50%** are hydrogen FC	**70%** MDV sales are electric; **30%** MDV sales hydrogen FC **100%** HDV sales are hydrogen FC
	Aviation	**40%** efficiency gain (FAA CLEEN 2); No renewable fuel adoption	**40%** efficiency gain (FAA CLEEN 2); **30%** of fuel use is renewable fuel
Industry	Industry efficiency	**25% decrease** in industry energy demand relative to no-increased-efficiency reference	
	Industry energy consumption	**53%** electric **34%** biomass**,** hydrogen, and natural gas with CCS	**39%** electric **48%** biomass**,** renewable fuels, hydrogen, and natural gas with CCS
Low-Carbon Fuels	Fuel utilization	**34 TBtu** of hydrogen, used in transportation (no hydrogen in natural gas distribution pipeline), and no advanced biofuels	**140 TBtu** of advanced biofuels; About **80 TBtu** of hydrogen, in transportation and within pipeline (7% H_2 by energy blended in natural gas distribution pipeline; 20% by volume)

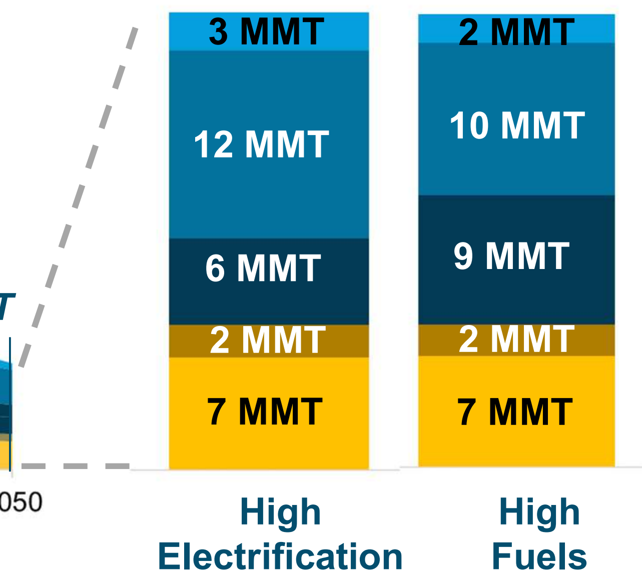
Direct emissions are reduced 85% below 1990 levels by 2050 in both scenarios

- Study assumes New England achieves “net zero” target, consistent with 85% direct emissions reductions relative to 1990 emissions
- Last 15% achieved through CO_2 removal strategies (not shown)

New England GHG Emissions



2050 Initial Snapshot of Remaining Emissions by Scenario

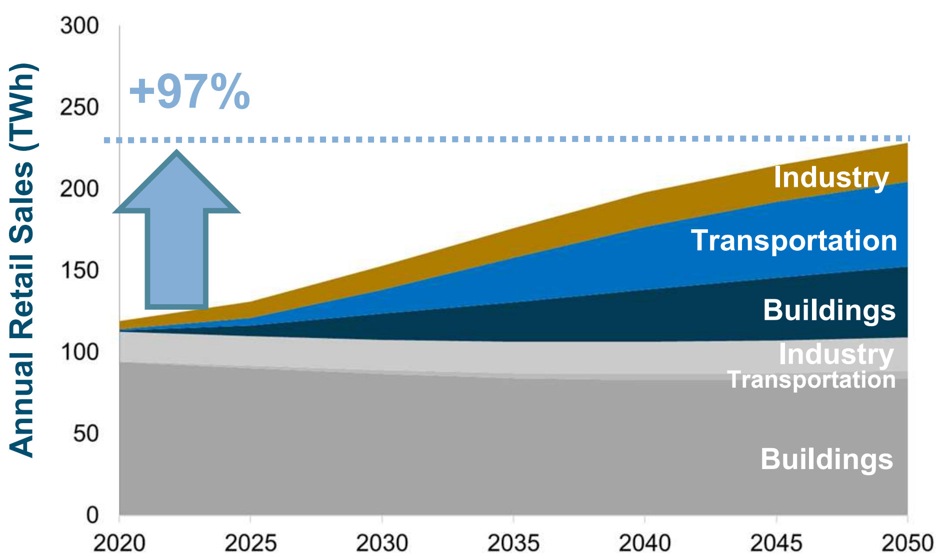


*Non-energy emissions include process emissions (CO_2, NOx, F-gases etc.), methane leakage, GHG emissions from agriculture and waste.

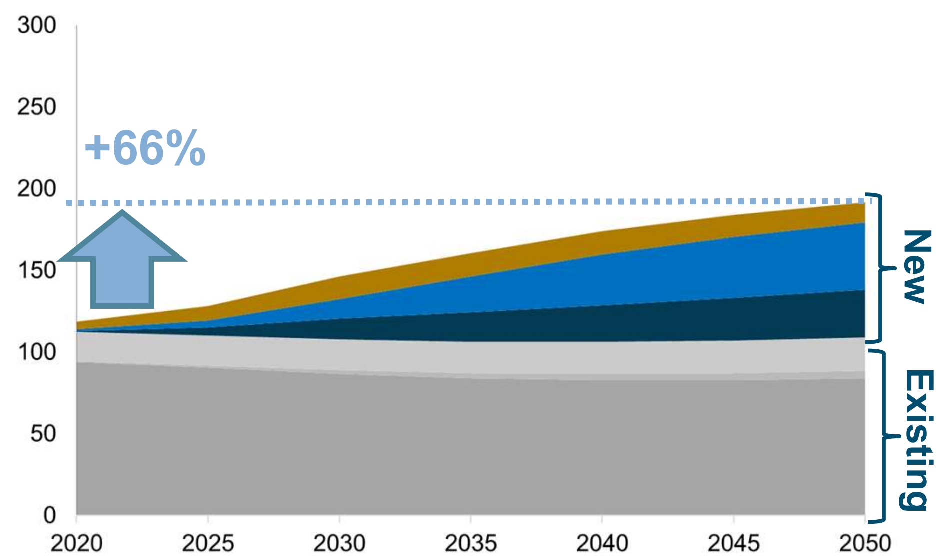
Electricity demand grows significantly under deep decarbonization

+ **Both scenarios see significant load growth, particularly from electrification of space heating and light-duty vehicles, compared to reference load demand (BAU)**
  - **High Electrification** scenario has high electrification of all building service demands, vehicles, and industry resulting in about 230 TWh of annual load in 2050
  - **High Fuels** scenario utilizes higher reliance on fuel blends and fuel switching to hydrogen and biofuels, thus has lower peak demand and a total electric load of about 192 TWh by 2050

High Electrification Scenario Load



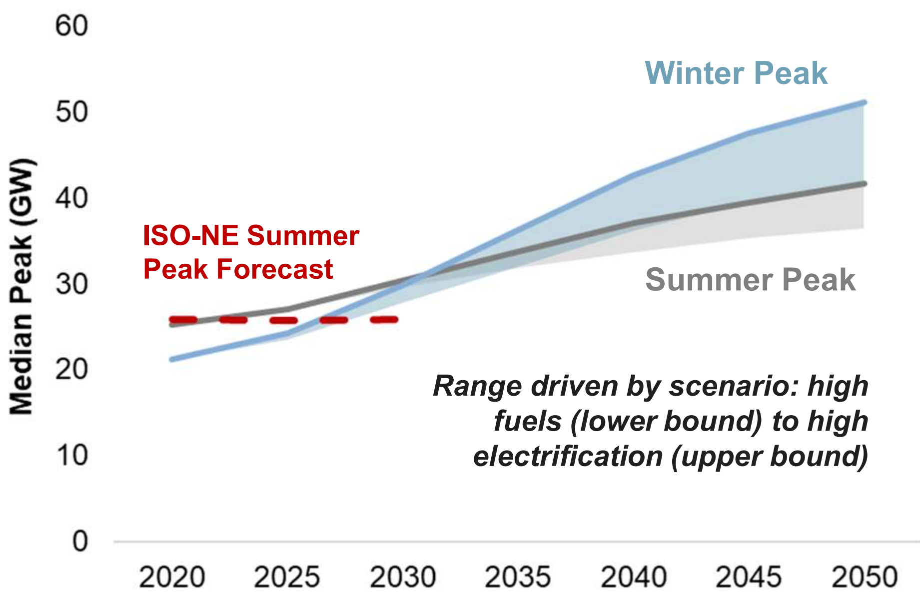
High Fuels Scenario Load



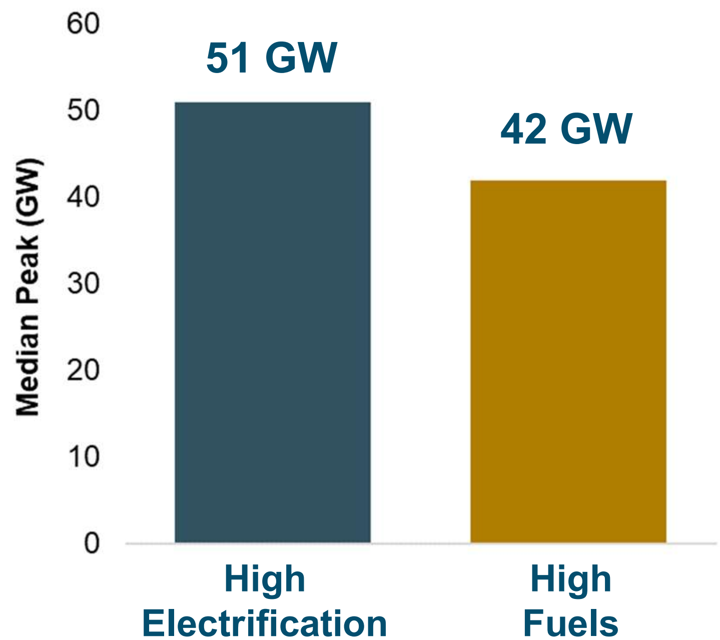
New England electricity system becomes winter-peaking in the 2030s

- **Median gross load peak (net of EE) assumed to increase from 25 GW in 2019 to 42-51 GW by 2050**
  - Winter peak exceeds summer in early to mid 2030s under both scenarios
  - 2050 peak impacts of electrification load mitigated by assuming diverse portfolio of heat pump technologies and sizing

