The Customer Action Pathway to National Decarbonization

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Introduction

Customer-driven adoption of GHG-reducing technologies will play a key role in achieving decarbonization targets

- Ambitious decarbonization targets are being set by states, counties, and cities
- Utilities and states are responding to these decarbonization targets by laying out pathways for achieving them
- We expect these targets to become more aggressive in the next few years at both the state and federal levels

The purpose of this study is to quantify the decarbonization impact of customers adopting new technologies and energy consumption behaviors in the next 10-20 years

- This study focuses specifically on the GHG reductions from the residential sector and light-duty vehicles (LDV)
- Brattle’s in-house models are used to estimate the load impact of customer adoption of new technologies and behaviors, and the corresponding GHG emissions impacts at the regional and national level

We quantify the total aggregate impact of ambitious but achievable adoption of new GHG-reducing technologies, rather than impacts that are incremental to what is already expected to be achieved under a *status quo* case

Customer Action Pathway to Decarbonization

Since 2005, annual U.S. energy-related greenhouse gas (GHG) emissions have declined by 878 MMT (or 13%)*

- 85% of the reductions are from reduced electric power sector generation emissions (e.g., reduced coal generation)

While the bulk of the decarbonization work to date focuses on understanding the impact of building a "greener grid", it is important to consider what can be achieved through customer-directed actions

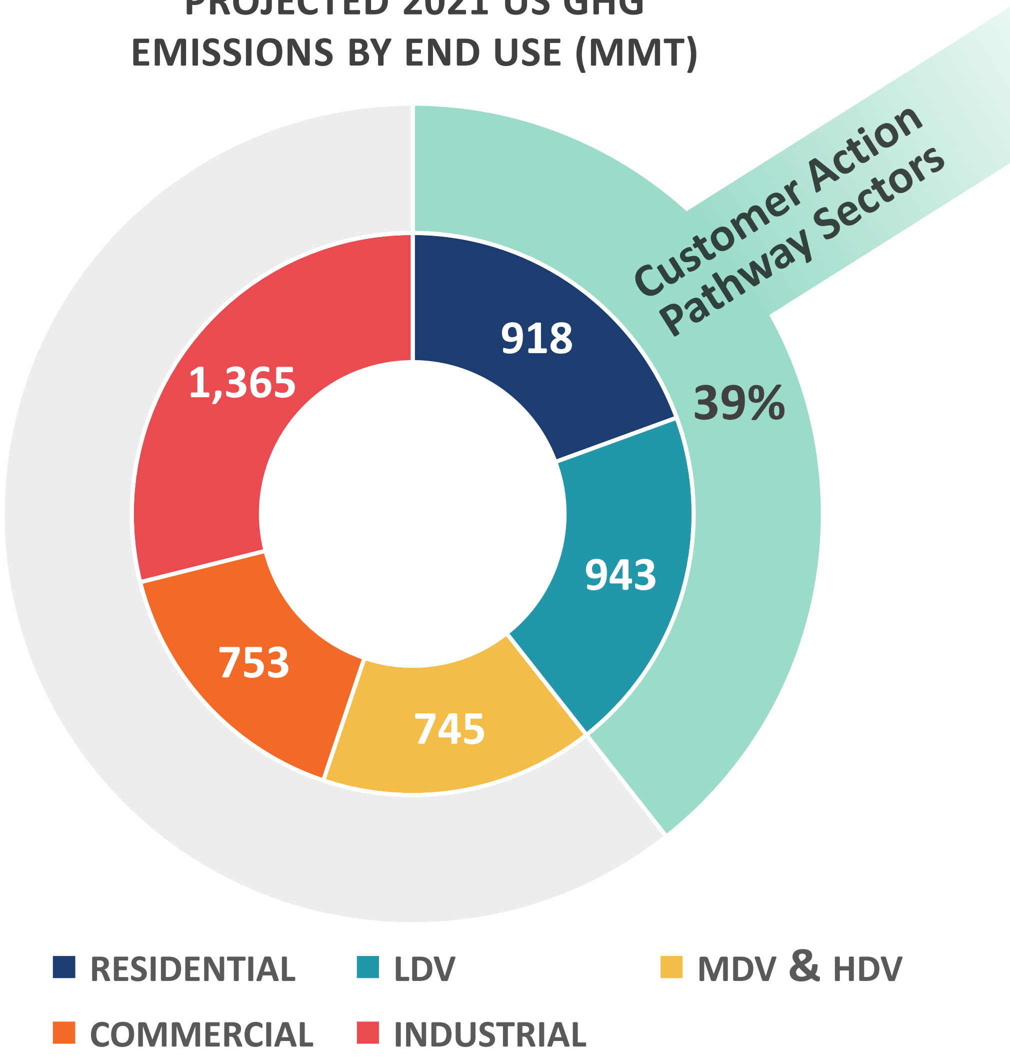
This report focuses on two sectors, **Residential** and **Light-Duty Vehicles**, in which customer actions have a direct impact on GHG emissions

- Residential and LDV sectors account for 1,861 MMT in 2021, or about 40% of total U.S. energy-related GHG emissions
- Customer adoption of GHG-reducing technologies combined with additional clean power generation will be necessary to reduce emissions

We refer to the customer-directed actions analyzed in this study as the "**Customer Action Pathway**" to decarbonization

*Source: EPA's GHG Inventory.

PROJECTED 2021 US GHG EMISSIONS BY END USE (MMT)



Source: EIA AEO 2021.

Customer Action Pathway GHG Reducing Technologies

- The primary sources of customer-specific energy demand and GHG emissions are from LDV transportation and residential electricity demand, followed by residential space and water heating
- GHG reducing technologies exist across all sources of energy demand and GHG emissions for customers to play an active role in achieving future GHG emissions reductions

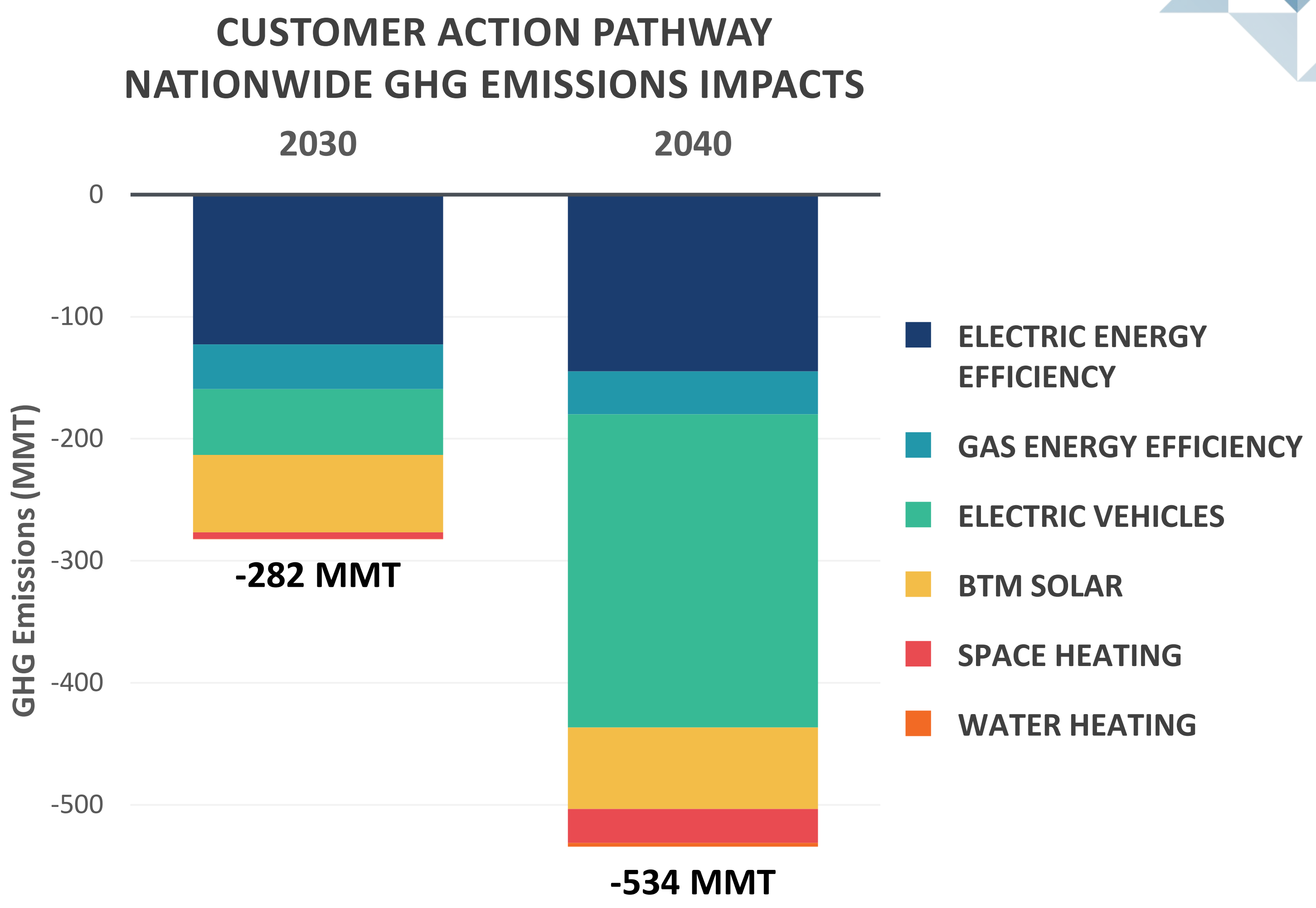
Emissions Source	2021 Energy Consumption	2021 GHG Emissions	GHG-Reducing Technologies (Modeled in this Study)	Non-Power Sector GHG Emissions	Power Sector GHG Emissions
Residential Electricity Demand*	21 Quads	598 MMT	BTM Solar	—	↓
			Electric Energy Efficiency (EE)	—	↓
LDV Transportation	14 Quads	943 MMT	BEVs and PHEVs	↓	↑
Residential Space Heating & Water Heating	10 Quads	446 MMT	Space Heating: Air-Source & Ground-Source Heat Pumps	↓	↑
			Water Heating: Air-Source Heat Pumps & Electric Resistance	↓	↑
			Gas Energy Efficiency	↓	—

*Includes total electricity consumption for all residential end uses.
Note: BTM Solar and EE reduce emissions from *all* residential demand. BEV stands for Battery Electric Vehicles and PHEV stands for Plug-In Hybrid Electric Vehicles.

Customer Action Pathway GHG Emissions Reductions

The Customer Action Pathway could reduce GHG emissions by 534 MMT in 2040

- Residential electric & gas energy efficiency have the greatest near-term impact reducing 2030 emissions by 158 MMT and 2040 emissions by 180 MMT
- Rising EV adoption increases avoided GHG emissions from 53 MMT in 2030 to 256 MMT in 2040
- Behind the meter (BTM) solar installed on residential homes reduces 2040 emissions by 67 MMT
- Residential space and water heating electrification reduces 2040 emissions by 31 MMT

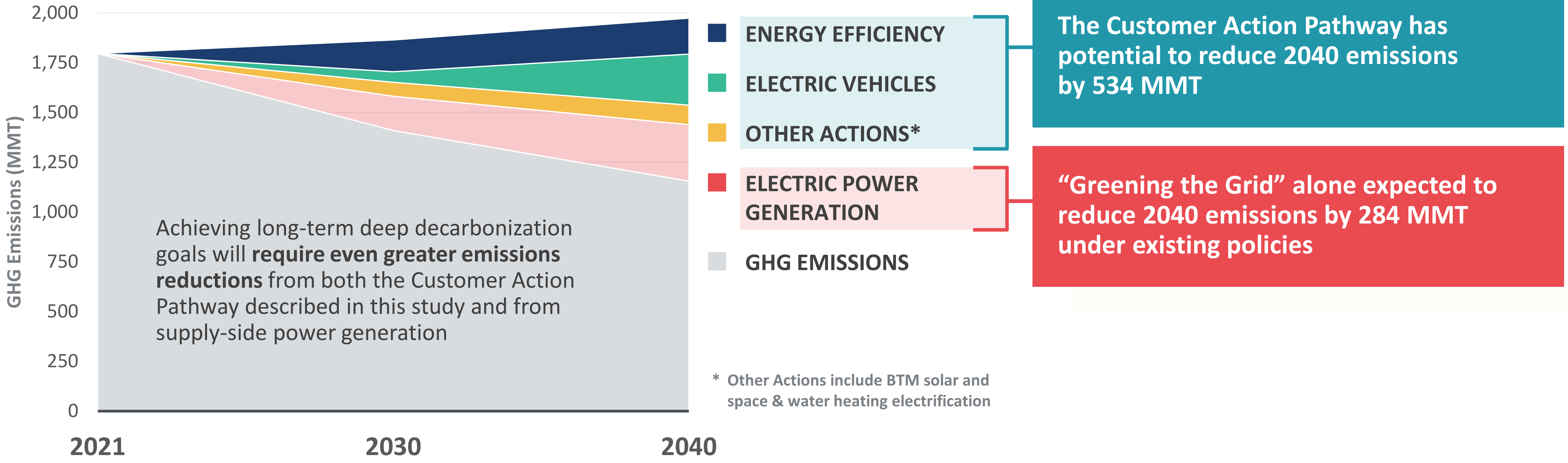


Note: GHG emissions reductions represent emissions reductions in 2030 and 2040 compared to baseline emissions without customer action to adopt low GHG technologies, but assuming declining power generation emissions.

