American Gas FOUNDATION

Renewable Sources of Natural Gas
Supply & Emission Reduction Assessment

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Overview

- The American Gas Association (AGA) uses the following definition for RNG: *Pipeline compatible gaseous fuel derived from biogenic or other renewable sources that has lower lifecycle carbon dioxide equivalent (CO2-eq) emissions than geological natural gas.*
- ICF conducted an assessment to outline the potential for RNG to contribute meaningfully and cost-effectively to greenhouse gas (GHG) emission reduction initiatives across the country.
- The report serves as an update *and* expansion to a 2011 report published by the American Gas Foundation (AGF) entitled *The Potential for Renewable Gas: Biogas Derived from Biomass Feedstocks and Upgraded to Pipeline Quality*.

Study Objectives

- The primary objective of the report is to characterize the resource and economic potential for RNG as a greenhouse gas (GHG) emission reduction strategy. Further, this report seeks to improve policy makers' understanding of the extent to which delivering RNG to all sectors of the economy can contribute to broader GHG emission reduction initiatives.
- Broadly speaking, the report seeks to answer three questions:
  - **What is the potential for RNG?** And over what timeline might it be available?
  - **What are the corresponding GHG emission reductions?**
  - **How much will it cost?** And what are the potential areas for cost reductions?

Feedstocks & Technologies

- **Feedstocks:** ICF developed low and high resource potential scenarios by considering RNG production from 9 feedstocks: landfill gas, animal manure, water resource recovery facilities (WRRFs), food waste, agricultural residues, forestry and forest product residues, energy crops, the use of renewable electricity, and the non-biogenic fraction of municipal solid waste (MSW).
- **Production Technologies**: Feedstocks were assumed to be processed using one of three technologies to produce RNG: 1) anaerobic digesters, 2) thermal gasification systems, and 3) power-to-gas (P2G) in combination with a methanation system.
- **Geography**: The data are presented by US Census Region.

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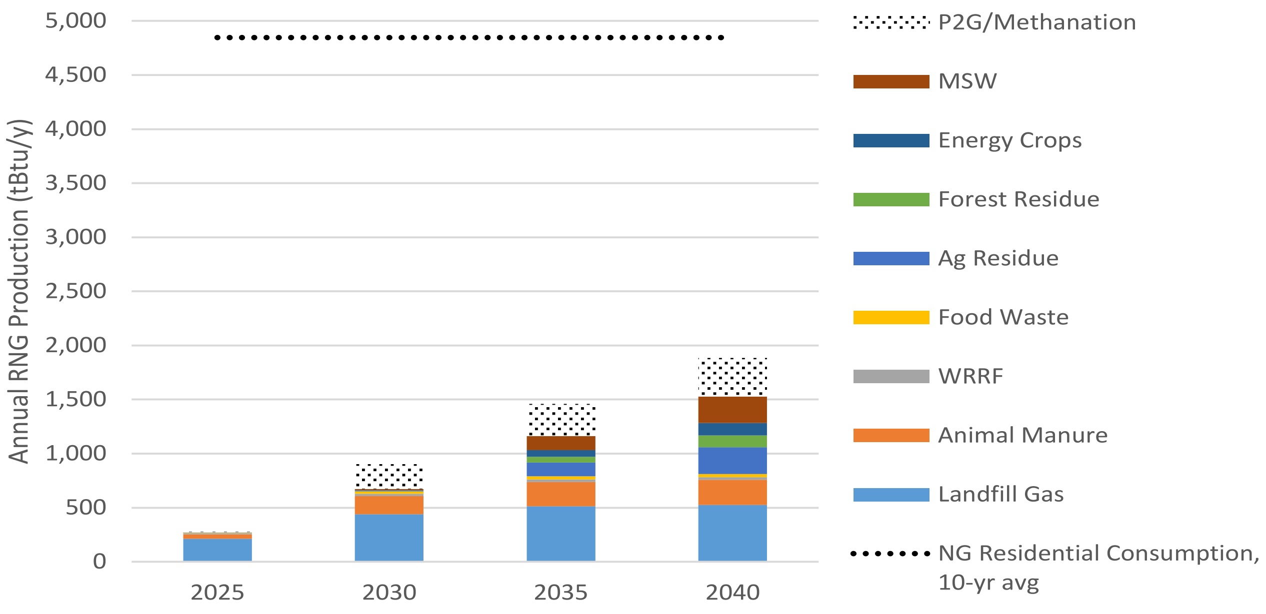
RNG Resource Assessment

