Low-Cost GHG Reductions from Higher End-Use Gas Efficiencies

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A. Background and Objectives

The Pathways study focused on the costs, volume and speed of GHG emission reductions in the U.S. residential and commercial building sectors from widespread adoption of emerging technologies for direct use of gaseous fuels[1)]

> The intent was to produce factual material that is objective, educational, and broadly useful to interested stakeholders, in the policy debate around the future role of gas in largely decarbonized energy systems.

> Pathways Phase 1 was completed for the American Gas Association (U.S. gas utilities) in 2018 and focused on GHG reduction potential at the customer level from emerging natural gas direct-use technologies in the residential and small commercial sectors.

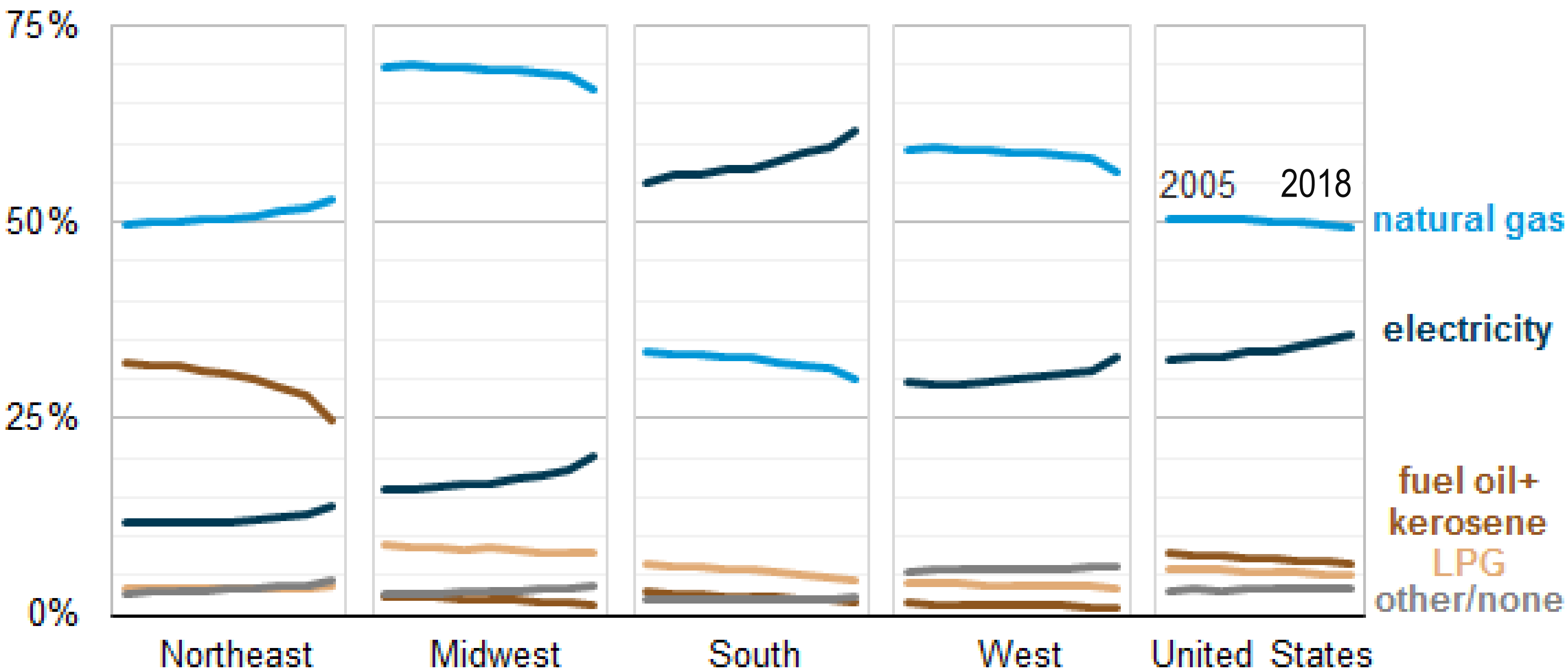
> Pathways Phase 2 was sponsored by the American Gas Foundation, AGA's educational arm. This 2019 phase of the project focused on the aggregate GHG reduction potential of emerging residential natural gas technologies across a range of policy scenarios

> The complementary abatement contributions from methane leakage reductions across the gas delivery value chain and from substitution of biogas or green hydrogen for natural gas were also considered.

1) Natural gas, biogas, synthetic green methane, green hydrogen

Natural gas is the dominant space and water heating fuel for all U.S. regions except South – supplying over 85% of peak day heat

Primary heating fuel choice (2005-2018)
[% of households within census division or nation]

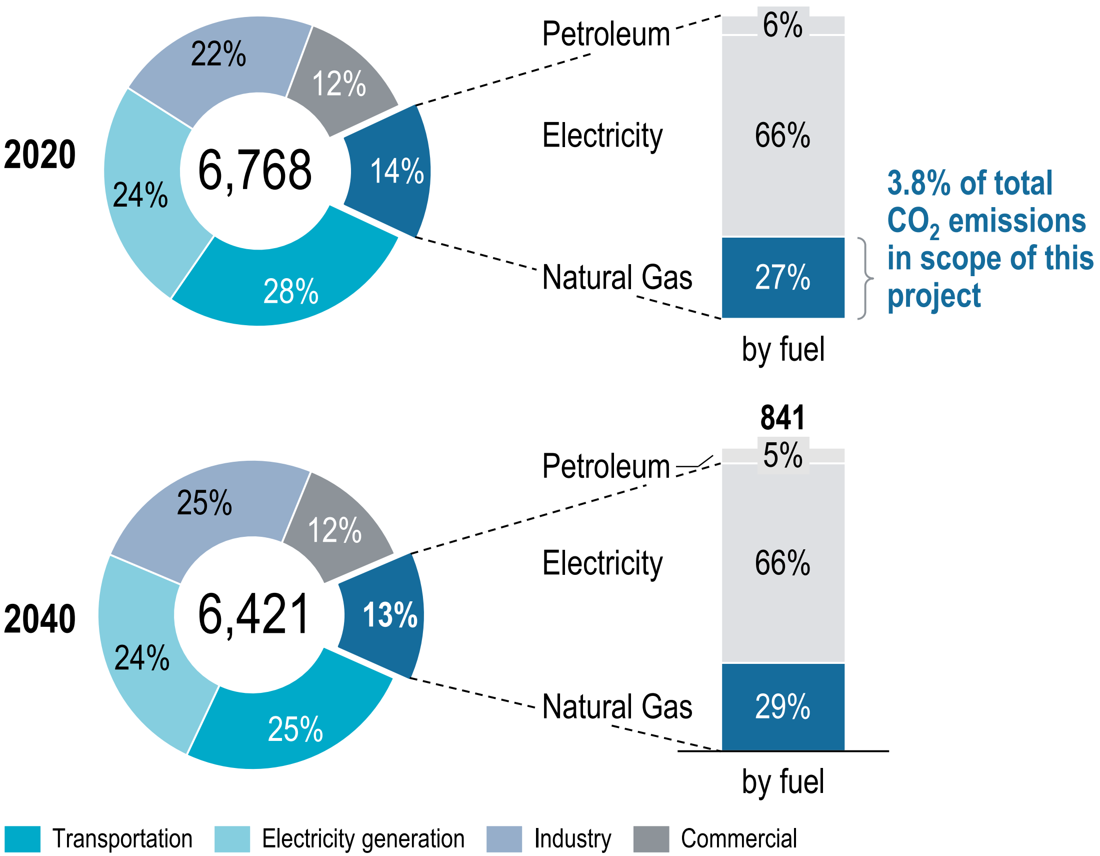


Note: Geographic areas based on Census regions. LPG is liquefied petroleum gas

Source: U.S. energy Information Administration, based on Census Bureau American Community Survey

Residential direct uses of natural gas represent 3.8% of the total US CO_2 emissions today

Total US CO_2 emissions [millions metric tons]