Customer Action Pathway Builds on Supply-Side Reductions

The Customer Action Pathway has the potential to **reduce GHG emissions by nearly twice as much as supply-side reductions alone** will contribute under existing policies

RESIDENTIAL AND LDV GHG EMISSIONS PROJECTIONS



* Other Actions include BTM solar and space & water heating electrification

Notes: Total emissions prior to Customer Action Pathway and electric power generation reductions assume 2021 residential emissions levels increase through 2040 with projected electricity, gas, and transportation demand from AEO 2021. Reduction in electric power generation emissions based on average power generation emissions rates (0.41 tons/MWh in 2021, 0.29 tons/MWh in 2030, and 0.23 tons/MWh in 2040) generated by Brattle's in-house capacity expansion model GridSIM (see slide 10). Future policies could accelerate both demand-side and supply-side emissions reductions.

Summary of Findings

Our results highlight the importance of customer-driven actions in achieving ambitious decarbonization goals

- Avoiding 534 MMTCO2 in 2040 is the same as retiring 135 coal plants (Source: EPA)
- Customer Action Pathway GHG emission reduction potential is about 2x greater than projected reductions from supply side decarbonization efforts alone by 2040 under current policies
- GHG reductions achieved through the Customer Action Pathway in 2040 is equivalent to nearly 60% of the annual GHG reductions achieved from all sectors from 2005 to 2021

Near-term emissions reduction potential driven by energy efficiency and BTM solar through 2030, while customer adoption of electric vehicles could provide the largest emissions reductions by 2040

- EE and BTM solar have greatest 2030 impact due to current customer familiarity and higher near-term power generation emission rates. While adoption of both technologies continues beyond 2030 at a slower rate, the emissions impact is less significant by 2040 due to the lower power generation emission rates
- EV adoption emissions impact increase significantly from 2030 to 2040 due to the 4x potential increase in the total EVs on the road and the lower power generation emission rates

Additionally, load flexibility (e.g., smart thermostat programs, time-varying rates) will be a critical part of the Customer Action Pathway

- Load Flexibility facilitates the integration of renewable energy resources, reduces renewable energy curtailment, and mitigates the need for system upgrades to serve rising peak demand

Methodology

High-Level Analytical Approach

Estimated GHG emissions reductions in 2030 and 2040 using the following approach:

- Identified "ambitious but achievable" nationwide residential customer adoption by 2030 and 2040 of each GHG reducing technology based on public studies and Brattle's prior work
- Applied customer adoption rates to each region's projected fuel demand in 2030 and 2040 based on AEO 2021 projections
- Developed hourly demand/generation forecasts to analyze power generation emissions impacts
- Estimated energy efficiency and BTM solar GHG emissions impacts:
  - Calculated avoided power generation GHG emissions based on hourly marginal emissions rates
- Estimated transportation, space heating and water heating electrification GHG emissions impacts:
  - Calculated avoided GHG emissions from direct fuel usage (e.g., reduced gasoline emissions)
  - Calculated incremental power generation GHG emissions based on hourly marginal emissions rates by region
  - Calculated net impact on GHG emissions

Ambitious but Achievable Customer Technology Forecasts

GHG REDUCTION TECHNOLOGY	APPROACH	2030 ADOPTION	2040 ADOPTION	REFERENCED PUBLIC FORECASTS*
Residential Electric Energy Efficiency	Create an U.S.-wide forecast based on public reports and Brattle studies	250 TWh annual savings; 1.5% savings/year from 2020 through 2030	320 TWh annual savings; 0.5% savings/year from 2030 through 2040	DOE meta-analysis, EPRI, NREL, Brattle reports
Residential Gas Energy Efficiency	Assume national % annual reductions are consistent with electric EE forecasts. Savings applied after heating electrification related gas demand reductions.	1.5% annual savings from 2020 through 2030	0.5% savings from 2030 through 2040	NREL, Center for Energy and Environment, Synapse, Brattle analysis comparing regional electric and gas EE potential
Residential BTM Solar	Create a region-specific forecast based on public reports	115 GW nationally; 16% of residential homes w/ BTM solar arrays	135 GW nationally; 20% of residential homes w/ BTM solar arrays	NYISO, ISO-NE, California Energy Commission, AEO, Vibrant Clean Energy

*See slide 28 for sources

Ambitious but Achievable Customer Technology Forecasts

GHG REDUCTION TECHNOLOGY	APPROACH	2030 ADOPTION	2040 ADOPTION	REFERENCED PUBLIC FORECASTS*
Battery Electric Vehicles (BEV) and Plug-In Hybrid Vehicles (PHEV)	Develop EV adoption forecast using Brattle model that projects future BEV and PHEV stock, % annual sales, vehicle turnover, and % electric vehicle miles traveled	40% of new vehicle sales; 16% of total vehicles	89% of new vehicle sales; 58% of total vehicles	Brattle modeling, benchmarked to public forecasts
Residential Space Heating Air-Source Heat Pumps and Ground-Source Heat Pumps	Apply the national adoption forecast from NREL EFS high scenario to regional space heating fuel demand forecasts	24% of demand electrified *(Note: 17% of space heating electrified as of 2020)*	45% of demand electrified	NREL's EFS High scenario (2018)
Residential Water Heating Air-Source Heat Pumps and Electric Resistance Heaters	Apply the national adoption forecast from NREL EFS high scenario to regional water heating fuel demand forecasts	37% of demand electrified *(Note: 34% of water heating electrified as of 2020)*	51% of demand electrified	NREL's EFS High scenario (2018)

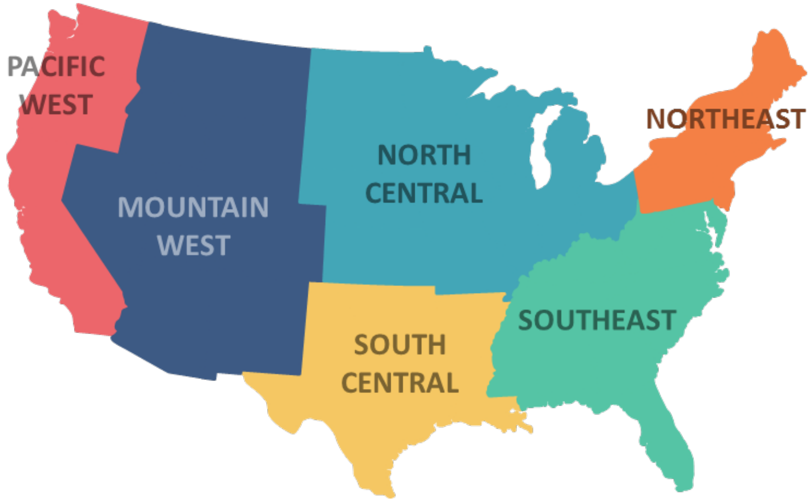
*See slide 28 for sources

Estimating GHG Emissions Impact of Electricity Demand

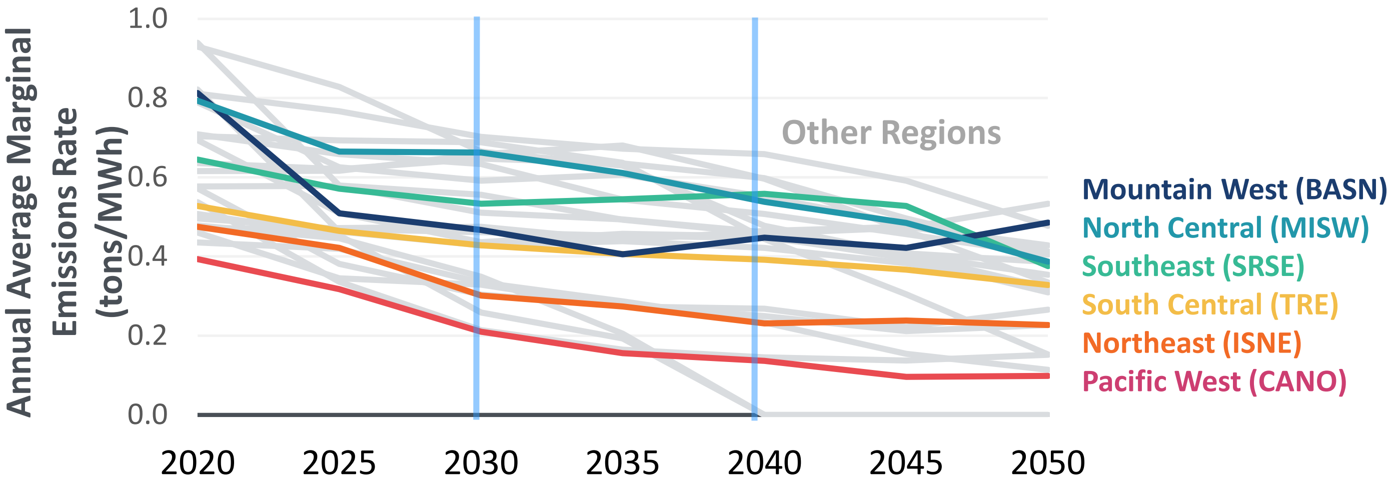
Estimate GHG emission impacts of electric load changes from customer-side technologies using projected electric power sector marginal emissions rates

- Projected hourly marginal emissions based on results of Brattle's GridSIM capacity expansion modeling for 25 U.S. EMM regions
- GridSIM modeling estimates renewable energy growth based on projected costs from NREL 2020 ATB (using Aggressive case) and existing state policies, national targets, and future economic conditions that lead to lower marginal emissions rates by 2040
- Our emissions baseline accounts for expected "greening of the grid" during the study timeframe (i.e., declining emissions levels)

AGGREGATED CENSUS REGIONS



ANNUAL-AVERAGE MARGINAL EMISSIONS RATE BY REGION



Source: Regional marginal emissions rates based on modeling completed for A National Roadmap for Grid-Interactive Efficient Buildings.

