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OPPORTUNITIES FOR REDUCING GREENHOUSE GAS EMISSIONS THROUGH EMERGING NATURAL GAS DIRECT-USE TECHNOLOGIES

An American Gas Foundation Study Prepared by:

Enovation
Partners

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Abbreviations

AEO	Annual Energy Outlook
AGA	American Gas Association
AGF	American Gas Foundation
AFUE	Annual Fuel Utilization Efficiency is a metric for combustion-based equipment (furnace)
BTU	British Thermal Unit is a unit of heat
CDD	Cooling Degree Days
CEF	Combined Energy Factor is the energy performance metric for clothes dryers
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide equivalent
EF	Energy Factor is a metric used to compare energy conversion efficiency of residential appliances and equipment
EIA	Energy Information Administration
EPA	Environmental Protection Agency
GHG	Greenhouse Gases
GTI	Gas Technology Institute
HDD	Heating Degree Days
IECC	International Energy Conservation Code
IoT	Internet of Things
kBtuh	1000 British Thermal Units per Hour
kW	Kilowatt is a unit of power
kWh	Kilowatt hour is a unit of energy
MicroCHP	Micro combined heat and power system – CHP less than 50kWh
MMT	Million metric ton
MT	Metric tons
MWh	Megawatt hour is a unit of energy
NREL	National Renewable Energy Laboratory
O&M	Operation and Maintenance
RNG	Renewable Natural Gas
UEF	Uniform Energy Factor is a metric used to compare energy conversion efficiency of residential and commercial water heaters

Executive Summary

A. Key Take-Aways

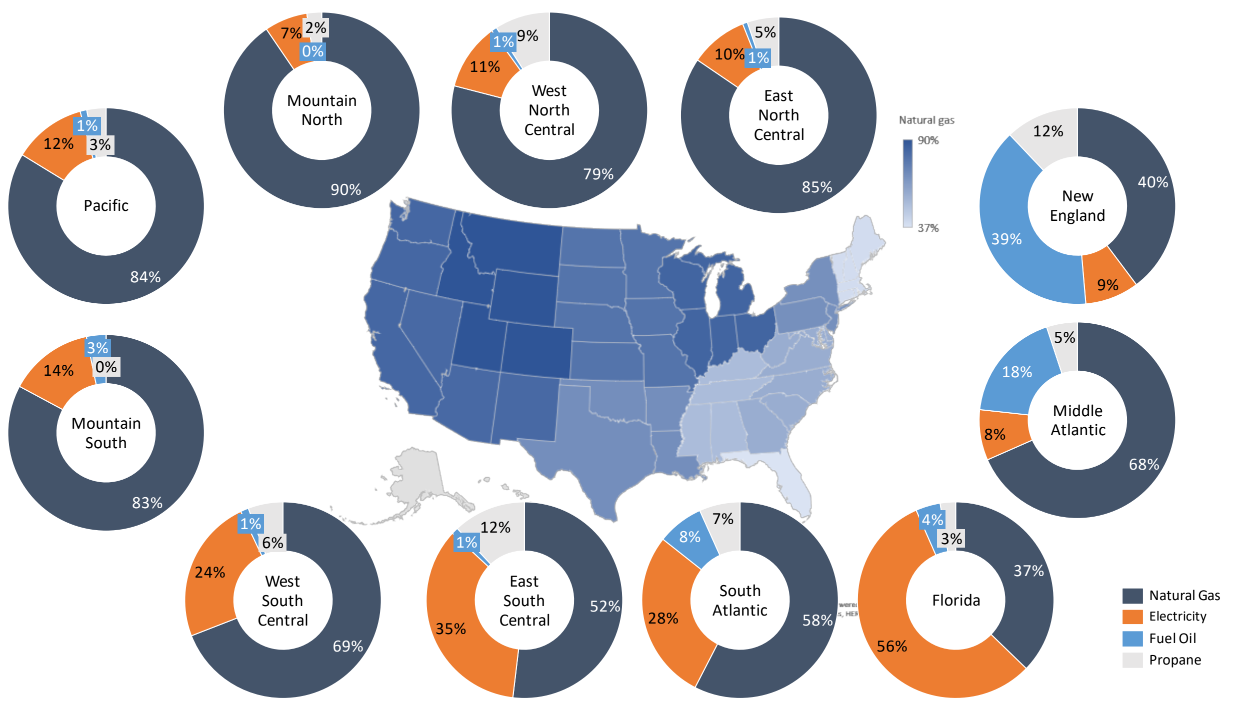
This study demonstrates how widespread adoption of emerging natural gas direct-use technologies can contribute significantly to achieving public goals of deep reductions in greenhouse gas (GHG) emissions in the U.S. residential sector, with much lower costs than other options under consideration. It's low hanging fruit that should be a core element considered for any responsible emissions reduction plan.

- U.S. residential natural gas emissions can be reduced by 24 percent through the advancement of more efficient emerging technologies, with average net savings (negative costs) of $51 per metric ton of CO_2 equivalent ("ton" or "MT" as used in this report). With higher levels of incentive support for emerging technologies, GHG emissions can be reduced by 40 percent, at the modest average cost of $66 per ton.
- No technological miracles are required. The natural gas direct-use technologies modeled in this study are either available now or are expected to roll out to market within three years.
- No policy mandates were assumed, e.g., bans of specific technologies or required levels of GHG emission reductions. The savings can be achieved by offering cost-effective incentives and allowing customers to make choices. Customers can consider the superior resiliency and comfort of highly efficient natural gas equipment in their buying decisions. Incentives can be removed once the gas technologies have achieved economic scale and equipment costs are competitive on their own.
- Higher direct-use efficiencies on the demand side can be complemented by increased use of carbon-neutral biogas and hydrogen (collectively "renewable gas") on the supply side, plus continued reductions in methane emissions along the gas delivery chain, to produce very deep cuts to residential GHG emissions from natural gas usage
- In the long-term world of deep decarbonization, direct use of natural gas and renewable gas can serve more intense energy uses more efficiently and effectively than all-electric solutions, which may be technically feasible but are much costlier and can require vast amounts of new infrastructure.
- There is no "one size fits all" solution to reducing GHG emissions. This study demonstrates how natural gas can be a core component of an integrated approach for achieving U.S. emissions reduction goals while providing options that allow gas utilities and their customers to choose what works best in their circumstances (resource base, types of energy demands, demographic mix).

B. Role of Natural Gas in Meeting Residential Energy Needs

Natural gas contributes more to meeting energy needs than many people realize. Maybe that's because furnaces, heat pumps and water heaters are out of sight and out of mind, just doing their job. Nonetheless, 58 percent of U.S. homes have natural gas service. Natural gas currently meets 68 percent of total U.S. residential space and water heating demands. That market share varies widely by region, as shown in Figure 1. Natural gas delivers more than 83 percent of annual heating energy to households in the East North Central, West North Central, Mountain North, Mountain South and Pacific regions. Replacing all that gas energy with electricity would require vast investments to increase production and delivery capacity. Meanwhile, the gas infrastructure to meet those demands is already in place. It can be a very valuable set of assets for delivering clean energy.

Figure 1 Natural Gas Share of Total Residential Energy Consumption for Space and Water Heating in 2018[1]



This report focuses on space heating, water heating and clothes drying in the residential sector. Space and water heating together account for 91 percent of residential gas consumption. Clothes drying amounts to less than 1 percent of gas use but has some impactful emerging technology. Cooking adds another 3 percent but has no major energy efficiency technologies for the residential market. The remaining demand is attributable to hot tubs, fireplaces, patio warmers and a variety of smaller volume uses. Due to their lower level of materiality, the GHG emissions reduction potential in these smaller direct uses was not assessed.

While emerging natural gas direct-use technologies offer step function gains in efficiency, natural gas direct-use efficiency has continued to improve in recent years. Innovations such as efficient burner

[1] Sourced from EIA.

designs and heat recapture technologies have successfully penetrated the market and delivered energy and emissions savings. Improvements in complementary technologies that reduce energy demands (tighter building envelopes, better insulation, smarter controls etc.) have also cut into residential gas consumption. Figure 2 shows the declining trend in natural gas consumption per household, with the trend in total residential natural gas consumption falling slowly while gas customer count grows robustly.

Figure 2 Trends in Total U.S. Residential Weather Normalized Natural Gas Consumption vs. Gas Customer Count (Source: American Gas Association)

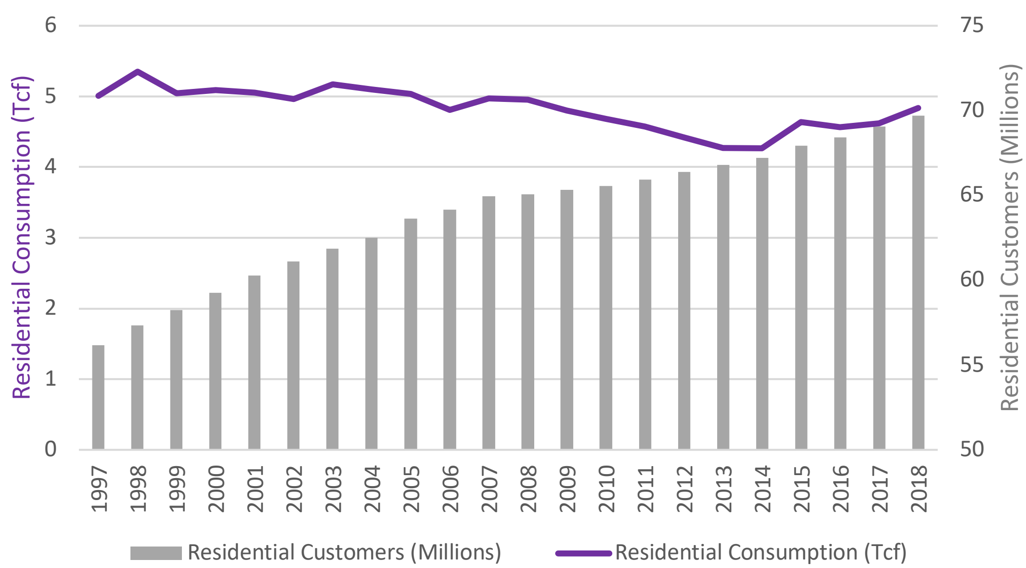
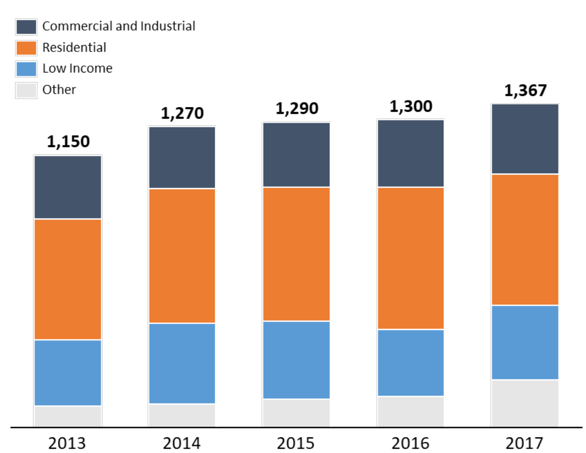


Figure 3 Natural Gas Utility Investments in Energy Efficiency Programs (Millions)[2]



The historical penetration of more efficient heating and water heating technologies was accelerated by the efforts of natural gas utilities. Their investments in energy efficiency programs, which typically take the form of incentive payments to customers who buy more efficient equipment and other forms of energy efficiency support, has grown steadily over the years (See Figure 3). Given the ambitious GHG emission reduction targets that have been adopted in many states, and the relatively low cost of achieving such reductions through more rapid adoption of more efficient direct-use technologies, that upward trend for natural gas utility spending on energy efficiency programs is expected to continue.

[2] Consortium for Energy Efficiency. State of the Efficiency Program Industry: Budgets, Expenditures, and Impacts 2018. http://www.cee1.org/annual-industry-reports, posted May 2019. © Copyright 2019 Consortium for Energy Efficiency. All rights reserved.

C. Innovation in Natural Gas Direct-Use Technologies

The pace of innovation in more efficient natural gas direct-use technologies has been accelerating in recent years. A predecessor study to this study, conducted for the American Gas Association in 2018, identified more than 120 different technology innovations that could significantly improve gas end use efficiency. These technologies are in various places along the research, development and demonstration spectrum. Some are still in the laboratory or early development. Some are in demonstration and almost ready for market. Some are ready for market but not yet penetrated.

These emerging natural gas direct-use technologies are quite diverse, as shown in list of identified technologies in the Appendix of the 2018 report.[3] Research facilities operated by several prominent gas industry players and universities or government agencies[4] will play important roles in developing, testing and commercializing these technologies.

The 2018 study concluded that, on a per customer basis, energy savings from deploying the most promising natural gas emerging technologies could reduce household natural gas consumption and GHG emissions by 20-45 percent, depending on the technology. That conclusion is broadly consistent with the findings below from this study.

D. Study objectives: Assessing Opportunities for Achieving Meaningful and Cost-Effective Emissions Reductions through Emerging Natural Gas Technologies

The intent of this American Gas Foundation report is to:

- provide factual information on how faster penetration of more efficient emerging natural gas direct-use technologies could contribute to meeting emissions reduction goals; and to
- compare the volume, timing and cost of such GHG emission reductions to other potential pathways.[5]

The following key questions are addressed in this study:

- How much could U.S. CO_2 emissions be reduced with current and emerging residential direct-use gas technologies by 2050?
- What is the expected unit cost of achieving these reductions?
- What savings or costs would customers see?
- What type and level of financial support would be needed to realize the full benefits of these technologies?

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[3] See pages 28-30 of the 2018 report. https://www.aga.org/globalassets/research--insights/reports/ghg-reduction-pathways_phase-1-report.pdf

[4] For example, Gas Technology Institute, Research and Innovation Center for Energy (owned by Engie), Gas and Heat Institute (Germany), Osaka Gas, Tokyo Gas, Korea Gas, University of California – Irvine, European Research Institute for Gas & Technology Innovation, National Renewable Energy Laboratory, to name a few.

[5] "Pathway" as used in this report is a combination of energy sources and technologies that over time can meet defined goals for reducing GHG emissions.

E. Analytical approach

The study modeled two scenarios with moderate and high levels of penetration of emerging natural gas direct-use technologies for space heating, water heating and clothes drying applications. Within the overall residential sector, natural gas use is mainly concentrated within two end-uses: space heating and water heating. These two end-uses are responsible for 91 percent of all residential sector natural gas consumption. Clothes drying end-use is responsible for less than percent and was also analyzed in both scenarios. The levels of penetration in each scenario were determined by the level of incentives introduced to accelerate the penetration of these technologies and summarized in the Table 1 below.

Table 1 Technology Penetration Levels Achieved by 2050 in Each End-Use[6] (percent of total units installed)

End-Use	Moderate Penetration scenario	High Penetration scenario
Space heating	74% (furnace) 10% (heat pump)	75% (heat pump)
Water heating	64%	92%
Clothes drying	22%	69%

The study results shown in the Introduction section below are attributable to the deployment of emerging natural gas direct-use technologies that are projected to be commercially available before 2023 (listed in the figure below). These technologies were selected from a long list of considered technologies forecasted to be commercially available before 2030. Even greater emissions reductions could be realized through even higher efficiency technologies commercially available after 2030. A high potential of emission reductions also exists in the commercial sector based on our review of the emerging technologies. However, only residential emissions are considered in this study. Overall results in both scenarios are highly sensitive to the levels of incentives provided, first costs and technology cost reduction over time. Additional details on scenario specific assumptions are further discussed in Section 4.2 of the report.

Table 2 Emerging High-Efficiency Natural Gas-Fired Technologies Selected for the Study[7]

End-Use	Moderate Penetration scenario	High Penetration scenario
Space heating	Natural gas furnace (AFUE 97%) Gas absorption heat pump (AFUE 1.4)	Gas absorption heat pump (AFUE 1.4)
Water heating	Gas heat pump water heater (1.3 UEF)	Gas heat pump water heater (1.3 UEF)
Clothes drying	Standard Energy Star certified dryer (CEF 3.49)	Standard Energy Star certified dryer (CEF 3.49)

[6] In addition to equipment turnover forecasted in the Baseline
[7] See additional discussion on technologies considered and selected for the study in Appendix E and F

G. Study conclusions: Less costly, quicker, deeper emission reductions

Less costly. This report concludes that advancing the penetration of emerging natural gas direct-use technologies for major end uses is a more cost-effective way to reduce GHG emissions in the residential sector than other options currently being considered by states and cities. The pathway including natural gas emerging technologies has a much higher volume of accessible low-cost options for GHG emissions reduction.