- > Natural gas direct use in residential sector accounts for 3.8% of total US CO_2 emissions in 2020
  - – Residential sector accounts for 14% of total emissions, of which natural gas accounts for 27%
- > By 2040, total emission will be reduced by 347MT (-5%), in which the residential sector will be reduced by 98MT (-10.4%)
  - – The emission reduction is driven by adoption of higher energy efficient technologies and switching from high CO_2 intensity fuels such as heating oil and propane

Source: EIA. AEO 2019 National Energy Modeling System, EIA Annual Energy Outlook 2019, Enovation Partners analysis

B. Approach

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Phase 1 objective: Identify innovative gas end use technologies and translate their impact into customer value & environmental benefits

Gas decarbonization pathways

1 Innovation area

1	Condensing Technology
2	Hot water heating / boilers
3	Kitchen
4	On-Site Generation
5	Burners
6	Heat Pumps
7	Changes to laundry processing
8	Solar Thermal / Heat Recovery
9	Improved Energy Management
10	Transportation
11	Building Envelope
12	Miscellaneous

2 Technologies

1. Condensing Technology
- Integrated contact condensing water heater
- In-situ flue burner - applying premix burners to storage GWH
- Transport Membrane Humidifier (TMH)
- High efficiency condensing condo packs
- Residential condensing water heater
- Condensing wall furnace
- Rooftop units - heating and cooling
- Condensing economizer

2. Boilers
- Tankless water heater
- Solar-assisted heating
- Thermal compression gas heat pump
- Combined space and water heating systems

en
- Combination steam and heat oven
- Boilerless stea

3 End-use pathways

4 Customer value

Affordability

Sustainability

Resilience

Comfort

12 Innovation areas

~100 Technologies

7 End use-pathways

26 Prioritized technologies

Note: Some technologies have multiple end uses and can be used in the residential and commercial sectors. These technologies are represented in all applicable sections

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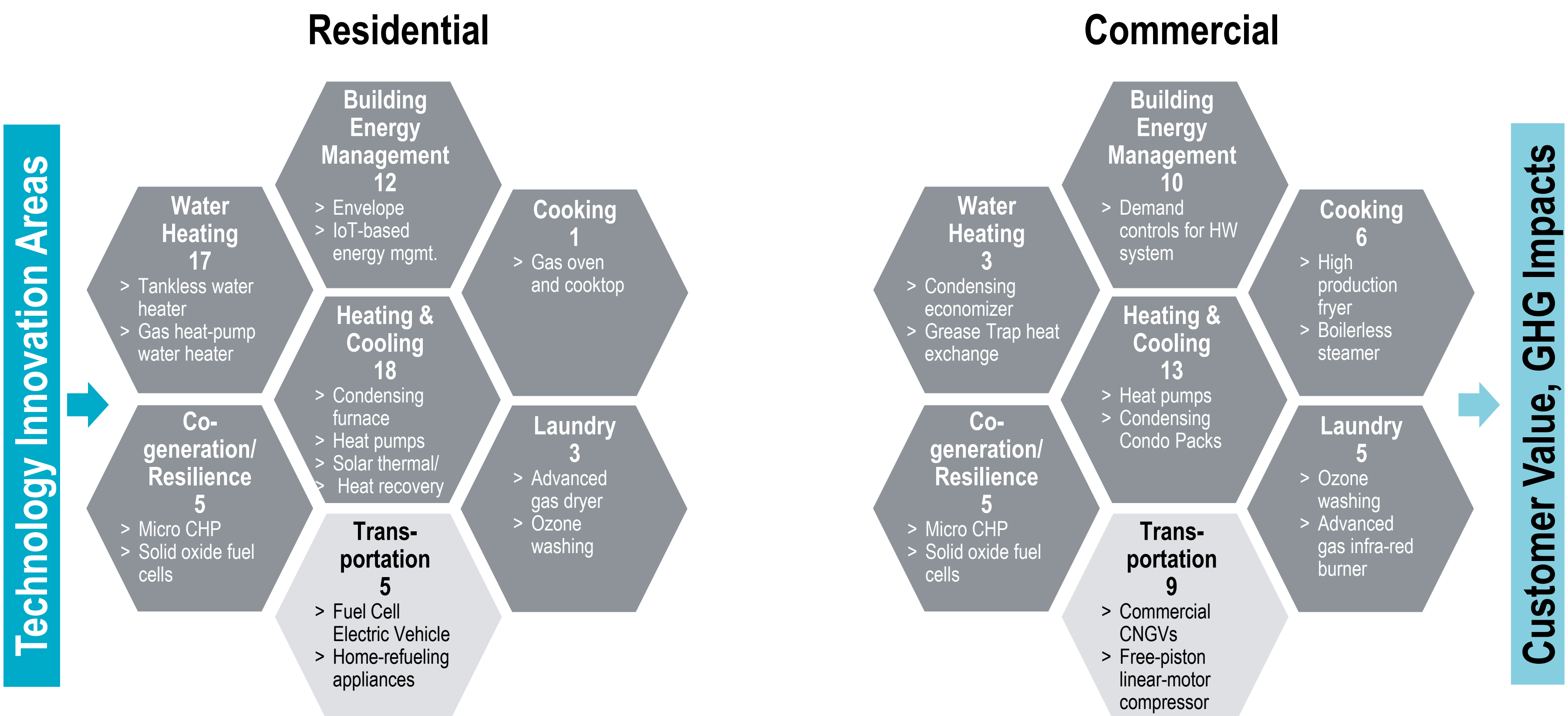
Extensive global research, interviews, workshops and webinars highlighted over 100 significant emerging gas technologies

Major end uses and representative technologies



Focus of the study | Outside of the main focus of the study

Notes: Total number of technologies exceeds 100 due to applicability to both sectors and multiple end uses

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All technologies were first assessed and then prioritized by level of impact and time to market, as well as several other secondary criteria

	Area	Assessment criteria
Primary	Energy and GHG Impacts	Impact on energy consumption (kWh/MMBtu)
		Impact on electric peak (kW) or gas peak (MMCFD)
		Overall efficiency improvement and GHG emissions reduction
		Accessible market size
	Technology Maturity	Commercial availability < 5 years
		Commercial availability 5 to 10 years
		Commercial availability 10 to 15 years
Secondary	Non-energy benefits	Effective use of waste heat
		Other factors – e.g., comfort; indoor air quality
	Economics	Overall economics
		Susceptible to use of renewable gas
		Highly dependent on turnover of current stock
	Regulatory/ Commercial Barriers	Technical barriers – relies on high GHG impact materials
		Practical barriers – space to install
		Safety
		Building codes
		Regulator-approved rebates
		LDC ability to market
	Scale	Standardization of configuration
		Ease of scaling up to produce modules at scale

> Assessment framework helped prioritize gas technologies based on relative level of impact and market readiness

> Additional research gathered data to serve as foundation for:
- Estimating energy savings and emissions impact at technology level
- Incorporating into relevant end use pathways
- Estimating energy savings and emissions impact at customer and pathway levels
- Mapping economics and barriers into expected market penetration rates

Combining emerging end-use technologies in the residential sector creates multiple pathways for customers to reduce GHG