Seasonal Peak Load Change

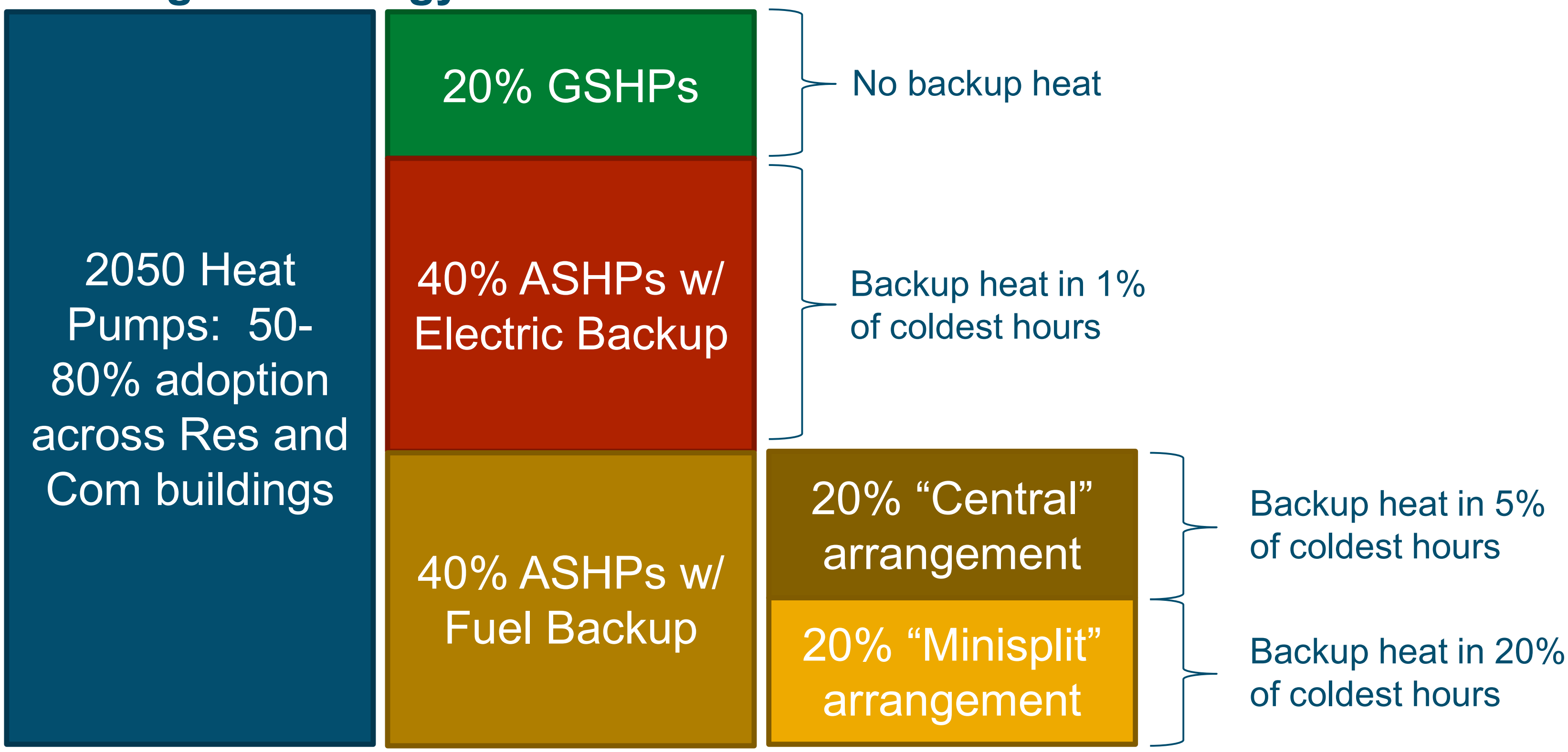


2050 Peak Load Snapshot



A mix of heat pump technologies is assumed to be adopted throughout New England

Heating Technology Mix Assumed



- **Mix of heat pump technologies is a key issue**
- **Encouraging oversizing or fuel backup to mitigate electric peak impacts will need to be a policy focus**

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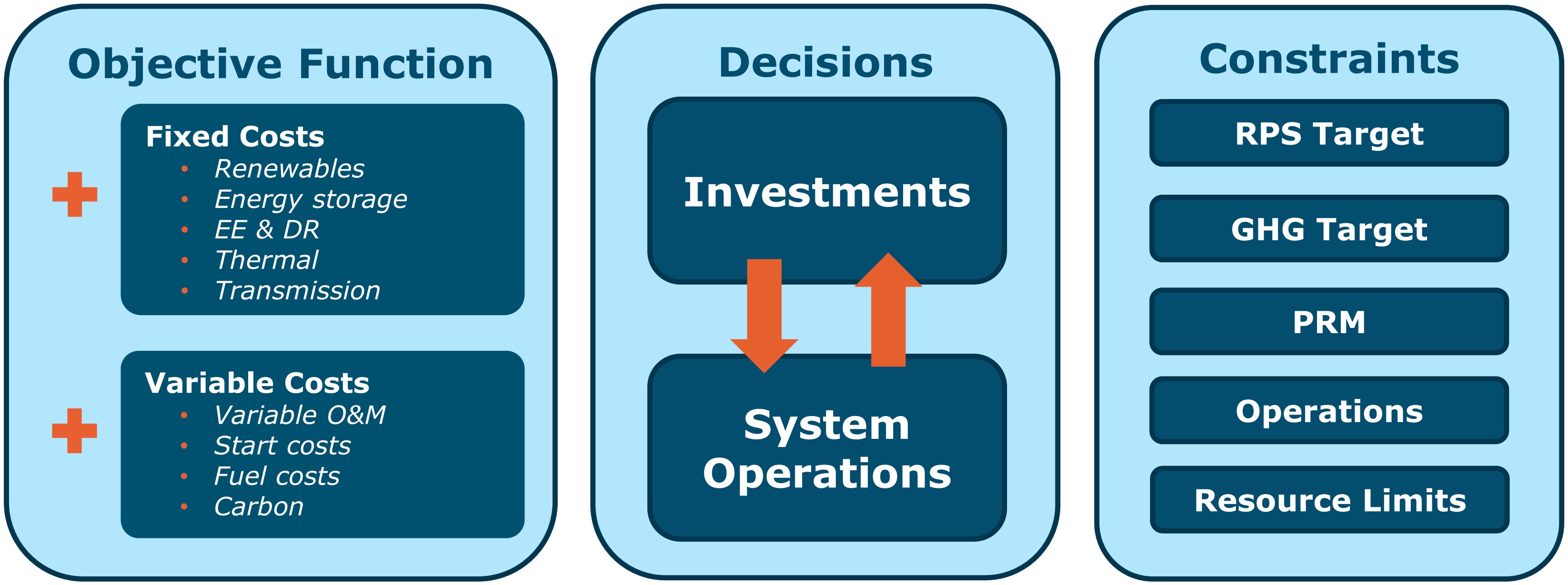
Electricity Resource Portfolios

Step 2: E3's RESOLVE model calculates optimal portfolio subject to GHG constraints

+ **RESOLVE co-optimizes investments and operations to minimize total net present value of the electric system cost through 2050**
  - Optimization directly captures linkages between investment decisions and system operations
  - RESOLVE is designed for systems with high levels of renewables and storage



Step 3: E3's RECAP model used to test resource adequacy in detail (iterative w/ 2)

+ **RECAP simulates thousands of years with different weather conditions to derive parameters for RESOLVE modeling**
  - Determines PRM needed to meet reliability standard of 1 day in 10 years
  - Calculates ELCC of different resources at varying penetrations and combinations
+ **Optimal RESOLVE portfolio tested for resource adequacy in RECAP**

Inputs

Load
- *Hourly load for many weather years*

Dispatchable Generation
- *Capacity*
- *FOR*
- *Maintenance*

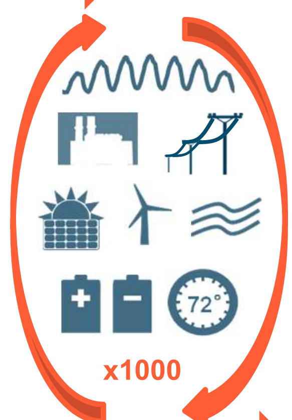
Renewables
- *Capacity*
- *Hourly generation profiles for many weather years*

Hydro
- *Hydro availability for many hydro years*
- *Max/min constraints*

Storage
- *Capacity*
- *Duration*
- *Roundtrip efficiency*
- *FOR*

Demand Response
- *Capacity*
- *Max # of calls*
- *Duration of each call*

Flexible Load
- *Capacity*
- *Max hours of shift*



Outputs

LOLH
- *Loss of load hours*
- *Hrs/yr of total expected lost load per year*

LOLE
- *Loss of load expectation*
- *Days/yr of total expected lost load per year*

ALOLP
- *Annual loss of load probability*
- *% probability of having a single loss of load in any given year*

EUE
- *Expected unserved energy*
- *MWh/yr of energy that cannot be served*

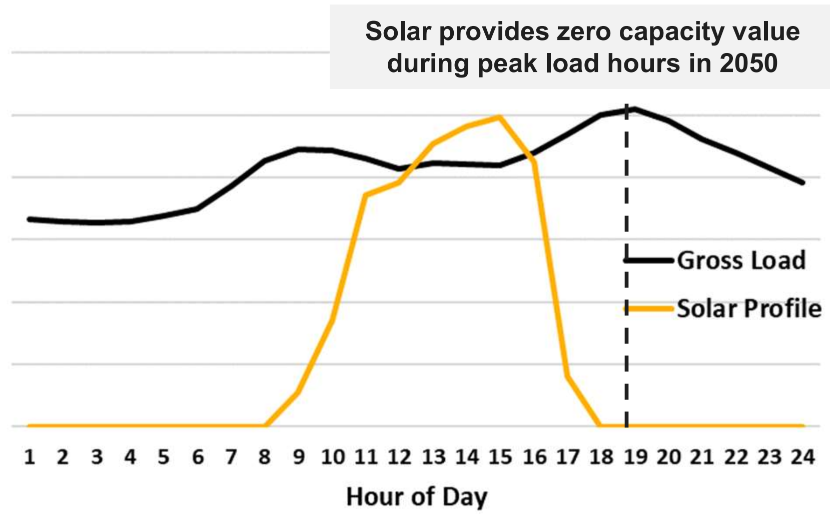
ELCC
- *Effective load carrying capability*
- *Equivalent quantity of 'perfect capacity' for a variable or energy-limited resource*

TPRM
- *Target planning reserve margin*
- *PRM required to achieve a specified reliability threshold (i.e. LOLH, LOLE, ALOLP, or EUE)*

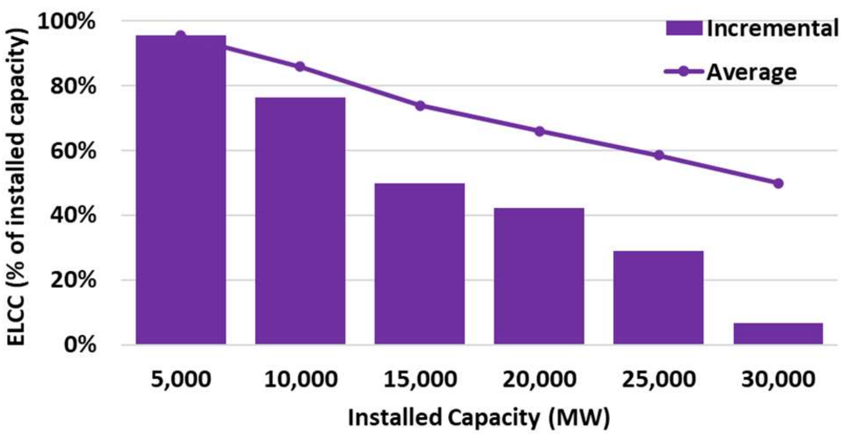
E3 estimated ELCCs for candidate wind, solar and storage resources

+ **ELCC is the amount of perfect capacity a resource can replace while providing the same reliability**
+ **ELCCs from RECAP used as input parameters to RESOLVE**
  + Standalone solar provides zero ELCC after 2035 due to non-coincidence with wintertime peaks

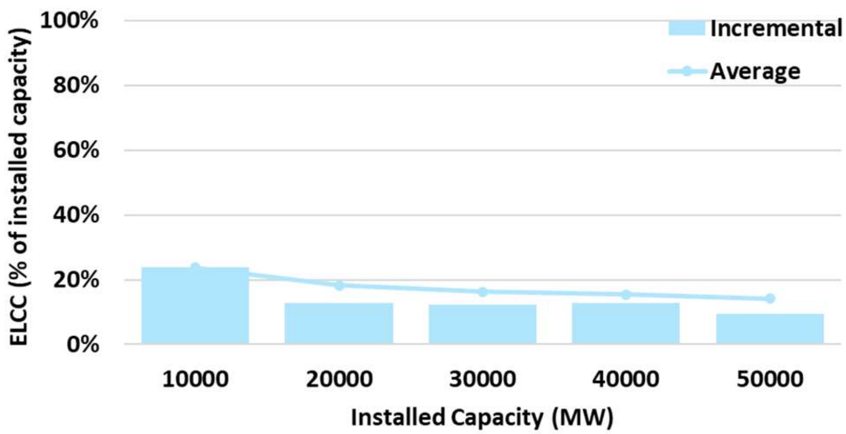
Typical day with high loads in 2050



2050 ELCC, 4-hour Storage

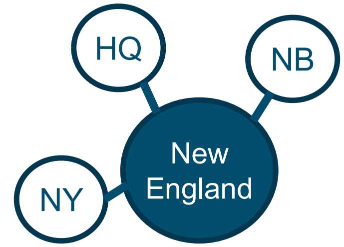


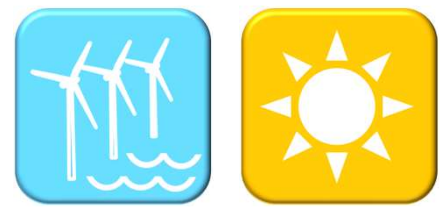
2050 ELCC, mix of NE Wind



Key Electricity Sector Assumptions

1. **Load:** Based on economy-wide decarbonization modeling.
2. **Candidate Resources:** Various combinations of renewables (onshore/offshore wind, solar), Canadian hydro, hydrogen/zero carbon fuel combustion, gas with CCS, nuclear SMR.
3. **Candidate Resource Costs:** Latest public estimates for resource costs based on NREL Annual Technology Baseline (ATB) 2019 and Lazard 5.0, with local adjustments.
4. **Fuel Prices:** Single natural gas price (Algonquin) assumed throughout New England, with seasonal variation reflecting fuel constraints. Zero-carbon fuel prices based on E3 research.
5. **Transmission:** Single load zone within NE, several internal and external resource zones with transmission needs.
6. **Imports:** Three external zones (Hydro Quebec, New Brunswick and New York) which can contribute to planning reserve margin using existing transmission.