Quicker. Because these emission reductions can be delivered by equipment in the market now or within three years, and would not require expensive and very time-consuming rebuilding of electric generation, transmission and distribution infrastructure (as would be the case for electrification solutions), they could be achieved earlier than with other options and could, over time, avoid higher cumulative amounts of emissions.

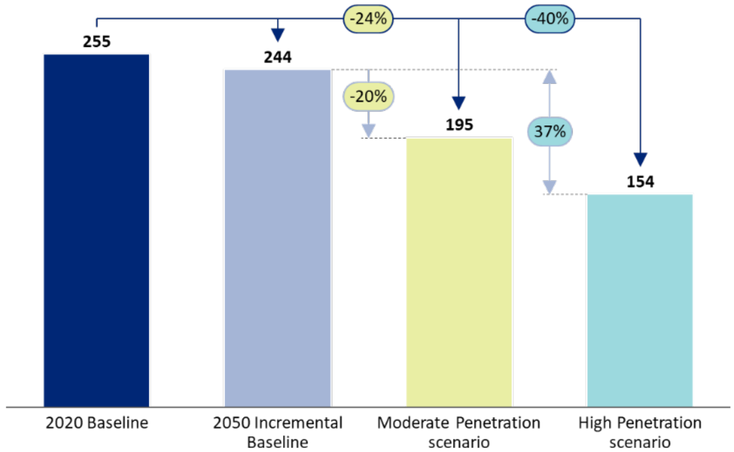
Deeper. A third advantage is that the GHG emissions reductions from emerging natural gas direct-use technologies could be deeper in the near term and medium term (through 2035-2040) in regions where substantial portions of electricity supplies will continue to come from coal or natural gas fired generation. Emissions reductions from reduced natural gas use will all count directly toward emissions reduction goals, while electrification solutions may actually increase GHG emissions in places where the grid has a high carbon footprint that reflects fuel mix and large thermodynamic losses of energy in converting fuel to electricity.

In the longer term, higher natural gas direct-use efficiencies on the demand side can be complemented by increased use of carbon-neutral renewable natural gas and hydrogen on the supply side, plus continued reductions in methane emissions along the gas delivery chain. This natural gas pathway could provide meaningful and cost-effective contributions towards reducing U.S. GHG emissions.

F. Key Findings

Under the High Penetration scenario, the residential sector could reduce overall annual CO_2 emissions by 101 million metric tons/year (MMT/year) by 2050 relative to the 2020 Baseline representing a 40 percent reduction in total residential natural gas emissions. With the Moderate Penetration scenario, 60 MMT of CO_2 or a 24 percent reduction in residential emissions could be reduced relative to the 2020 baseline. The reductions in residential emissions for the two scenarios relative to the Baseline emissions in 2020 and 2050 are shown in Figure 4.

Figure 4 CO_2 Emissions from Residential Natural Gas Use[8] (MMT of CO_2 per year)



In the High Penetration scenario, the 101 MMT of annual CO_2 reductions are achieved at a net cost of $66 per MT of CO_2 reduced. Under the Moderate Penetration scenario, 60 MMT of annual CO_2 reductions are achieved at a net *savings* of $51 per MT of CO_2 reduced. 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[9].

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.

From the consumer perspective, the High Penetration scenario achieves considerable savings. Nationally, for an average consumer in 2033 that installs the high-efficiency technology for space heating, water heating, and clothes drying could expect to save $271 each year over the lifetime of the equipment (levelized savings in 2020$).

[8] Emission reduction in High Penetration scenario includes reductions from complementary technologies (e.g. insulation, smart thermostats) in the amount of ~4 MMT of CO_2 per year

[9] Cost estimates are from *Implications of Policy-Driven Residential Electrification, AGA, 2018* study. While the cost estimates are not fully "apples-to-apples" comparison as the scope boundary of the referenced study is different from this report, it nevertheless serves as an important comparison point.

1. Introduction and Background

Greenhouse gas emissions reductions have been a central topic of modern-day environmental and political dialogue. Since 1990, the natural gas industry and gas utilities, in particular, have made significant contributions to reducing U.S. greenhouse gas emissions. Natural gas distribution system methane emissions declined 73 percent between 1990 and 2017 due in large part to the modernization of the gas distribution pipeline system.[10] The natural gas utility industry spent more than $22 billion annually to help enhance the safety of more than 2.4 million miles of natural gas distribution and transmission systems[11]. It also reduced emissions from distribution pipeline by 16 percent.[12]

Today, there are 69 million residential natural gas households in the United States. Since 1970, residential natural gas consumption has been essentially flat with only relatively small variations in annual residential gas demand each year due to weather. In turn, delivered gas volumes to residential consumers—and therefore residential gas CO_2 emissions— has remained virtually unchanged for nearly fifty years despite there being more than 32 million more residential customers than in 1970. The dynamic of a growing number of customers using the same amount of natural gas is the direct result of energy efficiency improvements, including tighter building envelopes, more efficient appliances and equipment, the effectiveness of natural gas utility efficiency programs, and behavior changes in energy consumption.

States that switched to natural gas from other high CO_2-intensity fuels such as heating oil and propane achieved greater emission intensity reduction. With these past accomplishments, this study examines how advancing and deploying highly efficient, emerging natural gas technologies could achieve meaningful emissions reductions over the next thirty years.

This study uses the Energy Information Administration's (EIA) Annual Energy Outlook (AEO) 2019 Reference Case as its Baseline and focuses on demand-side innovation for natural gas in the residential sector. Therefore, it assesses how emerging direct-use technology deployment and other complementary technologies could reduce the overall residential demand for natural gas through higher efficiency product offerings. The study does not contemplate other emissions reductions opportunities in the residential sectors such as the use of renewable natural gas (RNG) or hydrogen, fuel switching from more carbon-intensive fuels, or other approaches beyond what is already embedded as part of the EIA Reference Case.

[10] Reported by EPA
[11] Spending reported by AGA 2014 playbook
[12] Spending reported by AGA 2014 playbook

The boundary of the emission analysis is drawn around the burner tip. Therefore, methane emissions associated with natural gas production and transportations are not considered. Methane emissions at the burner tip are assumed to be minimal. In cases where the introduction of the new natural gas direct-use technology incurs additional electricity consumption, emissions associated with this incremental amount of electricity are included in the analysis.

2. Results

2.1. National Results

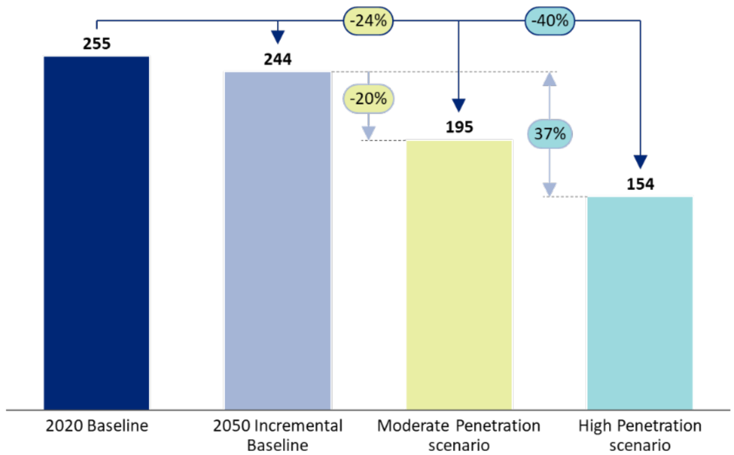
The study compared two modeled scenarios (see scenario descriptions in Table 3 below) with the 2020 Baseline based on the EIA's AEO 2019 Reference Case. The Moderate Penetration scenario models a moderate level of penetration of emerging, high-efficiency natural gas-fired technologies driven by moderate levels of incentives. The High Penetration scenario models a more accelerated but still realistic level of penetration of the same technologies supported by higher incentives that would likely pass energy efficiency program cost-effectiveness screens. The level of penetration of emerging, high-efficiency natural gas-fired technologies is driven by rational economic decision making on the part of the end-users (households)—not by policy mandates. Additional details on the model are specified in Appendix H. Discussion on selection of technologies and associated incentives assumed in the analysis is presented in Section 4.3 and Appendix F respectively.

Table 3 Scenario Descriptions

Key assumptions	Baseline	Moderate Penetration scenario	High Penetration scenario
Description	AEO2019	Moderate level of incentives accelerates penetration of emerging, high-efficiency natural gas-fired technologies: • Condensing furnace (AFUE 97%) • Space heating heat pump (AFUE 1.4) • Water heating heat pump (1.3 UEF) • Energy Star gas dryer (CEF 3.49)	Higher level of incentives accelerates the penetration of emerging, high-efficiency natural gas-fired technologies: • Space heating heat pump (AFUE 1.4) • Water heating heat pump (1.3 UEF) • Energy Star gas dryer (CEF 3.49)
Policies (i.e. energy efficiency standard and mandates)	Only currently implemented policies considered	The same as baseline	The same as baseline
Incentives	No new incentives	• Incentives vary by equipment type, state, and year • Amount of incentives is proportional to the avoided city gate cost of gas	• Incentive available for space and water heating heat pumps only • Amount of incentives is a higher portion of the avoided city gate cost of gas relative to Moderate Penetration scenario

Under High Penetration scenario, by 2050, total U.S. residential natural gas emissions could be reduced by 101 MMT relative to 2020 Baseline, representing a 40 percent reduction. Under Moderate Penetration scenario, residential natural gas emissions could be reduced by 60 MMT, representing a 24 percent reduction relative to the 2020 Baseline. These emission reduction results for the two scenarios are shown in Figure 4 below.

Figure 4 CO2 Emissions from Residential Natural Gas Use (MMT of CO2 per year)



It is important to note that the results of High Penetration scenario include emissions reductions attributable to complementary energy-efficiency technologies that could accompany the emerging, high-efficiency natural gas-fired equipment. Complementary technologies include water pipeline insulation and Internet-of-Things (IoT) devices like smart thermostats. These complementary technologies account for ~4 MMT of emissions reductions, representing 1.7 percent of the 2020 Baseline emissions. The methods to incorporate the complementary technologies ensure there was no double counting of any building efficiency-related measures that are already included as part of the EIA Baseline. Additional details on complementary technologies are summarized in Section 4.

Within the overall residential sector, natural gas use is mainly concentrated within two end-uses: space heating and water heating. In the 2020 Baseline these two end-uses are responsible for 91% of all residential sector natural gas consumption (space heating is responsible for 70% of consumption and water heating for 21%). Clothes drying end-use is responsible for less than 1% and was also analyzed in both scenarios. Other minor end-uses like cooking and cooling were not included in the scope of this study due to their relatively minor consumption volume and emission footprint or small emission reduction potential near term (before 2030).

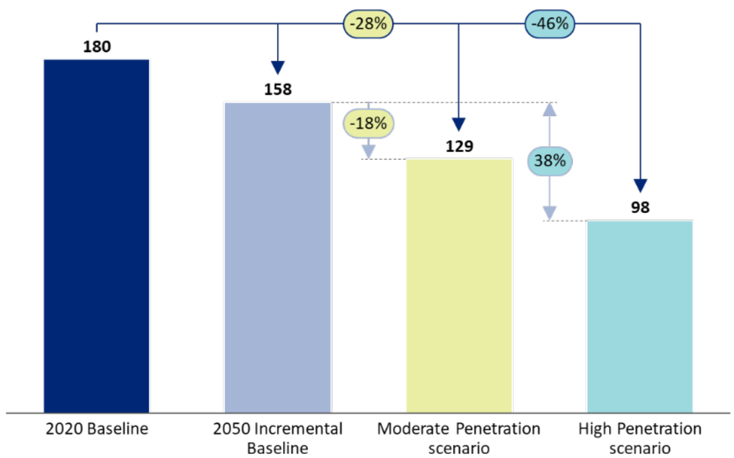
Emissions are reduced over the 2020-2050 timeframe in both scenario despite the absolute level of installed equipment units increasing significantly over the same period. Number of space heating unit increases by 36 percent, water heating units increase by 35 percent, and clothes drying units increase by 53 percent.

From the consumer perspective, High Penetration scenario achieves considerable savings. For example, nationally, an average consumer in 2035 that installs the space heating heat pump, water heating heat pump, and Energy Star clothes dryer could expect to save $271 each year over the lifetime of the equipment (levelized savings in 2020$). These results vary considerably by region which is further explored in the next section.

Space Heating

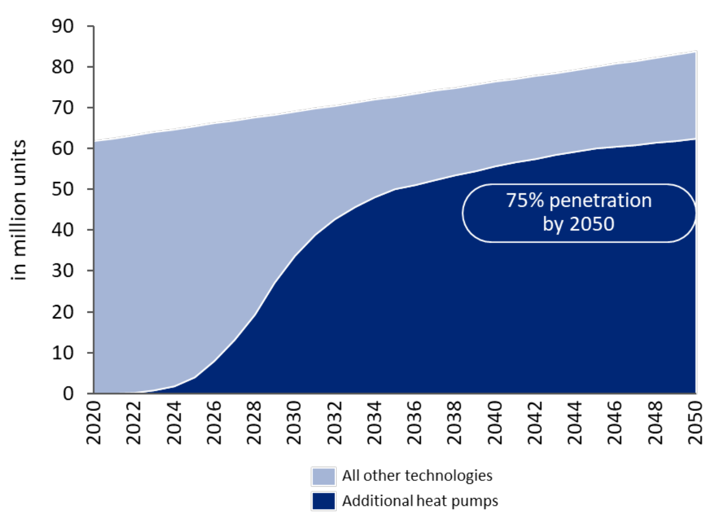
By 2050, using highly efficient condensing furnaces and heat pumps for space heating in Moderate Penetration scenario and space heating heat pumps in High Penetration scenario reduces emissions by 51 and 82 MMT (28 and 46 percent reduction relative to 2020 Baseline) respectively. The emission reduction results for the two scenarios are summarized in Figure 5 below.

Figure 5 CO_2 Emissions from Residential Natural Gas Use in Space Heating (MMT of CO_2 per year)



Nationally, under High Penetration scenario, natural gas heat pumps reach a 75 percent penetration by 2050. The associated costs of up to $3,200 per heat pump (in the form of the first cost incentive) for achieving these reductions result in a $66/ton cost of emissions reduction. The rate of penetration is shown in Figure 6 below. Regionally the penetration levels vary significantly. These differences are discussed in the next section.

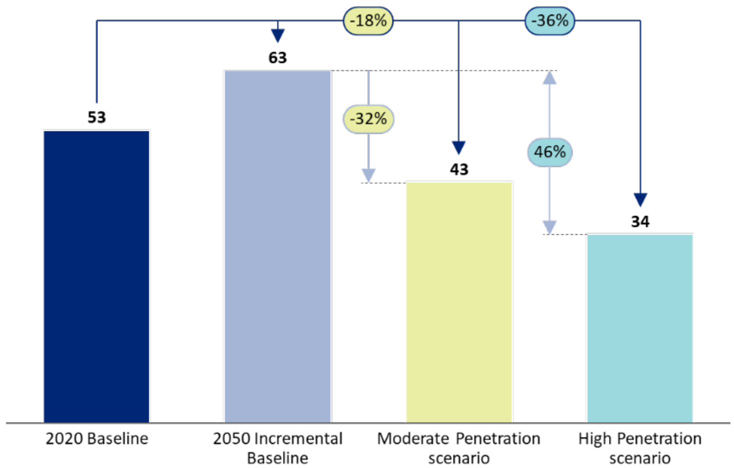
Figure 6 Additional Penetration of Space Heating Heat Pumps at the National Level in High Penetration Scenario (millions of units)



Water Heating

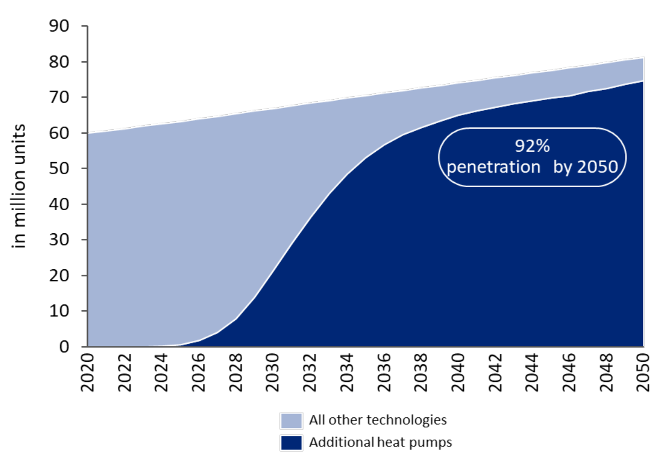
By 2050, using highly efficient heat pumps for water heating reduces CO_2 emissions by 9 and 19 MMT (18 and 36 percent reduction relative to 2020 Baseline) in Moderate Penetration and High Penetration scenarios respectively. The emission reduction results for the two scenarios are summarized in Figure 7 below.