Building Efficiency, 10-45%
> IoT based thermostat
> Building Envelope

Space Cooling, up to 45%
Space Heating, up to 40%
> Gas heat pump

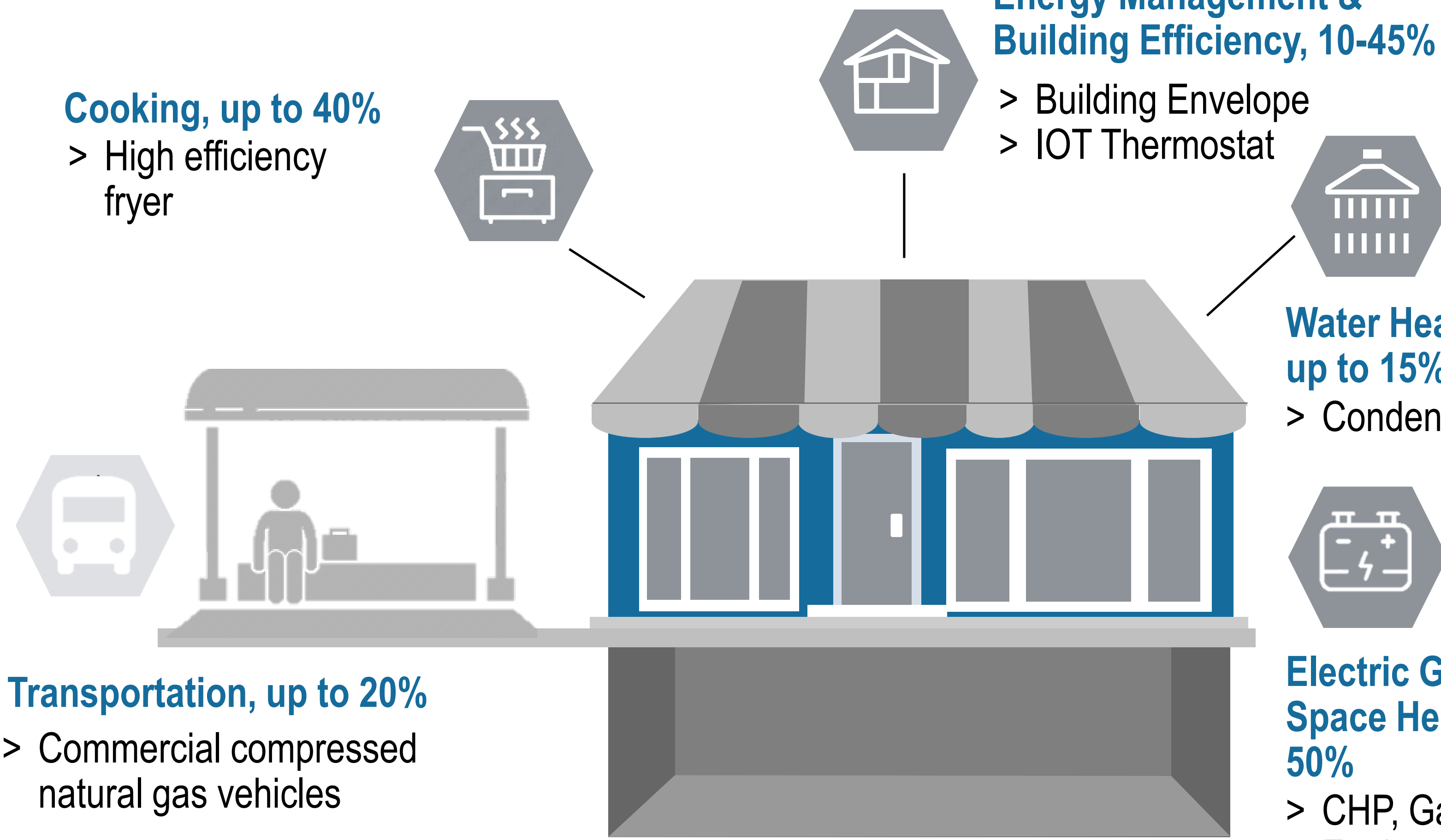
Water heating, up to 55%
> Absorption heat pump

Cooking, minimal change
> Gas stove
> Gas oven

Laundry, 55%
> Gas dryer
> Ozone washing

Notes: GHG reduction potential is estimated based on efficiency improvements over stock average gas equipment efficiency in 2016

Combining emerging end-use technologies in the small commercial sector creates multiple pathways for customers to reduce GHG



Cooking, up to 40%
> High efficiency fryer

Energy Management & Building Efficiency, 10-45%
> Building Envelope
> IOT Thermostat

Water Heating, up to 15%
> Condensing storage

Transportation, up to 20%
> Commercial compressed natural gas vehicles

Electric Generation & Space Heating, up to 50%
> CHP, Gas Recip Engine

Notes: GHG reduction potential is estimated based on efficiency improvements over stock average gas equipment efficiency in 2016

Phase 2 objective: Assess the costs, volume and speed of GHG impacts from accelerated adoption of more efficient gas direct use technologies at the US national level

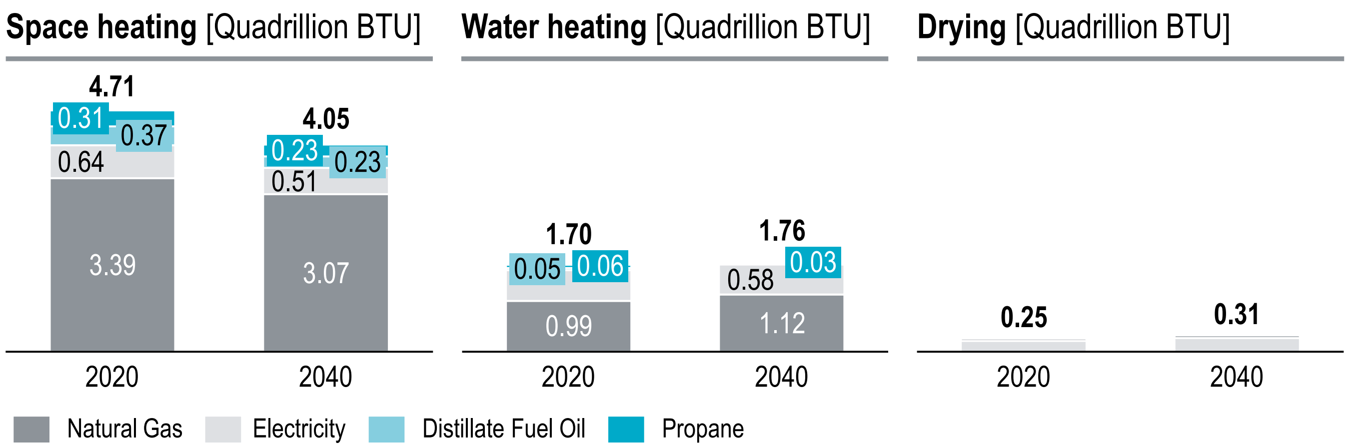
Gas decarbonization pathway scenarios

Assumptions	Base Case	Scenario 1: Accelerated Adoption of Near-Term High-Efficiency Technologies	Scenario 2: High Penetration Rates of Emerging High-Efficiency Technologies	Scenario 3: Decarbonization Through Emerging High-Efficiency Technologies and RNG
Policies and incentives	Current policies	> Current policies > Utility driven customer incentives	> Policies favoring emerging high efficiency gas technologies > Additional incentives provided to customers by utilities	> Policies favoring emerging high efficiency gas technologies > National policies favoring RNG > Additional incentives provides to customers by utilities
Natural gas technologies	Per AEO2019 with associated efficiency improvement curves	*Existing* and high probability *emerging* high efficiency technologies with higher penetration rates	*Existing* and *emerging* high efficiency technologies with high penetration rates	*Existing* and *emerging* high efficiency technologies with high penetration rates
All other technologies		The same as base case	The same as base case	The same as base case
Technology cost	Per AEO2019	Per GTI with some incentives	Per GTI with some incentives	Per GTI with some incentives
Fuel switching	Per AEO2019	Yes[1]	Yes[1]	Yes[1]
RNG	Per AEO2019	Per AEO2019	Per AEO2019	Increased production of RNG