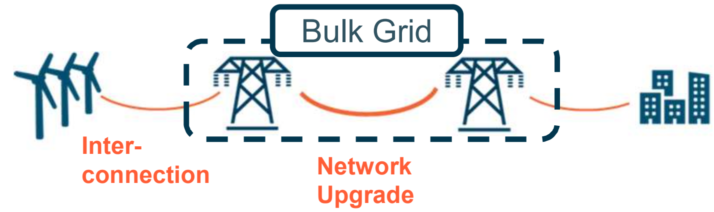


NREL NATIONAL RENEWABLE ENERGY LABORATORY LAZARD

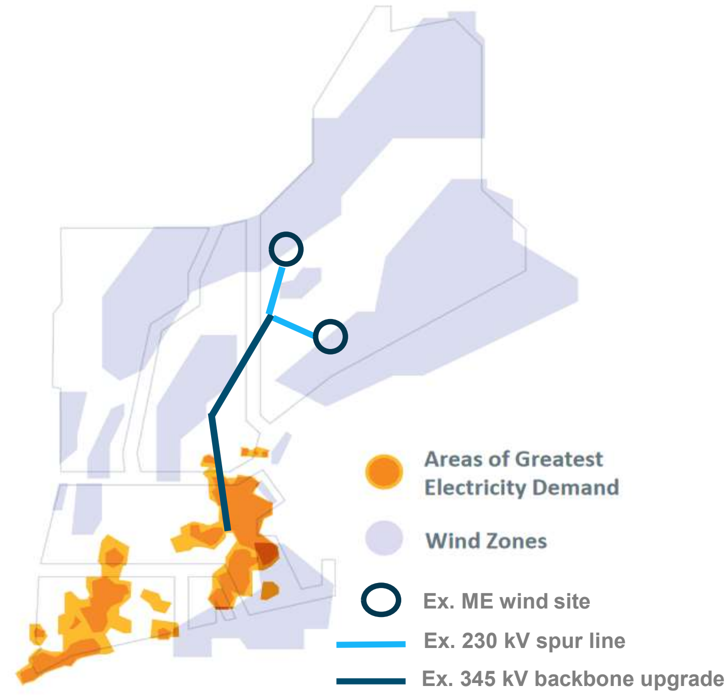
Transmission costs required to integrate renewables

+ **Types of modeled transmission costs**
  1. 230 kV interconnection (spur line) cost
     - Incurred by all new renewable projects (except distributed); based on NREL ReEDS
  2. 345 kV network (backbone) upgrade cost
     - Required once available headroom on existing transmission is exhausted
  3. 115k kV line
     - Incurred only by second tier of distributed solar
+ **Available headroom to serve load without 345 kV network upgrades**
  - Interstate headroom: 800 MW for NH+VT, 4 GW each for CT, MA, RI
  - Local headroom for utility solar: Utility-scale solar can be built up to 50% of the projected 2050 peak load (by state)
  - Offshore wind headroom estimated at 8 GW
  - DG solar: Up to 50% of technical potential; first tier (half) requires no transmission and the second tier (other half) requires 115 kV line

Transmission Components



Ex. ME onshore wind costs & associated transmission costs

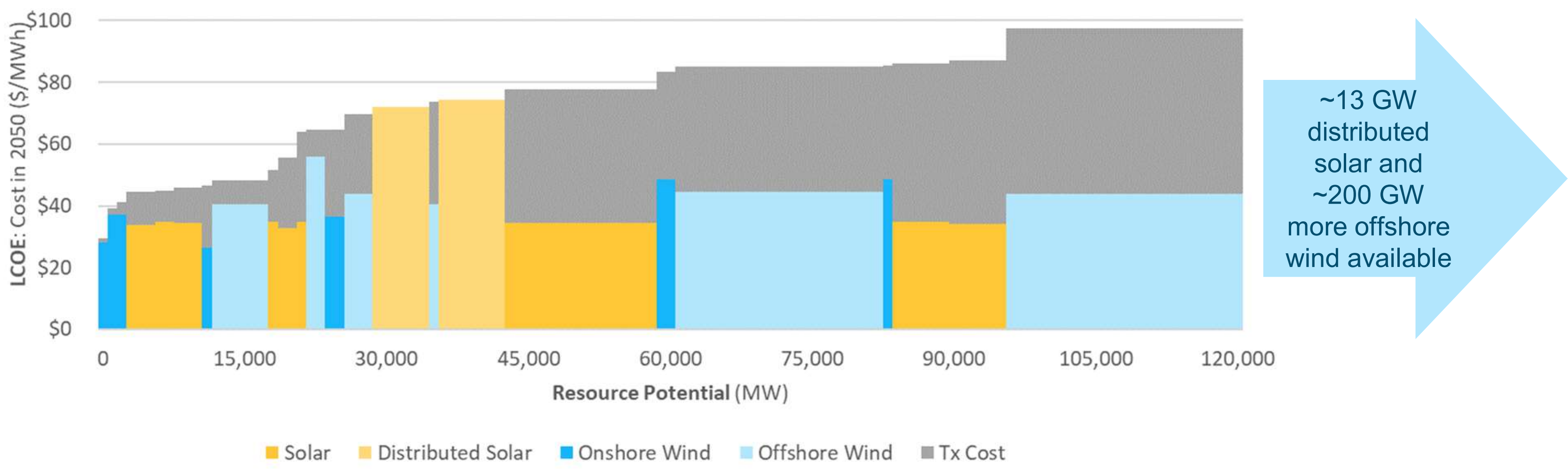


Source: Base map of demand and wind zones from ISO-NE

New England renewable supply curve developed from NREL data sources

+ **Supply curves for wind and solar from NREL**
  - New England has limited low cost onshore wind and solar, with significant offshore wind potential available with network upgrades
+ **E3 applied screens based on land use**
  - Land use screens: land equal to 4% of farmland for solar, 2% of farm + forest for wind in base case
  - Land restricted case with 2%/1% modeled as sensitivity
+ **Renewable supply curves provide useful indication of available resources and relative costs (RESOLVE selects resources based on value to portfolio)**

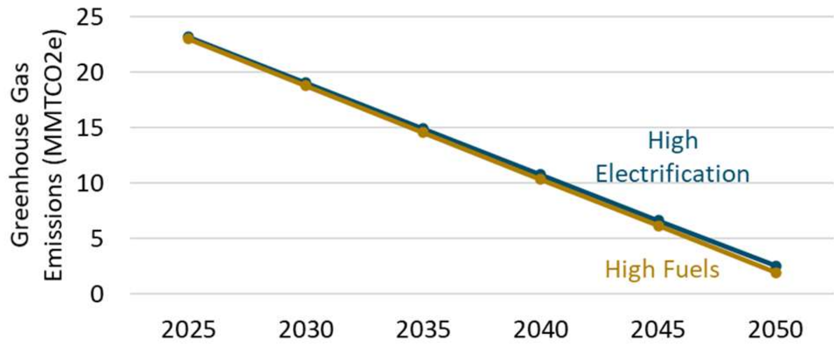
Renewable Supply Curve for New England in 2050 (includes Base Case Land Screen)



Resource availability in the Base Case and sensitivities

- **Base Case developed for both High Electrification and High Fuels load scenarios**
- **Several sensitivities test changes in technology and land availability**
- **Sensitivities also vary carbon targets, from 2x Base Case emissions to zero emissions by 2050**

Emissions Target



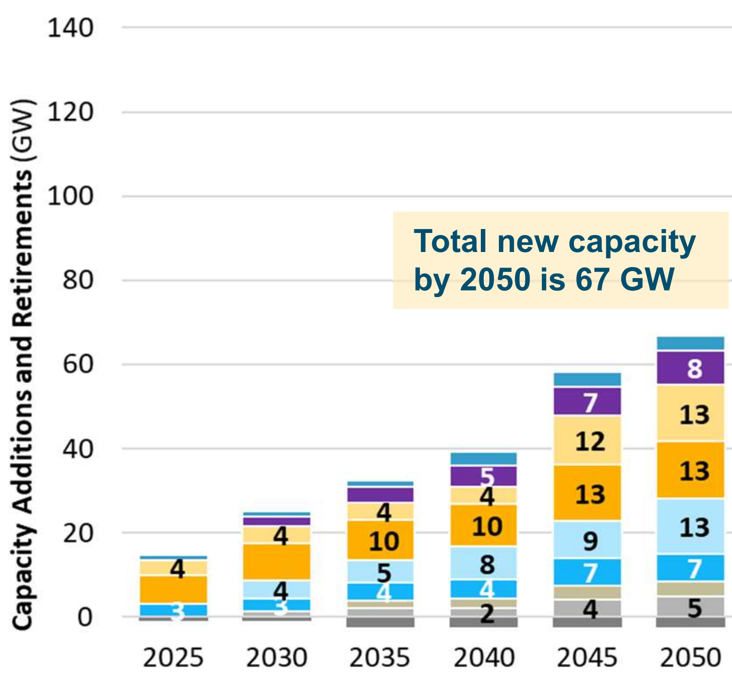
Resource Option	Available Options in New England Base Case	Range/Changes Evaluated in Sensitivities
Natural Gas Generation	• Simple cycle gas turbines • Combined cycle gas turbines	• No new gas units allowed • No new gas and retire all existing fossil
Renewable Generation	• Solar PV (4% farm) • Distributed solar (50% tech potential) • Onshore wind (2% forest + farm) • Offshore wind	• Solar PV: range from half base (2% farm area) to NREL technical potential • Onshore wind: range from half base (1% forest + farm) to NREL technical potential
Energy Storage	• Batteries (> 4 hr): model chooses duration	
Imports*	• Quebec hydro tier 1: turbine upgrades • Quebec hydro tier 2: new impoundments • New Brunswick: new onshore wind	
Clean Firm Generation	• Nuclear SMR up to amount such that total nuclear doesn't exceed about 3.5 GW in given model year	• Unlimited SMR • Unlimited CCS (with 90% capture) • Unlimited SMR + CCS
Demand Response**	• 740 MW + flexible EV charging load	

* In addition to new imports, existing imports from New York, Quebec and New Brunswick are modeled.
** Model includes load flexibility that acts as 'shift' DR, i.e., allowing about 4 GW to move in/out of each hour.