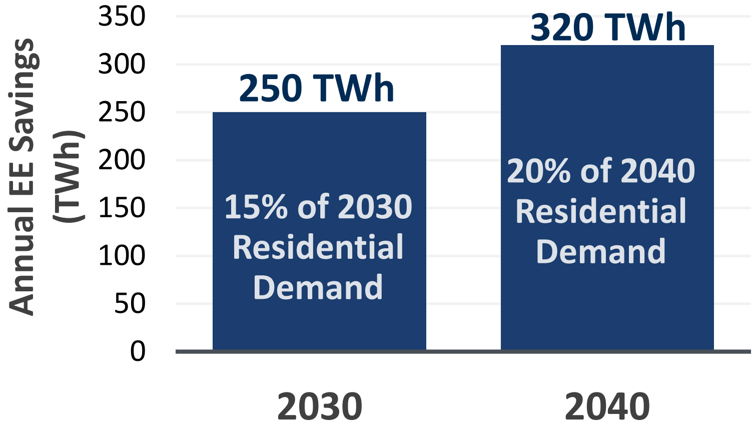
Electric Energy Efficiency Projected Adoption

Based on several national electric EE potential studies, we estimate that additional cost-effective EE measures could reduce U.S.-wide demand by about 250 TWh in 2030 (1.5%/year from 2021 to 2030) and 320 TWh in 2040 (an additional 0.5%/year from 2030 to 2040) relative to 2020

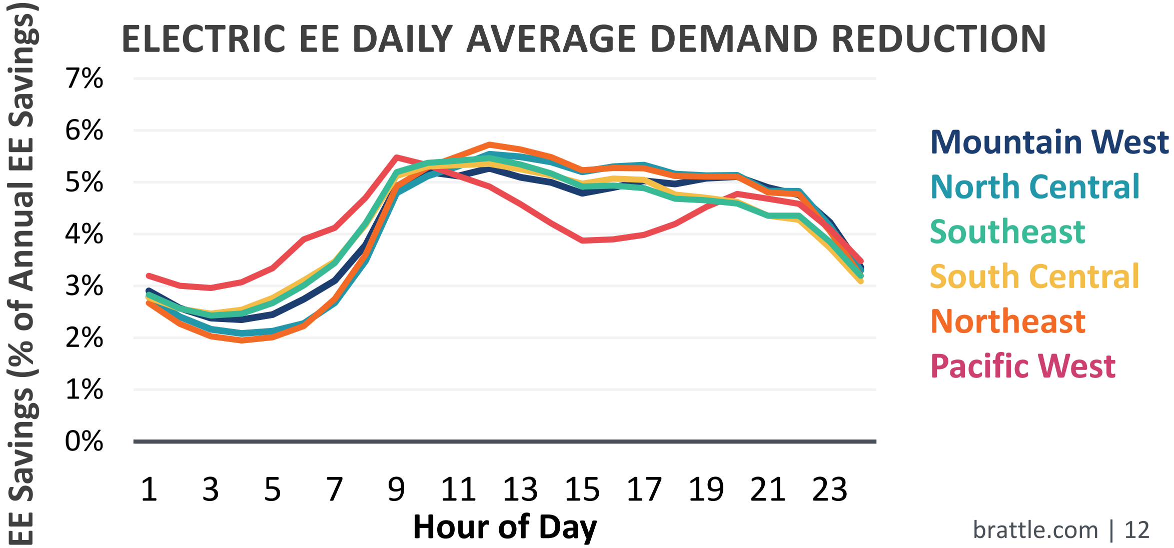
- EE measures include behavior change, installation of more efficient lighting, space heating & cooling, appliances (e.g., dryer, washing machine, dishwasher, refrigerator, and pool pump), and building envelope (e.g., insulation and windows)
- We forecast EE growth will slow once the majority of cost effective EE opportunities are largely implemented in the prior decade

We developed hourly EE profiles based on LBL data to reflect when EE measures reduce demand

NATIONWIDE RESIDENTIAL ELECTRIC EE SAVINGS



ELECTRIC EE DAILY AVERAGE DEMAND REDUCTION



Sources: See slide 28 for studies reviewed, including DOE's meta-data survey of 50 regional studies. Brattle analysis of data developed by LBNL as input to DOE's A National Roadmap for GEBs.

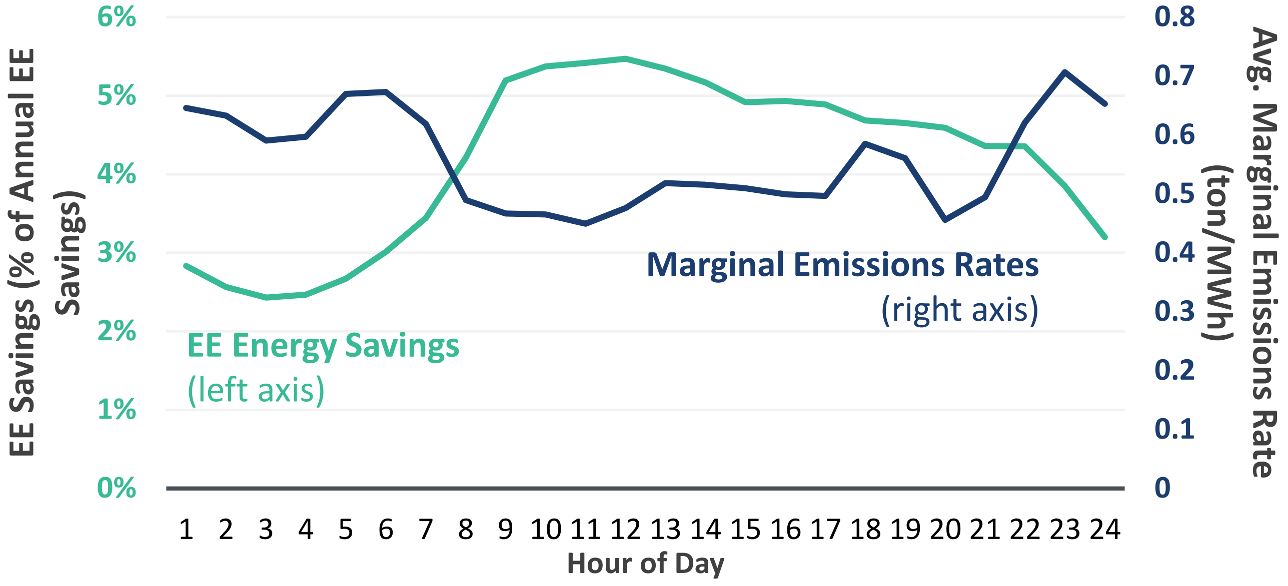
Electric Energy Efficiency GHG Emissions Reductions

We estimate avoided GHG emissions of EE based on the hourly profile and hourly marginal emissions rates by region

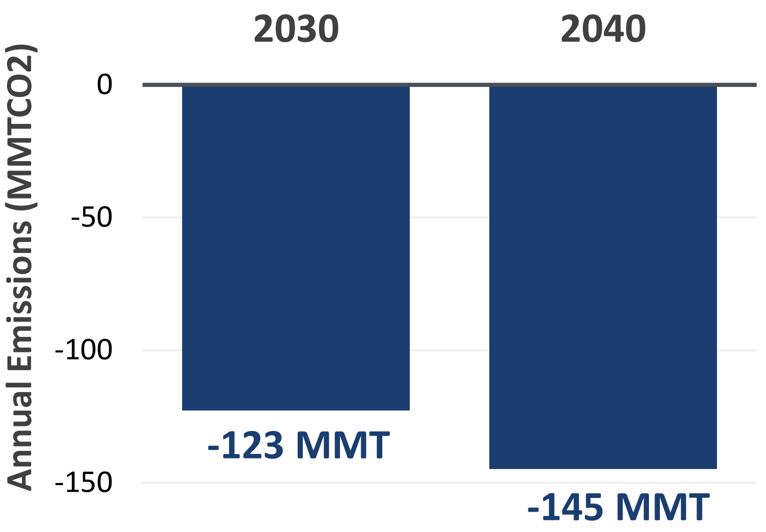
- For example, the average avoided emissions rates are about 0.5 ton/MWh in 2030 and 2040 for Southeast, as shown below
- EE impacts are largest during daytime hours when emission rates are lower due to renewable generation

Incremental electric EE installed across the U.S. will avoid 122 MMT of GHG emissions in 2030 and 145 MMT in 2040

SOUTHEAST RESIDENTIAL ELECTRIC EE 2040 AVERAGE EE PROFILE AND MARGINAL EMISSIONS RATES



NATIONWIDE RESIDENTIAL ELECTRIC EE GHG EMISSIONS REDUCTIONS



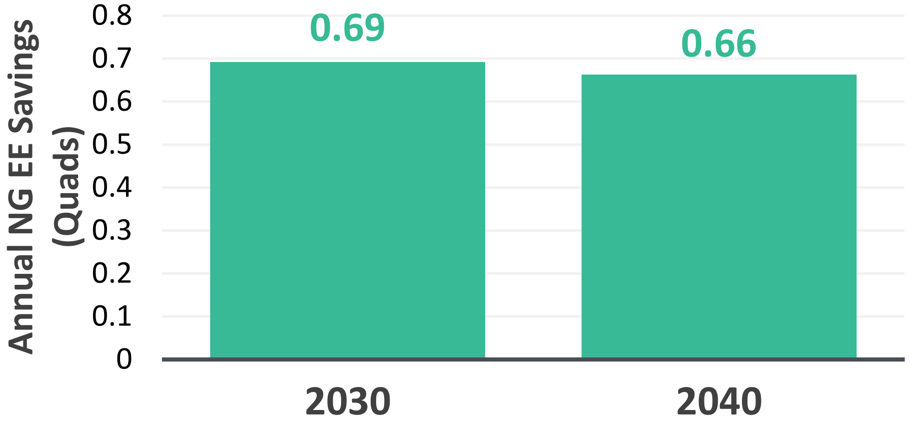
Gas Energy Efficiency Projected Adoption and GHG Reductions

Based on several national gas efficiency studies, we forecast that additional cost-effective gas EE measures could reduce residential gas demand by about 0.69 quads in 2030 (or 1.5%/year from 2021 to 2030) and 0.66 quads in 2040 (an additional 0.5%/year from 2030 to 2040, accounting for decreased demand due to electrification)

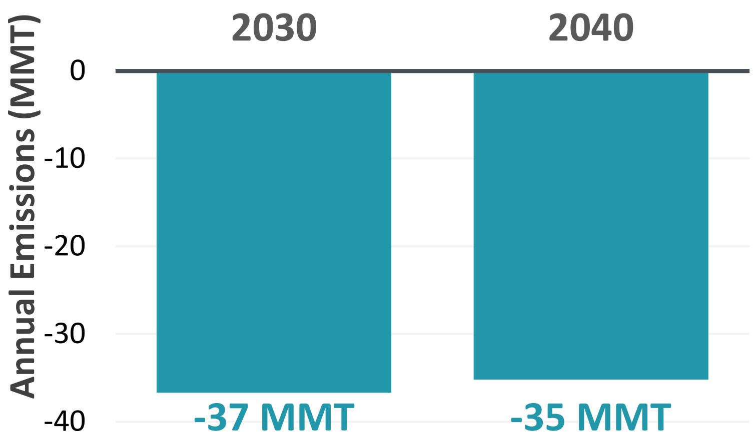
- Gas efficiency measures include insulation upgrades, targeted air sealing, and heating system improvements
- Public reports suggest annual gas EE savings are comparable with electric EE savings potential

We forecast that gas EE will grow at a higher rate through 2030, but will slow down once the cost effective opportunities are largely implemented in the prior decade and heating electrification adoption reduces demand

NATIONWIDE RESIDENTIAL GAS EE FUEL DEMAND SAVINGS



NATIONWIDE RESIDENTIAL GAS EE GHG EMISSIONS REDUCTIONS



Source: Energy savings based on a review of 5 national EE potential studies, including NREL and Synapse.

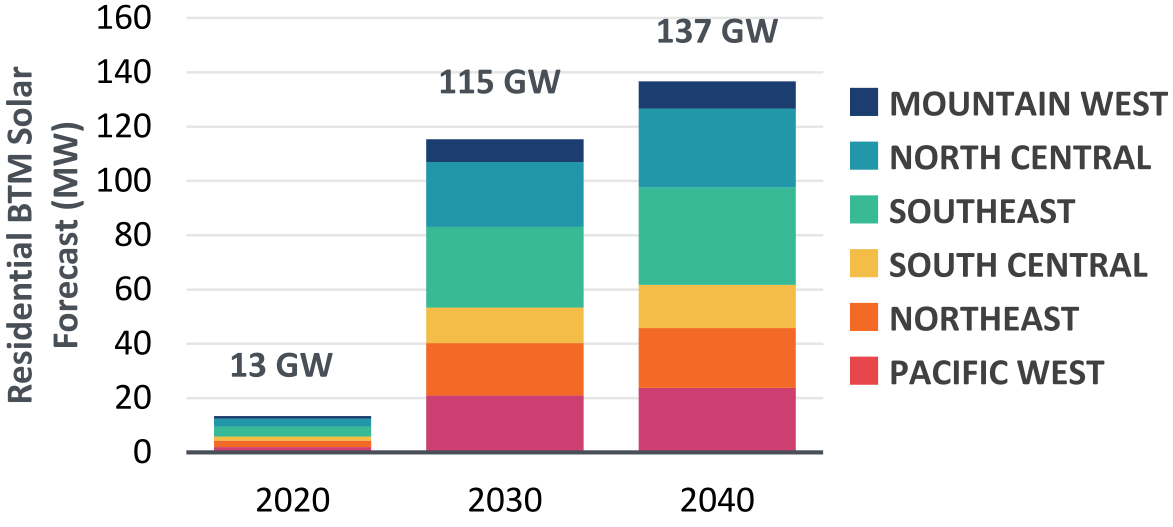
Behind-the-Meter (BTM) Solar Projected Growth

Based on several regional and national behind the meter solar capacity forecasts, we estimate an additional 115 GW of residential-sited BTM solar by 2030 relative to a 2021 baseline.

