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 CO₂ emissions today

Total US CO₂ emissions [millions metric tons]

- Natural gas direct use in residential sector accounts for 3.8% of total US CO₂ 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 CO₂ intensity fuels such as heating oil and propane

B. Approach
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
     - Combination steam and heat oven
     - Boilerless steam

3. End-use pathways
   - ~100 Technologies
   - 7 End use-pathways
   - 26 Prioritized technologies

4. Customer value
   - Affordability
   - Sustainability
   - Resilience
   - Comfort

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

Major end uses and representative technologies

### Residential

- **Water Heating**: 17
  - Tankless water heater
  - Gas heat-pump water heater

- **Heating & Cooling**: 18
  - Condensing furnace
  - Heat pumps
  - Solar thermal
  - Heat recovery

- **Co-generation/Resilience**: 5
  - Micro CHP
  - Solid oxide fuel cells

- **Transportation**: 5
  - Fuel Cell Electric Vehicle
  - Home-refueling appliances

- **Cooking**: 1
  - Gas oven and cooktop

- **Laundry**: 3
  - Advanced gas dryer
  - Ozone washing

### Commercial

- **Water Heating**: 3
  - Condensing economizer
  - Grease Trap heat exchange

- **Heating & Cooling**: 13
  - Heat pumps
  - Condensing Condo Packs

- **Co-generation/Resilience**: 5
  - Micro CHP
  - Solid oxide fuel cells

- **Transportation**: 9
  - Commercial CNGVs
  - Free-piston linear-motor compressor

- **Cooking**: 6
  - High production fryer
  - Boilerless steamer

- **Laundry**: 5
  - Ozone washing
  - Advanced gas infra-red burner

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

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**Technology Innovation Areas**

- **Building Energy Management**: 12
  - Envelope
  - IoT-based energy mgmt.

- **Building Energy Management**: 10
  - Demand controls for HW system

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**Customer Value, GHG Impacts**

- **Focus of the study**
- **Outside of the main focus of the study**
All technologies were first assessed and then prioritized by level of impact and time to market, as well as several other secondary criteria.

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

> 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.

**Space Cooling, up to 45%**
- Gas heat pump

**Space Heating, up to 40%**
- Gas heat pump

**Cooking, minimal change**
- Gas stove
- Gas oven

**Water heating, up to 55%**
- Absorption heat pump

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

**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

<table>
<thead>
<tr>
<th>Assumptions</th>
<th>Base Case</th>
<th>Scenario 1: Accelerated Adoption of Near-Term High-Efficiency Technologies</th>
<th>Scenario 2: High Penetration Rates of Emerging High-Efficiency Technologies</th>
<th>Scenario 3: Decarbonization Through Emerging High-Efficiency Technologies and RNG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Policies and incentives</td>
<td>Current policies &gt; Current policies &gt; Utility driven customer incentives</td>
<td>&gt; Policies favoring emerging high efficiency gas technologies &gt; Additional incentives provided to customers by utilities</td>
<td>&gt; Policies favoring emerging high efficiency gas technologies &gt; National policies favoring RNG &gt; Additional incentives provides to customers by utilities</td>
<td></td>
</tr>
<tr>
<td>Natural gas technologies</td>
<td>Per AEO2019 with associated efficiency improvement curves</td>
<td>Existing and high probability emerging high efficiency technologies with higher penetration rates</td>
<td>Existing and emerging high efficiency technologies with high penetration rates</td>
<td>Existing and emerging high efficiency technologies with high penetration rates</td>
</tr>
<tr>
<td>All other technologies</td>
<td>The same as base case</td>
<td>The same as base case</td>
<td>The same as base case</td>
<td>The same as base case</td>
</tr>
<tr>
<td>Technology cost</td>
<td>Per AEO2019</td>
<td>Per GTI with some incentives</td>
<td>Per GTI with some incentives</td>
<td>Per GTI with some incentives</td>
</tr>
<tr>
<td>Fuel switching</td>
<td>Per AEO2019</td>
<td>Yes¹</td>
<td>Yes¹</td>
<td>Yes¹</td>
</tr>
<tr>
<td>RNG</td>
<td>Per AEO2019</td>
<td>Per AEO2019</td>
<td>Per AEO2019</td>
<td>Increased production of RNG</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>End Use</th>
<th>2020</th>
<th>2040</th>
</tr>
</thead>
<tbody>
<tr>
<td>Space heating</td>
<td>4.71</td>
<td>4.05</td>
</tr>
<tr>
<td>Water heating</td>
<td>1.70</td>
<td>1.76</td>
</tr>
<tr>
<td>Drying</td>
<td>0.25</td>
<td>0.31</td>
</tr>
</tbody>
</table>

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 CO₂ 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.