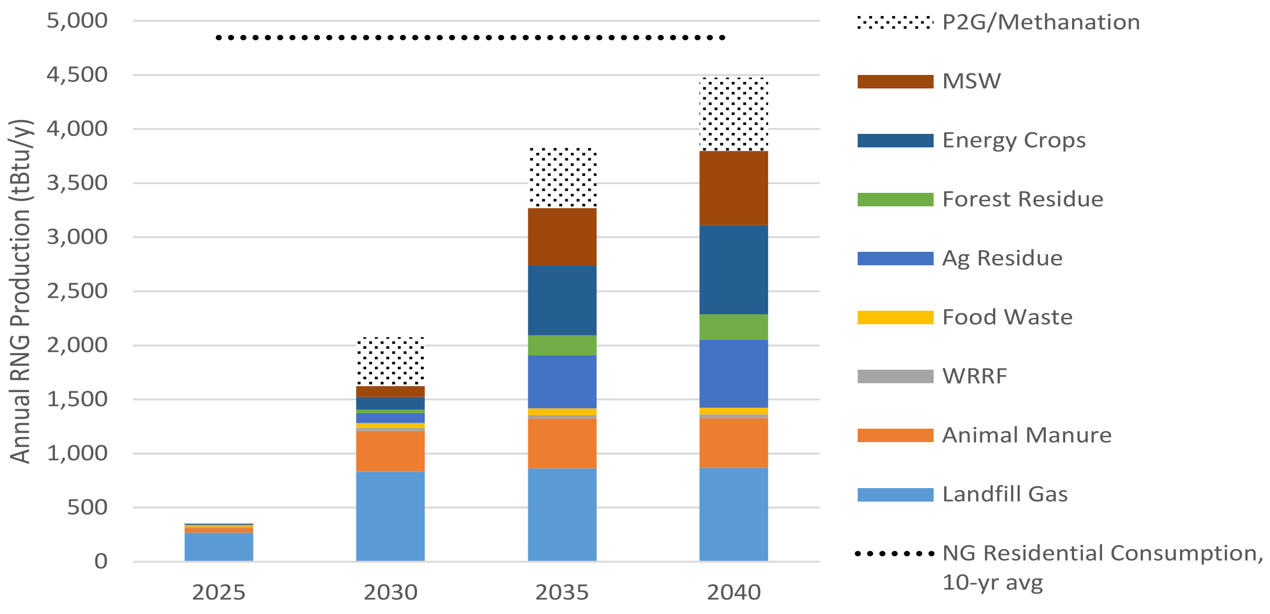
- In the **low resource potential scenario**, ICF estimates RNG production potential of 1,660 tBtu per year by 2040; increasing to 1,910 tBtu/year when including the potential for the non-biogenic fraction of MSW.
- In the **high resource potential scenario**, ICF estimates that about 3,780 tBtu/year of RNG can be by 2040; increasing to 4,510 tBtu/year when including the potential for the non-biogenic fraction of MSW.
- ICF also reports a **technical resource potential scenario** of nearly 13,960 tBtu—a production potential intended to reflect the RNG production potential without any technical or economic constraints.

RNG Resource Assessment, ctd.