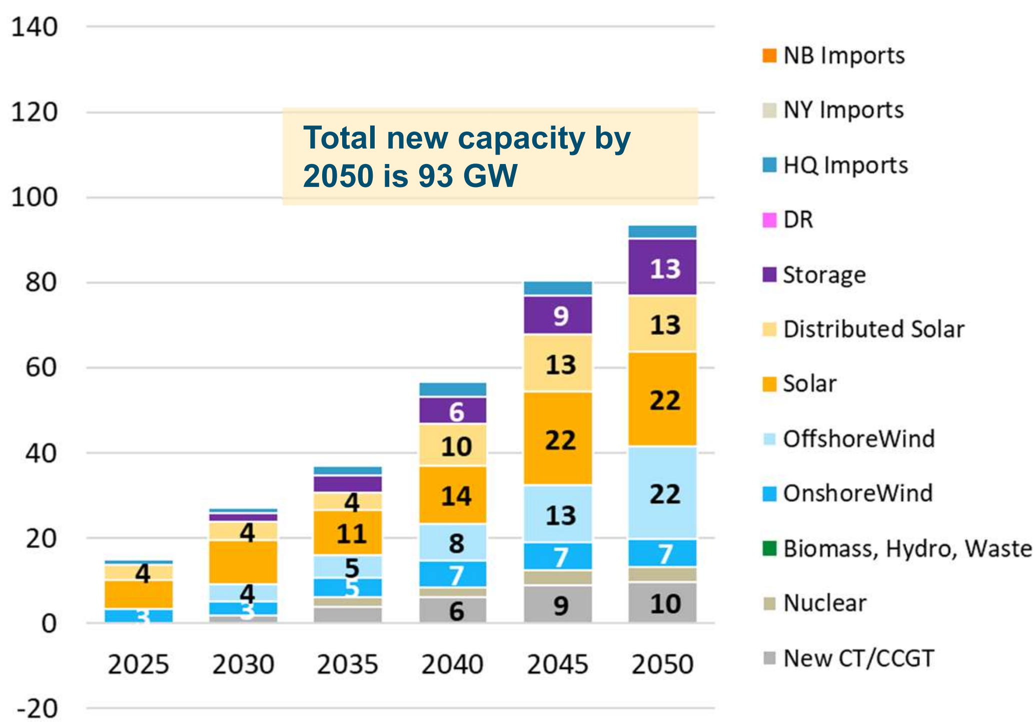
Results: Capacity Additions

+ **New capacity additions are dominated by renewables and energy storage, particularly offshore wind and solar**
+ **Although loads and resulting builds vary, both scenarios achieve over 95% zero emissions electric generation by 2050**

High Fuels



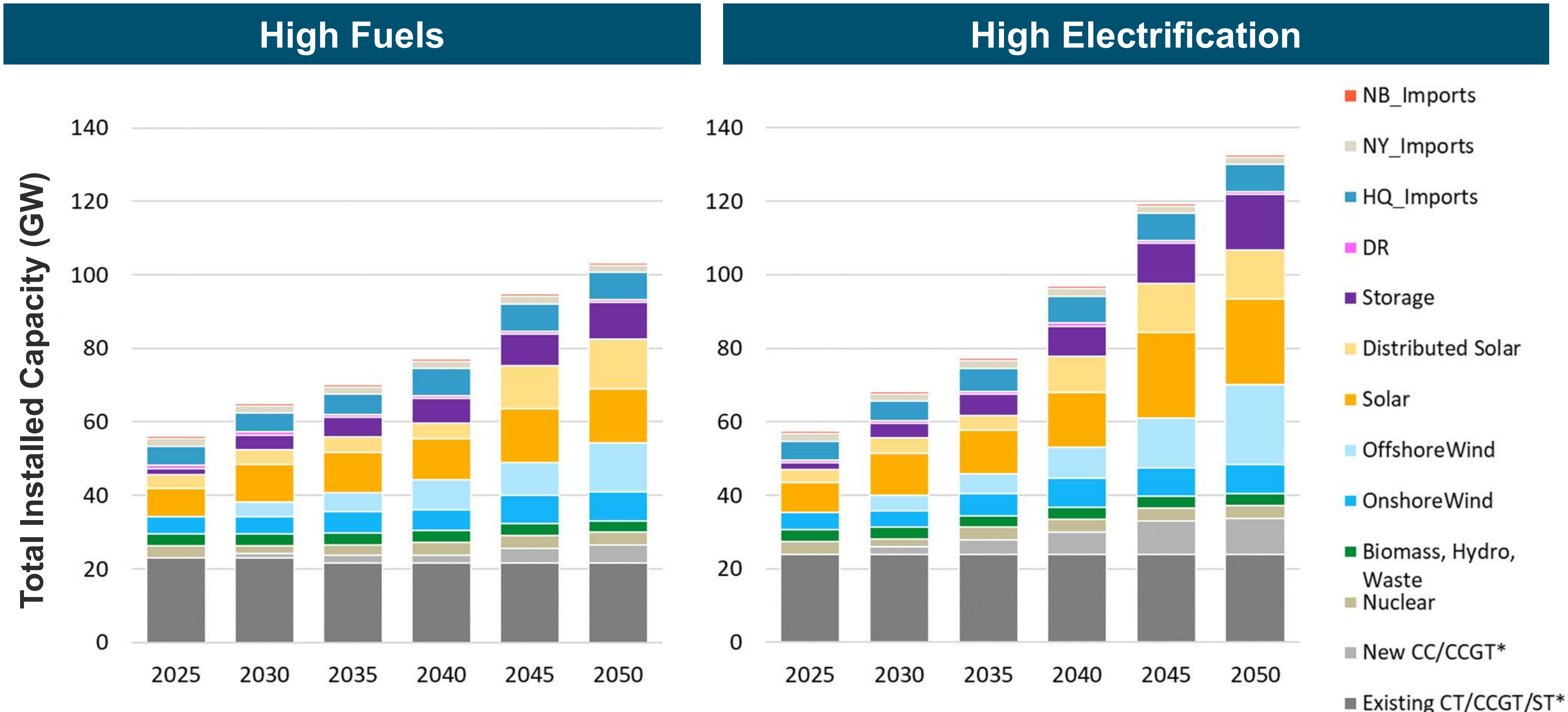
High Electrification



*CT/CCGT can burn natural gas and/or hydrogen blend

Results: Total Installed Capacity

- Most capacity is non-emitting by 2050, with wind, solar and batteries reflecting about 60% of capacity (slightly less in HF, slightly more in HE)
- Existing fossil and new gas is utilized to meet reliability needs and PRM; nuclear is also maintained/built to its model-imposed limit of ~3.5 GW

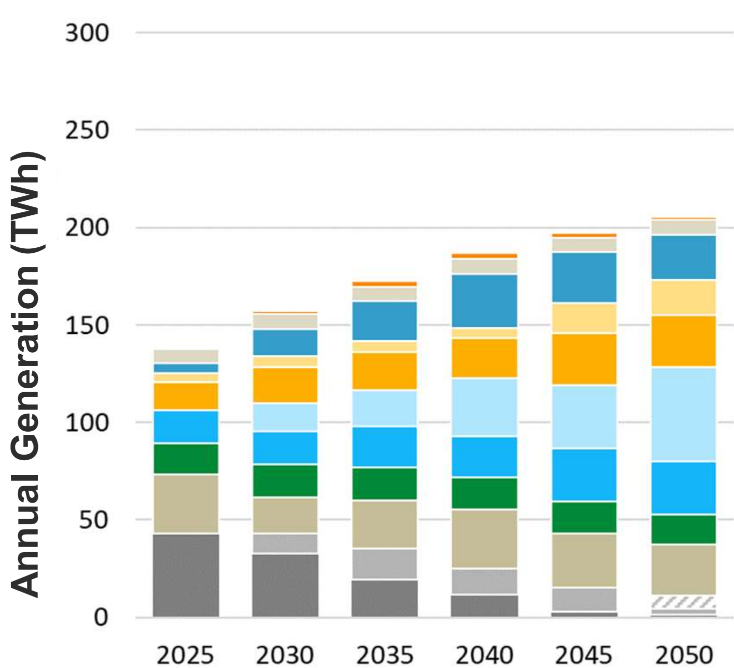


*CT/CCGT can burn natural gas and/or hydrogen.

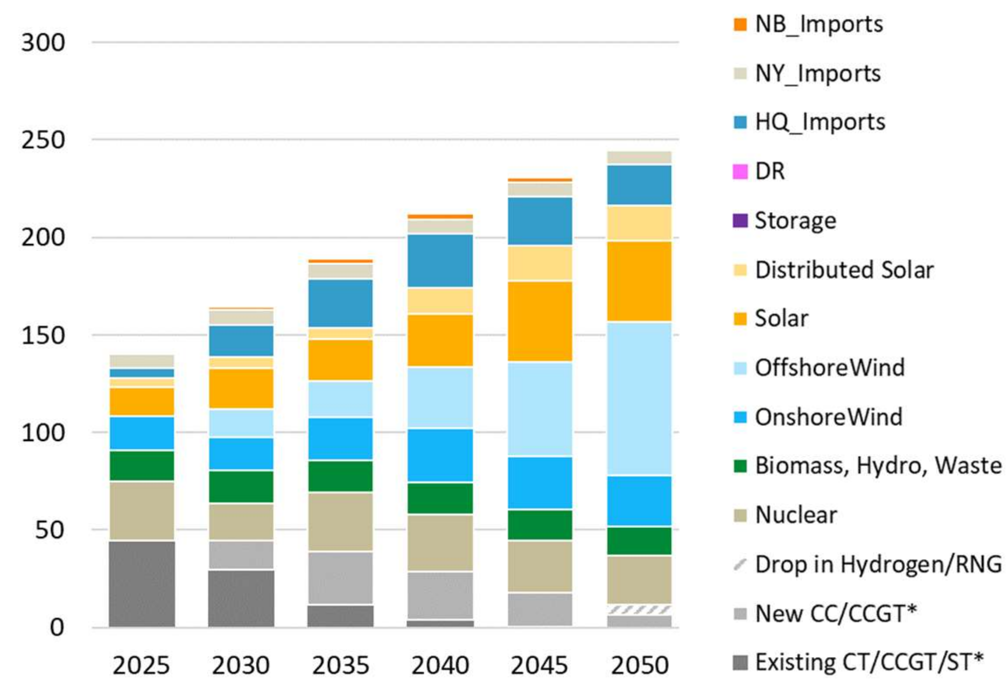
Results: Total Energy Generation

+ **Generation becomes dominated by renewables, with additional low/no carbon generation from nuclear, imports, hydrogen/zero-carbon fuel, and biomass, hydro and waste**

High Fuels



High Electrification

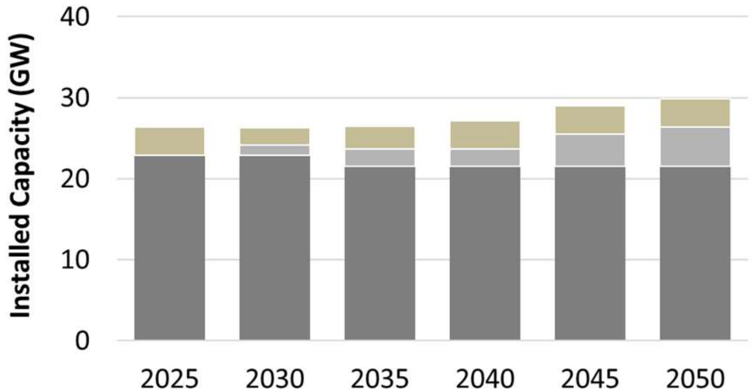


*CT/CCGT (new or existing) can burn natural gas and/or a zero-carbon fuel (assumed hydrogen in model)

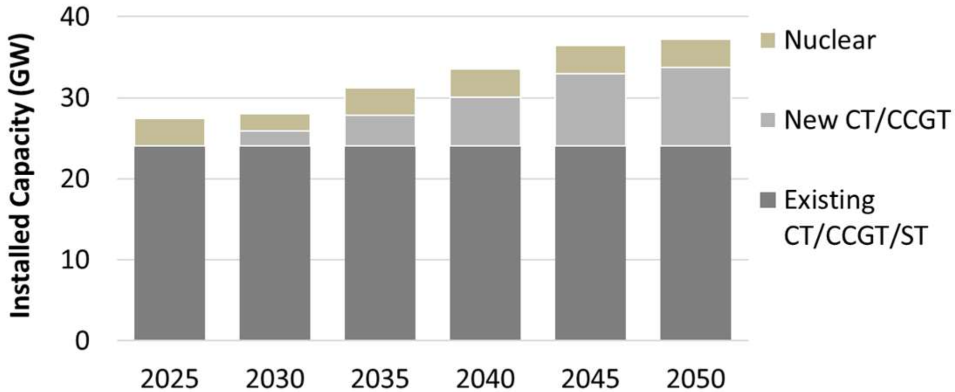
Role of Firm Generation

- The model retains significant gas and other fossil resources for reliability, but capacity factors decline substantially, with limited gas quantities burned by 2050
- In the future, firm generation can be provided by combustion-based generation, nuclear, or emerging long-duration storage technologies
  - Low-carbon firm generation may be achieved through reliance on zero-carbon fuels (hydrogen or biogas), nuclear, or by coupling generation with carbon-capture and storage