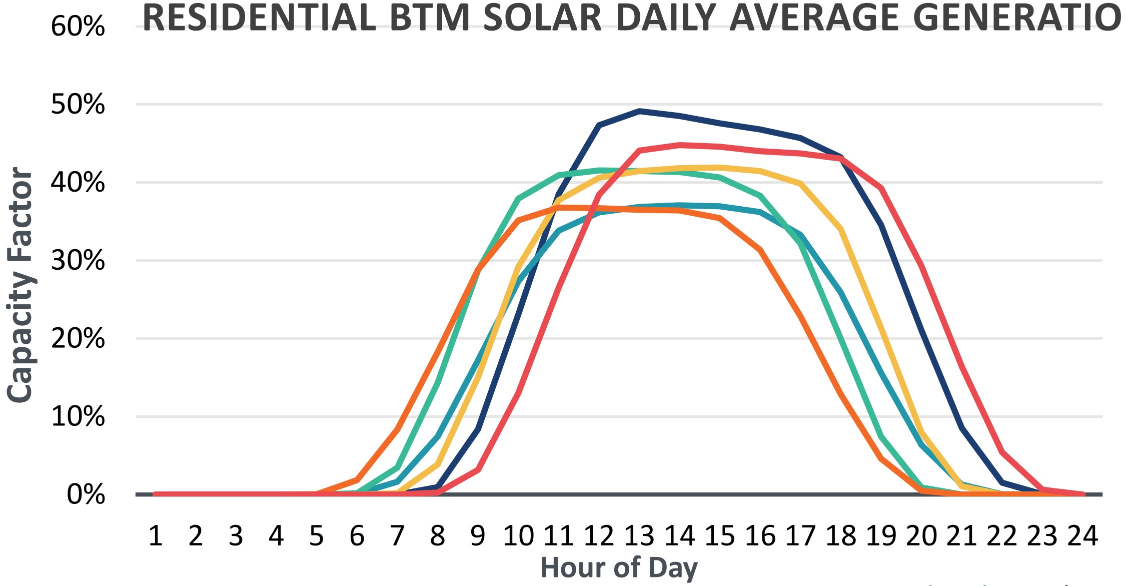
- Most of the increased capacity occurs in Pacific West and South Central through 2040
- 20% of residential households will have BTM solar assets by 2040
- We forecast growth will slow once the majority of cost effective BTM opportunities are largely implemented in the prior decade and grid electricity becomes greener

We estimate hourly BTM solar generation based on regional profiles produced from NREL ReV's data

RESIDENTIAL BTM SOLAR INSTALLED CAPACITY FORECAST



RESIDENTIAL BTM SOLAR DAILY AVERAGE GENERATION



Sources: Regional and national BTM solar studies: NYISO, ISO-NE, CEC, VCE, AEO.
BTM solar profiles: NREL's ReV database

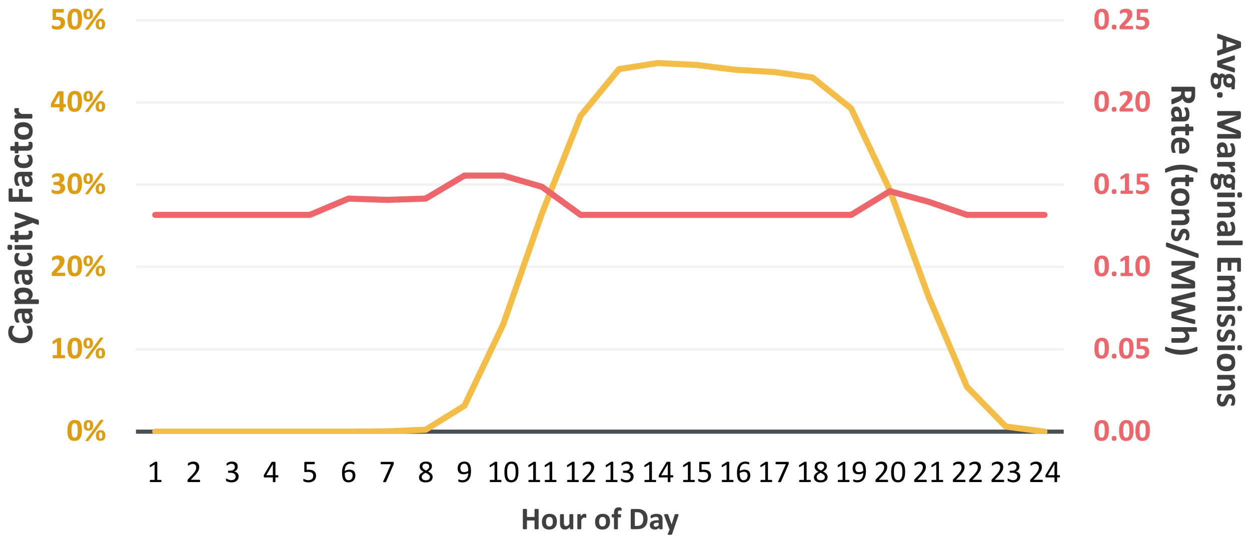
BTM Solar GHG Emissions Reductions

We estimate avoided GHG emissions of BTM solar based on the hourly solar generation profile and marginal emissions rates in each region

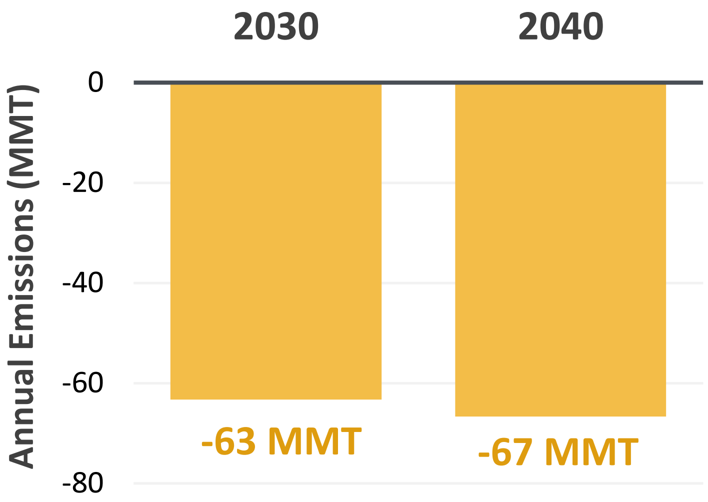
- Marginal emissions rates decline significantly by 2030 and 2040, especially in the regions with the most projected BTM solar
- Emissions rates are lowest when BTM solar is generating, such that the average avoided emissions rate decreases from 0.21 ton/MWh in 2030 to 0.13 ton/MWh in 2040, for Pacific West (as shown below)

Additional BTM solar installed across the country will avoid 63 MMT in 2030 and 67 MMT in 2040

PACIFIC WEST BTM SOLAR 2040 AVERAGE GENERATION AND MARGINAL EMISSION RATES



NATIONWIDE BTM SOLAR GHG EMISSIONS REDUCTIONS



Note: The potential impact of BTM storage coupled with rooftop solar was not modeled, but potentially could improve emissions reductions if shifting solar output to hours with higher emissions intensity.

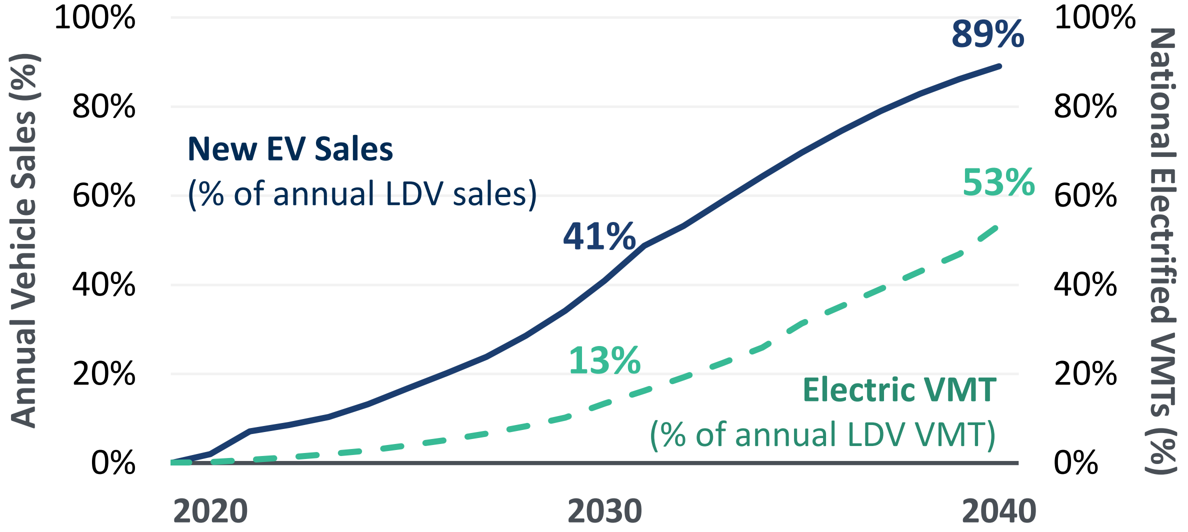
Light-Duty Vehicle Electrification Projected Growth

We used our internal light-duty EV adoption model to forecast annual EV sales and total electric miles driven

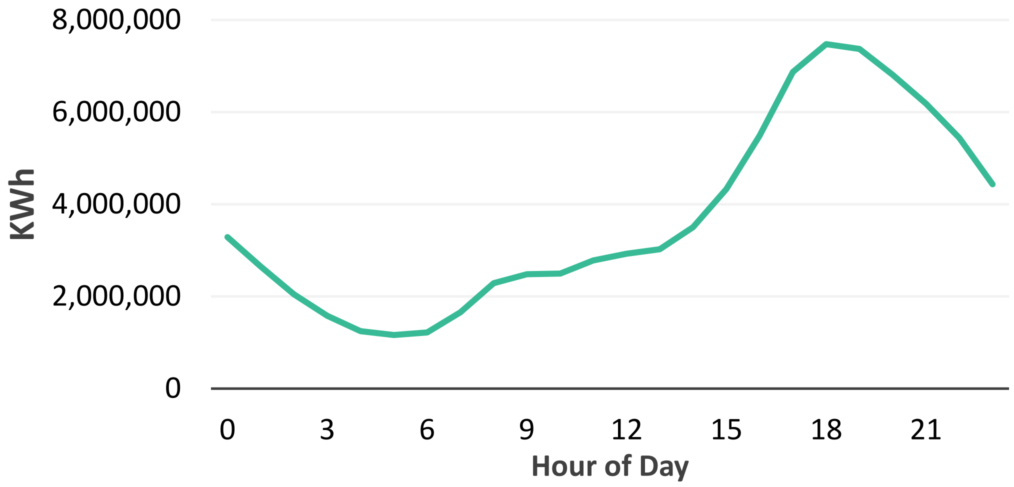
- Under an ambitious scenario, EV sales could increase to 41% in 2030 and 89% in 2040
- Achieving this level of EV sales by 2030 will require additional EV models than currently announced, faster decline in vehicle costs, wide-spread charging infrastructure and greater customer awareness of the benefits of EVs
- Electric miles driven rises to 13% in 2030 and 53% in 2040, accounting for vehicle stock rollover and BEV/PHEV split

We estimate hourly EV charging load by region based on the EV adoption forecast, region-specific total VMTs, monthly driving patterns, EV efficiency, and daily charging profiles from EVI-Pro Lite