Figure 7 CO_2 Emissions from Residential Natural Gas Use in Water Heating (MMT of CO_2 per year)



Nationally, under High Penetration scenario, heat pump water heaters achieve a 92 percent penetration by 2050, at the cost of $62/ton. The relatively low first cost differential between the Baseline water heater (see detail discussion on equipment cost in Appendix F) and the heat pump water heater used in Moderate and High Penetration scenarios, along with the widespread use of water heating equipment throughout the country, allows this technology to achieve high levels of penetration and emissions reductions at a relatively low cost per ton. The rate of penetration is shown in Figure 8 below. The differences in regional levels of penetration levels are discussed in the next section.

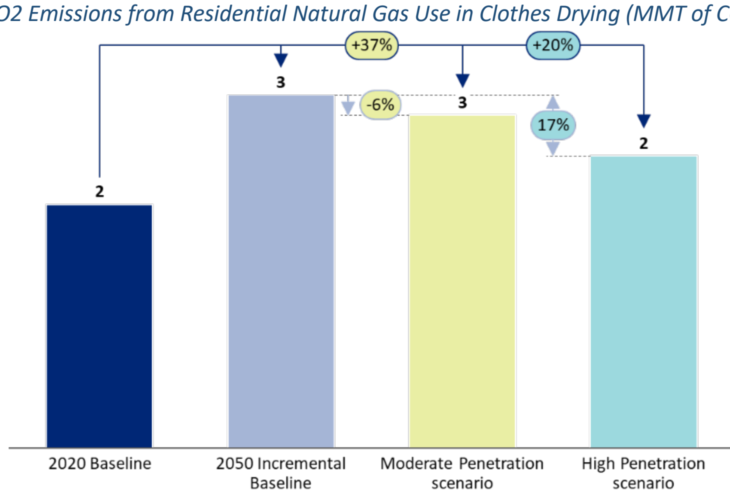
Figure 8 Additional Penetration of Water Heating Heat Pumps at the National Level in High Penetration Scenario (millions of units)



Clothes Drying

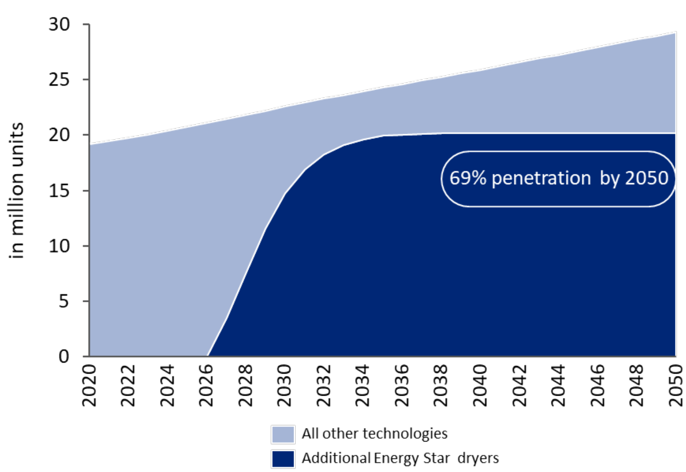
By 2050, measuring relative to 2020 Baseline results in a small increase in emissions from cloths drying end-use. This is because the number of clothes drying units increases by 53% in the EIA Baseline. The associated emissions increase more due to number of units than reductions achieved due to the higher efficiency dryers. Relative to 2050, high efficiency dryers can reduce emissions by 0.2 and 0.5 MMT (6 and 17 percent reduction relative to 2050 Baseline) in Moderate Penetration and High Penetration scenarios respectively. Relative to 2020 Baseline, Moderate Penetration scenario results in a 37 percent increase and High Penetration scenario results in a 20 percent increase in emissions due to the inherent increase in emissions between 2020 and 2050. The emission reduction results for the two scenarios are summarized in *Figure 9* below.

Figure 9 CO2 Emissions from Residential Natural Gas Use in Clothes Drying (MMT of CO_2 per year)



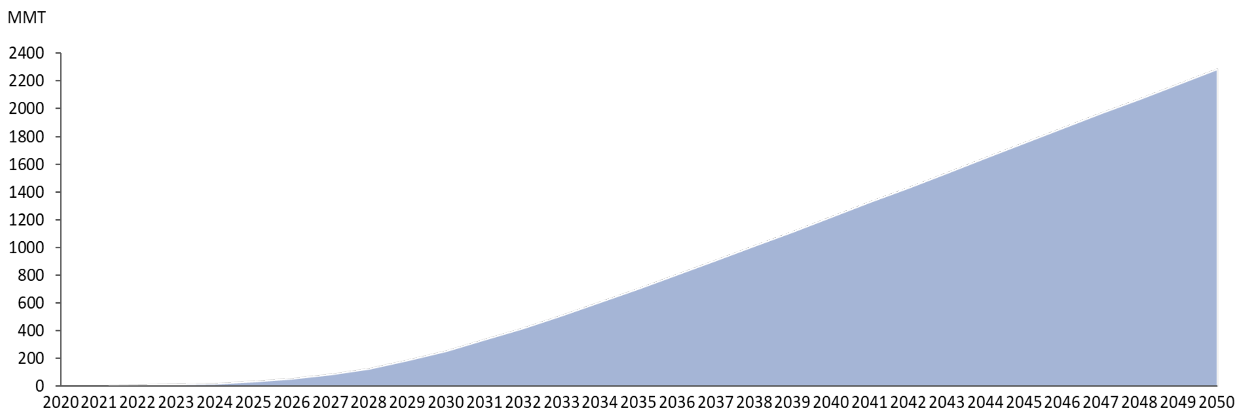
Nationally, under High Penetration scenario, the penetration of standard Energy Star certified dryer achieves a 69 percent penetration. The rate of penetration is shown in Figure 10 below. The differences in regional levels of penetration levels are discussed in the next section.

Figure 10 Additional Penetration of Energy Star Dryers at the National Level in High Penetration Scenario (millions of units)



Overall, across the three end-uses, High Penetration scenario achieves a cumulative 2,286 MMT of CO_2 emissions reductions by 2050 at an average reduction of 76 tons each year between 2020 and 2050 with almost half the total volume of reductions (1,143 MMT) achieved by 2040 (as show in Figure 11). By 2050, these reductions are achieved at a cost of $66/ton (relative to 2020), which is significantly less than other CO_2 abatement options, including electrification for residential end-uses estimated at $572-806 per MT and atmospheric removal of CO_2, estimated at $94-232 per MT[13].

Figure 11 Cumulative Emission Reduction 2020-2050 (MMT) in High Penetration Scenario, Relative to 2020 Baseline



2.2. Regional Results

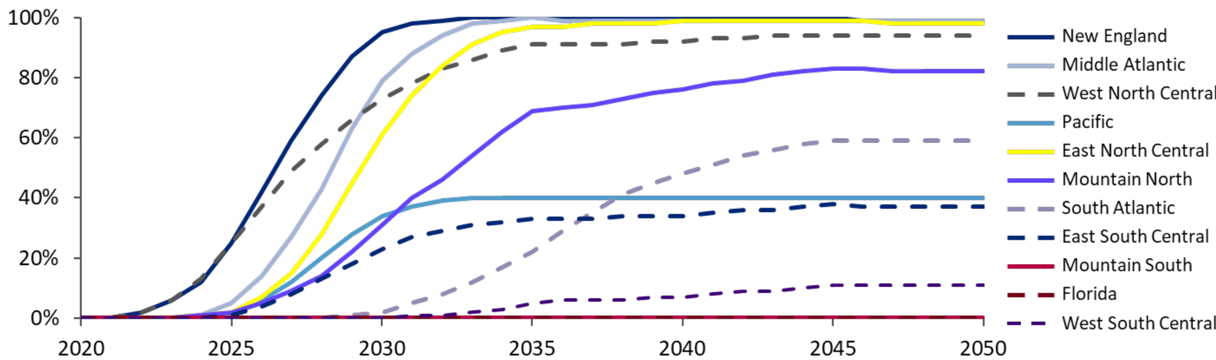
At a regional level, significant differences in penetration levels and the cost of emissions reduction exist between the three end-uses analyzed. These differences are discussed below.

Space Heating

In terms of penetration, regions with higher space heating requirements like New England, East North Central and Middle Atlantic have higher levels of penetration, while regions with lower heating requirements like Florida, West South Central, and Mountain South have lower levels of penetration. Figure 12 shows the level of penetration as percentage of new annual installations by year and region over time under the High Penetration scenario.

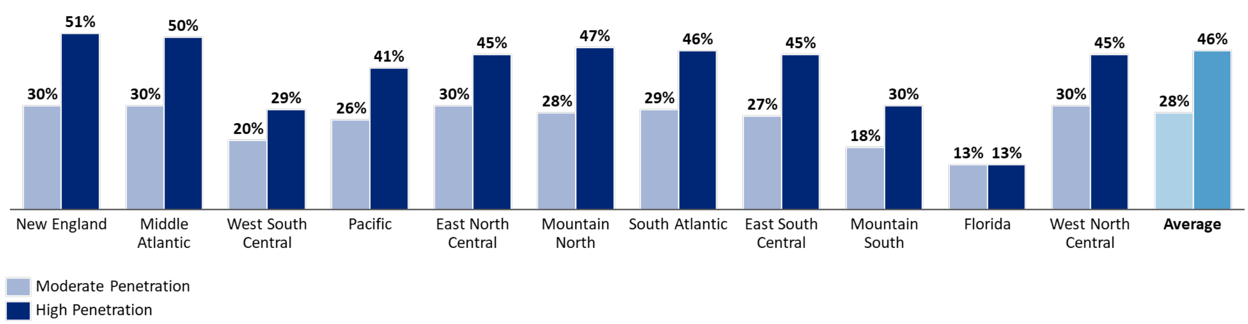
[13] Cost estimates are from *Implications of Policy-Driven Residential Electrification, AGA, 2018* study. While the cost estimates are not fully "apples-to-apples" comparison as the scope boundary of the referenced study is different from this report, it nevertheless serves as an important comparison point.

Figure 12 Regional Annual New Installments of Heat Pumps for Space Heating Under the High Penetration Scenario



Levels of emissions reductions are directly linked to the level of penetration. Consequently, regions with higher penetration also have higher levels of emissions reductions as shown in Figure 13.

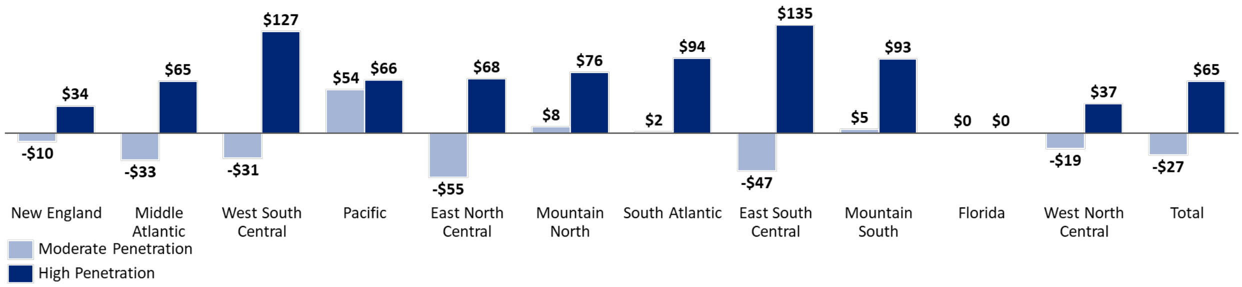
Figure 13 CO_2 Emission Reduction Percentage by 2050 for Space Heating by Scenarios[14]



The cost of abatement is the costs of providing incentives to consumers to offset the first cost of equipment. The amount of incentives varies widely by region due to the different levels of savings seen by consumers from installing high-efficiency gas-fired equipment. In general, if the cost savings during the lifetime of such equipment are high, the level of needed incentives is lower. Figure 14 below provides the regional distribution of abatement costs. As can be observed, colder climates need the least amount of incentives due to high cost saving achieved during the lifetime of equipment.

[14] Introduction of high-efficiency gas-fired technologies in low heating requirements regions such as Florida produces only low level of energy cost savings (or no cost saving in the first cost are considered) making the adoption of these technologies harder even with incentives which are limited to the avoided natural gas cost. Therefore, no incentives were introduced in Florida as the incentive cost would not be as cost beneficial for CO_2 reduction in comparison to other regions.

Figure 14 CO_2 Emission Abatement Cost/Ton for Space Heating[8]

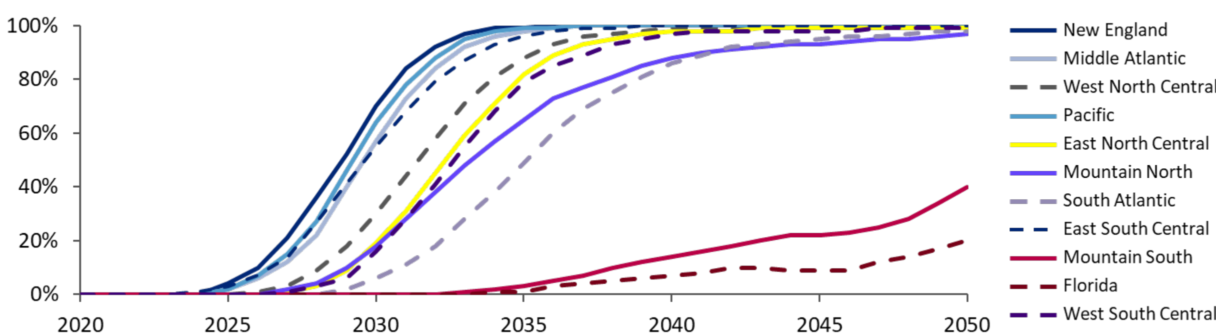


While emissions are reduced over the 2020-2050 timeframe, the absolute level of installed equipment for space heating grew by 36 percent over the same period. As a result, the emissions reduction per unit of equipment is an important metric. At a national level, furnaces in the Baseline produce ~3 tons of CO_2 while natural gas heat pumps in the scenarios modeled produce 1.8 tons[15] of CO_2 which represents a 42 percent decline.

Water Heating

Regional levels of penetration and emission reductions are less pronounced in water heating in comparison to space heating because the water heating requirements are less dependent on climate and more dependent on the ground water temperatures. Nearly all regions achieve significant levels of penetration, as shown in Figure 15 below.

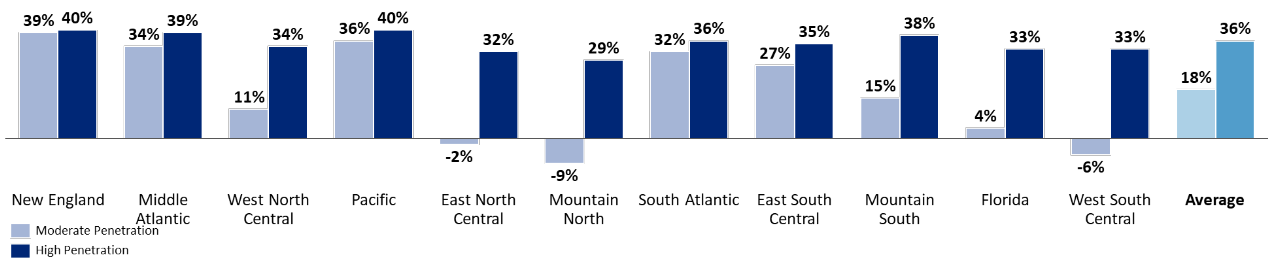
Figure 15 Regional New Annual Installations of Heat Pumps for Water Heating by 2050 Under High Penetration Scenario



Based on the levels of penetration, most regions achieve high rates of emissions reductions. Even regions like Mountain South and Florida, which had lower levels of penetration for space heating, achieve robust levels of penetration for water heating resulting in emissions reductions of over 30 percent. Regional water heating emissions reductions are summarized in Figure 16 below.