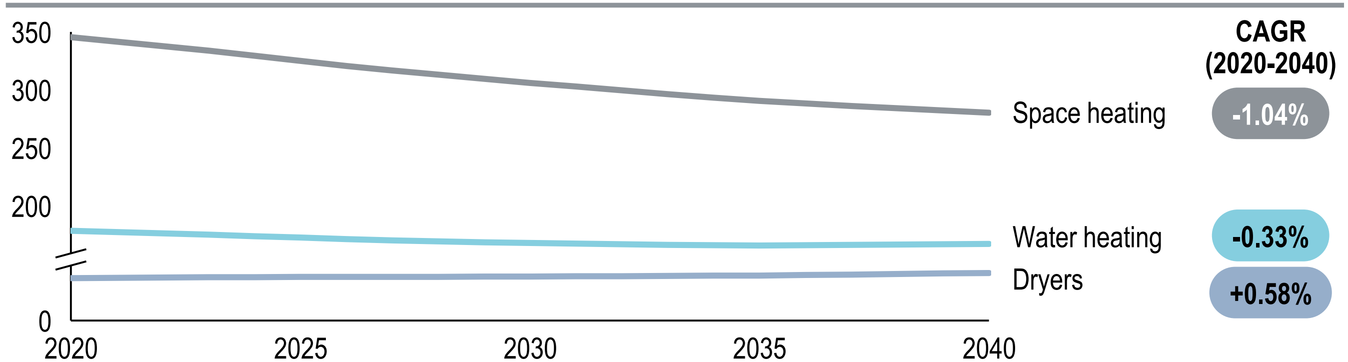
1) Additional fuel switching (beyond the base case) from electricity and other fuels to gas

Natural gas usage and emissions in US EIA's base case will decrease significantly through 2040 - primarily due to higher efficiencies

Base case fuel consumption by end use in 2020 vs 2040



National residential emission outlook 2020 – 2040 [million tons]



> Overall residential sector emission will be reduced by 71 MT by 2040 and is driven by the reduction in space heating sector (-65 MT) and water heating (-11MT), which outweighs the increased emission from dryer sectors (+4 MT)

> Space heating emission reduction is driven by several pathways: improved energy efficient technology and shift away from high CO_2 intensity fuels at burner tip
  – Energy consumption for residential space heating will decline by 0.7%, reducing from 2020 levels of 4.7 to 4.05 quad BTUs by 2040

> While the overall water heating emission is reduced by 11MT by 2040, natural gas consumption will increase by 0.3%, driven by increased use of natural gas appliances

> Drying sector emission have increased historically due to increased natural gas consumption

Source: EIA

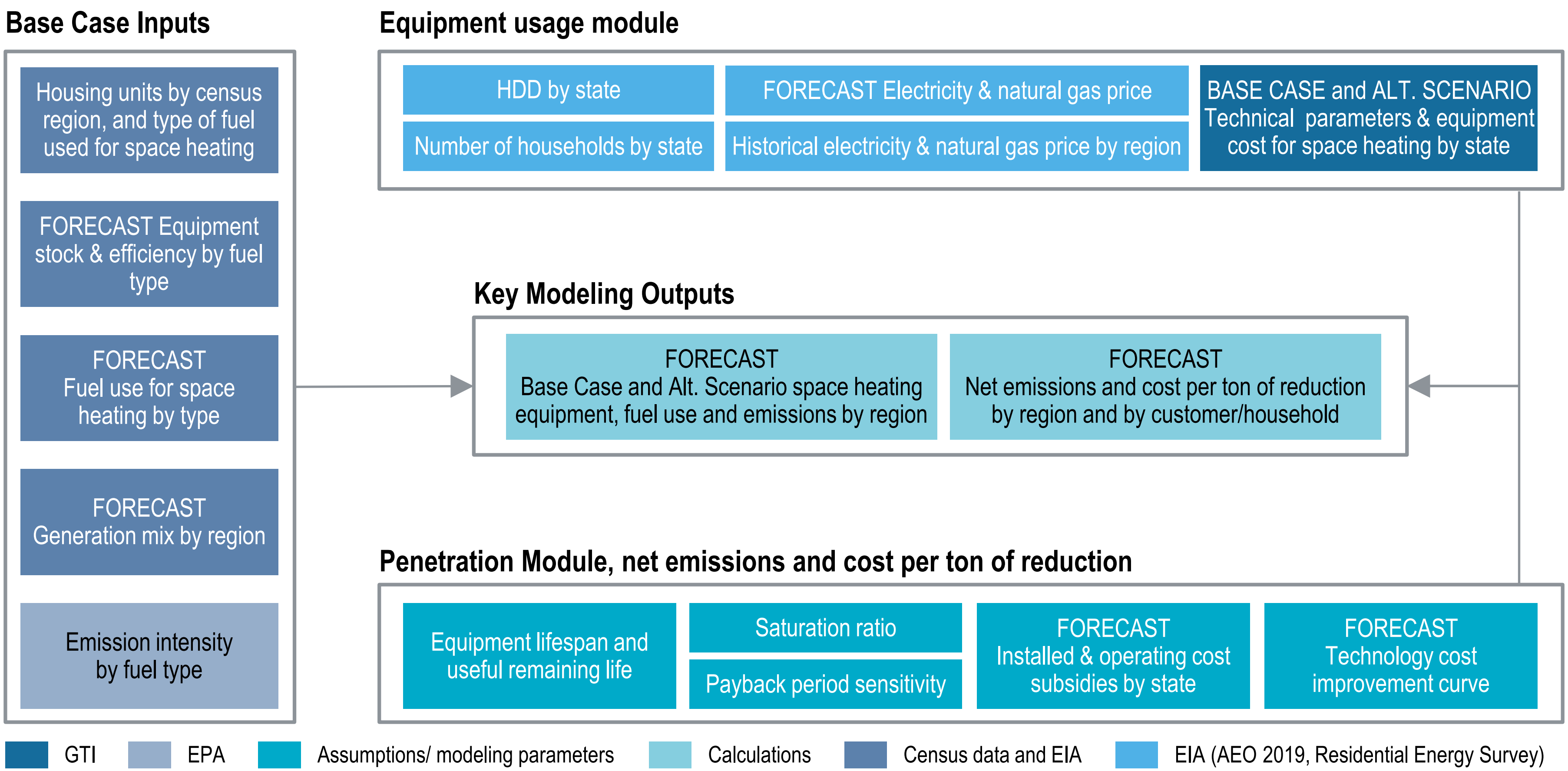
The following technologies were selected for modeling by scenario, based on the relative cost-effectiveness of potential GHG reduction

End-Use	Scenario 1 (commercially available by 2022)	Scenario 2, 3 (commercially available before 2030)
	Natural gas furnace (AFUE 97%)	Natural gas furnace (AFUE 97%) Gas absorption heat pump (AFUE 1.4)
	Gas heat pump water heater (1.3 UEF)	Gas heat pump water heater (1.3 UEF)
1)	Gas standard cooking range	Gas standard cooking range
	Standard Energy Star certified dryer (CEF 3.49)	Standard Energy Star certified dryer (CEF 3.49)
1)	Gas internal combustion engine micro CHP (electric efficiency 28%-30%)	Solid oxide fuel cell micro CHP (electric efficiency 40%)

1) Modeled, but not included in the final results
Source: Roland Berger

Established data sources and methodologies were used to build technology usage and market penetration rates in Phase 2