NATIONWIDE LDV ELECTRIFICATION FORECAST



SOUTHEAST LDV HOURLY CHARGING PROFILE



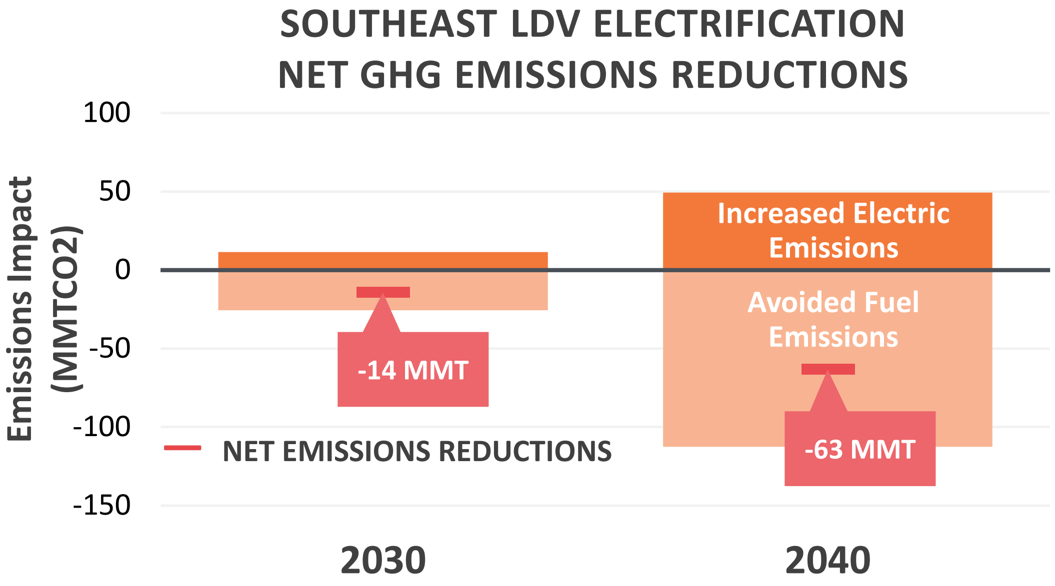
Sources: Brattle's internal EV adoption forecast model. Electric VMT forecast assumes about 70% BEVs in 2030 and 80% in 2040 (30% PHEVs in 2030 and 20% in 2040), and PHEVs use electric motor for 50% of miles driven; EVI Pro Lite

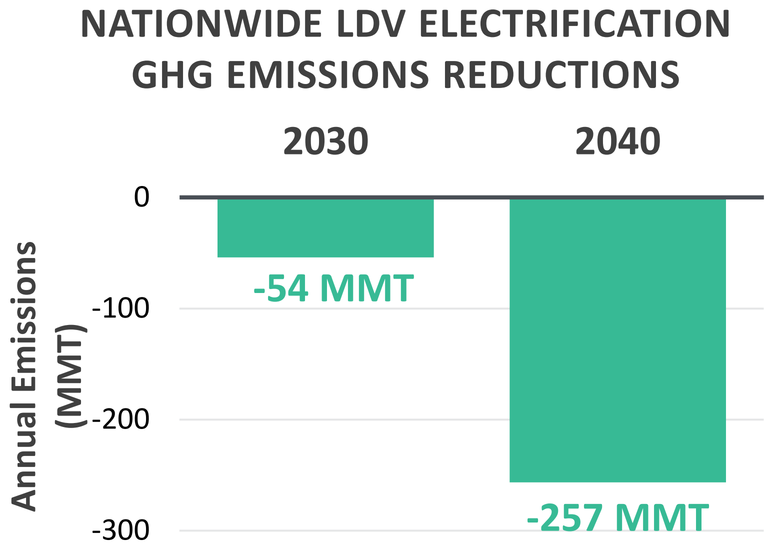
Light-Duty Vehicle Electrification GHG Emissions Reductions

We first calculate the reduction in GHG emissions from decreasing the use of diesel and gasoline fuels for ICE vehicles and then the increase in electric sector GHG emissions from the additional charging demand

- The Southeast has the largest vehicle electrification potential compared to other regions based on fleet size.
- Emissions savings per EV increase from 2030 to 2040 due to increase in adoption and declining power sector emissions rates

Vehicle electrification could result in a net reduction in GHG emissions of 54 MMT in 2030 and 257 MMT in 2040





Space Heating Electrification Projected Growth

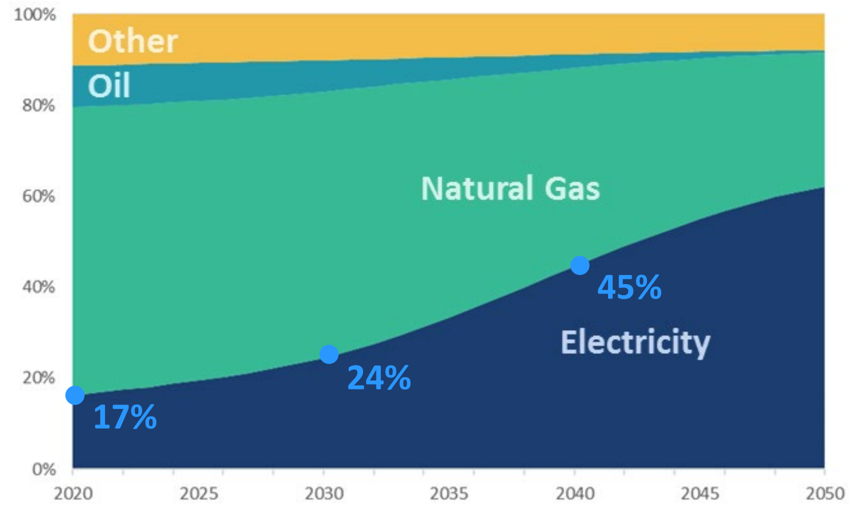
While 17% of space heating is currently met by electric sources (e.g., resistance heating and heat pumps), NREL projects that space heating electrification will increase to 24% of heating demand in 2030 and 45% in 2040 in its High Scenario

- Natural gas furnaces currently serve 63% of space heating, distillate fuel oil serves 9% and other fuels (e.g., propane) serve 11%
- Electrification adoption reduces space heating fuel demand (in Btus) by 35% in 2040 (other fuel market share drops from 83% to 55%)

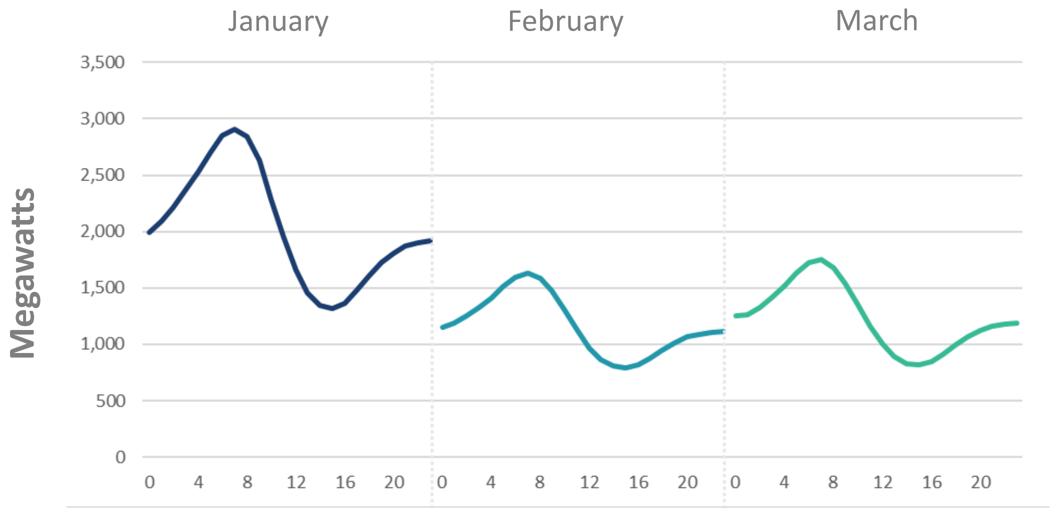
We estimate hourly space heating electricity demand by region taking into account AEO's forecasted annual fuel demand, efficiency of existing technologies and heat pumps (80% ASHP/20% GSHP), and historical seasonal and daily patterns of space heating fuel demand

Notes: Daily shape based on EPRI load profiles with adjustments for monthly heating demand and ASHP efficiency based on hourly 2018 temperatures.
Source: NREL Electrification Futures Study.

NATIONWIDE RESIDENTIAL SPACE HEATING FUEL FORECAST (HIGH ELECTRIFICATION SCENARIO)



NORTHEAST SPACE HEATING HOURLY ELECTRICITY DEMAND (JANUARY – MARCH 2040)



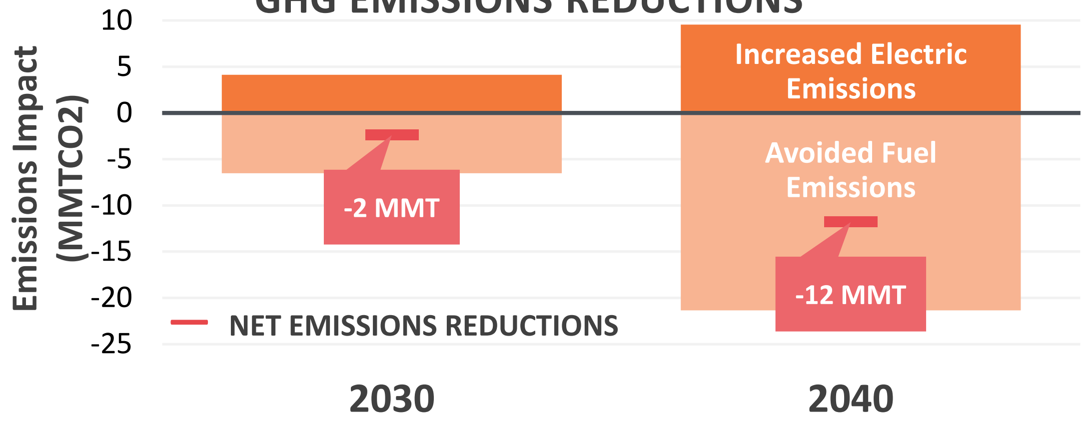
Space Heating Electrification GHG Emissions Reductions

We first calculate the reduction in emissions from decreasing the use of GHG-emitting fuels for space heating and then the increase in electric sector emissions from the additional electricity demand

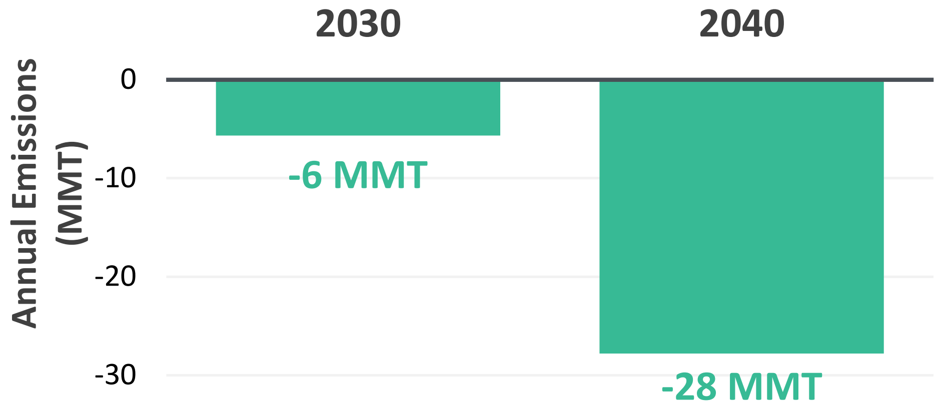
- Emissions reductions vary across regions and are highly concentrated in the Northeast, where fossil fueled heating is prevalent
- With an increasingly decarbonized electric sector, electrification emissions offset a smaller portion of the avoided fuel emissions

Space heating electrification could result in a net reduction in GHG emissions of 5 MMT in 2030 and 28 MMT in 2040, lower than other sectors due to lower adoption rates and greater offsetting electric sector emissions than EVs