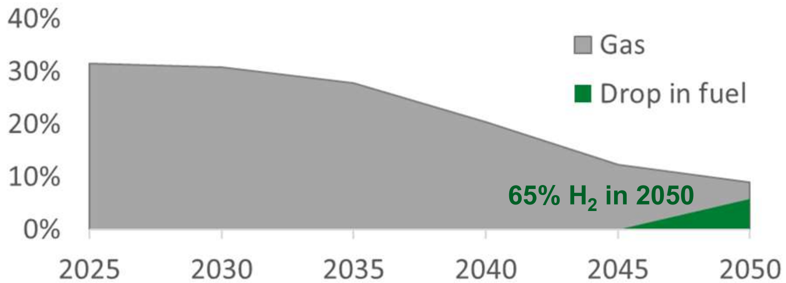
High Fuels Scenario – Firm Capacity (Existing and New Fossil and Nuclear)



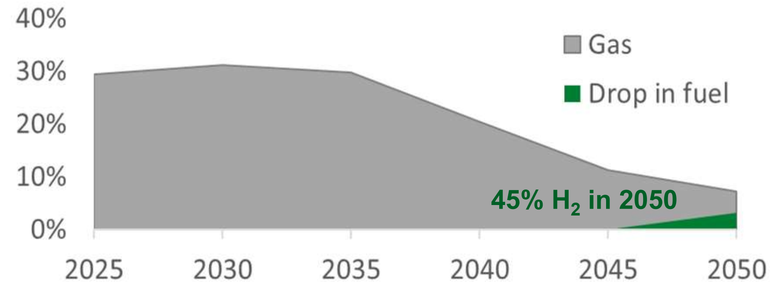
High Electrification Scenario – Firm Capacity (Existing and New Fossil and Nuclear)



High Fuels Scenario - Gas Capacity Factor (%)



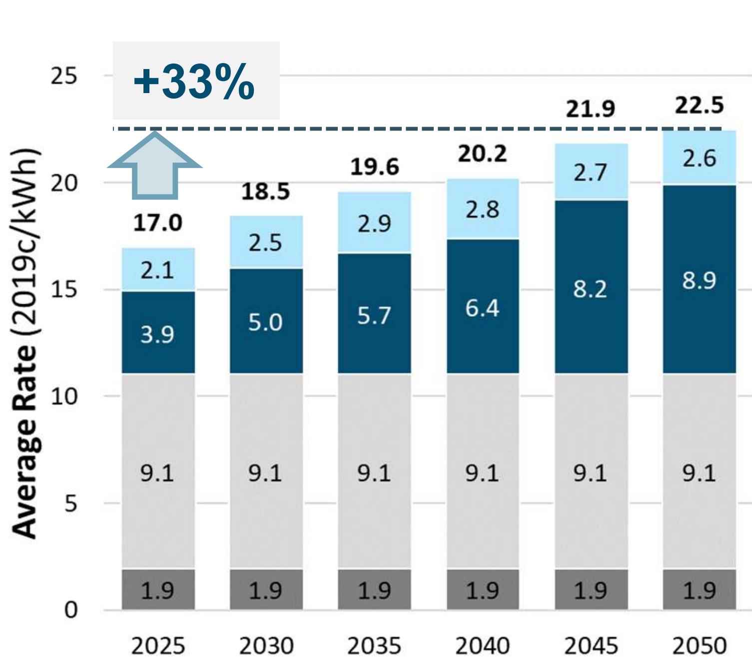
High Electrification Scenario - Gas Capacity Factor (%)



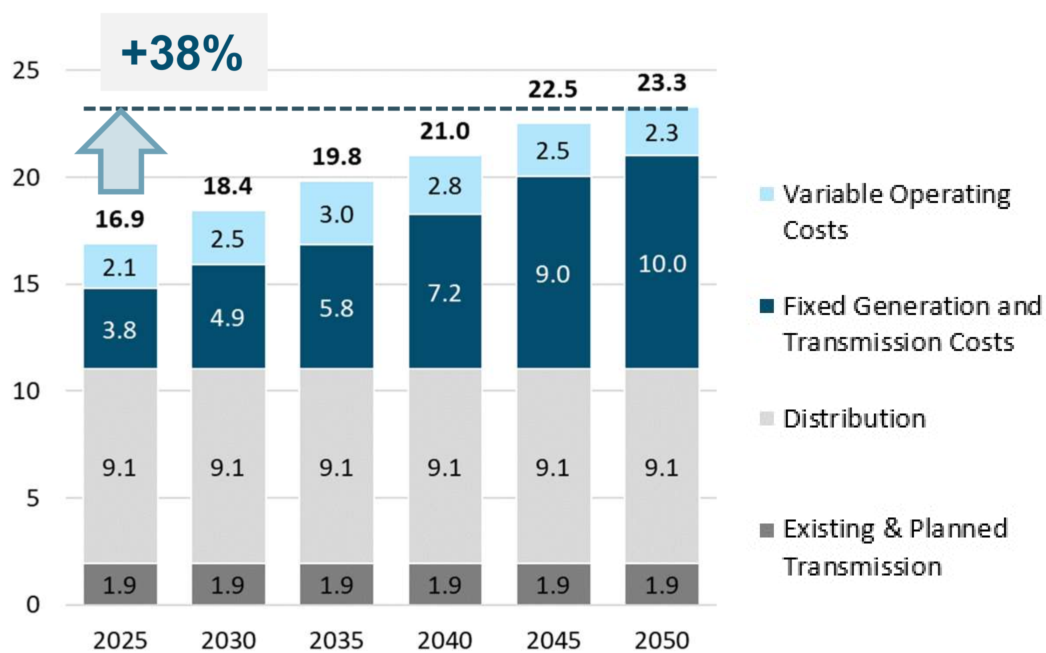
Results: System Cost/Rate

+ **Average electric rates increase with significant infrastructure build for new generation, which includes transmission upgrades and spur line costs, and slightly increasing variable costs resulting in a CAGR of 1.3% to 1.5% by 2050**
  - About 60% of the rate increase results from load growth and about 40% from the deep decarbonization resource mix (assuming reference 2050 resource mix of about 50% renewables)
+ **Retail rates will differ based on customer class**

High Fuels

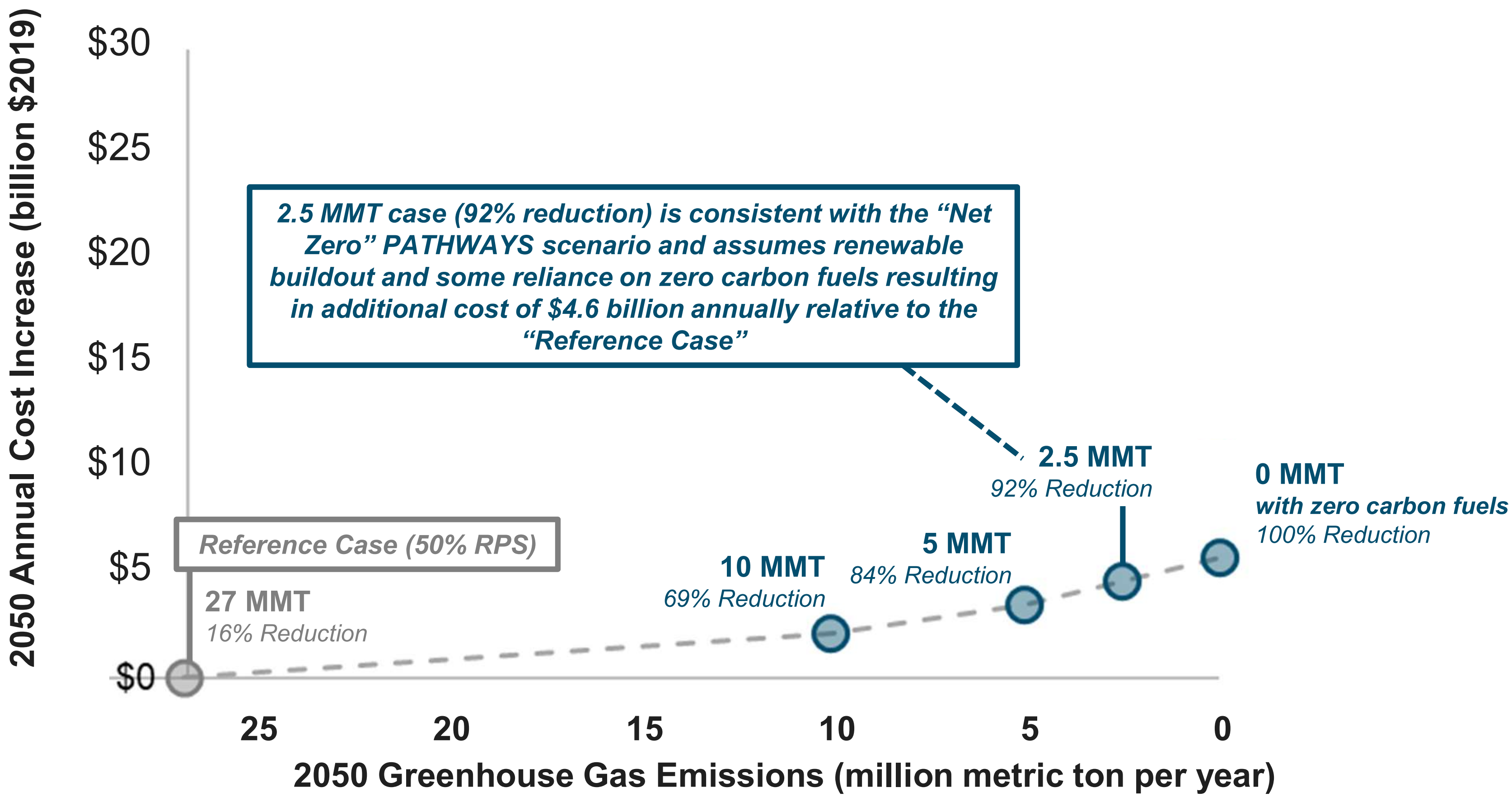


High Electrification



2050 Electricity Sector Abatement Costs under High Electrification Loads

High Electrification Scenario GHG Abatement Costs



Cost increases are reported relative to the hypothetical Reference Case (50% RPS).
Reductions relative to 2016 emissions of 32 MMT estimated based on EPA SIT database and import emissions for all New England States.