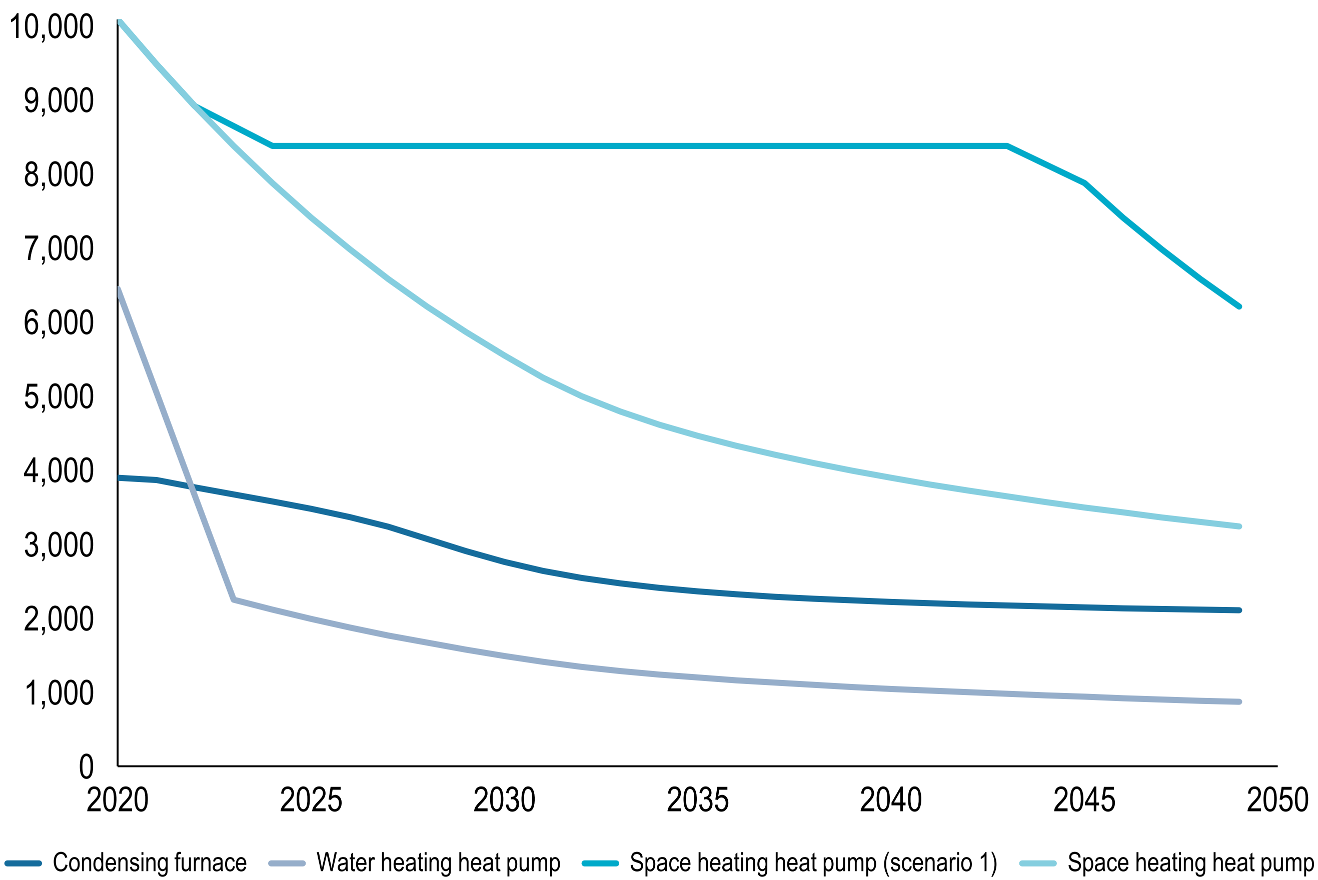
Space heating example



Note: Penetration module methodology derived from NREL

Equipment unit cost of natural gas technologies declines with increased scale and cumulative experience

Natural gas appliance installed cost decline curves[1] (2020 USD/unit)

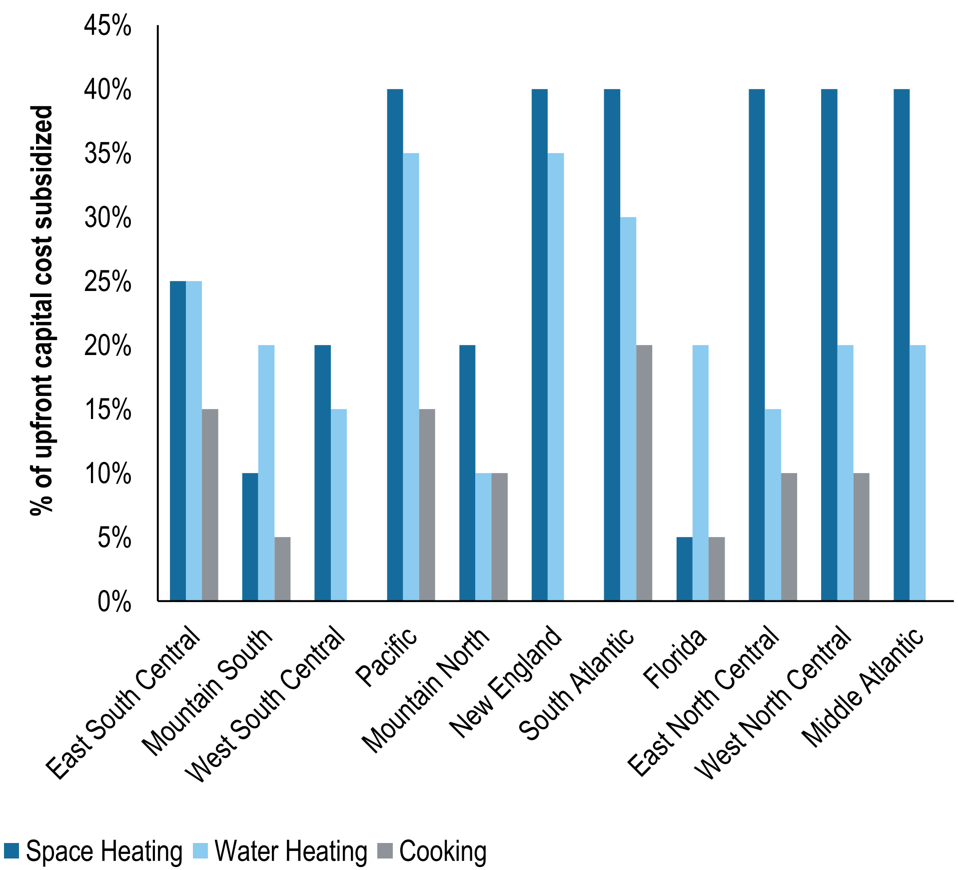


- We developed forward cost curves for the technologies used in our analysis based on the historical cost decline curves of similar appliances
- Cost curve decline rate dependent on first cost and level of adoption of the technology
- Scenario 2 introduced higher level of incentive, which reduced the first cost, increasing the adoption causing a rapid decline in the cost curve
- Cost curves shown here are representative and are a function of the number of units entering the market in a given year

1) The cost decline curve is composed of appliance cost which declines with experience and scale and installation cost which also declines with experience but at much lower rate;
2) The cost decline curves are adjusted to nominal values for the analysis
Source: Roland Berger analysis; Incorporating Experience Curves in Appliance Standards Analysis, LBNL; GTI

The impacts of first cost incentives on acceleration of market penetration and achievement of scale/learning benefits were analyzed by U.S. region and use case

Level of capital cost[1] subsidy assumed (by use case and region)



1) capital cost = installed cost + retail margin

> Chosen technology alternatives are generally economic relative to Base Case for all use-cases and do not require subsidies for long-term penetration. However, high first costs will likely make progress slow.

> For accelerated penetration, we modeled subsidies range between $100-$1,200/unit
  – Subsidies were capped at 40% of total capital cost
  – Additional subsidies rapidly escalate cost/ton of emissions reduction with little further acceleration of market penetration

> Level of subsidy for space and water heating calculated to arrive at a net cost of CO_2 emissions ($/ton) close to that in Base Case

> Space heating requires the highest levels of subsidies, ranging between 5% to as high as 40% in colder regions
  – Colder regions such as New England have higher gas consumption, as well as larger equipment size, therefore could allow for large subsidies while maintaining a total cost per ton CO2 close to the base case

> Despite the larger cost differential in water heating technologies between the Base Case and the scenarios, level of subsidy required is usually lower, as compared to space heating due to higher efficiency gains and greater relative reductions in operating cost

> Depending on emission intensity of electricity, subsidy support for cooking is only required for select regions, ranging between 5-20%

> For all new technologies, a glide path achieving 8% cost reduction in nominal terms by 2031 due to cost improvements was assumed (Source: NREL)

Fisher-Pry methodology was used to apply S-curves to consumer buying decisions, for modeling technology adoption

Five classes of technology adoption characteristics

Characteristics	A	B	C	D	E
Time to saturation	5 years	10 years	20 years	40 years	>40 years
Technology factors					
Equipment Life	<5 years	5-15 years	15-25 years	25-45 years	>40 years
Equipment Replacement					
Technology Experience	None	Minor	Unit operation	Plant section	Entire plant
Industry Factors	New to US only	New to US only	New to US only	New	New
Growth (% per year)	>5%	>5%	2-5%	1-2%	<1%
Attitude to Risk	Open	Open	Cautious	Conservative	Adverse
External Factors					
Government Regulation	Forcing	Forcing	Driving	None	None
			Scenario 2,3	***Scenario 1***	