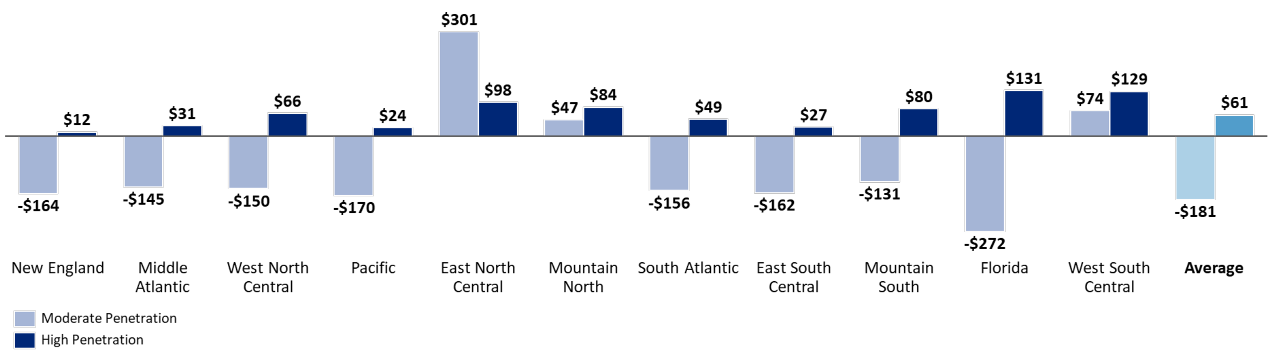
[15] Baseline emissions are estimated from EIA average space heating unit emissions, average space heating heat pump emissions are estimated from the GTI's Energy Planning Analysis Tool (EPAT).

Figure 16 Emission Reduction Percentage by 2050 for Water Heating by Scenarios



These reductions translate to a regional cost of emissions reductions ranging between -$272/ton (savings) to $301/ton. The following figure summarizes these regional differences.

Figure 17 Emission Abatement Cost/Ton for Water Heating



While emissions are reduced over the 2020-2050 timeframe, the absolute level of installed equipment for space heating grew by 35 percent over the same period. On a national per unit basis, the baseline water heater produces 0.9 tons of CO_2 while the heat pump water heater produces 0.5 tons of CO_2, representing a 44 percent improvement[16].

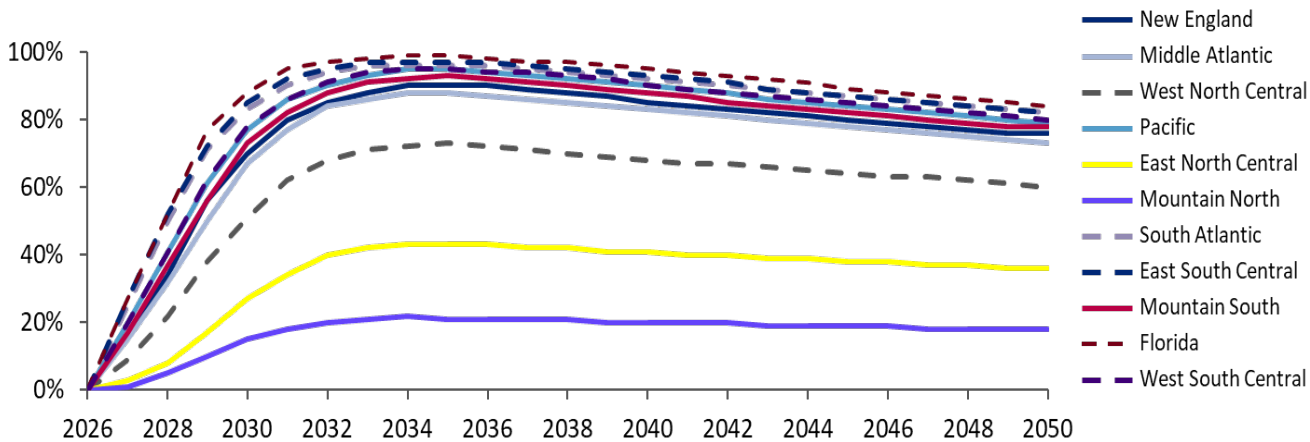
Clothes Drying

In 2020 the Baseline, most clothes dryers are electric. Therefore, share of emissions associated with natural gas dryers is relatively small. According to the EIA 2019 AEO, the total number of natural gas dryers grows by 53 percent from 2020 to 2050, and associated emissions increase by 45 percent in the Baseline during this timeframe. As discussed in previous section, relative to 2050, high efficiency dryers can reduce emissions by 0.2 and 0.5 MMT (6 and 17 percent reduction relative to 2050 Baseline) in Moderate Penetration and High Penetration scenarios respectively. However due to large increase in the overall number of drying units there is still an increase in natural gas clothes dryer emissions relative to the 2020 Baseline by 37 and 20 percent in the Moderate and High Penetration scenarios.

[16] Baseline emissions are estimated from EIA average water heating unit emissions, average water heating heat pump emissions are estimated from the GTI's Energy Planning Analysis Tool (EPAT).

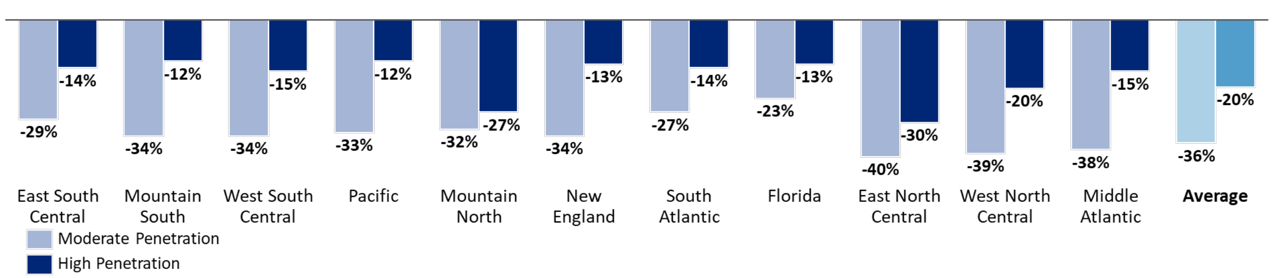
The differences in penetration by region are attributable to the initial distribution of gas-fired clothes dryers. After 2035, once most regions achieve high levels of penetration, the level of incentive support is reduced, resulting in a small decline in the number of new installations from that point onwards. Figure 18 below shows the regional penetration of clothes dryers.

Figure 18 Regional New Annual Installations of Dryers by 2050 Under High Penetration Scenario



Based on these levels of penetration, Figure 19 summarizes the regional level of emissions reductions.

Figure 19 Emission Reduction Percentage by 2050 for Dryers by Scenarios[17]



On a per-unit basis, the standard efficiency clothes dryer used in the Baseline produce 0.15 tons of CO_2 while the clothes dryers in the two scenarios produce 0.12 tons of CO_2, a 20 percent reduction[18].

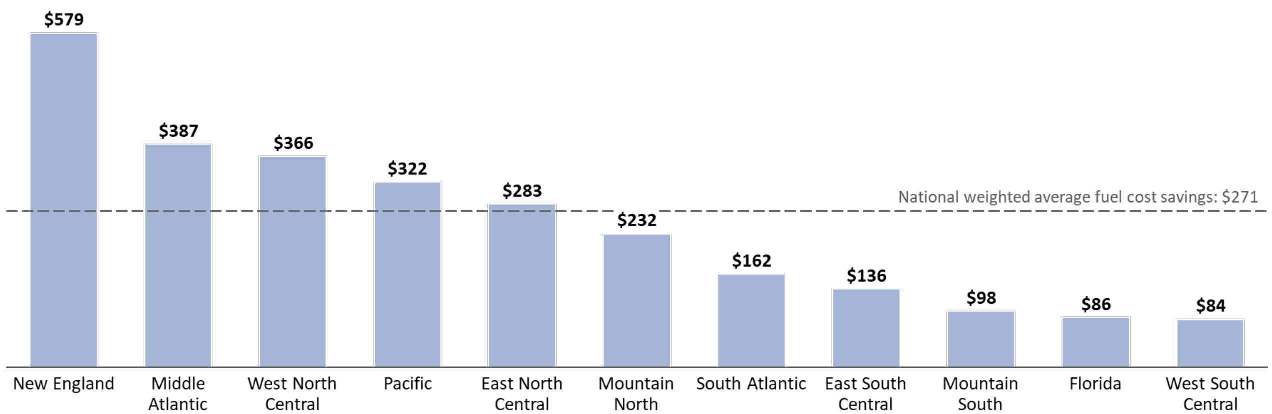
Customer Impact

From a customer perspective, the level of savings varies considerably by the climate where the equipment is used. The more severe the heating season a location experiences (and therefore the more energy is needed for

[17] Negative values indicate emission increase due to the emission increase in the Baseline outpacing efficiency savings
[18] Baseline emissions are estimated from EIA average natural gas dryer emissions, average Energy Star certified dryer emissions are estimated from the GTI's Energy Planning Analysis Tool (EPAT).

heating) the more savings the customer would realize. Figure 20 shows the regional distribution of customer savings in the sample year 2035.

Figure 20 Regional Customer Savings from Space Heating, Water Heating and Drying by Region in 2035 (2020$)

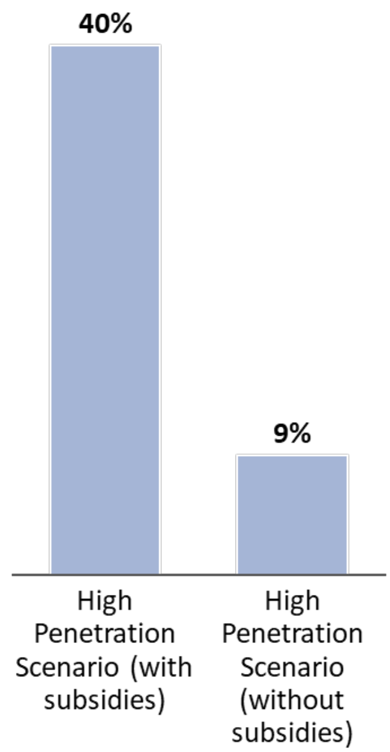


2.3. Quantifying the Impact of Incentives

Like with all energy efficiency cost-effectiveness evaluations, the role of incentives in accelerating the penetration of emerging natural gas technologies and resulting emissions reductions is apparent. However, since even Moderate Penetration scenario contains moderate levels of incentives, it is not possible to completely isolate the impact of such support. In addition, there is an iterative relationship between incentive levels and the rate at which technology costs decline due to learning curve and scale effects. Therefore, to accurately quantify the impact of incentives, the technology cost decline rate must also be adjusted to reflect the absence of incentives and the lower volumes of equipment installed. Additional details on the learning curve and scale effects and impact on technology cost decline rates is provided in Appendix G.

Based on the cumulative impact of no incentives, and associated technology cost curve decline rate (less rapid decline compared to the scenarios with incentives), this standalone analysis estimated the emission reductions and cost per ton of abatement. Under High Penetration scenario, a 40 percent reduction in emissions is achieved at a cost of $66/ton. Without incentives and associated scale effects, only a 10 percent reduction in emissions is achieved, but at a *net savings* of $51/ton. This is summarized in Figure 21.

Figure 21 Impact of Incentives on Emission Reductions (% reduced relative to 2020 Baseline)



Without incentives all emissions reductions achieved are 'automatic' and based on the unsubsidized lifetime cost comparison between the Baseline and the emerging, high-efficiency technology option. Since the penetration achieved is driven by economic payback considerations in a world free of carbon pricing, it implies that it is more cost effective to adopt the new technology. Therefore, the net cost of making the switch is negative. In other words, the consumers save money, while also reducing overall emissions by adopting the new technology. This process is accelerated and enhanced by incentives, but at a higher cost. The appropriate level of incentive support will accelerate the penetration of beneficial new technologies, with major long-term benefits in terms of lower costs and emissions.

3. Conclusions

In both scenarios emerging high-efficiency natural gas-fired technologies were shown to have substantial impact on residential CO_2 emissions relative to the 2020 Baseline from the EIA AEO 2019 Reference Case Scenario. Furthermore, Moderate Penetration scenario that deploys moderate levels of incentive support result in net *savings* of $52/MMT. From consumer perspective both scenarios result in substantial savings. High Penetration scenario examined a more accelerated, yet realistic penetration of emerging natural gas technologies using higher incentives. As shown in Figure 22 below, this scenario reduces emissions by ~101 MMT per year relative to the 2020 Baseline by 2050, representing a 40 percent decline. The reductions in emissions are achieved at a total cost of $66 per MT.

Figure 22 CO_2 Annual Emission Reduction 2020-2050 (MMT/year) Relative to 2020 Baseline

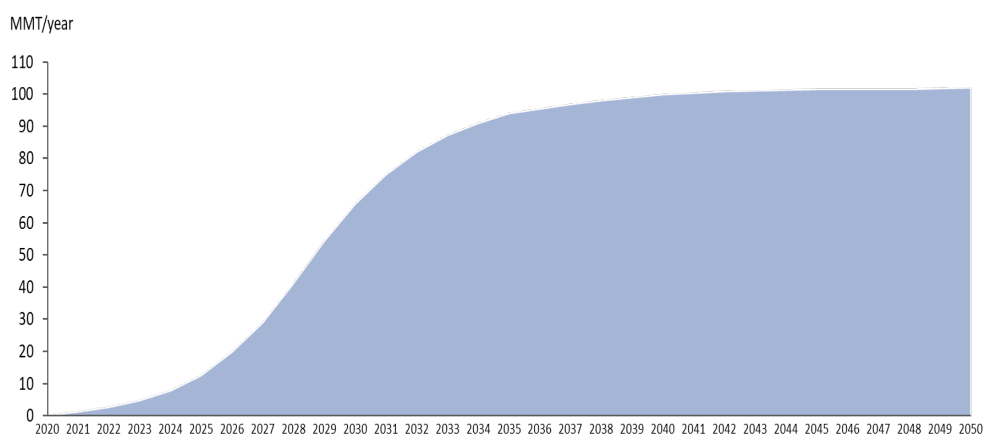
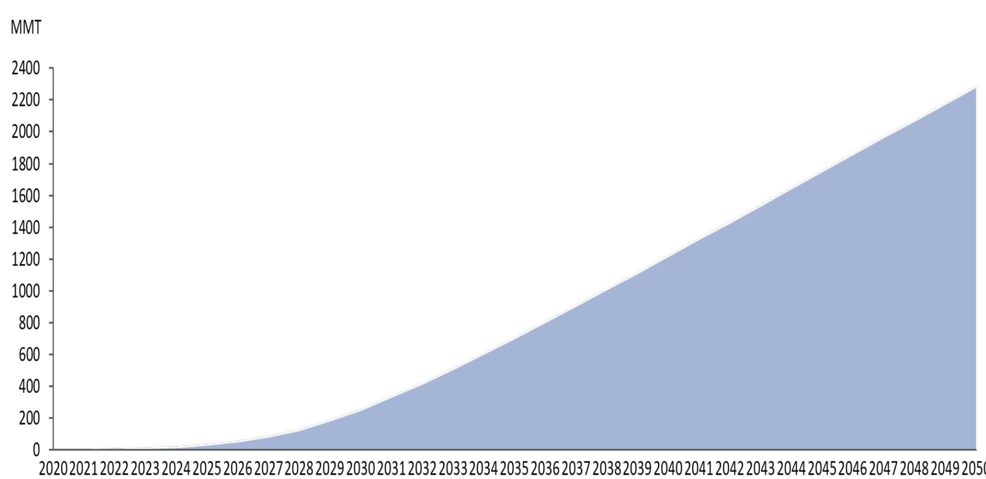


Figure 23 below shows that High Penetration scenario achieves cumulative emissions reductions of 2,286 MMT of emissions from 2020 to 2050 (relative to 2020 Baseline), with almost half the total volume of reductions (1,143 MMT) achieved by 2040.

Figure 23 Cumulative Emission Reduction under High Penetration Scenario 2020-2050 (MMT) Relative to 2020 Baseline



To summarize, this study demonstrates how the effective penetration of emerging natural gas direct-use technologies can provide significant contributions towards reducing emissions in the U.S. residential sector in a cost-effective and consumer friendly manner.