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

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

**Base Case Inputs**
- Housing units by census region, and type of fuel used for space heating
- FORECAST Equipment stock & efficiency by fuel type
- FORECAST Fuel use for space heating by type
- FORECAST Generation mix by region
- Emission intensity by fuel type

**Equipment usage module**
- HDD by state
- Number of households by state
- FORECAST Electricity & natural gas price
- Historical electricity & natural gas price by region
- BASE CASE and ALT. SCENARIO Technical parameters & equipment cost for space heating by state

**Key Modeling Outputs**
- FORECAST Base Case and Alt. Scenario space heating equipment, fuel use and emissions by region
- FORECAST Net emissions and cost per ton of reduction by region and by customer/household

**Penetration Module, net emissions and cost per ton of reduction**
- Equipment lifespan and useful remaining life
- Saturation ratio
- Payback period sensitivity
- FORECAST Installed & operating cost subsidies by state
- FORECAST Technology cost improvement curve

**Assumptions/ modeling parameters**
- GTI
- EPA
- Assumptions/ modeling parameters
- Calculations
- Census data and EIA
- EIA (AEO 2019, Residential Energy Survey)

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)

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

> 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
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)

> 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 CO\(_2\) 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)

\(^1\) capital cost = installed cost + retail margin
Fisher-Pry methodology was used to apply S-curves to consumer buying decisions, for modeling technology adoption

Five classes of technology adoption characteristics

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time to saturation</td>
<td>5 years</td>
<td>10 years</td>
<td>20 years</td>
<td>40 years</td>
<td>&gt;40 years</td>
</tr>
<tr>
<td>Technology factors</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Equipment Life</td>
<td>&lt;5 years</td>
<td>5-15 years</td>
<td>15-25 years</td>
<td>25-45 years</td>
<td>&gt;40 years</td>
</tr>
<tr>
<td>Equipment Replacement</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Technology Experience</td>
<td>None</td>
<td>Minor</td>
<td>Unit operation</td>
<td>Plant section</td>
<td>Entire plant</td>
</tr>
<tr>
<td>Industry Factors</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>New to US only</td>
<td></td>
<td></td>
<td>New to US only</td>
<td>New</td>
<td>New</td>
</tr>
<tr>
<td>Growth (% per year)</td>
<td>&gt;5%</td>
<td>&gt;5%</td>
<td>2-5%</td>
<td>1-2%</td>
<td>&lt;1%</td>
</tr>
<tr>
<td>Attitude to Risk</td>
<td>Open</td>
<td>Open</td>
<td>Cautious</td>
<td>Conservative</td>
<td>Adverse</td>
</tr>
<tr>
<td>External Factors</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Government Regulation</td>
<td>Forcing</td>
<td>Forcing</td>
<td>Driving</td>
<td>None</td>
<td>None</td>
</tr>
</tbody>
</table>

> 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

<table>
<thead>
<tr>
<th>Region</th>
<th>% Reduced</th>
<th>Subsidy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mountain North</td>
<td>38%</td>
<td>$800-$1,800</td>
</tr>
<tr>
<td>West North Central</td>
<td>37%</td>
<td>$1,080-$2,500</td>
</tr>
<tr>
<td>East North Central</td>
<td>37%</td>
<td>$970-$2,300</td>
</tr>
<tr>
<td>New England</td>
<td>45%</td>
<td>$1,400-$3,200</td>
</tr>
<tr>
<td>Pacific</td>
<td>32%</td>
<td>$800-$1,900</td>
</tr>
<tr>
<td>Mountain South</td>
<td>19%</td>
<td>none</td>
</tr>
<tr>
<td>West South Central</td>
<td>18%</td>
<td>$440-$1,020</td>
</tr>
<tr>
<td>East South Central</td>
<td>37%</td>
<td>$630-$1,440</td>
</tr>
<tr>
<td>Florida</td>
<td>-</td>
<td>none</td>
</tr>
<tr>
<td>Middle Atlantic</td>
<td>43%</td>
<td>$1,090-$2,500</td>
</tr>
<tr>
<td>South Atlantic</td>
<td>39%</td>
<td>$560-$830</td>
</tr>
</tbody>
</table>

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

Source: Roland Berger analysis

National Level Results (Scenario 2)

- **Emission Reduction**: 46%
- **Cost**: $90/ton
- **Consumer Impact**
  - Mean savings of $220/year
- **Technology Penetration**: 85%
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