Est. Annual RNG Production, Low Resource Potential Scenario



Est. Annual RNG Production, High Resource Potential Scenario

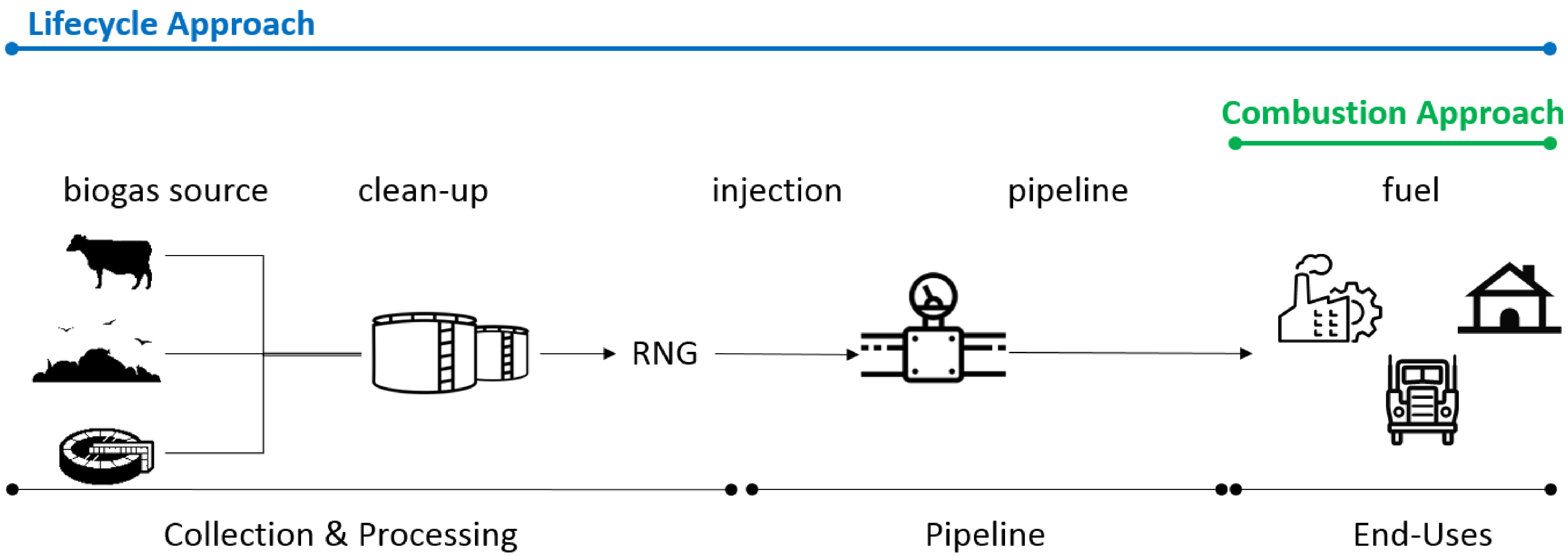


For the sake of comparison, the 10-year average (2009 to 2018) for residential natural gas consumption nationwide is 4,846 tBtu; this is shown as the black-dotted line in both figures.

RNG Resource Assessment, ctd

- **Diversity of supply potential**: A diverse array of resources can contribute to RNG production.
  - In the near-term future, we assume that most RNG continues to be produced using anaerobic digestion paired with conditioning and upgrading systems.
  - The post-2025 outlook for RNG will increasingly rely on thermal gasification of sustainably harvested biomass, including agricultural residues, forestry and forest product residues, and energy crops.
  - The long-term outlook for RNG growth will depend to some extent on technological advancements in power-to-gas systems.