NORTHEAST SPACE HEATING ELECTRIFICATION GHG EMISSIONS REDUCTIONS



NATIONWIDE SPACE HEATING ELECTRIFICATION GHG EMISSIONS REDUCTIONS



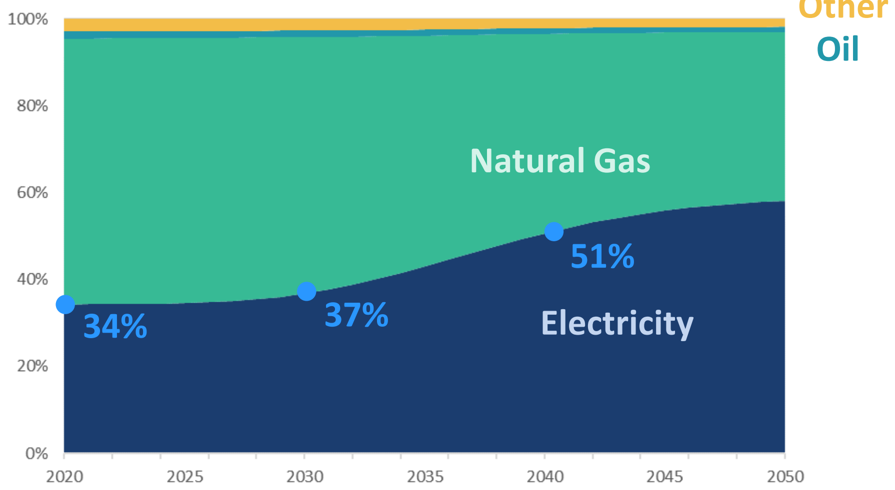
Water Heating Electrification Projected Growth

A larger share of water heating (34%) is currently met by electric sources and NREL projects that water heating electrification will rise slightly to 37% in 2030 and then increase to 51% in 2040 in its High Scenario

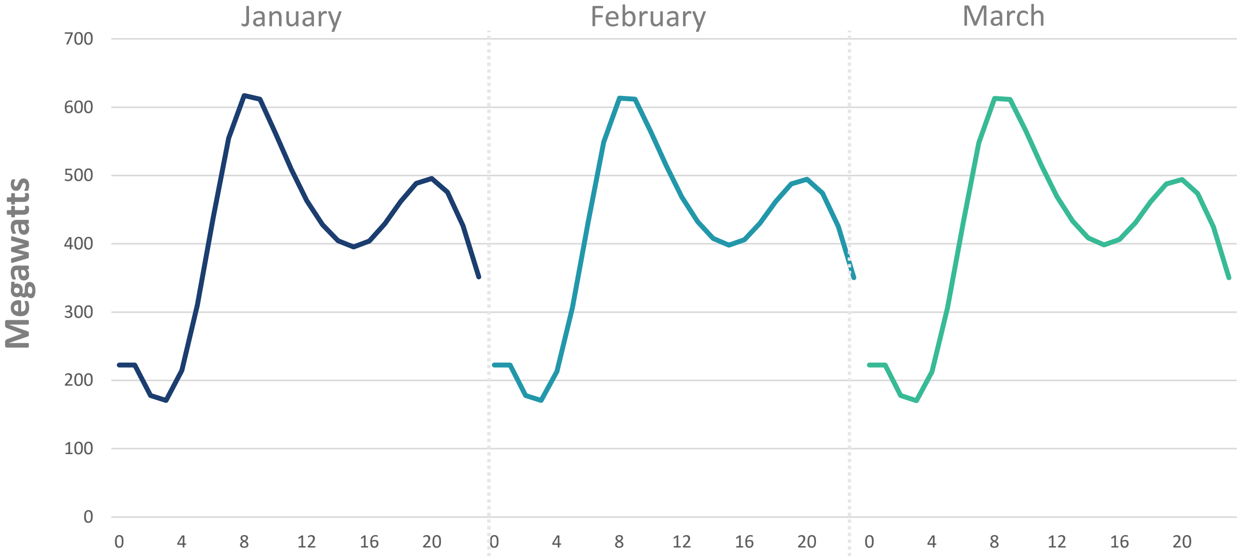
- Natural gas water heaters make up the majority of other water heaters (61%)
- Electrification adoption reduces water heating fuel demand by 26% in 2040 (market share drops from 66% to 49%)

Similar to space heating, we estimate hourly water heating electricity demand by region taking into account the forecasted annual fuel demand, efficiency of gas and electric water heaters (50% ASHP/50% electric resistance), and historical seasonal and daily patterns of water heating fuel demand

NATIONWIDE RESIDENTIAL WATER HEATING FUEL FORECAST (HIGH ELECTRIFICATION SCENARIO)



NORTHEAST WATER HEATING HOURLY ELECTRICITY DEMAND (JANUARY – MARCH 2040)



Notes: See appendix, slide 36 for details.
Source: NREL Electrification Futures Study.

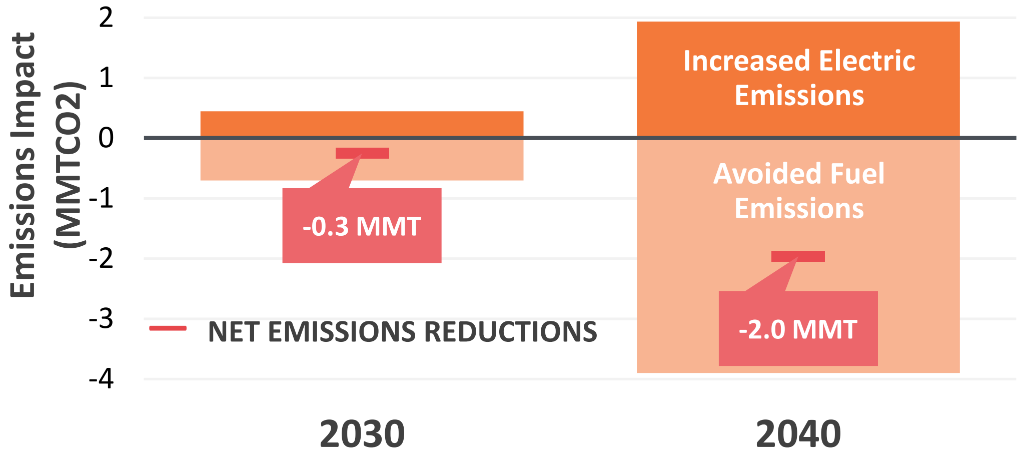
Water Heating Electrification GHG Emissions Reductions

Similar to space heating, we first calculate the reduction in emissions from decreasing the use of GHG-emitting fuels and then the increase in electric sector GHG emissions from the additional water heating demand

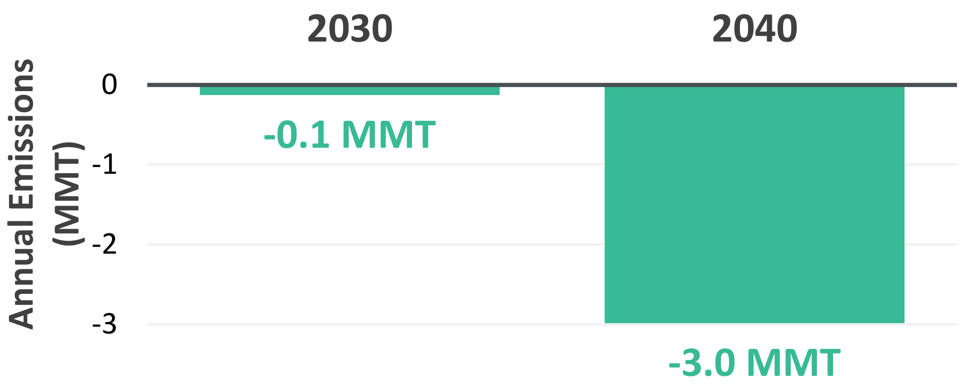
- The Northeast and Pacific West have the most fossil fueled water heating and potential for fuel switching savings
- An increasingly decarbonized electric sector reduces the offsetting power sector emissions from electrification

Water heating electrification could result in a net reduction in GHG emissions of 1 MMT in 2030 and 3 MMT in 2040

NORTHEAST WATER HEATING ELECTRIFICATION GHG EMISSIONS REDUCTIONS



NATIONWIDE WATER HEATING ELECTRIFICATION GHG EMISSIONS REDUCTIONS



Sources:

Load flexibility will facilitate the transition to a decarbonized grid

- Load flexibility refers to managing customer load and distributed energy resources to provide overall value to the power grid and to consumers
- Load flexibility has an indirect but large role in decarbonizing the power grid, by facilitating the integration of renewables and potentially shifting load away from hours with high emissions
- There is a significant amount of untapped load flexibility potential in the residential sector. This will grow as more customers adopt EVs, batteries, smart thermostats, and other technologies
  - A 2019 Brattle study estimated that national load flexibility potential is 200 GW in 2030 (roughly 20% of peak demand)
  - More than half of the untapped potential comes from the residential sector
- Achieving this potential will require deliberate efforts to remove significant technical, market, and regulatory barriers

DECARBONIZATION BENEFITS OF LOAD FLEXIBILITY

- Reduce renewables curtailment by shifting usage to hours of low net load
- Reduce or shift usage away from hours with high marginal emissions rates
- Improve economics of solar PV by mitigating the late evening ramp in net load otherwise caused by these resources
- Facilitate cost-effective adoption of electrification by mitigating load impacts of new electricity-intensive end-uses
- Provide real-time grid balancing services needed when increasingly dependent on intermittent generation resources

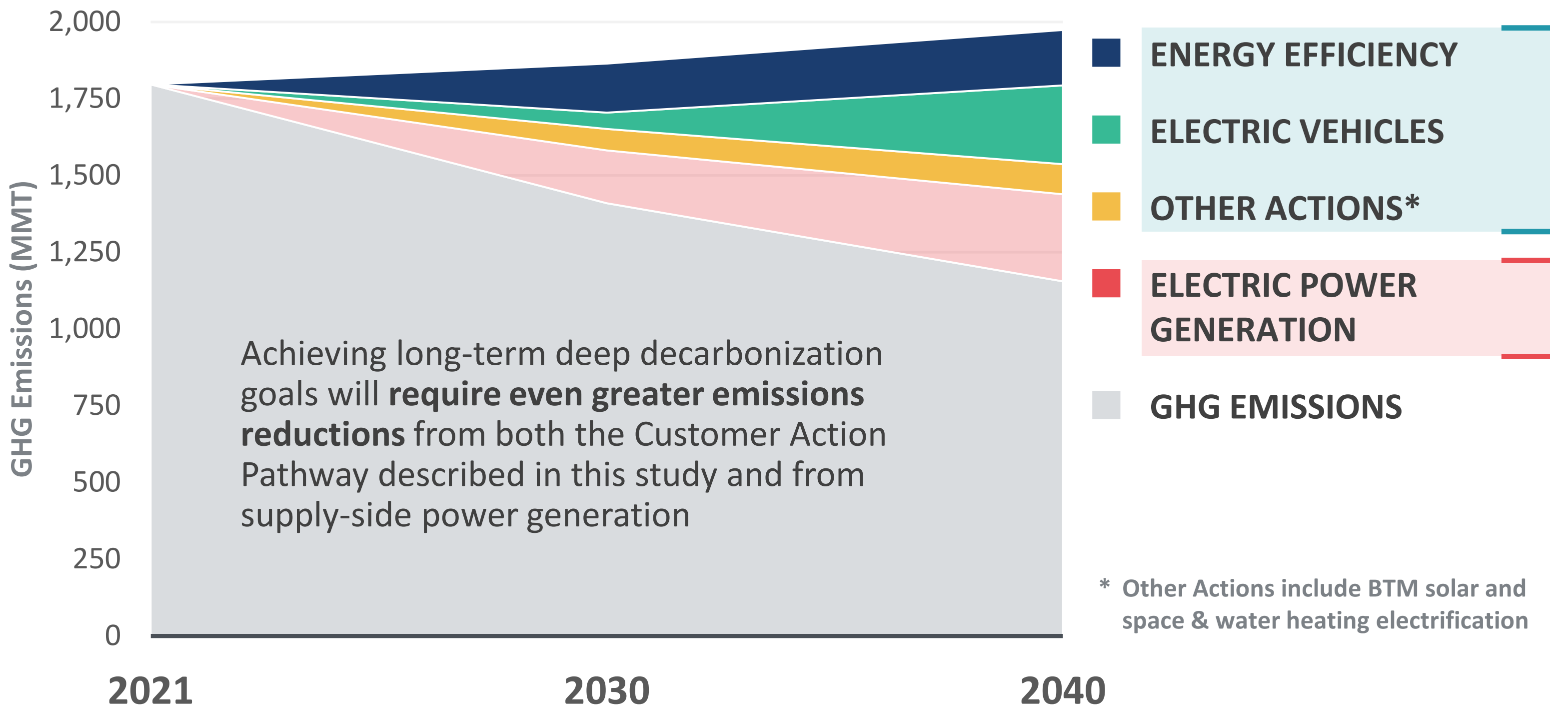
Source: Ryan Hledik, Ahmad Faruqui, Tony Lee, John Higham, "The National Potential for Load Flexibility," June 2019.