- > Market penetration in our analysis depends on the simple payback as an input
- > Fisher-Pry S-curves provide the rate of adoption of technology as a function of the technology characteristics and market conditions for an existing market of known size
- > The rate at which technologies are adopted depends on several market characteristics: technology characteristics (e.g., technology economics, new vs. retrofit); industry characteristics (e.g., industry growth, competition); and external factors (e.g., government regulation, trade restrictions)
- > Although the methodology was not specifically developed for natural gas end-use technologies it is often adopted for technologies in difference industries (e.g., modeling of PV penetration)
- > Adoption curve needed to be adjusted based on the equipment turnover rate as well as its remaining value at the year for which payback was calculated

Source: NREL, Roland Berger

C. Results

Smart, temporary subsidies[1)] for high efficiency technologies can drive substantial cost-effective reduction in GHG emissions

Regional residential emission reductions by 2050 and range of subsidies applied for heat pumps for space heating

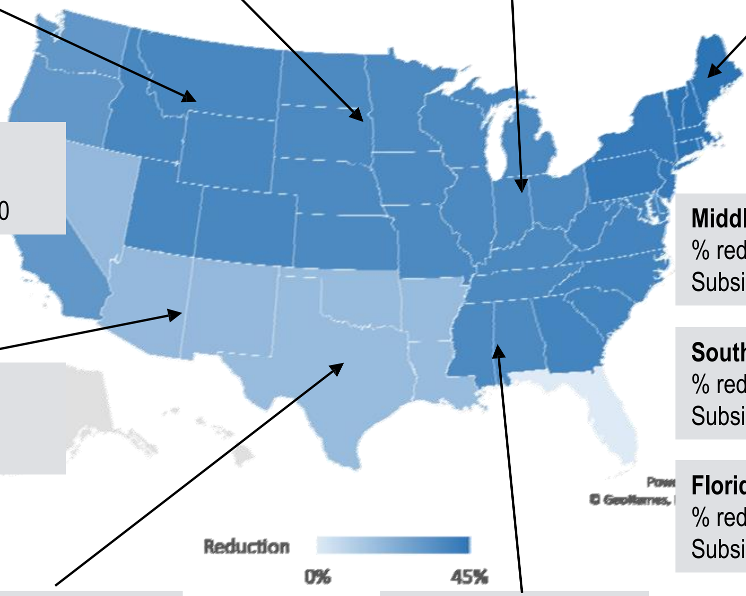
Mountain North
% reduced: 38%
Subsidy: $800-1,800

West North Central
% reduced: 37%
Subsidy: $1,080-2,500

East North Central
% reduced: 37%
Subsidy: $970-2,300

New England
% reduced: 45%
Subsidy: $1,400-3,200

Pacific
% reduced: 32%
Subsidy: $800-1,900



Middle Atlantic
% reduced: 43%
Subsidy: $1,090-2,500

South Atlantic
% reduced: 39%
Subsidy: $560-830

Florida
% reduced: -
Subsidy: none

Mountain South
% reduced: 19%
Subsidy: none

West South Central
% reduced: 18%
Subsidy: $440-1,020

East South Central
% reduced: 37%
Subsidy: $630-$1,440

National Level Results (Scenario 2)

Emission Reduction
46%

Cost
$90/ton

Consumer Impact
Mean savings of $220/year

Technology Penetration
85%

1) Based on percentage of commodity cost savings and removed after adequate scale is achieved

Source: Roland Berger analysis

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Smart, temporary subsidies[1)] for high efficiency technologies can drive substantial cost-effective reduction in GHG emissions

Regional residential emission reductions by 2050 and range of subsidies applied for heat pump water heaters

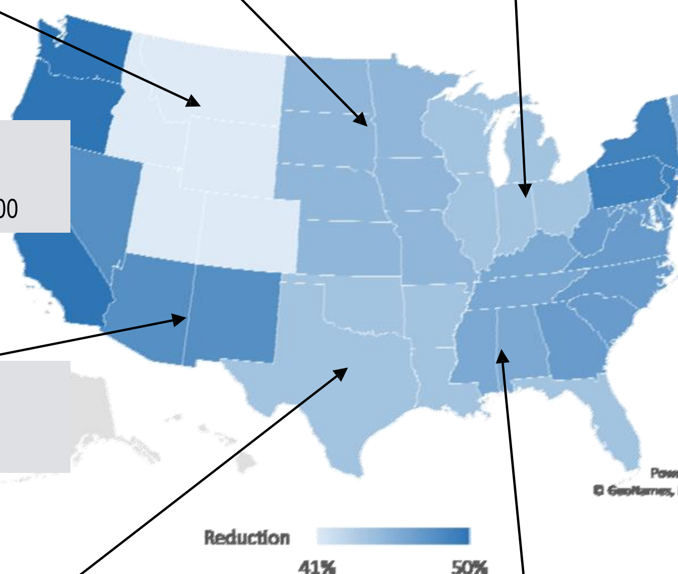
Mountain North
% reduced: 41%
Subsidy: $500-600

West North Central
% reduced: 45%
Subsidy: $600-700

East North Central
% reduced: 44%
Subsidy: $600-700

New England
% reduced: 45%
Subsidy: $800-1,000

Pacific
% reduced: 50%
Subsidy: $850-1,000



Middle Atlantic
% reduced: 49%
Subsidy: $800-900

South Atlantic
% reduced: 47%
Subsidy: $800-900

Mountain South
% reduced: 48%
Subsidy: 600-800

Florida
% reduc ed: 44%
Subsidy: $600-800

West South Central
% reduced: 44%
Subsidy: $600-800

East South Central
% reduced: 46%
Subsidy: $600-800

National Level Results (Scenario 2)

Emission Reduction
36%

Cost
$39/ton

Consumer Impact
Mean savings of $143/year

Technology Penetration
96%

1) Based on percentage of commodity cost savings and removed after adequate scale is achieved

Source: Roland Berger analysis

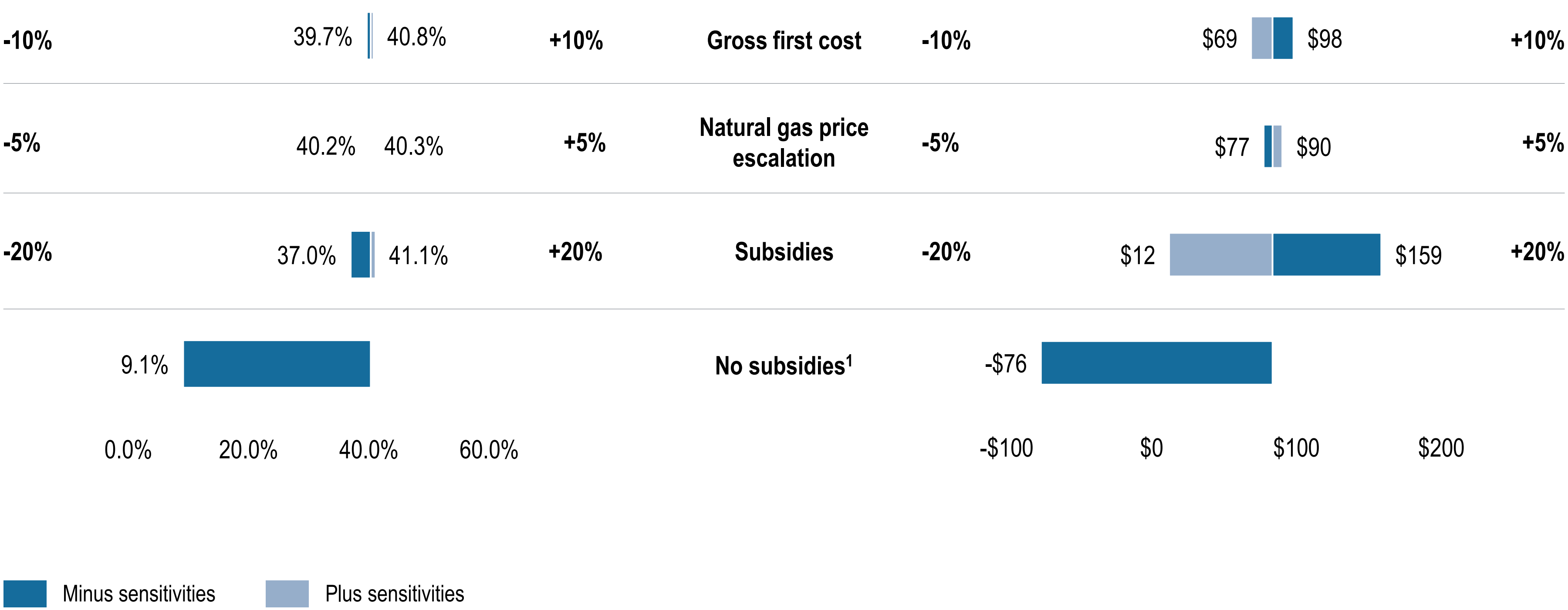
Overall CO_2 reductions in 2050 are most sensitive to the amount of subsidies