Greenhouse Gas Emissions of RNG

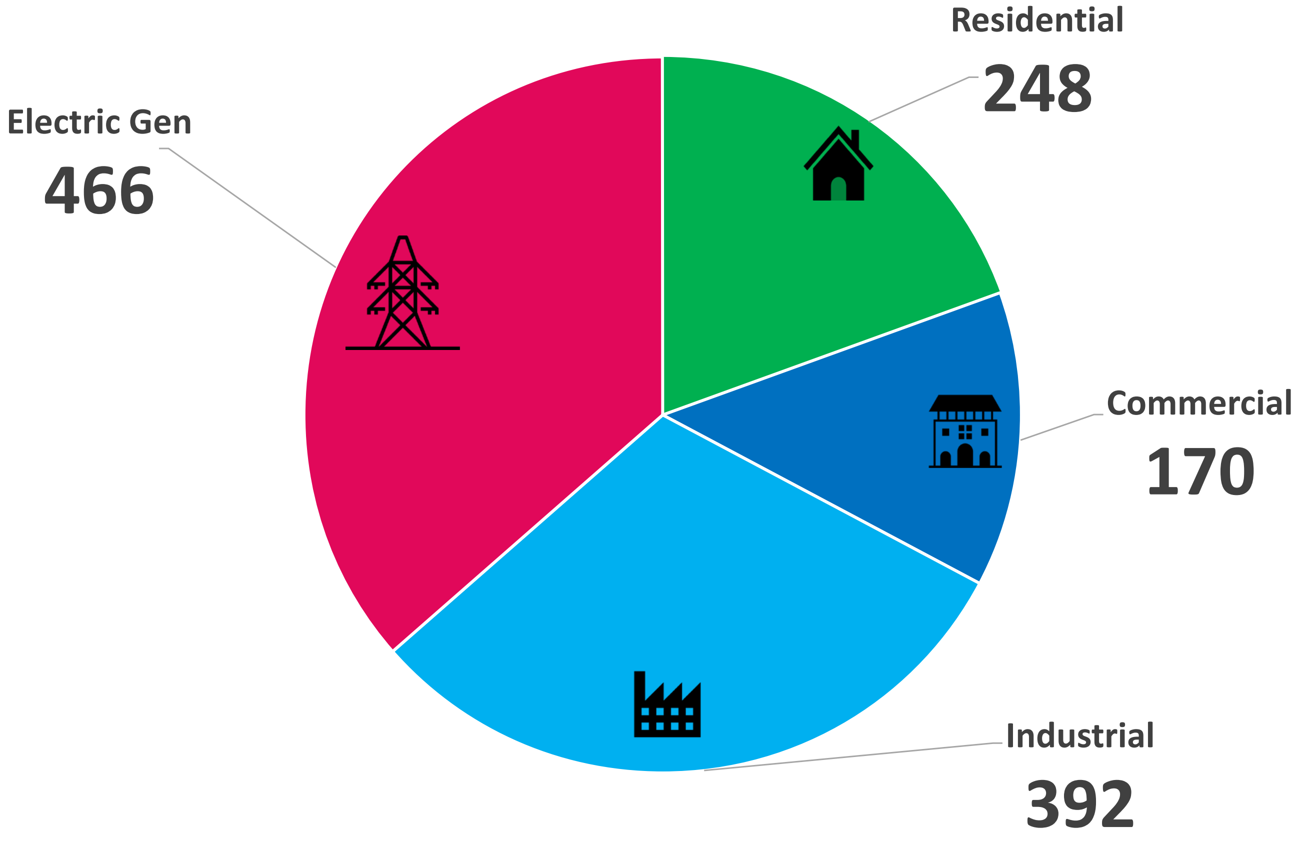


- **Combustion-based accounting** is the standard approach for most volumetric GHG targets, inventories and mitigation measures (e.g., RPS programs, etc.)
- **Lifecycle accounting** for GHG emissions from RNG can vary substantially between feedstocks and production methods.

GHG Emissions Reductions from RNG

- ICF estimates that RNG deployment could achieve 101 to 235 MMT of GHG emission reductions by 2040.
- By comparison, the figure to the right shows the average annual CO2 emissions from natural gas across different sectors; notably GHG emission reductions in the high resource potential nearly offset entirely emissions from the consumption of natural gas in the residential sector.

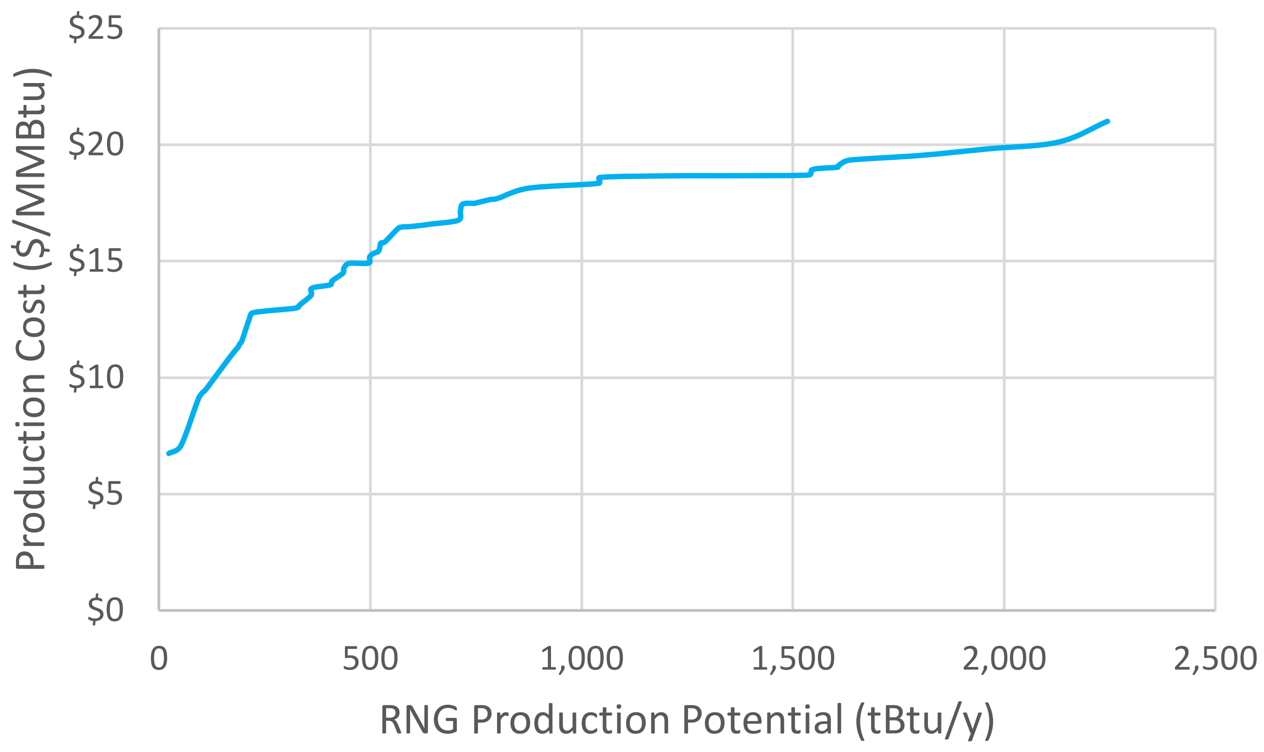
Average Annual CO_2 Emissions (in MMT) from Natural Gas Consumption, 2009-2018