4. Methodology and Key Assumptions

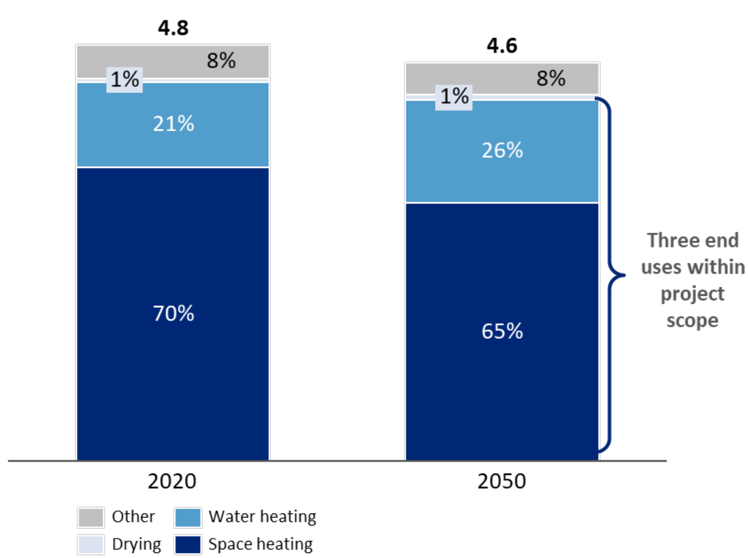
4.1. Baseline (AEO 2019 Outlook)

EIA's Reference Case from the 2019 Annual Energy Outlook (AEO) was used as the Baseline for this analysis. The AEO forecasts supply and demand conditions in domestic energy markets through 2050. Its forecasts are segmented by end-use and fuel type and include both physical and financial estimates (fuel volumes, prices, and emissions). The Reference Case "represents EIA's best assessment of how the U.S. and world energy markets will operate through 2050, based on many key assumptions."[19] Refer to Appendix B for Baseline details.

End-Uses

For this analysis, Enovation Partners focused on the residential end-use with natural gas as the primary fuel source. Within the residential sector, space heating, water heating, and clothes drying were prioritized due to their relative share of total natural gas consumption as well availability of technologies with significantly higher energy efficiency than current installed base. This is shown below.

Figure 24 2020 and 2050 Natural Gas Use in Residential Sector (Quads of Natural Gas)[20]



Enovation Partners also considered other end-uses like cooking and micro-combined heat and power units, but these were not included in this study due to their relatively smaller contribution to the total residential natural gas use and potential to reduce CO_2 cost-effectively near term.

[19] Energy Information Administration. *Annual Energy Outlook 2019*. Page 5 https://www.eia.gov/outlooks/aeo/pdf/aeo2019.pdf
[20] Source: EIA AEO 2019 Reference Case Scenario

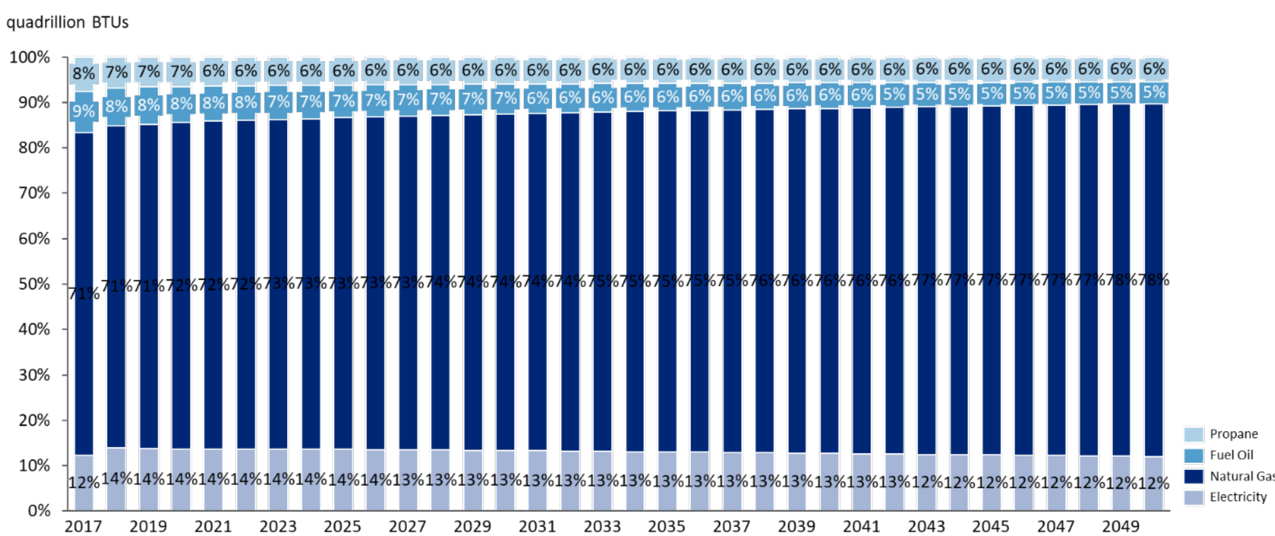
Regions

Regions in the model are defined to capture the differences in climate zones, environmental policies, and equipment costs. They are in line with the available census data and climate regions data, including Building America climate zones and IECC climate zones. They are further refined by the associated heating degree days (HDD) and cooling degree days (CDD), which led to an additional split of Mountain and Atlantic Regions. In total, there are 11 regions defined in the model, showed in Appendix A.

Fuel Switching

While natural gas is the focus of the analysis, the Baseline forecast also includes other fuels used within the three prioritized end-uses. The relative shares of emissions from fuels within the three end-uses evolve over time, which implies that the Baseline forecast includes trends of fuel-switching within the end-uses, most significantly relating to propane and fuel oil being displaced by natural gas and electricity. It is important to emphasize that apart from this inherent level of fuel switching assumed in the Baseline, no additional fuel-switching was modeled for this analysis. The fuel switching assumed in the EIA Baseline for space heating is reflected in Figure 25.

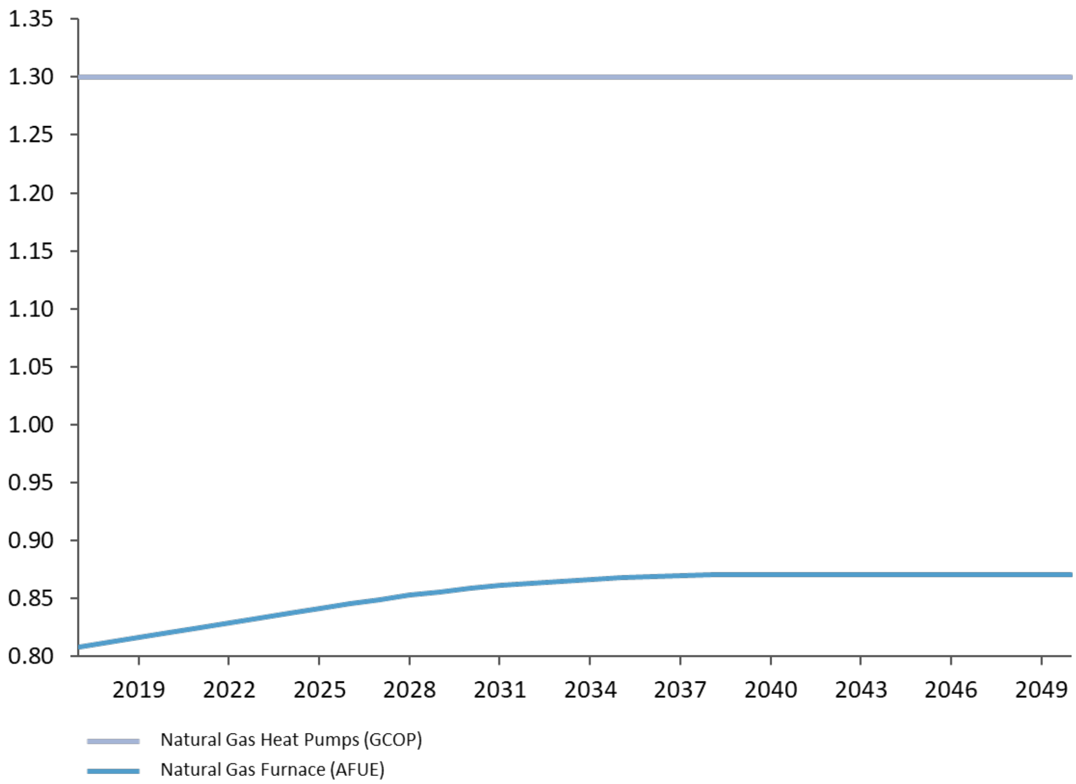
Figure 25 Fuel Mix in Space Heating Consumption Over Time



Stock Average Efficiency Improvement

The Baseline results also include assumptions relating to efficiency improvements in the various equipment for each end-use. Figure 26 below shows a snapshot of average efficiency improvement over time for natural gas space heating equipment.

Figure 26 Stock Average Equipment Efficiency 2020-2050 for Space Heating (EIA Baseline)



The EIA Baseline assumes only modest improvements in efficiency over the forecast horizon. These small improvements translate into reduced fuel consumption and, consequently, reduced emissions per equipment over time. Enovation Partners used the average efficiency for each end-use to develop specific equipment cost profile (first cost, installation cost, annual operating, and maintenance cost) using publicly available information and expert reviews.[21] For example, for the average equipment stock efficiency for natural gas-fired space furnaces is 81 percent assumed in the EIA Baseline in 2017, the cost profile for a natural gas furnace AFUE 81 percent was used. For each region, specific labor cost adders and operation and maintenance cost modifiers were included to develop region-specific cost profiles for each equipment type. Additional details on equipment cost and operating details are summarized in Appendix G.

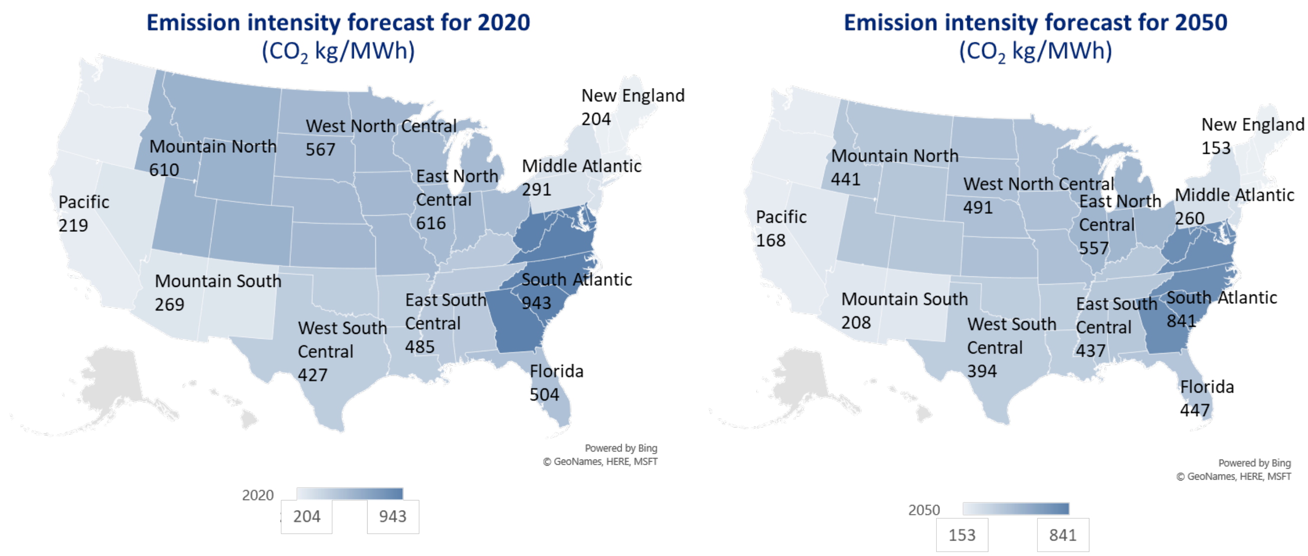
Baseline emission intensity

For the Baseline as well as scenarios developed for this analysis, emission intensity factors for various fossil fuels were sourced from the Environmental Protection Agency (EPA). For electricity, specific emission intensity factors were developed by region based on the current and forecasted generation

[21] Expert review includes inputs from GTI

mix in each region. Regional differences and improvements in grid emission intensity over time is summarized in the figure below.

Figure 27 Snapshot of Emission Intensity in 2020 and 2050

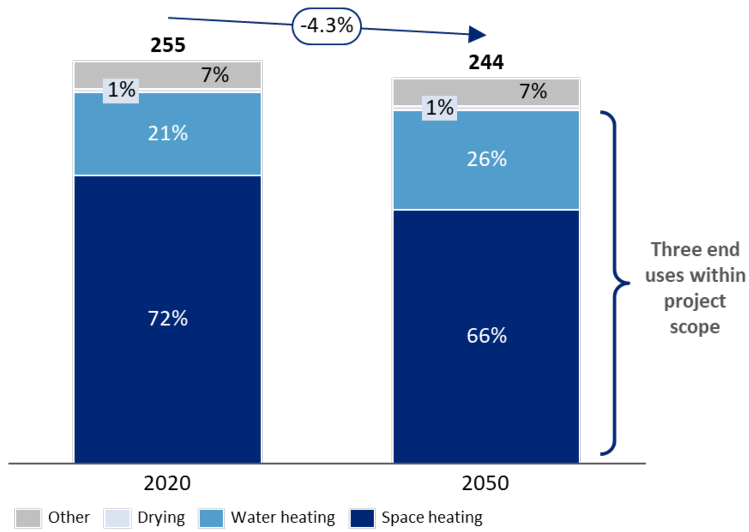


In general, as renewable energy sources and clean natural gas replaces coal and oil-fired generators, average grid CO_2-emission intensity declines over time. This improved grid emission intensity was incorporated into both the Baseline as well as the scenario analysis.

Baseline Emission Results

Based on the inputs and assumptions specified above, the EIA Baseline forecasts a 14 percent reduction in total fuel use (all fuels) across the three main end-uses. Specifically, for natural gas, the Baseline forecasts a 4.3 percent reduction in emissions from all three use-cases between 2020 and 2050. These results are summarized in the figure below.

Figure 28 EIA 2019 AEO Reference Case Residential Sector Natural Gas Emission Forecast by End-Uses (MMT)



Although the Baseline forecasts overall reduction in emissions, the total number of natural gas-fired equipment stock across all the end-uses increases over the forecast horizon, implying that the Baseline level of efficiency improvements alone are significant enough to overcome the absolute level of demand (equipment stock) increase in the Baseline. The scenarios modeled in this study aim to determine how much further demand-side efficiency improvements could improve emissions reductions and quantify the associated cost.

4.2. Scenarios and Selected Technologies

In addition to the Baseline, Enovation Partners developed two alternative scenarios to evaluate the impact of high-efficiency natural gas technologies on emissions and associated costs. The *Moderate Penetration* scenario is designed to demonstrate the impact of adopting high-efficiency technologies based on traditional levels of incentives. The *High Penetration* scenario is designed to evaluate the penetration impact of the emerging technologies evaluated in the study through higher levels of incentive support.

To quantify the level of emission reductions achieved, and to evaluate the cost associated with those reductions, the results of scenarios are individually compared against the 2020 Baseline.
It is important to highlight that both scenarios assume consumers use rational economic decision-making when evaluating equipment options without any external policy mandates. In general, the probability that a given household will adopt a new technology increases for a lower payback period along with a low remaining useful life of existing equipment. As an illustrative example, the probability that new equipment will be purchased is greater if it's payback period (relative to existing equipment) is three years and the useful remaining life of existing equipment is three years than if the payback

period is ten years and the remaining useful life is also ten years. Additional details on the modeling logic for new equipment penetration is provided in Appendix H.

The list of technologies selected for analysis in both scenarios is summarized in Table 2.

Table 2 Emerging High-Efficiency Natural Gas-Fired Technologies Selected for the Study[22]

End-Use	Moderate Penetration Scenario	High Penetration Scenario
Space heating	Natural gas furnace (AFUE 97%) Gas absorption heat pump (AFUE 1.4)	Gas absorption heat pump (AFUE 1.4)
Water heating	Gas heat pump water heater (1.3 UEF)	Gas heat pump water heater (1.3 UEF)
Clothes drying	Standard Energy Star certified dryer (CEF 3.49)	Standard Energy Star certified dryer (CEF 3.49)

All efficiencies stated in the table above and throughout the document are appliance rated (or design) efficiencies as defined by DOE and not the actual efficiencies used in the analysis. It is a known fact that heap pumps performance degrades with declining outside temperatures or in other words the actual energy efficiency of heat pump-based technologies is worse in cold climates. This performance degradation was accounted for in the analysis.
In addition to the technology differences, the scenarios also differ in terms of the level of incentive support provided for each technology.