2050 Electricity Sector Abatement Costs under High Electrification Loads

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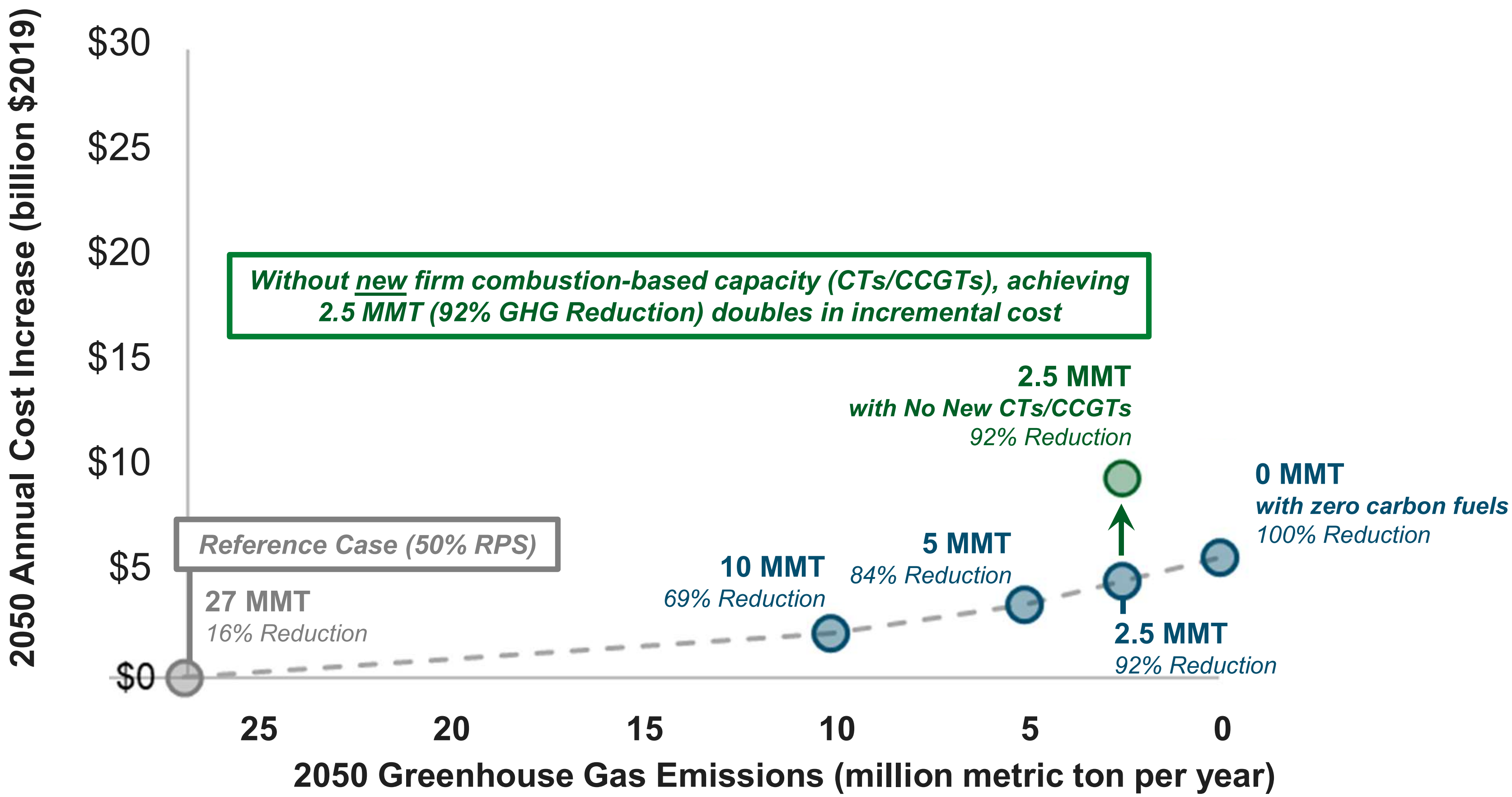

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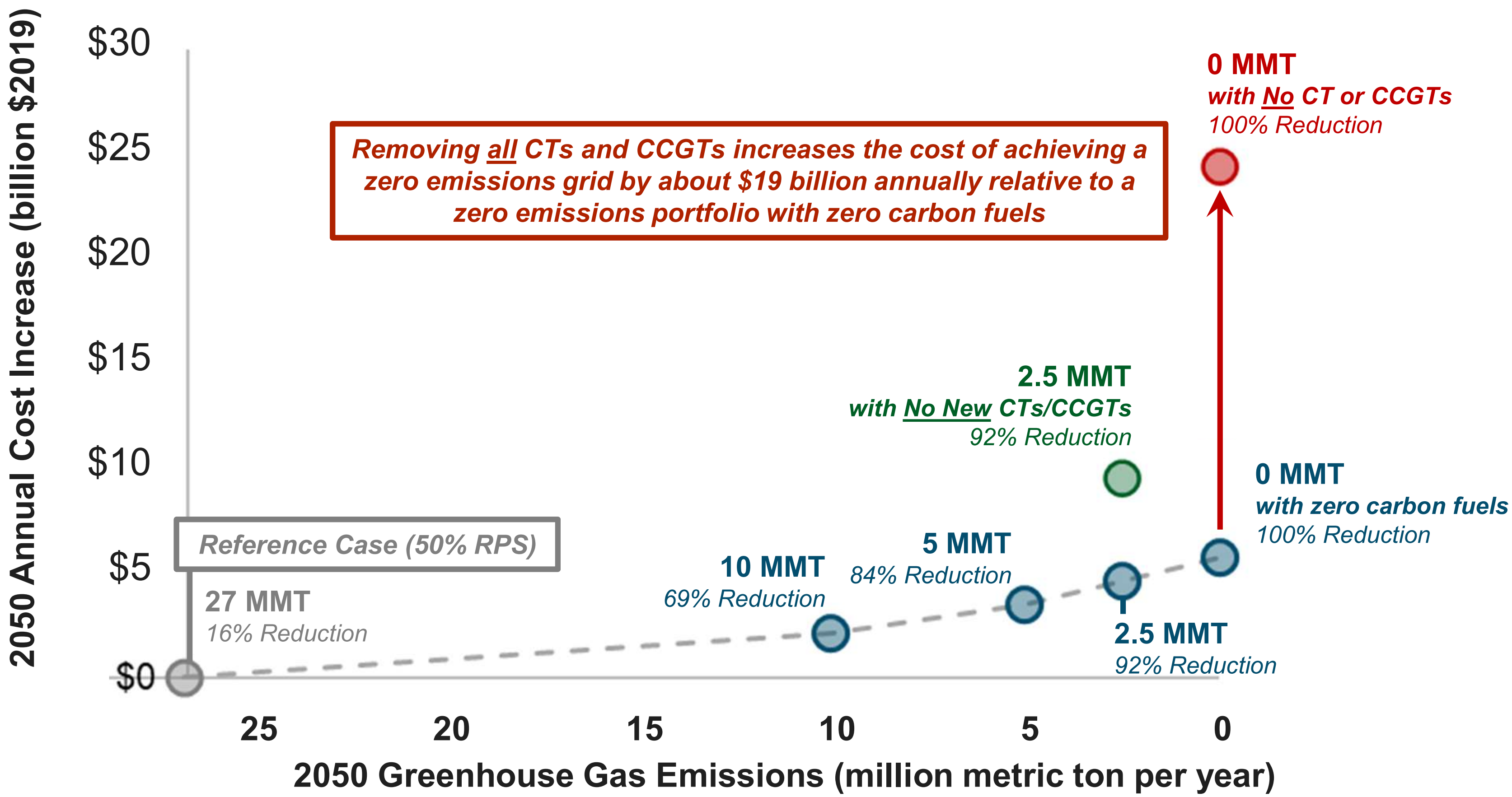

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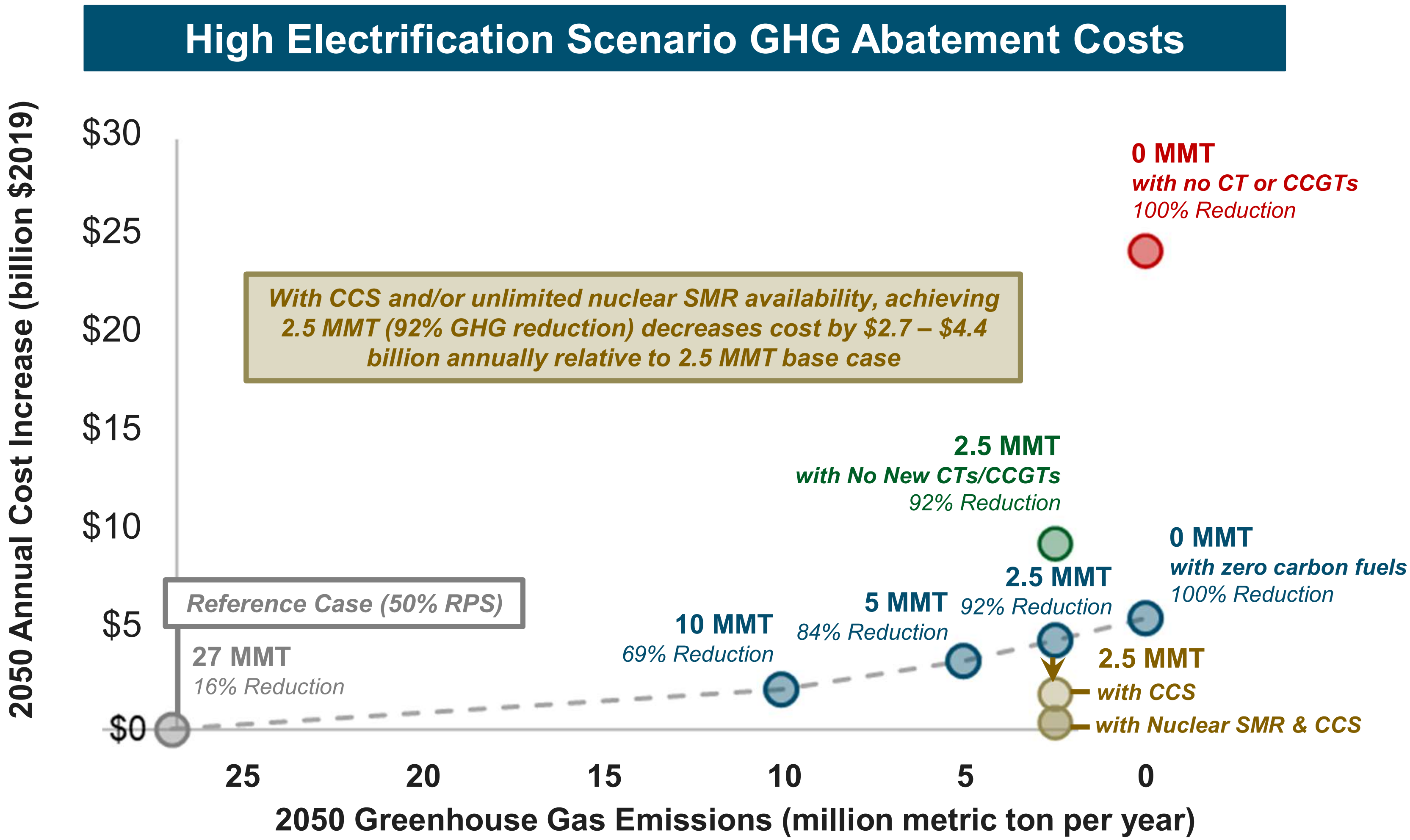
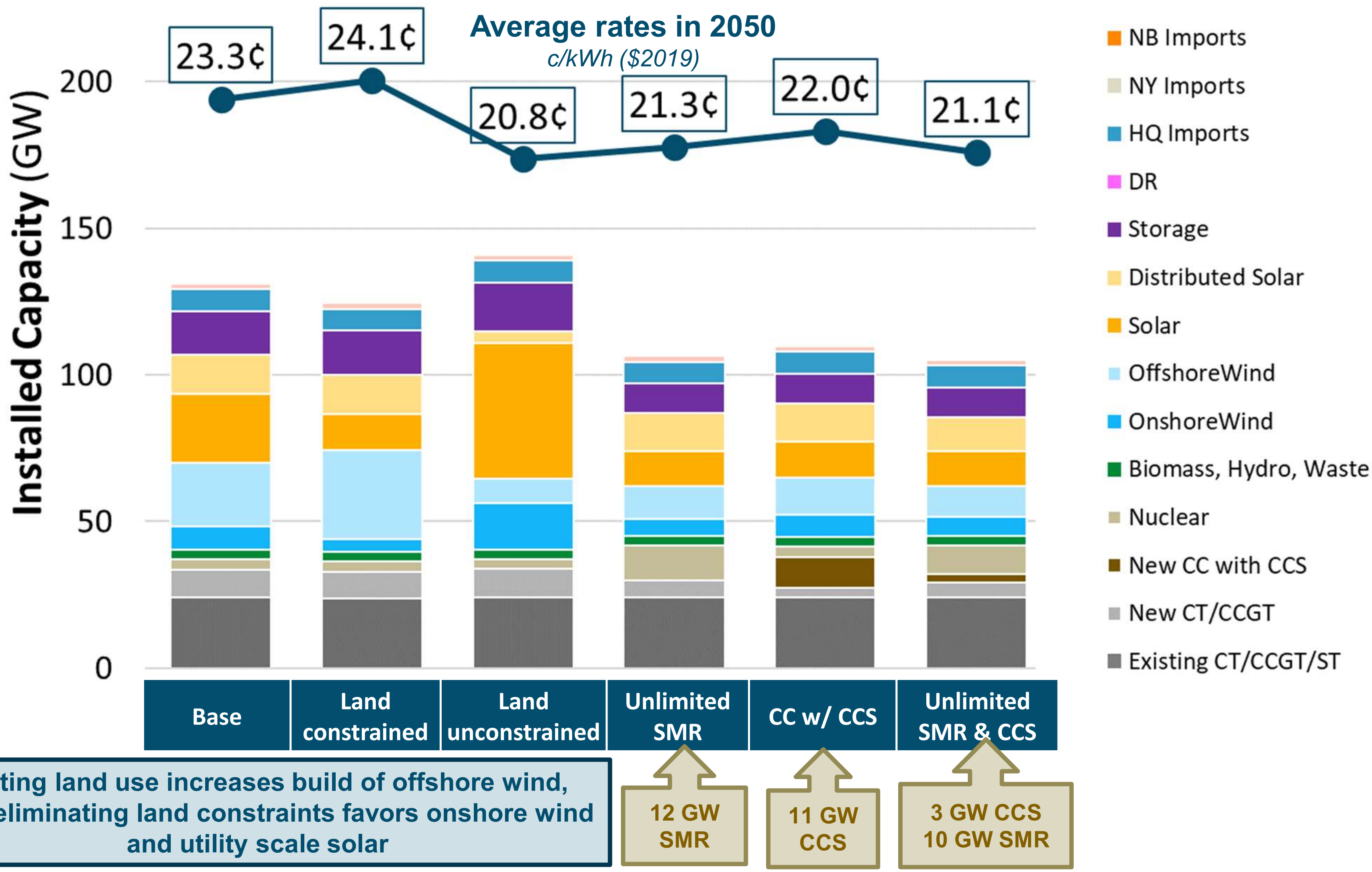
2050 Electricity Sector Abatement Costs under High Electrification Loads