RNG Cost Assessment

- ICF estimates that the majority of the RNG produced in the high resource potential scenario is available in the range of $7-$20/MMBtu, which results in a cost of GHG emission reductions between $55/ton to $300/ton in 2040.
- ICF finds that there is also potential for cost reductions as the RNG for pipeline injection market matures, production volumes increase, and the underlying structure of the market evolves.

Combined RNG Supply-Cost Curve in 2040



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RNG Cost Assessment: Achieving Cost Reductions

- Advanced manufacturing play an important role in making RNG more cost-competitive with geological natural gas and other fossil-based resource.
- To help achieve more significant reductions, the various aspects of RNG production need to be modular, autonomous, process intensive and manufactured in large numbers.
- Consider, for instance, that the DOE's EERE's Rapid Advancement in Process Intensification Deployment (RAPID) Institute focused on developing breakthrough technologies in industries such oil and gas, pulp and paper and various domestic chemical manufacturers.
- A similar effort dedicated towards RNG and other biomass conversion technologies could help reduce costs substantially.

Key Findings

- **ICF's assessment of RNG potential in the United States demonstrate that there is significant resource potential in both the low and the high cases considered**—and in both, ICF used moderately conservative assumptions with respect to the utilization of feedstocks and technological advancements.

- **ICF's updated assessment also illustrates the diversity of RNG resource potential as a GHG emission reduction strategy**—there is a portfolio of potential feedstocks and technologies that are or will be commercialized in the near-term future that will help realize the potential of the RNG market.

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Key Findings, ctd

- **ICF's analysis of the potential for P2G systems, paired with methanation suggests that the technology could make a significant contribution to RNG production by 2040.** However, ICF notes that the role of P2G systems as a contributor to RNG production requires further analysis and study.
- **In the low resource potential and high resource potential scenarios presented, RNG deployment could achieve 101 to 235 MMT of GHG emission reductions by 2040.** The high end estimate is the equivalent of reducing GHG emissions from the use of NG in the residential sector by 95%.
- **ICF estimates that the majority of the RNG produced in the high resource potential scenario is available in the range of $7-$20/MMBtu, which is equivalent to $55/ton to $300/ton in 2040.**

Questions?

Contact information

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Appendix

Technology Overview

- RNG is produced over a series of steps–namely collection of a feedstock, delivery to a processing facility for biomass-to-gas conversion, gas conditioning, compression, and interconnection and injection into the pipeline.
  - **Anaerobic digestion**: Microorganisms break down organic material in an environment without oxygen in a digester or reactor. The organic material is broken down over days, and the gaseous products of that process contain a large fraction of methane and carbon dioxide. The biogas is subsequently upgraded and conditioned to yield methane.
  - **Thermal gasification**. A biomass feedstock is converted into a mixture of gases referred to as syngas, including hydrogen, carbon monoxide, steam, carbon dioxide, methane, and trace amounts of other gases. This process generally occurs at high temperatures and varying pressures (depending on the gasification system).
  - **Power-to-Gas.** Hydrogen is produced via electrolysis, powered by renewable electricity (as a feedstock); in this report we assume that the hydrogen is then methanated.