<table>
<thead>
<tr>
<th>Region</th>
<th>% reduced</th>
<th>Subsidy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mountain North</td>
<td>41%</td>
<td>$500-600</td>
</tr>
<tr>
<td>West North Central</td>
<td>45%</td>
<td>$600-700</td>
</tr>
<tr>
<td>East North Central</td>
<td>44%</td>
<td>$600-700</td>
</tr>
<tr>
<td>New England</td>
<td>45%</td>
<td>$800-1,000</td>
</tr>
<tr>
<td>Pacific</td>
<td>50%</td>
<td>$850-1,000</td>
</tr>
<tr>
<td>Mountain South</td>
<td>48%</td>
<td>600-800</td>
</tr>
<tr>
<td>West South Central</td>
<td>44%</td>
<td>600-800</td>
</tr>
<tr>
<td>East South Central</td>
<td>46%</td>
<td>600-800</td>
</tr>
<tr>
<td>Florida</td>
<td>44%</td>
<td>$600-800</td>
</tr>
<tr>
<td>Middle Atlantic</td>
<td>49%</td>
<td>$800-900</td>
</tr>
<tr>
<td>South Atlantic</td>
<td>47%</td>
<td>$800-800</td>
</tr>
</tbody>
</table>

**National Level Results (Scenario 2)**

- **Emission Reduction**: 36%
- **Cost**: $39/ton
- **Consumer Impact**: Mean savings of $143/year
- **Technology Penetration**: 96%

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

Source: Roland Berger analysis
Overall CO₂ reductions in 2050 are most sensitive to the amount of subsidies

### Sensitivity analysis for emission reductions [%]

<table>
<thead>
<tr>
<th>Change from 40% in Scenario 2</th>
<th>Gross first cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>-10%</td>
<td>39.7%</td>
</tr>
<tr>
<td>-5%</td>
<td>40.2%</td>
</tr>
<tr>
<td>-20%</td>
<td>37.0%</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Change from $84/ton in Scenario 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>-10%</td>
</tr>
<tr>
<td>-5%</td>
</tr>
<tr>
<td>-20%</td>
</tr>
</tbody>
</table>

### Sensitivities

- **Minus sensitivities**: $76
- **Plus sensitivities**: $159

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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.

References:
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$_{2e}$]

- Behavioral changes
- Building envelope
- High efficiency direct end use technologies
- Green hydrogen
- Renewable natural gas / biogas

- Fugitive methane
- 51%+ emissions reduced for $74 billion/yr
- 88%+ emissions reduced for $16 billion/yr

- Atmospheric CCS
- Renewable natural gas / biogas - difficult
- Renewable natural gas / biogas - easy

- 100% emissions reduced with CCS for $24 billion/yr
- 100% emissions reduced with CCS for $31 billion/yr

Residential gas decarbonization - electricity options
[USD / ton CO$_{2e}$]

- Building envelope
- Fugitive methane
- Electrification of remaining building gas usage
- Atmospheric CCS

- Behavioral changes
- - $190
- - $617

- 51%+ emissions reduced for $74 billion/yr
- 88%+ emissions reduced for $16 billion/yr

- 100% emissions reduced with CCS for $24 billion/yr
- 100% emissions reduced with CCS for $31 billion/yr

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$_2$e]

### Natural gas innovations – Assumptions & rationale
- ~590 m tons CO$_2$e 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 CO$_2$e 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

<table>
<thead>
<tr>
<th>1</th>
<th>Supply innovation</th>
<th>2</th>
<th>Delivery enhancement</th>
<th>3</th>
<th>Demand &amp; natural gas technology innovation (efficient use)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; Maximizing cost-effective production of renewable natural gas (RNG or biogas)</td>
<td>&gt; Reducing fugitive methane leaks during the following steps of the value chain:</td>
<td>&gt; Improvement and adoption of high efficiency residential technologies, specifically in:</td>
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<td>&gt; Scale adoption of power to gas (P2G), including:</td>
<td>– Transportation/distribution</td>
<td>– Space heating</td>
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<tr>
<td>– Hydrogen displacement of natural gas</td>
<td>– Meters</td>
<td>– Water heating</td>
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<tr>
<td>– Hydrogen methanation</td>
<td>– Behind the meter at homes</td>
<td>– Drying</td>
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<tr>
<td>&gt; Switching from carbon-intensive fuels (e.g., propane, heating oil, kerosene) to natural gas</td>
<td>&gt; Implementing hydrogen ready infrastructure</td>
<td>&gt; Implementing behavioral changes towards energy efficiency</td>
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</tbody>
</table>

- **40-50% reduction in CO$_{2e}$ emissions**
- **5-10% reduction in CO$_{2e}$ emissions**
- **35-45% reduction in CO$_{2e}$ emissions**

Source: Enovation Partners analysis, Roland Berger
## Contributing team from Roland Berger LP and Gas Technology Institute

<table>
<thead>
<tr>
<th>Name</th>
<th>Title</th>
<th>Organization</th>
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<tbody>
<tr>
<td>Bill Kemp</td>
<td>Director</td>
<td>Roland Berger</td>
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<tr>
<td>Bob Zabors</td>
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<tr>
<td>Tim Kingston</td>
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