4.3. Incentives and Cost of Emission Reductions

Incentives

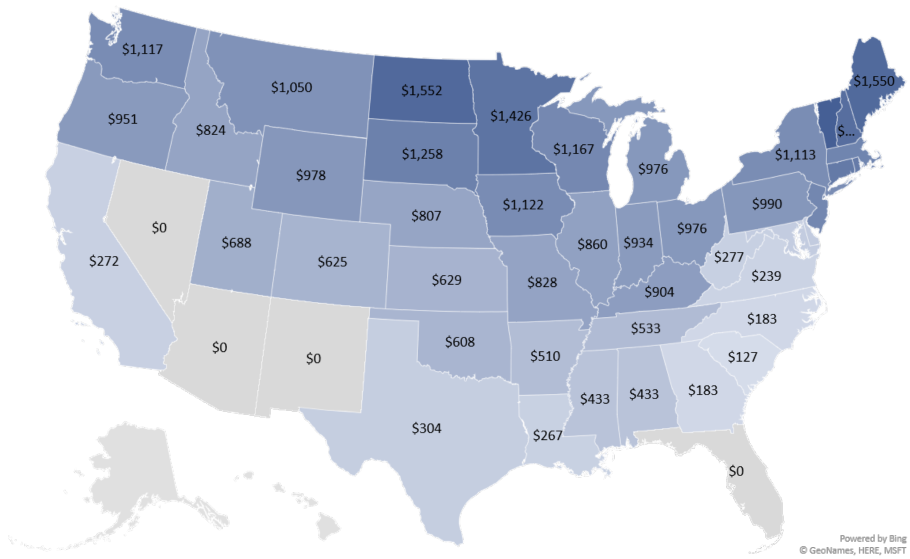
Incentives play a key role in overcoming the higher first cost associated with more efficient technologies as well as market development for emerging technologies. For this analysis, only capital cost incentives were considered because most typical utility efficiency programs do not subsidize fuel and other operating costs. Higher levels of capital cost incentives directly reduce the payback period for the equipment upgrade, improving the probability that the new equipment will enter the market and displace the baseline technology. The incentives are even more important for consumers with low or moderate-income levels as well as landlords of rental housing. Existence of support for incentives for emerging, high-efficiency natural gas-fired technologies sends a powerful signal to equipment manufacturers to prioritize getting them to the market quicker and at scale making their cost therefore cheaper to the consumer creating a virtuous cycle and accelerating adoption.

Incentives amounts are based on a modified total resource cost methodology. Specifically, the level of incentive support available for each region is a function of the value of the fuel cost saved by deploying the higher

[22] See additional discussion on technologies considered and selected for the study in Appendix E and F

efficiency technology, relative to the Baseline equipment. As a result, in regions where the high-efficiency technology can achieve the greatest reductions, higher level of support is likely to result from energy efficiency cost-effectiveness evaluation processes. This logic helps naturally promote the penetration of technologies where their operations are most economical. Figure 29 below illustrates this approach.

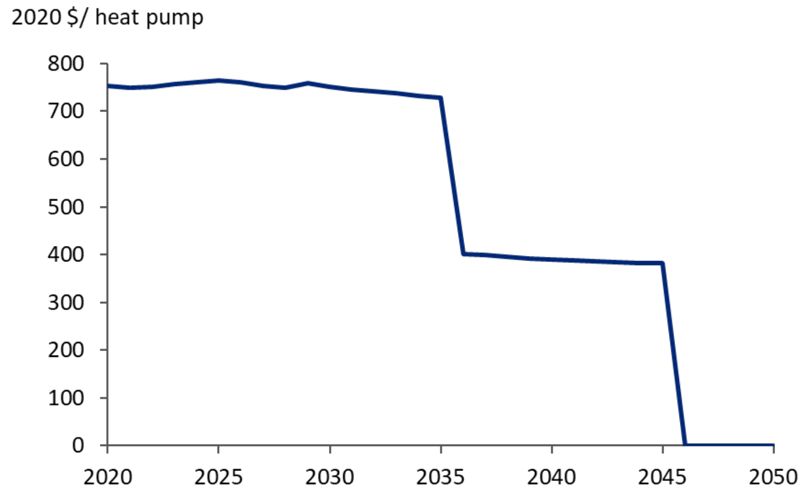
Figure 29 Example of Regional Differences in Incentives – Snapshot of Incentives in 2020 for Space Heating in Moderate Penetration Scenario ($ per heat pump)



The specific incentive amounts are determined by first calculating the avoided cost savings by state every year through the forecast horizon. The avoided cost is calculated from the difference between fuel consumption with baseline versus the high efficiency technology and the fuel cost is assumed to be the volumetric cost of natural gas at citygate. Then a percentage of these savings is applied in a form of incentive support towards the capital cost of equipment. The exact percentage was determined by optimizing the level of incentive support to minimize the long-term cost of abatement while most effectively promoting the penetration of new technology.

The overall incentives amount and timing are therefore modified to achieve high penetration at reasonable costs. The level of incentive support was also modified by scenario with High Penetration scenario emerging, high-efficiency natural gas-fired technologies generally receiving higher incentives relative to Moderate Penetration scenario. Initially relatively high level of incentives was required to accelerate penetration of technologies. This initial wave of penetration allowed for the equipment cost to come down substantially by 2035 reducing the need for continuing high level of incentive support, but still needing some level of support. Therefore, incentives were reduced beginning 2036. The incentives were designed to taper off in the long run once the technologies achieve sufficient market share (as shown in Figure 30 below). This approach was used in both scenarios with the difference only in the level of incentive support.

Figure 30 Average Incentive for Space Heating Heat Pump 2020-2050 in High Penetration scenario



In summary, the timing and amount of incentives are calibrated by region to maximize penetration and minimize the cost of emissions reduction.

Table 4 below summarized the level of incentives applied in the analysis by end-use, type of equipment, scenario, and time period.

Table 4 Summary of Assumed Incentives by Scenario and End-Use ($/Unit)

End-Use	Moderate Penetration Scenario	High Penetration Scenario
Space Heating	2020-2035 $100 - $1,600 per furnace	2020-2035 NA
	2020-2035 $300 - $3,000 per heat pump	2020-2035 $250 - $3,300 per heat pump
	2036-2045 $80- $1,350 per furnace	2036-2045 NA
	2036-2045 $200 - $2,400 per heat	2036-2045 $125 - $1,550 per heat pump
Water Heating	2020-2035 NA	2020-2035 $300 - 1,500 per heat pump
	2036-2045 NA	2036-2045 NA
Clothes Drying	2020-2035 NA	2020-2035 $40 - $250 per unit
	2036-2045 NA	2036-2045 $20 - $125 per unit

Cost of Emission Reductions

The emission reductions cost is calculated by determining levelized cost of installing, operating, and maintaining the new equipment per year net of levelized cost of installing, operating, and maintaining baseline equipment. The installed cost of equipment in this case includes the cost of incentive for the new equipment and operating cost includes the cost of natural gas and electricity (e.g. for HVAC blower, controls), if applicable. This calculation is performed every year and in every state with the updated inputs by the model.

Because operating cost savings are considered in addition to capital cost of equipment the net emission reduction cost could be negative even though the capital cost of new equipment is always higher than the cost of baseline equipment. Hence Moderate Penetration scenario resulted in *savings* as opposed to High Penetration scenario *cost*.

In calculating the levelized cost of equipment a discount rate of 6% was used. There is a lot of debate on the appropriate discount rate to be used in this type of calculation. A mid-point between 5% and 7% discount rates used by EPA's previous and current social cost of carbon calculation was chosen for this analysis[23].

The emission reductions due to accelerated penetration of emerging, high-efficiency gas-fired technologies are calculated by subtracting total annual emissions from the new equipment (from natural gas and electric consumption, if applicable) from the annual emissions that would have been produced if the equipment was not replaced that year. The latter is determined by the emissions and number of equipment units in the Baseline for a given year and state. Electric emissions are determined by the electric generation mix (refer to Appendix I for additional detail on electric generation mix). This calculation is performed every year and in every state with the updated inputs by the model. The total emission reductions across the country due to accelerated penetration of emerging, high-efficiency gas-fired technologies calculated by the model are added to the emission reductions in the Baseline for a given year.

Cost of annual emission reductions per MT are then calculated by dividing the emission reduction cost by the CO_2 emission reductions achieved as described above.

[23] In EPA's Social Cost of Carbon dated 2016 discount rates of 5%, 3% and 2.5% were used. In the most recent revision of EPA's Social Cost of Carbon 7% and 3% discount rates were used in the context of climate change

Savings by consumer

When reporting annual savings by consumers similar levelized cost calculations as describe above are performed. However, the cost of incentives is not included as they would not be borne by the consumer directly.

4.4. Complementary Technologies

In addition to the select equipment, a list of complementary technologies for the three end-uses were also examined for the potential of achieving additional fuel savings cost-effectively. To avoid double-counting of efficiency savings, complementary technologies that are already included in the Baseline were excluded from the model. The selected complementary technologies are also estimated to have shorter payback period than their lifetime.

Table 5 List of Complementary Technologies Examined and Selected

End-use	Technology Considered	Included in EIA Baseline	Efficiency Savings	Assumed cost (2020 $)
Space heating	IoT smart thermostat	no	9.5-13%	$250
	Building Envelope • Attic • Sidewall • Duct sealing • Air filters	yes	10-20%	NA
Water heating	Water pipeline insulation	no	2-4%	$15
	Intelligent water heater controller	no	NA	NA
	Temperature control shower faucet	no	-4%-2.5%	NA

(shaded) Included in the model

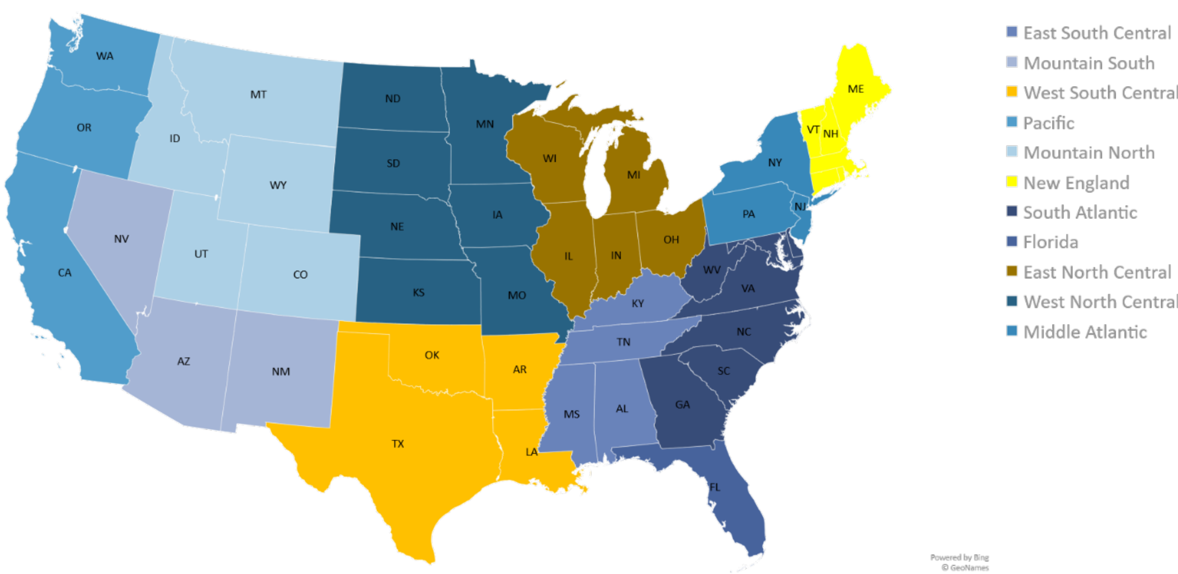
Efficiency savings are applied to the existing household for the relevant scenarios as a one-time efficiency gain. To account for household stock efficiency improvement, they are also faded out over time.

Appendix

A. Geographical Regions

The geographical regions in the model are intended to capture the differences in residential energy consumption due to climate and equipment size and use variations. The number of heating and cooling degree days varies across regions and impacts energy consumption. Thus, from the initial regions that were selected based on available census data, they were further refined based on climate zone data to account for HDD and CDDs, which led to the split of Mountain and Atlantic regions.[24] The equipment geographical categories from EIA are mapped against census climate geographical segments to create the list of regions in the study.

Figure 31 Defined Regions in the Model



B. Baseline Detail

All inputs and assumptions for Baseline are sourced from public sources, including EIA and NERC. Baseline creates a forecast of regional equipment stock, average stock efficiency, energy consumption, and emissions by fuel type for the period 2020-2050. For Baseline emission forecasts, the study refers to the U.S. Energy Information Administration (EIA) 2019 Annual Energy Outlook (AEO). EIA's 2019 AEO projects domestic energy markets through 2050, based on various assumptions, including macroeconomic growth, world oil prices and technological advancement. The 2019 AEO includes a comprehensive emission forecast for all fuels and end-uses. In the study, only natural gas-related emissions in the residential sector are considered. Furthermore, the study focuses on only three end-

[24] Building America climate zones and IECC climate zones

uses in the residential sector: space heating, water heating, and clothes drying, which account for about 93 percent of total residential natural gas emissions in 2020.

The study did not make additional assumptions and adjustments to the EIA 2019 AEO to create the Baseline. AEO already assumed some level of fuel switching, technology efficiency improvement, and building efficiency improvement over time. First, most states are already progressing towards cleaner fuel mix consumption from higher carbon intensity fuels, such as fuel oil, to low carbon intensity fuel, such as natural gas. Second, there is gradual efficiency improvement assumed due to cost improvement of highly efficient technology over time. Third, AEO included currently-available government energy programs and standards that will improve building efficiency over time.

As shown in Figure 32 below, in 2020 residential natural gas emissions is projected to represent about 5 percent of the total CO_2 emissions. The 2019 AEO also projects that total natural gas CO_2 emission in the residential sector will be reduced by 11 MMT from 255 MMT in 2020 to 244 MMT in 2050 (see Figure 25 below). The reduction is the adoption of higher energy-efficient technologies.

Figure 32 Total US CO_2 Emissions by Sector in 2020 (percent of total and MMT)

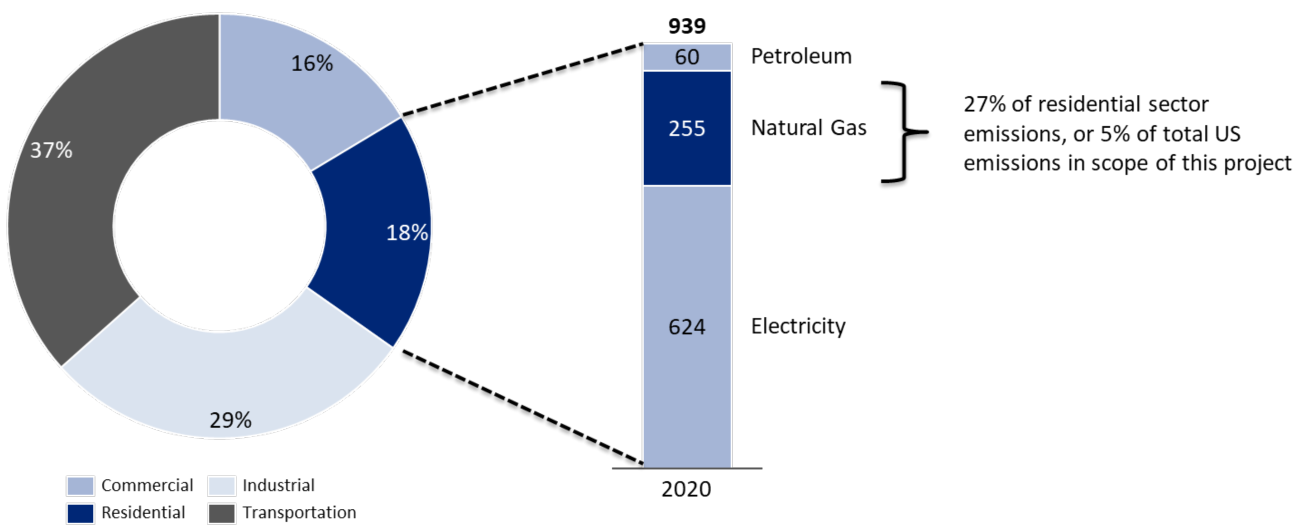
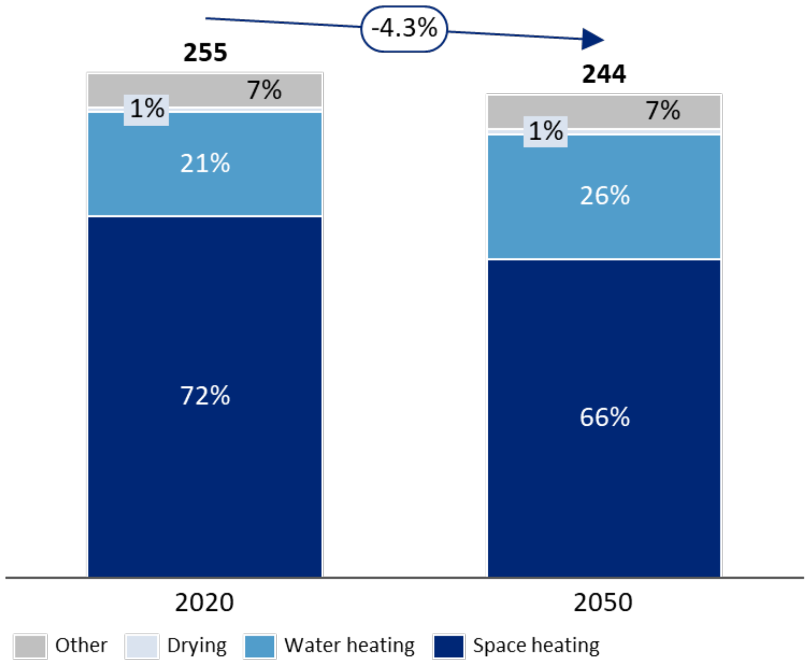


Figure 25 EIA 2019 AEO Reference Case Residential Sector Natural Gas Emission Forecast by End-Uses (MMT



C. Consumption Drivers

Residential fuel consumption is driven by the number of heating degree days, average stock equipment efficiency and fuel requirements.