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RNG Feedstocks for Anaerobic Digestion

- **Landfill Gas:** The anaerobic digestion of organic waste in landfills produces a mix of gases, including methane (40-60%).
- **Animal Manure**: Manure produced by livestock, including dairy cows, beef cattle, swine, sheep, goats, poultry, and horses.
- **Water Resource Recovery Facilities**: Wastewater consists of waste liquids and solids from household, commercial, and industrial water use; in the processing of wastewater, a sludge is produced, which serves as the feedstock for RNG.
- **Food waste**: Commercial food waste, including from food processors, grocery stores, cafeterias, and restaurants, as well as residential food waste, typically collected as part of waste diversion programs.

RNG Feedstocks for Thermal Gasification

- **Agricultural residue:** The material left in the field, orchard, vineyard, or other agricultural setting after a crop has been harvested. Inclusive of unusable portion of crop, stalks, stems, leaves, branches, and seed pods.
- **Forestry and forest product residue:** Biomass generated from logging, forest and fire management activities, and milling. Inclusive of logging residues, forest thinnings, and mill residues. Also materials from public forestlands, but not specially designated forests (e.g., roadless areas, national parks, wilderness areas).
- **Energy Crops:** Inclusive of perennial grasses, trees, and some annual crops that can be grown specifically to supply large volumes of uniform, consistent quality feedstocks for energy production.

RNG from Thermal Gasification of MSW

- **Municipal Solid Waste**: Refers to the non-biogenic fraction of waste that would be landfilled after diversion of other waste products (e.g., food waste or other organics), including construction and demolition debris, plastics, etc.
  - *Note that gas produced from the thermal gasification of MSW does not satisfy AGA's definition of RNG because it is not from a biogenic or renewable source; however, it does have lower lifecycle CO2e emissions than geological natural gas. As a result, MSW as a resource was assessed in this study, but is presented separately from the other feedstocks considered.*

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RNG from P2G

- **Power-to-Gas** is a form of energy technology that converts electricity to a gaseous fuel. Electricity is used to split water into hydrogen and oxygen, and the hydrogen can be further processed to produce methane when combined with a source of carbon dioxide. If the electricity is sourced from renewable resources, such as wind and solar, then the resulting fuels are carbon neutral.
- The key process in P2G is the production of hydrogen from renewably generated electricity by means of electrolysis. There are three electrolysis technologies with different efficiencies and in different stages of development:
  - Alkaline electrolysis
  - Proton exchange membrane
  - Solid oxide electrolysis

Resource Assessment: Feedstock Utilizations

RNG Feedstock	Low Resource	High Resource
LFG	• 40% of the LFG facilities that have collection systems in place • 30% of the LFG facilities that do not have collections systems in place • 50% of EPA's candidate landfills	• 65% of the LFG facilities that have collection systems in place • 60% of the LFG facilities that do not have collections systems in place • 80% of EPA's candidate landfills
Animal manure	• 30% of technically available animal manure	• 60% of technically available animal manure
WRRF	• 30% of WRRFs with a capacity greater than 7.25 million gallons per day	• 50% of WRRFs with a capacity greater than 3.3 million gallons per day
Food waste	• 40% of the food waste available at $70/dry ton	• 70% of the food waste available at $100/dry ton
Agricultural residue	• 20% of the agricultural residues available at $50/dry ton	• 50% of the agricultural residues available at $50/dry ton
Forestry and forest product residue	• 30% of the forest and forestry product residues available at $30/dry ton	• 60% of the forest and forestry product residues available at $60/dry ton
Energy crops	• 50% of the energy crops available at $50/dry ton	• 50% of the energy crops available at $70/dry ton
Municipal solid waste (MSW)	• 30% of the non-biogenic fraction of MSW available at $30/dry ton	• 60% of the non-biogenic fraction of MSW available at $100/dry ton
P2G	• 50% capacity factor for dedicated renewables	• 80% capacity for dedicated renewables

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Resource Assessment: Low Resource Potential

- Total estimate: about **1,910 tBtu/y by 2040**.
- For the sake of comparison, the United States has consumed on average 15,850 tBtu of natural gas over the last ten years in the residential (4,846 tBtu), commercial (3,318 tBtu), transportation (36 tBtu), and industrial sectors (7,652 tBtu).