Sensitivity analysis for emission reductions [%]

Change from 40% in Scenario 2

Sensitivity analysis for cost per ton of emission reductions [$/ton]

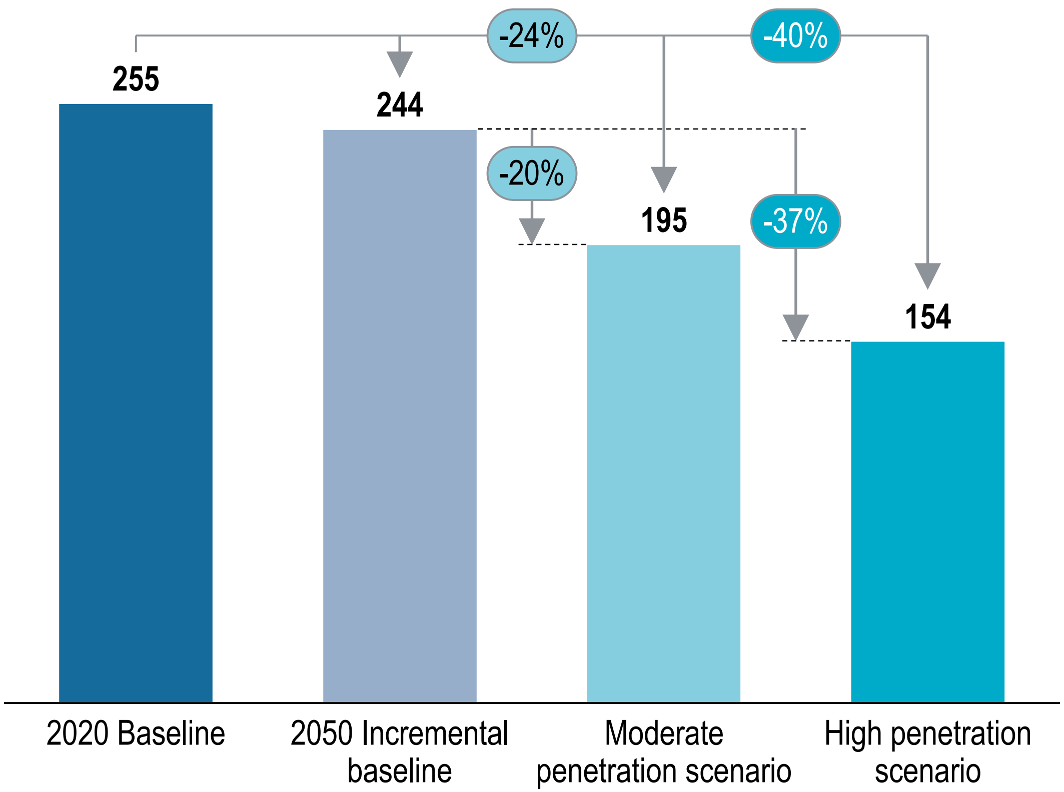
Change from $84/ton in Scenario 2



1) "No subsidies" sensitivity recalculated the cost decline curve to reflect lower penetration
Note: Only the 3 major end-uses are included in the analysis

High efficiency technologies could dramatically reduce CO2 emissions by 2050 relative to the baseline (before considering RNG/hydrogen)

CO_2 emissions from residential direct use of natural gas (million tons of CO_2,per year by 2050)



> In the High Penetration scenario, the 101 MMT of annual CO_2 reductions (40%) are achieved at a net cost of $66 per MT of CO_2.

> Under the Moderate Penetration scenario, 60 MMT of annual CO_2 reductions (24%) are achieved at a net *savings* of $51 per MT of CO_2 .

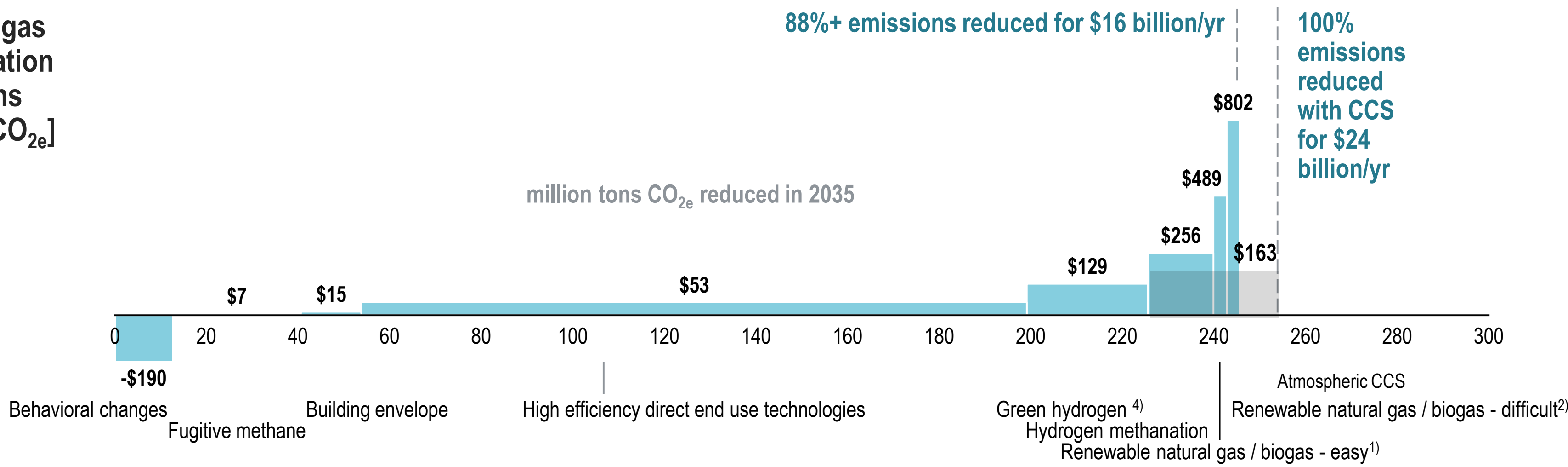
> Under either scenario, the CO_2 reductions are significant on a national scale, and at costs per ton that are low relative to other potential options for reducing emissions such as electrification at $572-806 per MT and atmospheric removal of CO_2 at $94-232 per MT.

> These levels of CO_2 emission reductions are achieved despite the overall increase in number of equipment units in each end-use analyzed. For example, in space heating the total number of equipment units increases by 36 percent from 2020 to 2050, in water heating by 35 percent, and in clothes drying by 53 percent.