Depending on the region, annual average HDDs vary. The colder the region, the higher number of HDD, which would require more energy consumption for space heating. Thus, annual average HDDs by region are collected and forecasted over time to estimate the trend in heating requirement changes over time.

The household size determines the size of equipment (kBtuh) and the total fuel needed. For each region, the following types of households are tracked to determine total fuel consumption by region:

1. Mobile
2. Single family (detached)
3. Single family (attached)
4. Multi-family apartment building (2-4 units)
5. Multi-family apartment building (5+ units).

For each end-use, a baseline level of average equipment stock efficiency estimates was derived from the 2019 AEO.

D. Commodity Pricing Forecast

Both natural gas and electric historical residential rates and forecasts are from EIA.

EIA creates national-level price projections for natural gas and electricity residential rates which are the basis for the regional rate forecasts developed in the Enovation Partners for this study. Historical residential rates for the past 30 years were collected and used to derive regional level forecasts. The model used these regional rate trends to develop regional deviations from the national average, which are then applied to national forecast.

In developing the electric rate forecast the same method was used as described above for natural gas. The following figures provide the regional rate forecasts for both natural gas and electricity.

Figure 33 Natural Gas Rate Forecast by Region

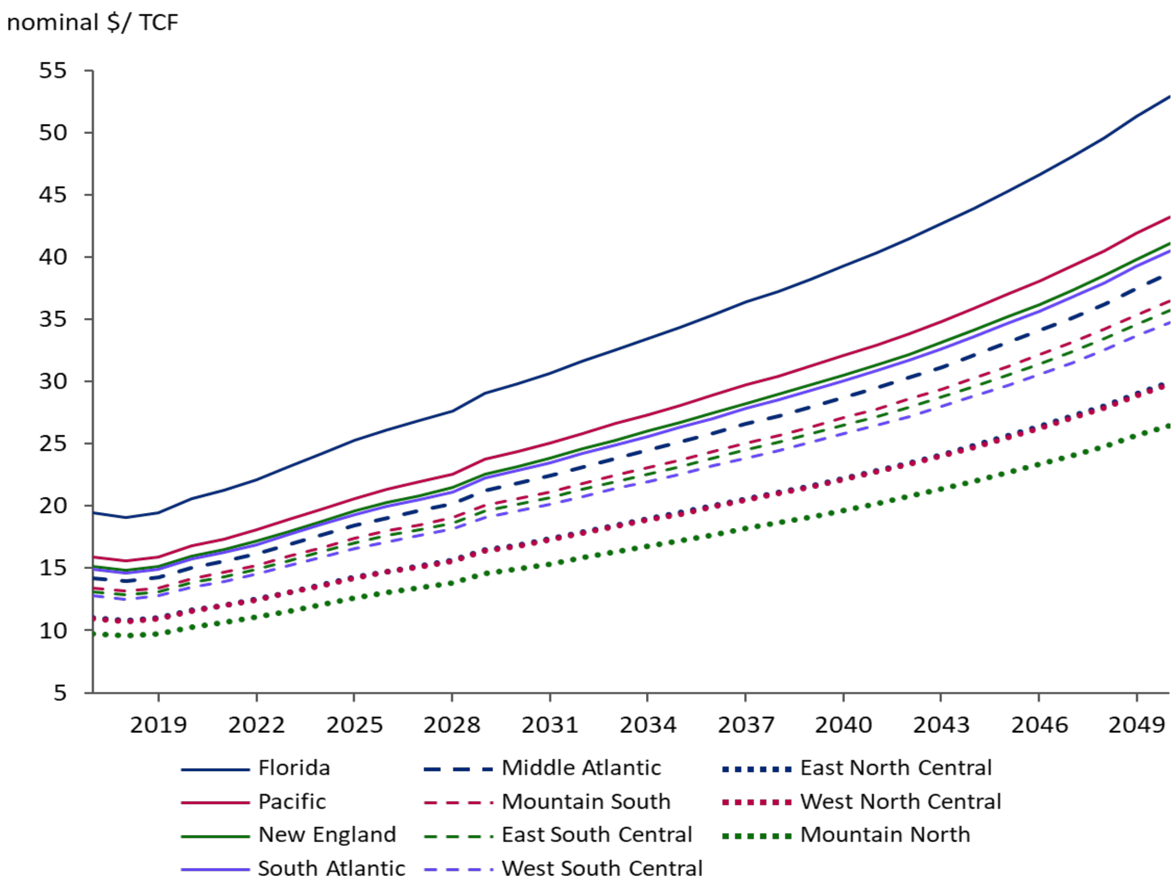
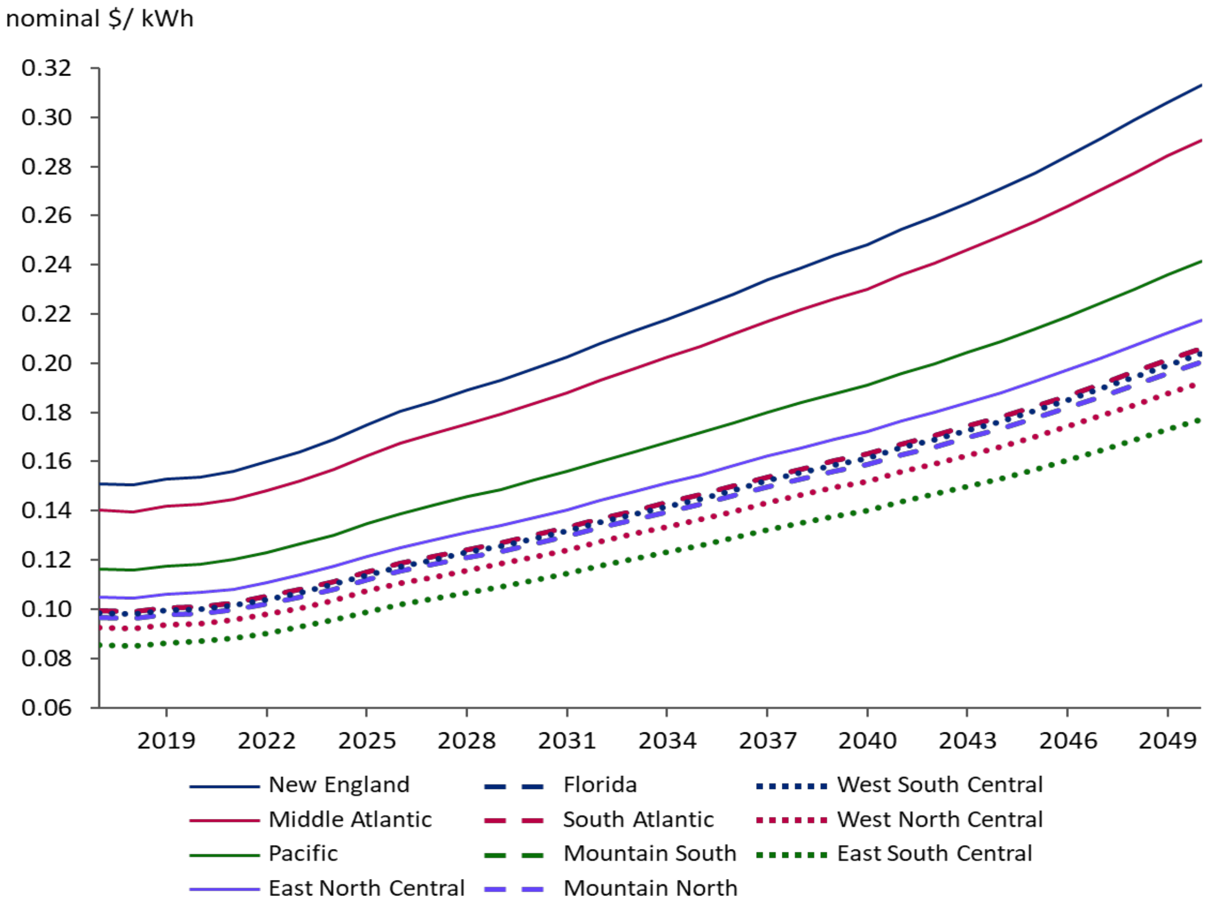


Figure 34 Electricity Rate Forecast[25] by Region



E. Selection and Modeling of Equipment

The initial long list of emerging high-efficiency technologies screened for the three end-uses was based on the findings in 2018 AGA *Greenhouse Gas Emission Reduction Pathways*[26] report prepared by Enovation Partners. Additional promising technologies were also reviewed for their potential with several experts. The long list of technologies was filtered down to a select few based on commercial availability in the near term and cost effectiveness regarding the CO_2 emission reduction potential. This short list is presented in Table 6 and includes the list of technologies that were selected for further analysis.

[25] Electricity rate forecast is based on most recent available EIA forecast and does not include impact from any potential policies, e.g. electrification
[26] https://www.aga.org/globalassets/research--insights/reports/ghg-reduction-pathways_phase-1-report.pdf

Table 6 List of Emerging Technologies Considered

End-use	Technology	Commercial availability (year)	Efficiency (EF, AFUE, electric efficiency)	First Cost ($)
Space heating	**Condensing Gas Furnace**	**Now**	**97%**	**$3,895**
	Gas Absorption Heat Pump	**2022**	**140%**	**$8,376**
	Energy Star Condensing Gas Boiler	Now	95%	$5,500
	Gas Absorption Heat Pump Boiler	2022	130%	$13,770
	Thermal Compression Gas Heat Pump Boiler	2030	160%	$16,473
Water heating	Gas Storage Condensing	Now	0.77	$2,840
	Gas Tankless	Now	0.84	$2,196
	Gas Tankless Condensing	Now	0.95	$3,191
	Gas Hybrid	Now	0.96	$2,313
	Solar Thermal with Gas Storage	Now	1.00	$9,000
	Gas Heat Pump Water Heater	**2022**	**1.30**	**$2,250**
	Self-Powered High Efficiency Tankless	2030	1.10	$2,875
Dryer	**Energy Star Gas Dryer**	**Now**	**3.48**	**$675**
	Next Gen Energy Star Gas Dryer	2030	4.00	$844
MicroCHP	Gas IC-Engine Driven System 1.5 kW	2022	23%	$20,000
	SOFC 2.0kW 2030	2030	40%	$20,000
	SOFC 1.5kW 2030	2030	60%	$35,000

Selected for the analysis

The above listed technologies were further analyzed, and a single representative technology was selected for each end-use as a reasonable proxy for simplicity of the modeling.[27] This selection of a single technology does not imply that it is necessarily the most promising or best suited for every home. Many other technologies exist and might be in fact better suited in some situations (e.g. gas boilers would be more likely to be replaced with heat pump boilers).

The equipment modeled in the Baseline is based on the equipment characteristics in EIA 2019 AEO. For example, 2019 AEO assumes average natural gas-fired space heating equipment stock to be AFUE 81% in 2017, thus in the model the baseline equipment was modeled as an 81% AFUE natural gas-fired furnace. The average equipment stock efficiency increases over time, which was considered in the baseline equipment modeling. Specific equipment type used for modeling of the baseline technology is included in the Table 7 below.

[27] Two technologies were selected for space heating for the High Penetration scenario because condensing furnace and space heating heat pump are fundamentally different technologies, and each has significant advantages over the other

All efficiencies stated in the Table 6 and throughout the document are appliance rated (or design) efficiencies as defined by DOE and not the actual efficiencies used in the analysis. It is a known fact that heap pumps performance degrades with declining outside temperatures or in other words the actual energy efficiency of heat pump-based technologies is worse in cold climates. This performance degradation was accounted for in the analysis.

F. Selected Equipment Cost

As mentioned above the equipment selected for the two scenarios was screened based on the potential for CO_2 reduction and payback period (cost effectiveness). While there are many promising emerging, high-efficiency natural gas-fired technologies that are being developed, they may be more expensive compared to the currently installed equipment in the household. Since the model assumes consumers pay both the initial equipment costs as well as the energy costs and that they make rational economic decisions,[28] representative technologies with the potential to achieve the shortest payback period were selected for the analysis. The costs and performance parameters of the emerging technologies as well as the Baseline technologies are estimations[29] and listed below in Table 7.

Table 7 Select Equipment Performance and Cost Characteristics

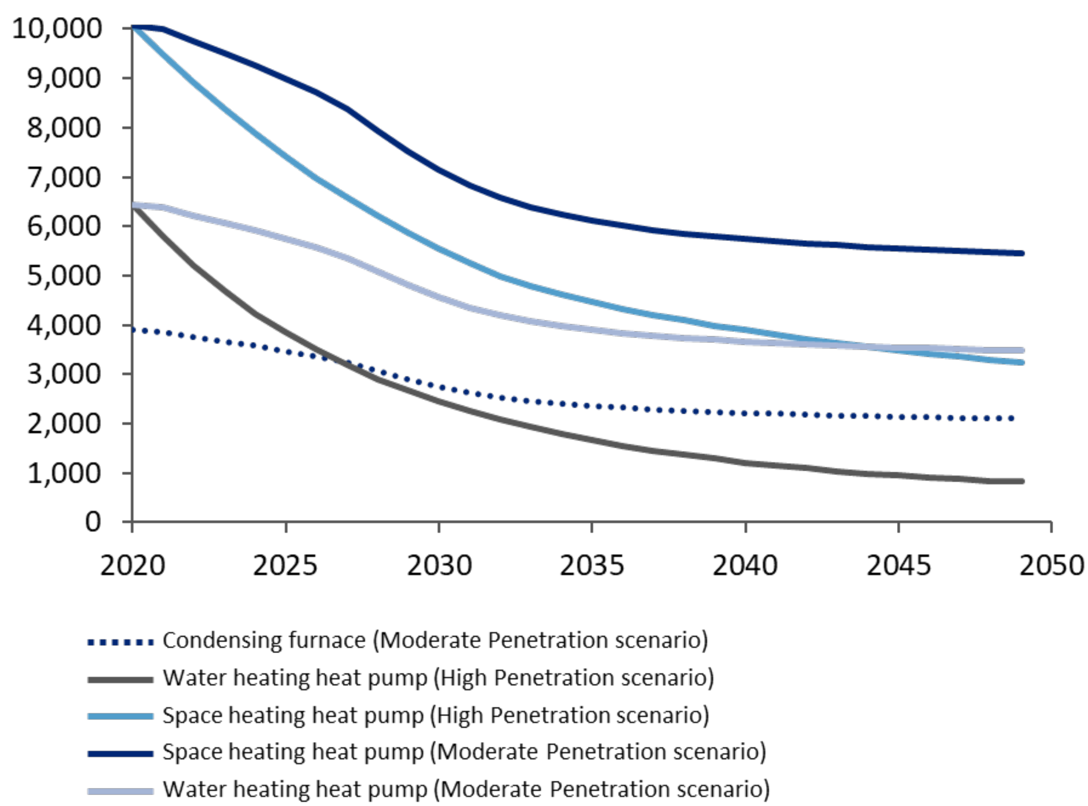
End-use	Technology	Unit Size	Gas Consumption (therms)	Installation Cost ($/unit)	Retail Cost ($/unit)
Space Heating	Natural gas furnace (AFUE 80%)	40-100 kBtuh	82-891	$900-2,500	$800-$2,000
	Natural gas furnace (AFUE 97%)	40-90 kBtuh	68-742	$900-2,500	$960-$3,200
	Gas absorption heat pump (AFUE 1.4)	NA	46-553	$1,900-3,400	$5,500-8,200
Water Heating	Natural gas storage water heater (0.64 UEF)	10-60 gallons	157-244	$730	$120-$600
	Gas heat pump water heater (1.3 UEF)	60 gallons	80-116	$2,250	
Clothes Drying	Standard gas dryer (CEF 2.69)	NA	35	$540-940	
	Energy Star certified gas dryer (CEF 3.49)	NA	25	$680-1,175	

[28] Consumers make purchasing decision based on the shortest payback period, which considers the first cost and fuel savings
[29] Estimations are sourced from GTI, AGA primarily and cross-checked with the following sources: HomeWyse. com, HomeAdvisor.com, EnergyHomes.org, HomeDepot.com, HomeSteady.com

G. Equipment Cost Decline

Equipment installed cost is comprised of first (retail) cost and installation cost. An installed cost decline curve for each select technology over time was assumed in the model. When a new technology is commercialized, the retail price will often be much higher than the common equipment used in households today. However, there is evidence[30] of manufacturing and installation costs of residential appliances decline in real term over the last several decades. The cost decline is driven by manufacturing and installation efficiency gain over cumulative experience and scale. Thus, forward-looking cost curves (see Figure 35 below) were developed for the select technologies based on the historical cost decline curves of similar appliances.