Feedstock	RNG Potential: Low Scenario (in tBtu/y)									
	New England	Mid-Atlantic	East North Central	West North Central	South Atlantic	East South Central	West South Central	Mountain	Pacific	Total
RNG from biogenic or renewable resources										
Landfill Gas	13.3	57.5	106.2	28.6	88.4	35.7	65.3	38.3	95.2	528.4
Animal Manure	8.0	12.1	30.3	44.5	31.7	18.9	36.0	28.7	21.0	231.2
WRRF	1.1	4.5	5.5	1.3	3.4	1.0	2.0	1.2	4.0	24.0
Food Waste	1.8	5.0	5.7	1.9	6.0	0.8	1.4	0.9	5.6	29.2
Sub-Total, AD	***24.2***	***79.1***	***147.8***	***76.3***	***129.5***	***56.4***	***104.7***	***69.1***	***125.8***	***812.8***
Ag Residue	0.0	3.7	57.0	144.4	10.0	2.9	10.7	10.9	14.9	254.6
Forestry and Forest Residue	3.6	4.8	9.7	6.5	37.6	20.6	16.3	2.7	6.8	108.6
Energy Crops	0.2	2.2	1.5	35.4	18.1	9.3	56.5	0.2	0.0	123.4
Sub-Total, TG	***3.8***	***10.7***	***68.2***	***186.3***	***65.7***	***32.8***	***83.5***	***13.8***	***21.7***	***486.6***
Renewable gas from MSW										
MSW	14.4	40.6	45.9	17.7	56.9	11.2	15.3	8.8	45.4	256.2
RNG from P2G / Methanation										
P2G / Methanation										357.7
Totals	**42.3**	**130.5**	**261.8**	**280.4**	**252.1**	**100.3**	**203.4**	**91.7**	**192.9**	**1,913.2**

Resource Assessment: High Resource Potential

- Total estimate: **4,510 tBtu/y by 2040**.
- For the sake of comparison, the United States has consumed on average 15,850 tBtu of natural gas over the last ten years in the residential (4,846 tBtu), commercial (3,318 tBtu), transportation (36 tBtu), and industrial sectors (7,652 tBtu).

Feedstock	RNG Potential: High Scenario (in tBtu/y)									
	New England	Mid-Atlantic	East North Central	West North Central	South Atlantic	East South Central	West South Central	Mountain	Pacific	Total
RNG from biogenic or renewable resources										
Landfill Gas	21.7	94.3	173.8	47.3	145.0	59.1	106.2	32.9	155.2	865.6
Animal Manure	16.0	24.2	60.6	88.9	63.4	37.7	71.9	57.5	42.1	462.3
WRRF	1.6	6.3	6.6	2.0	5.1	1.6	3.1	1.7	5.5	33.5
Food Waste	3.1	8.8	9.9	4.1	13.1	4.2	8.0	2.9	9.8	63.9
Sub-Total, AD	**42.4**	**133.6**	**250.9**	**142.3**	**226.6**	**102.6**	**189.2**	**125.0**	**212.6**	**1,425.3**
Ag Residue	0.1	9.2	142.6	361.0	26.9	7.3	28.8	27.3	37.3	640.5
Forestry and Forest Residue	7.3	9.7	19.3	13.0	75.2	41.3	37.1	19.3	13.6	235.8
Energy Crops	0.5	9.4	64.4	260.0	77.3	91.6	330.5	3.9	0.0	837.6
Sub-Total, TG	***7.9***	***28.3***	***226.3***	***634.0***	***179.4***	***140.2***	***396.4***	***50.5***	***50.9***	***1,713.9***
Renewable gas from MSW										
MSW	32.4	91.6	103.4	46.1	136.3	43.2	83.2	50.1	108.5	694.8
RNG from P2G / Methanation										
P2G / Methanation										678.7
Totals	**80.5**	**245.2**	**569.4**	**819.4**	**532.0**	**283.5**	**658.1**	**222.5**	**359.4**	**4,512.6**