Conclusions

Customer Action Pathway Builds on Supply-Side Reductions

The Customer Action Pathway has the potential to reduce GHG emissions by nearly twice as much as supply-side reductions alone will contribute under existing policies

RESIDENTIAL AND LDV GHG EMISSIONS PROJECTIONS



* Other Actions include BTM solar and space & water heating electrification

The Customer Action Pathway has potential to reduce 2040 emissions by 534 MMT

"Greening the Grid" alone expected to reduce 2040 emissions by 284 MMT under existing policies

Notes: Total emissions prior to Customer Action Pathway and electric power generation reductions assume 2021 residential emissions levels increase through 2040 with projected electricity, gas, and transportation demand from AEO 2021. Reduction in electric power generation emissions based on average power generation emissions rates (0.41 tons/MWh in 2021, 0.29 tons/MWh in 2030, and 0.23 tons/MWh in 2040) generated by Brattle's in-house capacity expansion model GridSIM (see slide 10). Future policies could accelerate both demand-side and supply-side emissions reductions.

Summary of Findings

Our results highlight the importance of customer-driven actions in achieving ambitious decarbonization goals

- Avoiding 534 MMTCO2 in 2040 is the same as retiring 135 coal plants (Source: EPA)
- Customer Action Pathway GHG emission reduction potential is about 2x greater than projected reductions from supply side decarbonization efforts alone by 2040 under current policies
- GHG reduction achieved through the Customer Action Pathway in 2040 is equivalent to nearly 60% of the annual GHG reduction achieved from all sectors from 2005 to 2021

Near-term emissions reduction potential driven by energy efficiency and BTM solar through 2030, while customer adoption of electric vehicles could provide the largest emissions reductions by 2040

- EE and BTM solar have greatest 2030 impact due to current customer familiarity and higher near-term power generation emission rates. While adoption of both technologies continues beyond 2030 at a slower rate, the emissions impact is less significant by 2040 due to the lower power generation emission rates
- EV adoption emissions impact increase significantly from 2030 to 2040 due to the 4x potential increase in the total EVs on the road and the lower power generation emission rates

Additionally, load flexibility (e.g., smart thermostat programs, time-varying rates) will be a critical part of the Customer Action Pathway

- Load Flexibility facilitates the integration of renewable energy resources, reduces renewable energy curtailment, and mitigates the need for system upgrades to serve rising peak demand

Appendix

Sources

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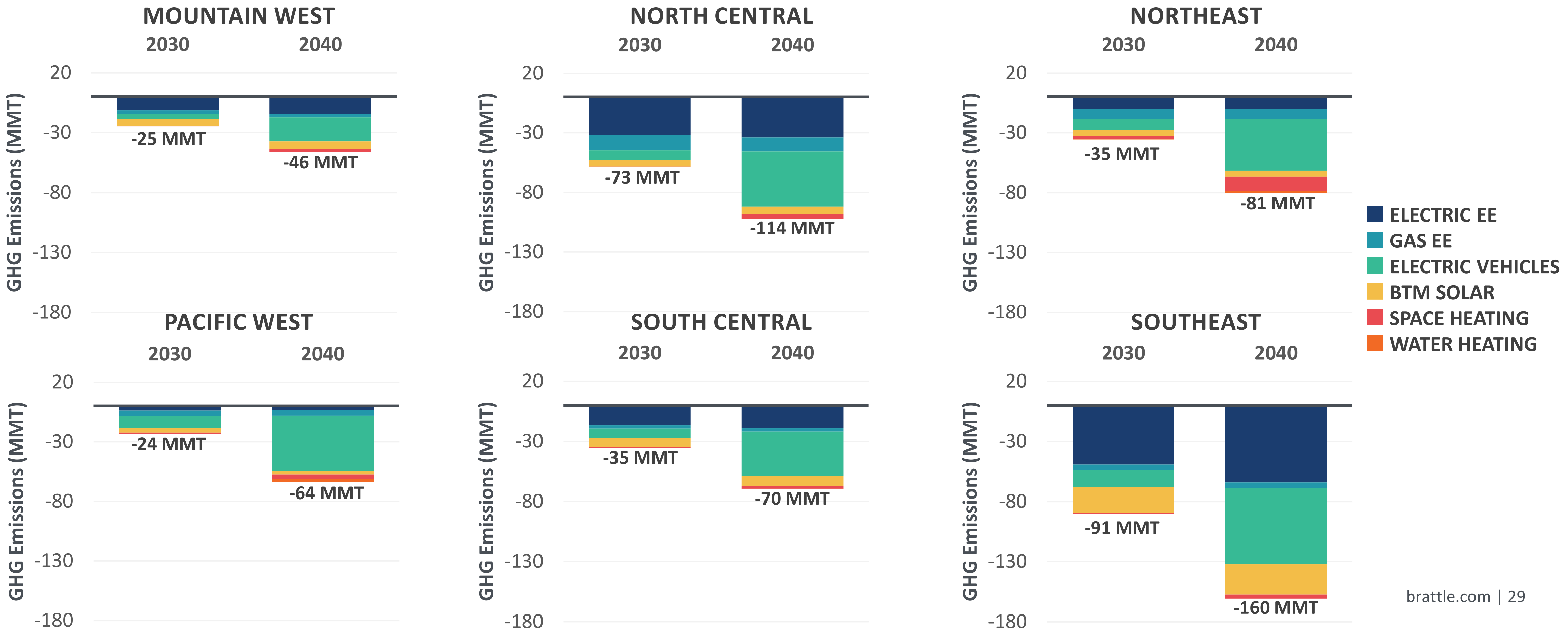
Customer Action Pathway by Region

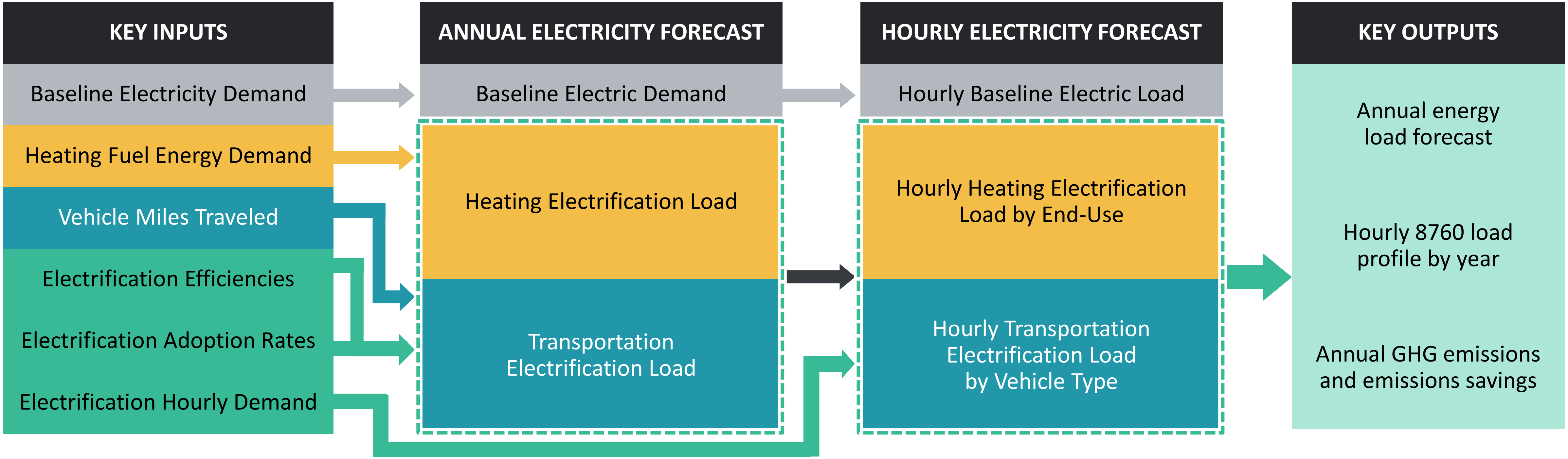
While our analysis primarily focused on nationwide impacts of the Customer Action Pathway, the indicative regional results shown below demonstrate that GHG reductions are likely to vary by region based on the projected transportation and heating energy demand, electric sector marginal emissions rates, and total population



Electrification of Transportation and Heating

We rely on Brattle's Decarbonization, Electrification & Economic Planning (DEEP) Model to develop the electrification-related demand forecast

- The electrification forecast is based on an annual projection of heating fuel energy demand and vehicle miles traveled
- Electric heating and EV adoption rates are used to estimate the fraction of annual demand and miles traveled electrified over time
- Technology efficiency projections and hourly load shapes are used to convert annual demand into hourly outputs



GridSIM Model Framework

INPUTS

Supply
- Existing resources
- Fuel prices
- Investment/fixed costs
- Variable costs

Demand
- Hourly demand for representative days
- Capacity needs

Transmission
- Zonal limits
- Intertie limits

Regulations, Policies, Market Design
- Capacity market
- Carbon pricing
- State energy policies and procurement mandates

GridSIM OPTIMIZATION ENGINE

Objective Function
- Minimize NPV of Operating and Investment Costs

gridSIM

Constraints
- Market Design and Co-Optimized Operations
  - Capacity
  - Energy
  - Ancillary Services
- Regulatory & Policy Constraints
- Resource Operational Constraints
- Transmission Constraints (not modeled in this instance)

OUTPUTS

Generation Additions and Retirements (Clean Energy Additions)

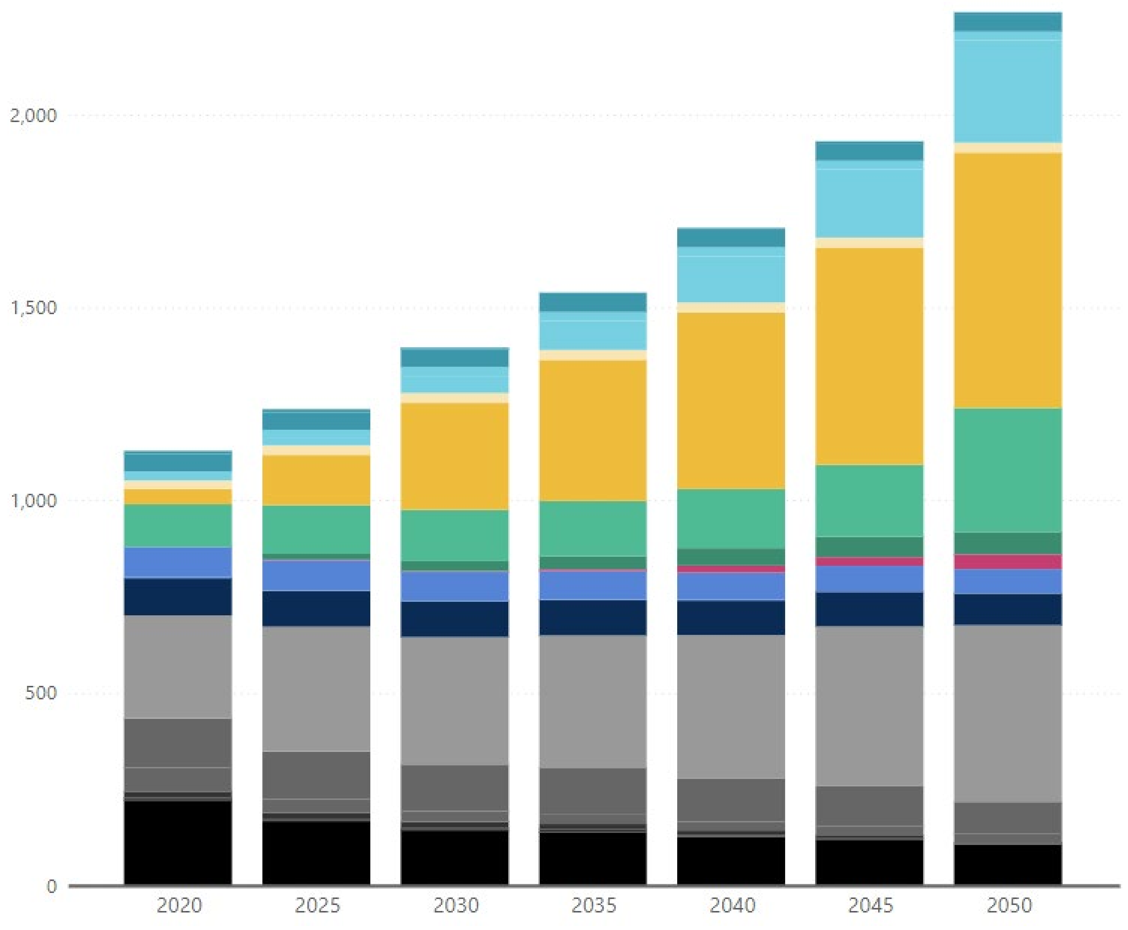
Hourly Operations

Hourly Energy Market Price (Supplier Revenues, Energy Costs to Customers)