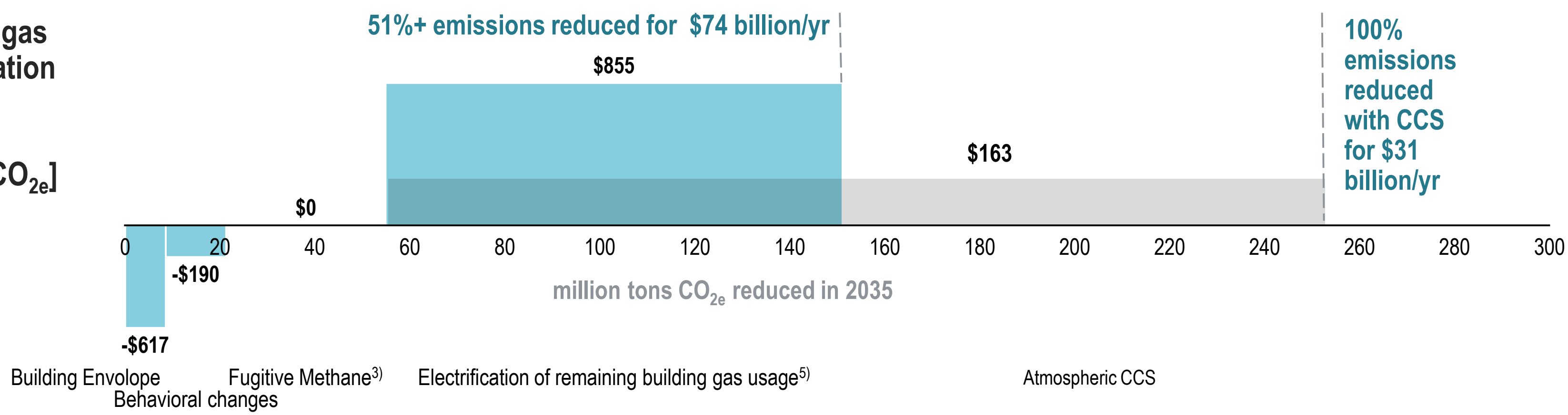
Source: Enovation Partners analysis, Roland Berger

Gas and electric options for US residential gas decarbonization – with and without atmospheric CCS (backstop technology)

Residential gas decarbonization – gas options [USD / ton CO_{2e}]



Residential gas decarbonization - electricity options [USD / ton CO_{2e}]

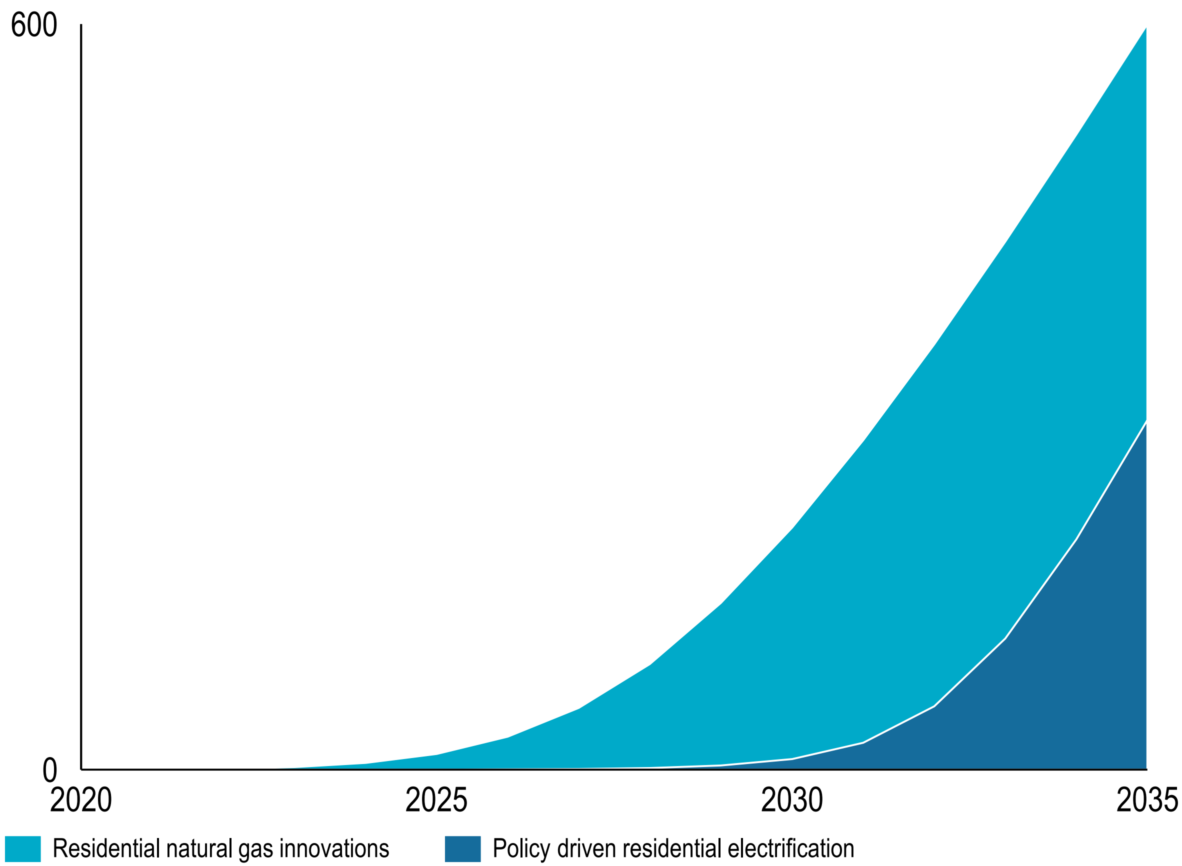


1) Relating to feedstock that is easily accessible for the generation of renewable natural gas / biogas; 2) Relating to feedstock that is not easily accessible for the generation of renewable natural gas / biogas; 3) Fugitive methane emissions under electrification pathway is zero cost because it is achieved by avoiding natural gas use; 4) Green hydrogen quantity is limited to 10% blending by volume to avoid infrastructure upgrades required for higher H2 blends; 5) Cost per ton for electrification of remaining gas usage sourced from ICF, inflated by 2% to consistently report all costs in 2019 $ terms

Source: EIA, ICF, AGF, NPGA, desktop research, Roland Berger

In the medium term, residential gas innovations provide significantly more GHG reductions at a faster rate than building electrification

2035 cumulative residential US GHG reduction forecast [m tons of CO_{2e}]



Natural gas innovations – Assumptions & rationale

- **~590 m tons CO2e** cumulatively reduced by 2035 – **~15% reduction** of residential natural gas emissions by 2035
- Leveraging existing channels & incentives
- Using US made equipment
- Provides faster/easier delivery of infrastructure upgrades
- Quicker implementation driven by cheaper available solutions

Policy driven residential electrification – Assumptions & rationale

- **~280 m tons CO2e** cumulatively reduced by 2035 – **~7% reduction** of residential natural gas emissions by 2035
- Slower uptake on delivery of infrastructure upgrades and realization of GHG reductions
- High Capex investment requires longer lead-times to get new assets running
- Year over year GHG reductions assumes an "S" curve in adoption rates

Source: Enovation Partners analysis, ICF, Roland Berger

More efficient end use could complement abatement in gas supply and delivery, to cut US residential GHG emissions by 90+% by 2035 while avoiding expensive retrofits and electric system build-out

Residential natural gas innovations pathways

1 Supply innovation

- Maximizing cost-effective production of renewable natural gas (RNG or biogas)
- Scale adoption of power to gas (P2G), including:
  - Hydrogen displacement of natural gas
  - Hydrogen methanation
- Switching from carbon-intensive fuels (e.g., propane, heating oil, kerosene) to natural gas

40-50% reduction in CO_{2e} emissions

2 Delivery enhancement

- Reducing fugitive methane leaks during the following steps of the value chain:
  - Transportation/ distribution
  - Meters
  - Behind the meter at homes
- Implementing hydrogen ready infrastructure

5-10% reduction in CO_{2e} emissions

3 Demand & natural gas technology innovation (efficient use)

- Improvement and adoption of high efficiency residential technologies, specifically in:
  - Space heating
  - Water heating
  - Drying
- Implementing behavioral changes towards energy efficiency
- Updating the residential building envelope with energy efficient materials & technology

35-45% reduction in CO_{2e} emissions

Source: Enovation Partners analysis, Roland Berger

Contributing team from Roland Berger LP and Gas Technology Institute



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