Figure 35 Forecasted Installed Appliance Cost Decline Curve (2020 $/unit)



The rate of cost decline is directly proportional to the number of units of equipment installed. For the forecast period in the analysis, the curves shown above are based on the projected number of new high-efficiency equipment installed. With lower levels of incentives, less units are installed, resulting in a flatter cost decline curve through time.

Mature technologies modeled in the Baseline also experience cost decline although at much slower rate. This cost decline was also considered in the analysis.

[30] *Incorporating Experience Curves in Appliance Standards Analysis*, Environmental Energy Technologies Division of Lawrence Berkeley National Lab, 2012

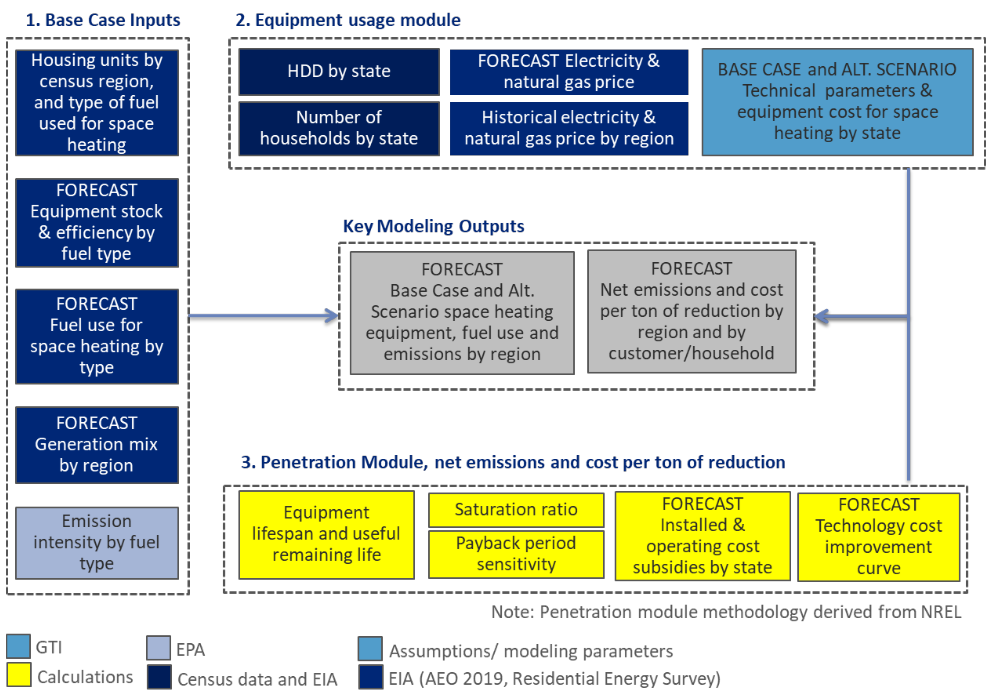
H. Model Description

Baseline and scenarios are technology and fuel agnostic and are not biased towards promoting any specific technology/fuel. The model assumes rational economic behavior for a customer who is paying both the up front and operational costs of the energy service, which determines the purchasing decision in the model. Consumers under rational economic behavior would select the equipment based on the lowest lifecycle cost, which takes into consideration of first cost differentials and fuel savings.

There are three modules in the model:

1. Baseline inputs module
2. Equipment usage module
3. Penetration module.

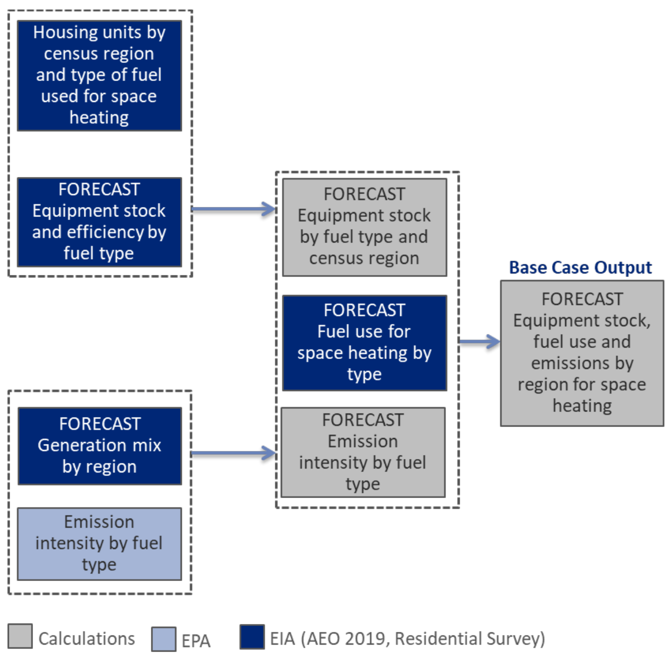
Figure 36 Methodology at a Glance



1. Baseline inputs module

All inputs are from EIA 2019 AEO. The model proportionally allocates national-level data to regional level estimates based on HDD or the number of housing units. Where appropriate, the model maintains the historical regional proportions throughout the forecast period. For details of baseline refer to Appendix B.

Figure 37 Baseline for Space Heating

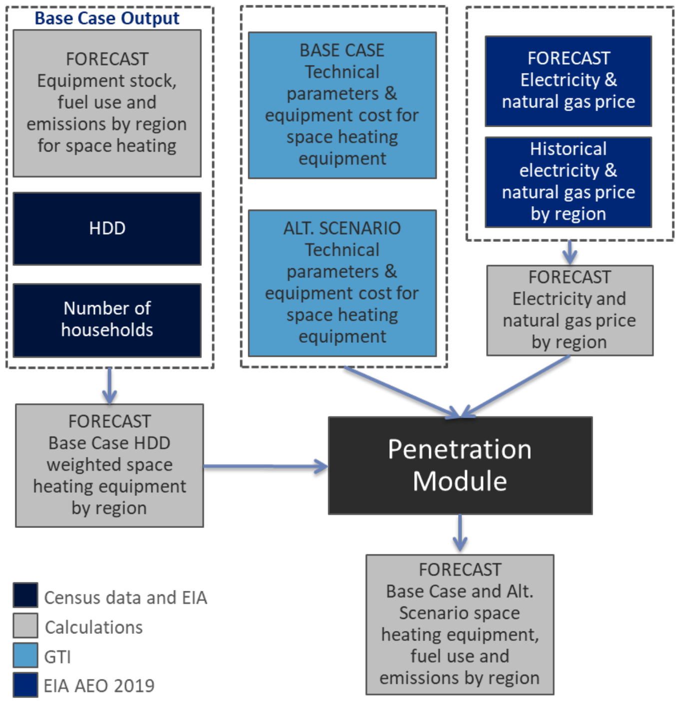


2. Equipment usage module

This module generates output of forecast for equipment stock count, fuel use, and emissions, which feeds into the penetration module. The inputs included outputs from Baseline module (equipment stock, fuel use and emission by region), technical information of equipment (equipment fuel consumption and unit size), and cost information (variable and installed cost)[31]. Payback period calculations for each select technology are based on equipment level technical and cost information.

[31] Technical information of equipment is from GTI; cost estimates are sourced from GTI, AGA primarily and cross-checked with the following sources: HomeWyse. com, HomeAdvisor.com, EnergyHomes.org, HomeDepot.com, HomeSteady.com

Figure 38 Equipment Usage Module



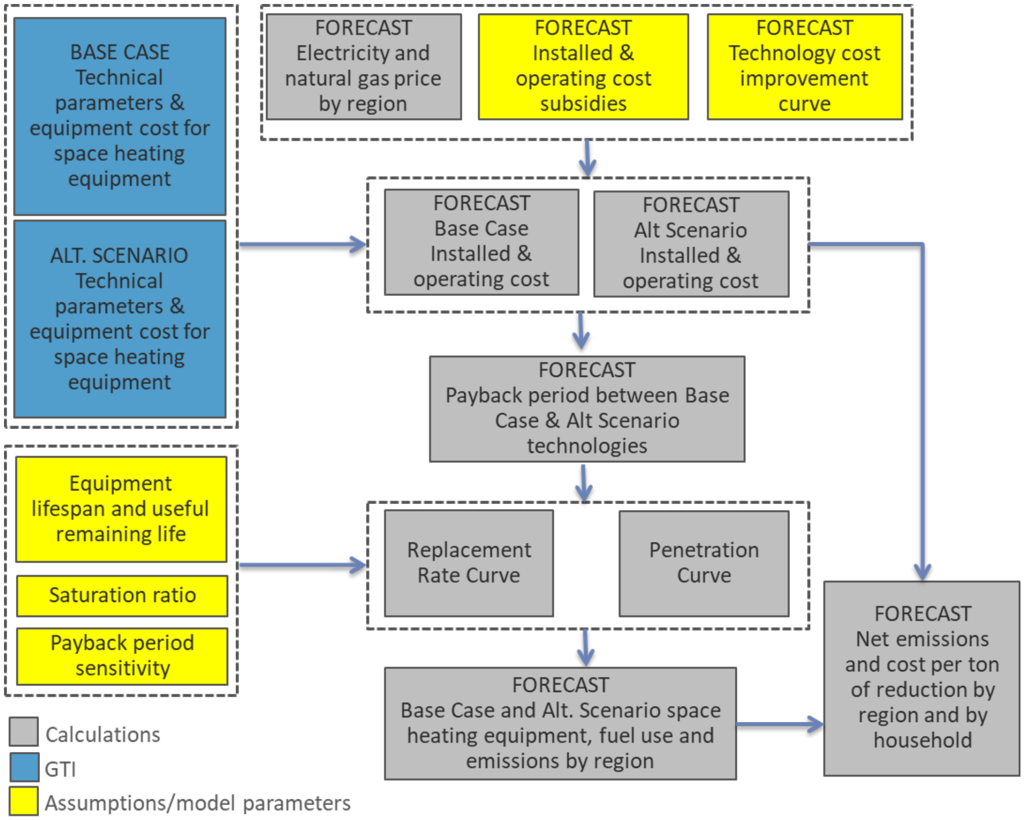
3. Penetration module

This module generates a forecast for emissions and cost per ton of CO_2 reduction by region.
The inputs of the module included outputs from the Equipment usage module and Baseline module to develop two key variables in the model: *replacement rate curve* and *penetration rate curve*.
The *Penetration rate curve* is the proportion of new installments that will be the select technologies over the years in the model. The concept of penetration curve was originally developed for solar PV, but it is technology agnostic. It depends primarily on comparing payback periods between technology and fuel alternatives[32].

The *Replacement rate curve* tracks the proportion of equipment that will be replaced over the years in the model. It uses payback period to calculate the proportion of replacement by comparing payback period against its remaining useful life. The replacement curve is driven by the natural turnover of equipment. If the remaining useful life of given equipment is five years, and the payback period for new equipment is only four years, the replacement curve provides the probability that a given household will choose to replace their existing unit with the new technology now instead of waiting for its end of useful life. The smaller the gap between payback period and remaining useful life, the greater the probability that new equipment will be installed. The penetration curve and replacement curve for each end-use are recalculated each year for each region.

[32] *Market Penetration of New Energy Technologies*, 1993, NREL

Figure 39 Penetration Module

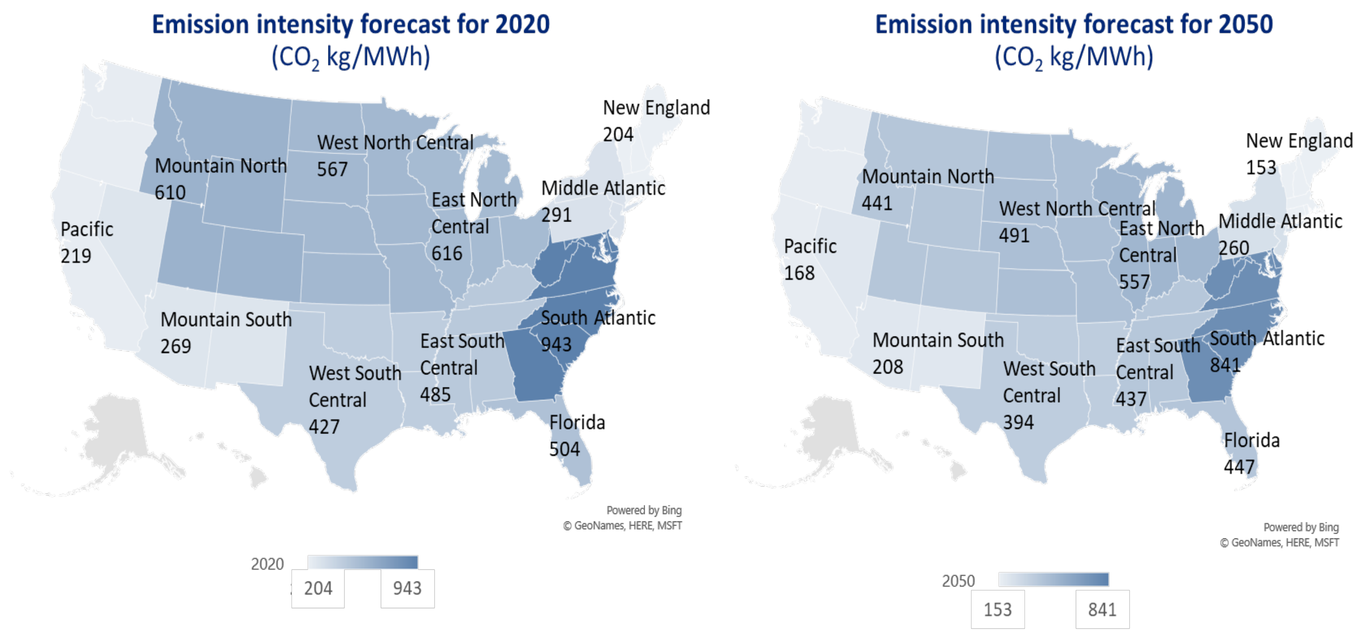


I. Electric Emission Intensity by Region

Emission intensity inputs are from EIA.

It is defined by fuel mix consumption and varies by region. The model made a simple linear interpolation between 2020 and 2035 and assumed the intensity remains constant after 2035. Regions that have made progress towards switching to low-intensity fuel will have lower emission intensity by 2050, compare to regions that still uses high-intensity fuels.

Figure 27 Snapshot of Emission Intensity in 2020 and 2050



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