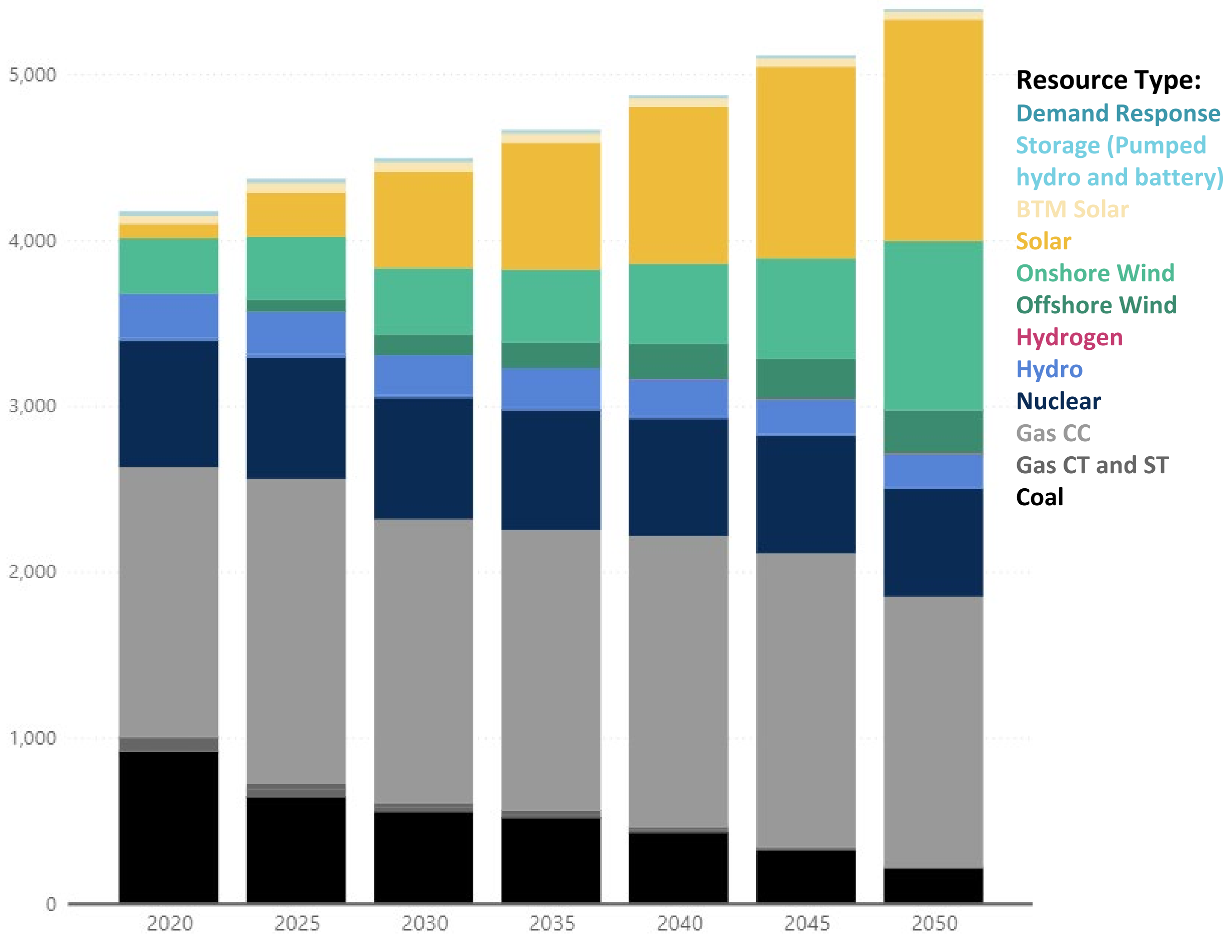
Emissions

Example GridSIM Projection of Generation and Capacity

Modeled U.S. Capacity (GW)



Modeled U.S. Generation (TWh)

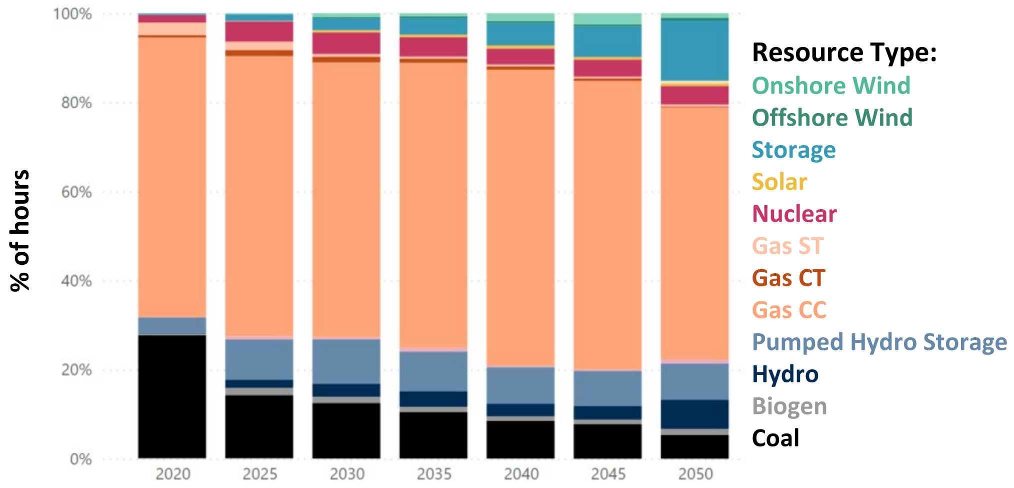


Projected Marginal Emissions Rate from GridSIM (Ex. MISO)

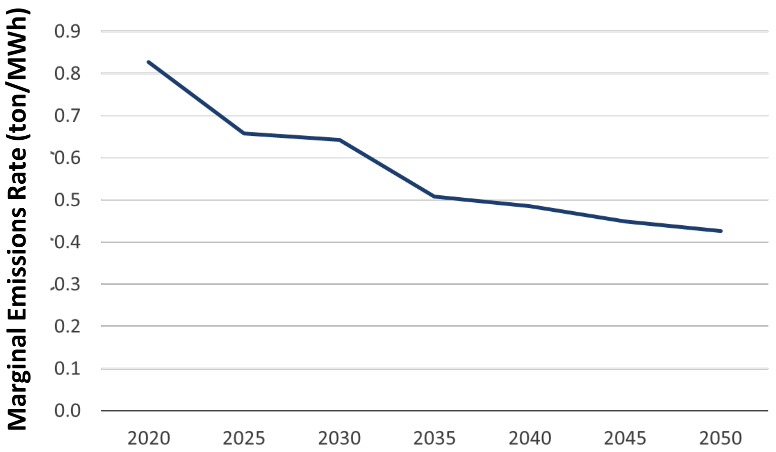
Brattle's GridSIM model forecasts hourly marginal emission rates for 25 EIA regions through 2050 accounting for changing resource mix

- Marginal generator in MISO is a Gas CC in most hours with a trend away from coal and towards battery storage
- Marginal emissions rates are projected to decline from 0.8 tons/MWh in 2020 to 0.5 tons/MWh in 2040

Share of Year that Each Resource is Marginal (MISO)



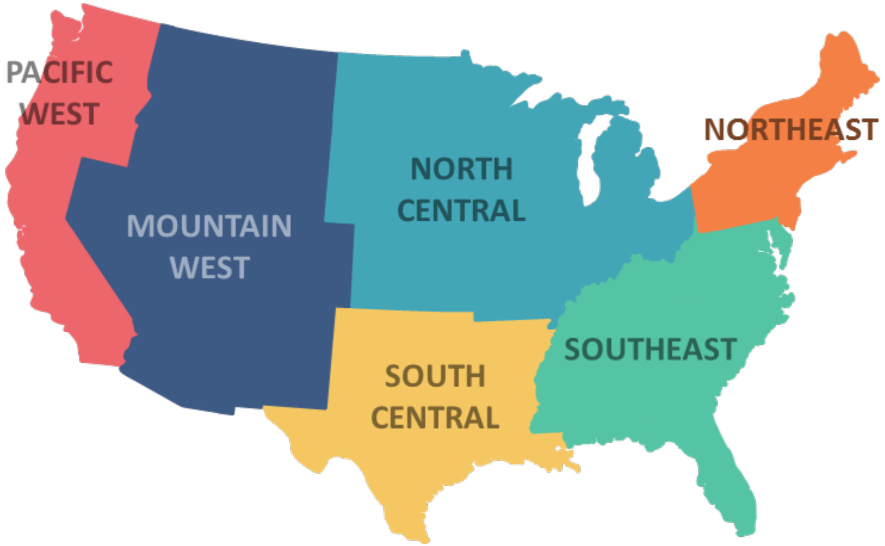
Projected Marginal Emission Rate (MISO)



These marginal emissions rates do not account for new clean energy resources added/removed from a significant change in demand so we will want to account for that in our analysis

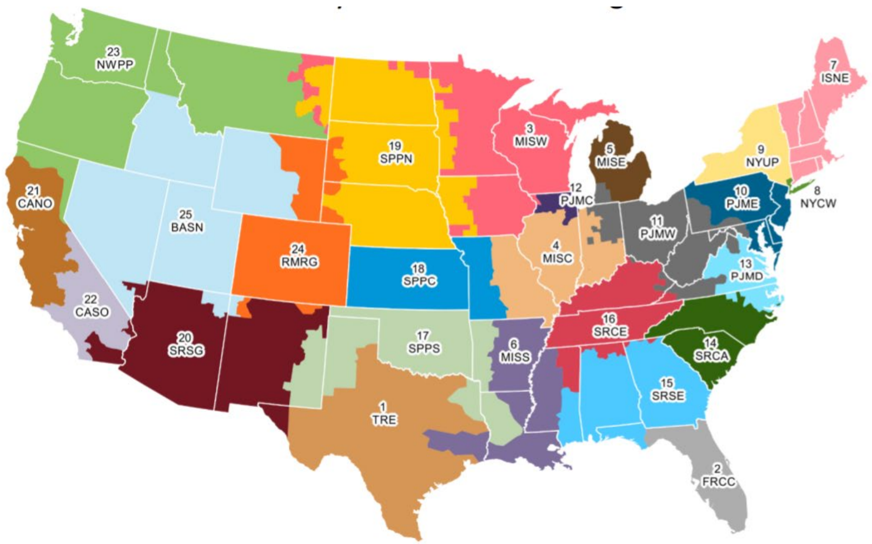
Electric Sector Marginal Emissions Rates

Aggregated Census Regions
(Customer-Side Technology Impacts)



Census Region	Representative EMM Region
Pacific West	CANO
Mountain West	BASN
North Central	MISW
South Central	TRE
Northeast	ISNE
Southeast	SRSE

EMM Regions
(GridSIM Marginal Emissions)



Source: EIA EMM Map

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Additional Reading on Decarbonization and Load Flexibility

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Clarity in the face of complexity

Brattle