Cost increases are reported relative to the hypothetical Reference Case (50% RPS).
Reductions relative to 2016 emissions of 32 MMT estimated based on EPA SIT database and import emissions for all New England States.

2050 Sensitivity Comparison of Installed Capacity and Rates (High Electrification)

All cases achieve 2.5 MMT/y 2050 GHG electricity sector emissions, consistent with economy-wide "Net Zero"



Limiting land use increases build of offshore wind, while eliminating land constraints favors onshore wind and utility scale solar

High Electrification - 2050 Sensitivity Comparison: Effective Capacity

All cases achieve 2.5 MMT/y 2050 GHG electricity sector emissions, consistent with economy-wide "Net Zero"

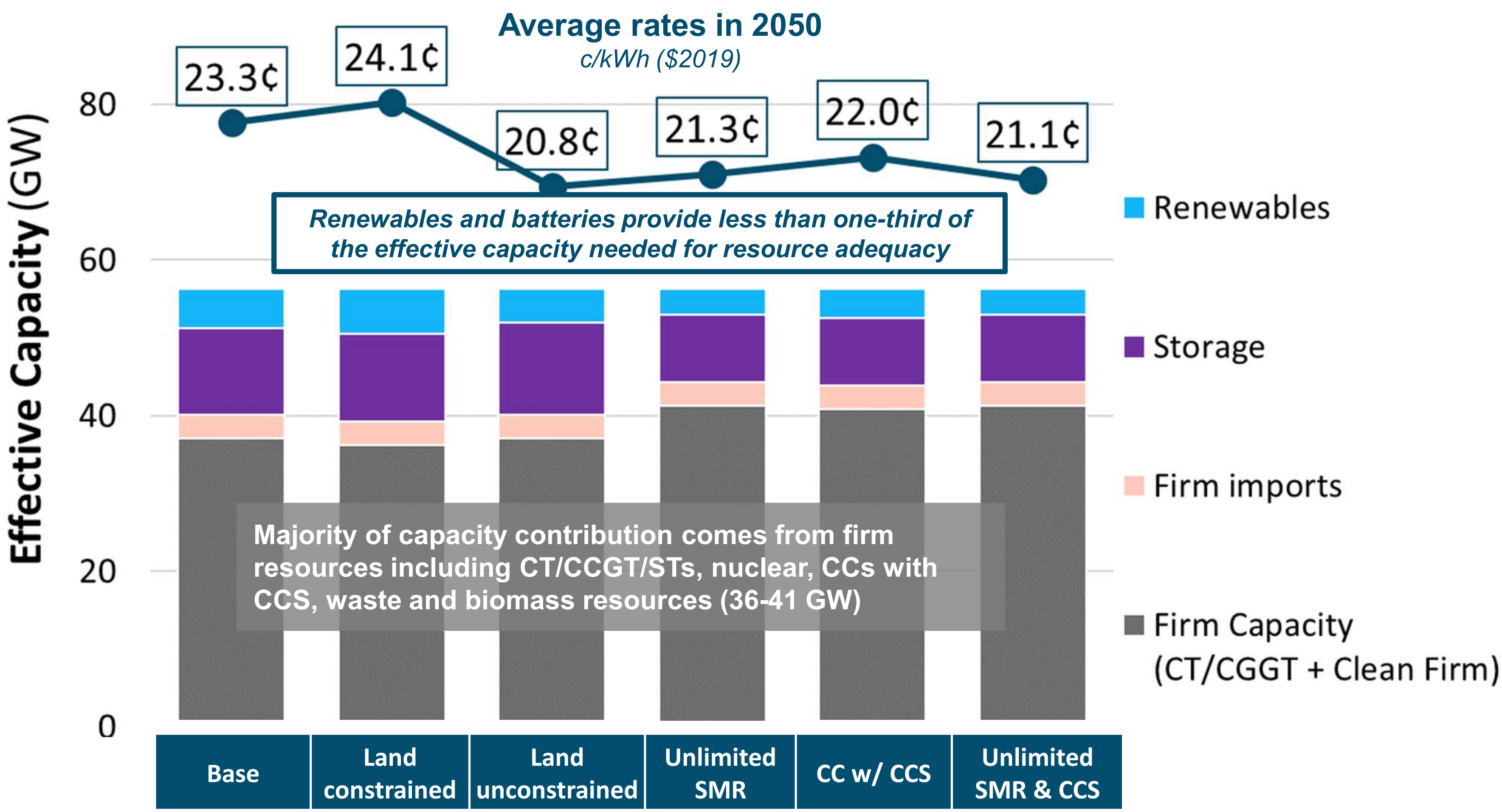


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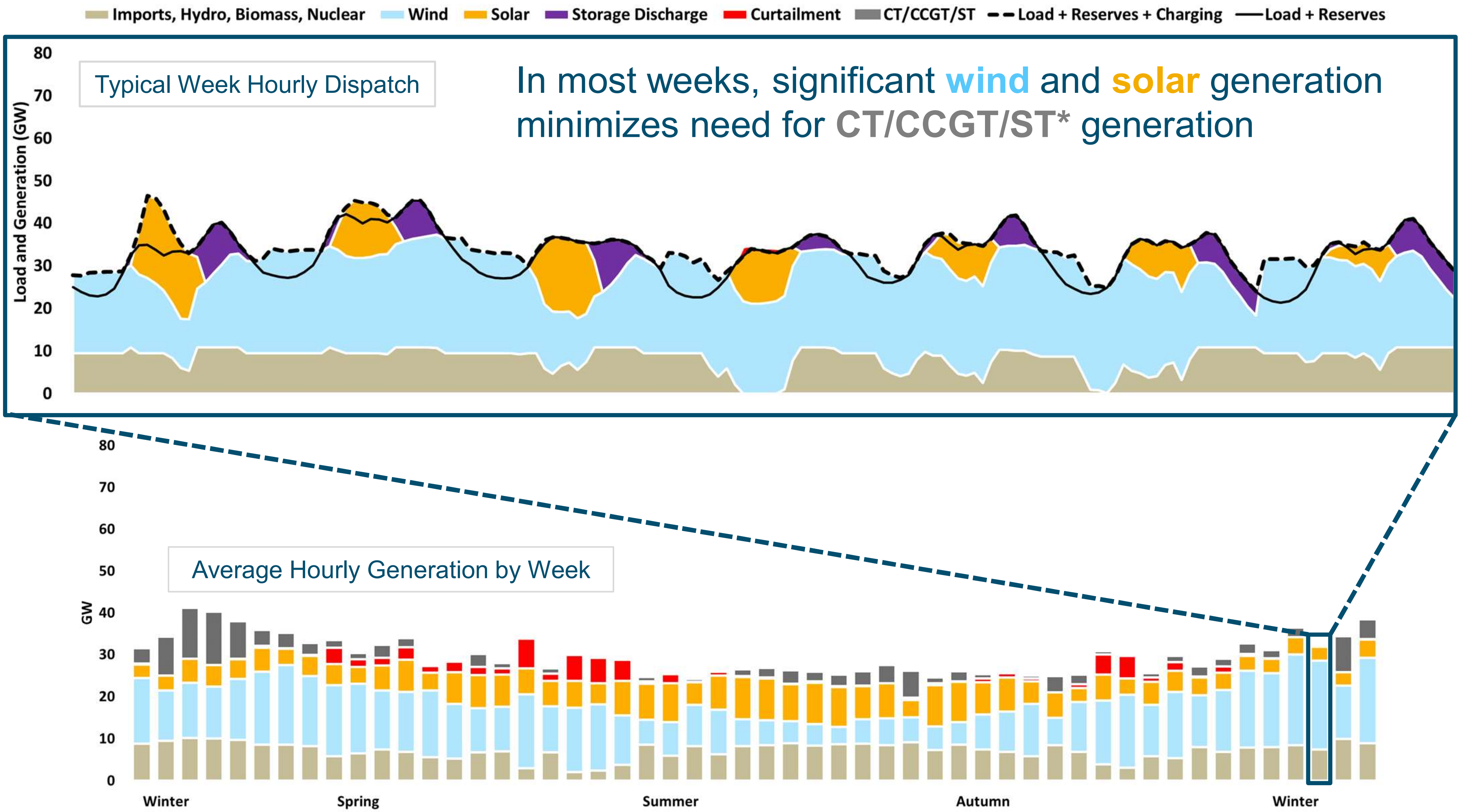
Illustration of 2050 Electricity Sector Reliability Challenge

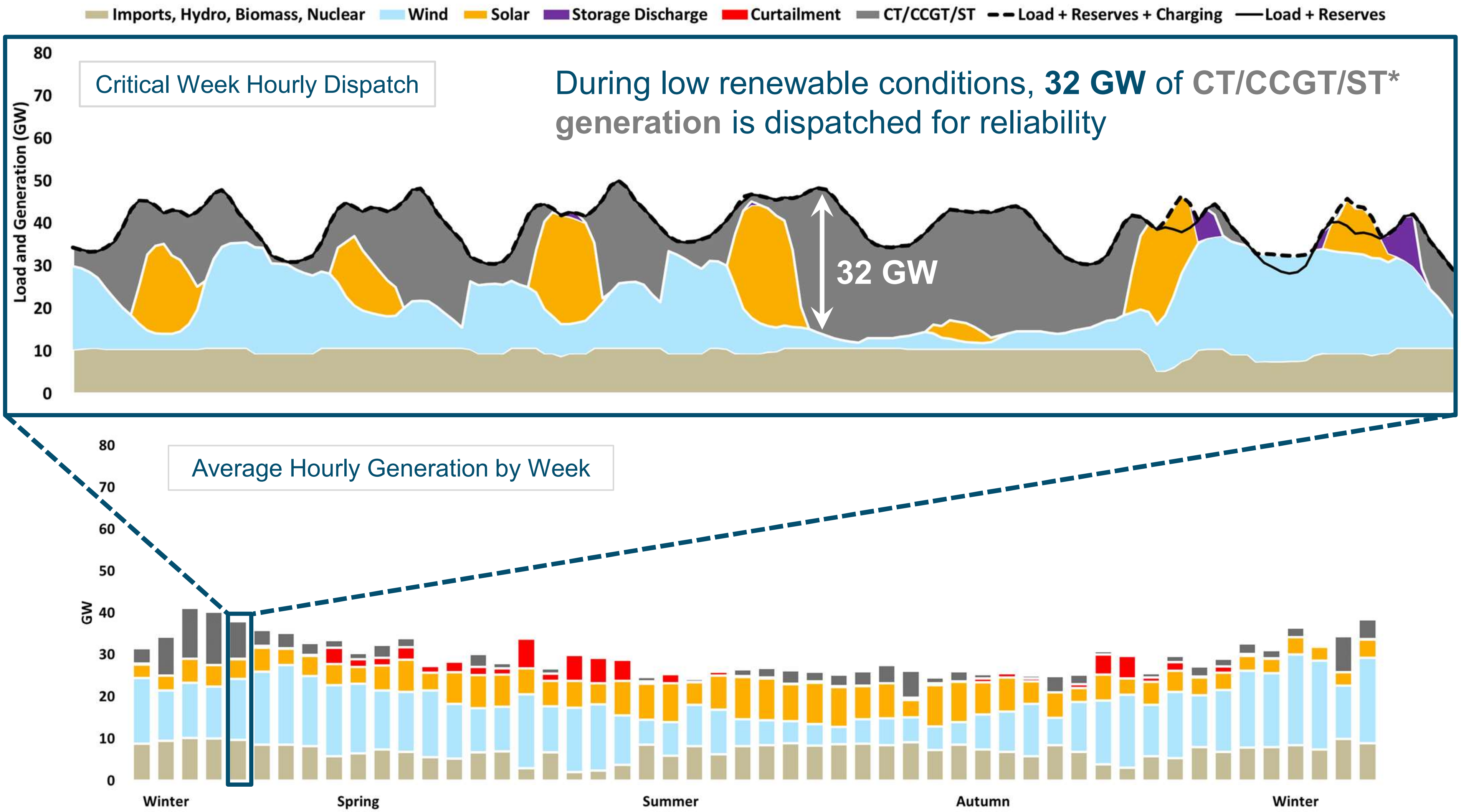
Typical Week Dispatch in High Electrification Base Case



High Electrification Base Case

** Could represent natural gas, hydrogen, or other zero-carbon fuel blend burned in CT/CCGT, or dispatchable long-duration storage if viable technology emerges. More generally, this could represent any firm capacity, e.g. nuclear SMRs and Gas with CCS could also play this role.*

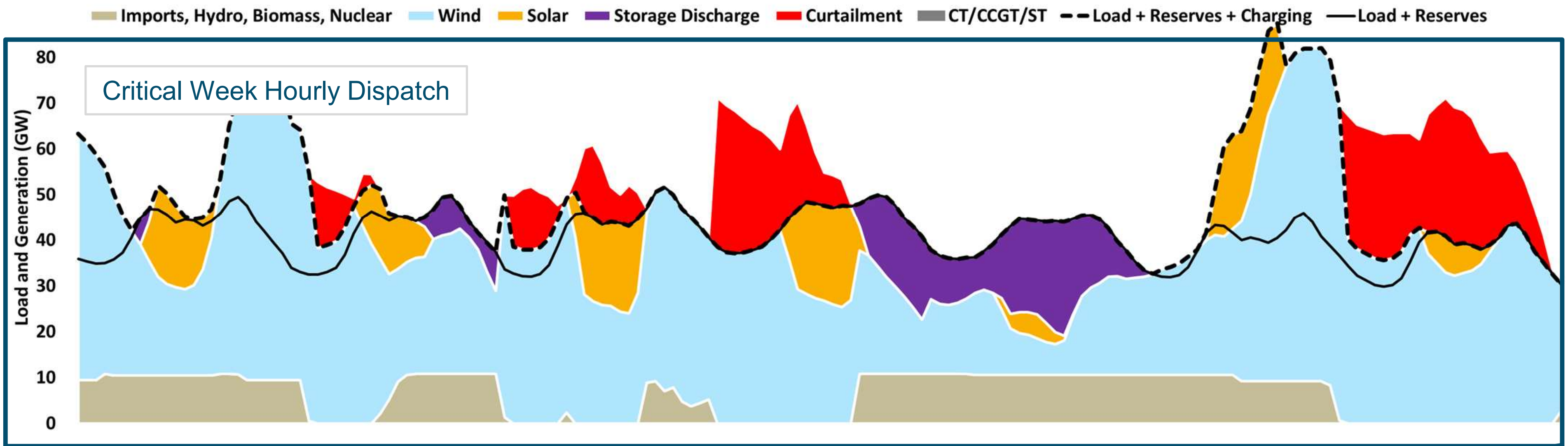
Critical Week Dispatch in High Electrification Base Case

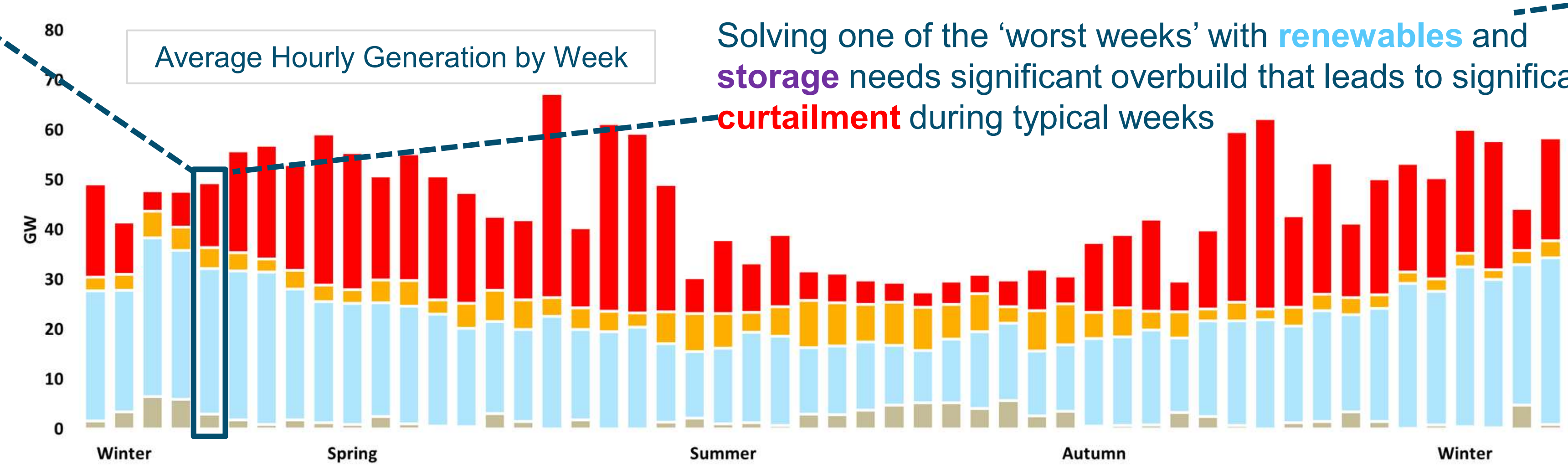


High Electrification Base Case

** Could represent natural gas, hydrogen, or other zero-carbon fuel blend burned in CT/CCGT, or dispatchable long-duration storage if viable technology emerges. More generally, this could represent any firm capacity, e.g. nuclear SMRs and Gas with CCS could also play this role.*

Critical Week Dispatch With No Gas/ Hydrogen (High Electrification Scenario)





Solving one of the 'worst weeks' with **renewables** and **storage** needs significant overbuild that leads to significant **curtailment** during typical weeks

No CTs, CCGTs or STs Available

Key Findings

Key Findings

1. **Electricity demand will increase significantly in New England over the next three decades under all plausible low-carbon scenarios**
   - Electricity demand grows by 66 - 97 percent
2. **A significant quantity of renewable generation is selected in every case, particularly solar and offshore wind**
   - Land and transmission availability will likely be constraining factors
3. **The New England system requires 30-37 GW of thermal capacity through 2050 in all cases**
   - Thermal resources operated at increasingly low capacity factors over time
   - It is expected that some form of low-carbon fuel will be available to reduce the carbon intensity of this use
4. **Cases with broader sets of available solutions have lower costs and lower technology risks**
   - Firm, low-carbon technologies such as advanced nuclear, CCS or hydrogen could play a significant role
   - Increasing the availability of land-based wind and solar also reduces cost

Thank You

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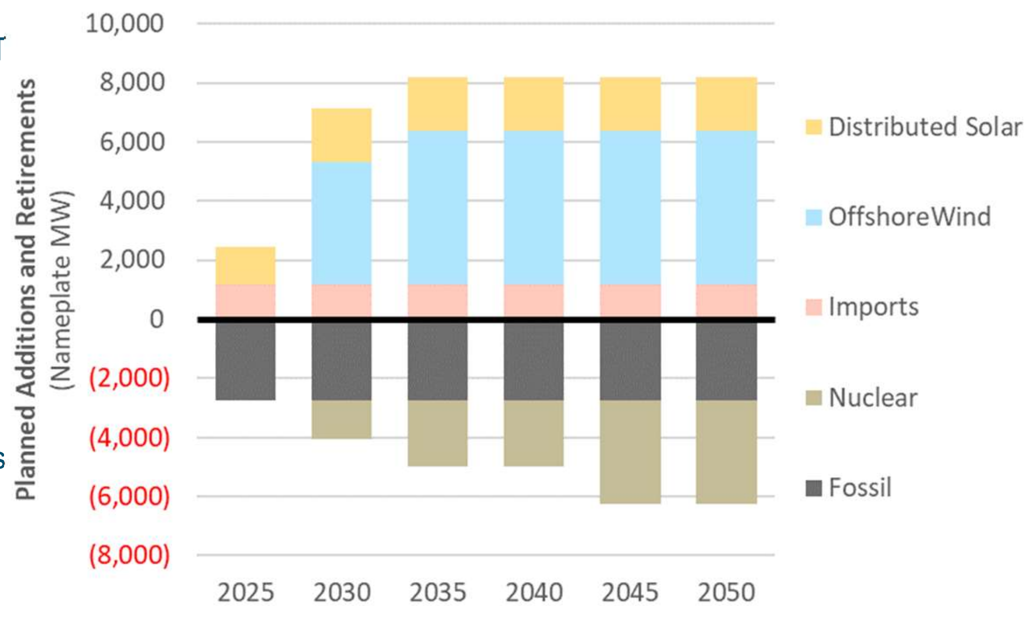
Appendix

Planned Additions and Retirements

- **Modeling incorporates planned builds and retirements in New England**
- **Planned additions**
  - Distributed solar per ISO NE PV forecast from CELT report
  - Offshore wind:
    - MA target: 3.2 GW by 2035
    - CT target: 2 GW by 2030
  - Imports: 1,200 MW of NECEC line (1,090 firm)
- **Planned retirements**
  - Announced fossil plants per ISONE announcements (post-2020)
    - Mystic (1,744 MW)
    - Mystic Dual Unit (617 MW)
    - Bridgeport (700 MW)
  - Nukes are assumed to retire at end of current contract, but builds could reflect license extension*
    - 2030: Seabrook (1,250 MW)
    - 2035: Millstone Unit 2 (870 MW)
    - 2045: Millstone Unit 3 (1,230 MW)

Planned Additions and Retirements (MW)



* Model allows new nuclear builds -- which could reflect license extensions, repowering, or actual new builds -- but limits total nuclear capacity in all model years to about 3.5 GW.