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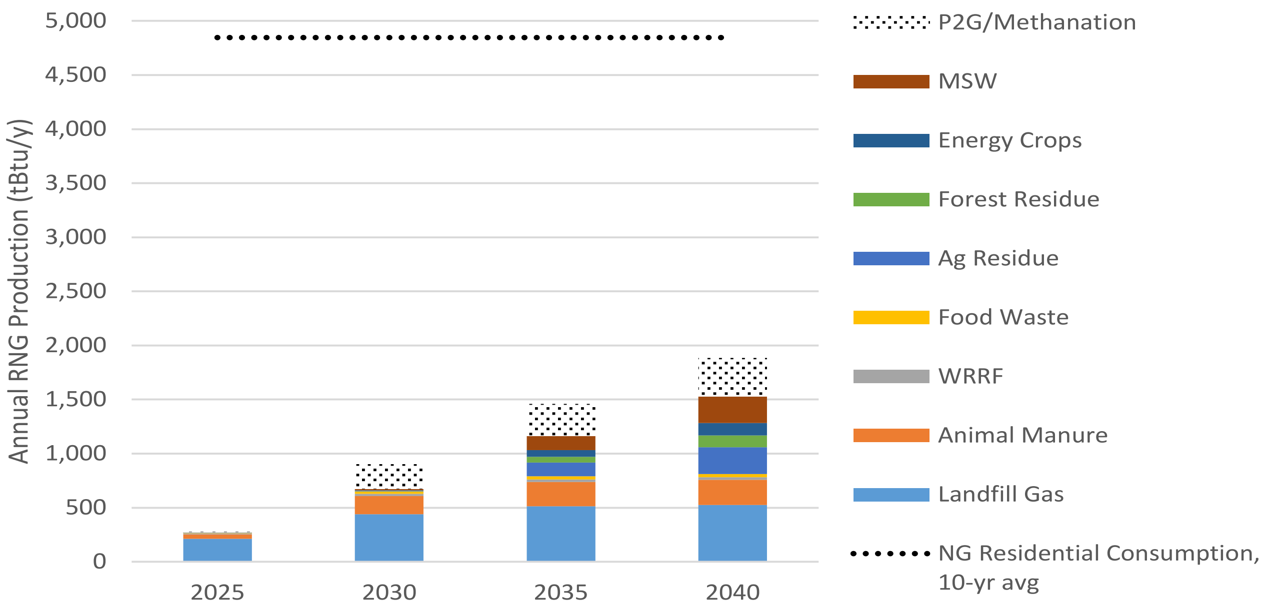
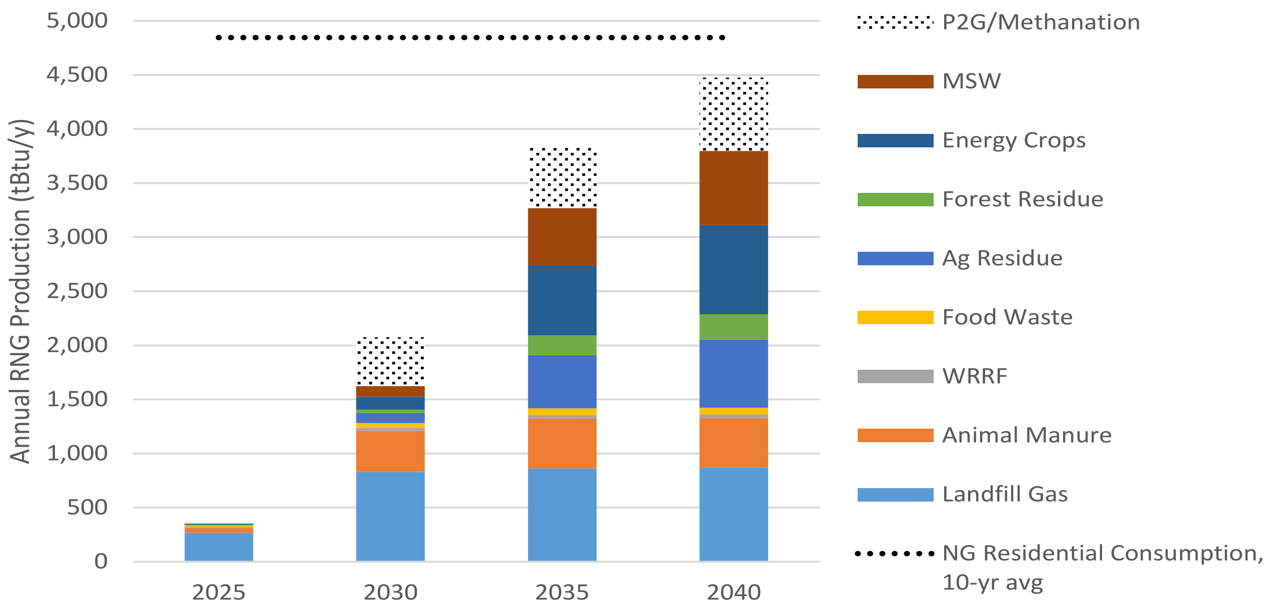
Resource Assessment: Temporal Aspects of RNG Deployment

Est. Annual RNG Production, Low Resource Potential Scenario



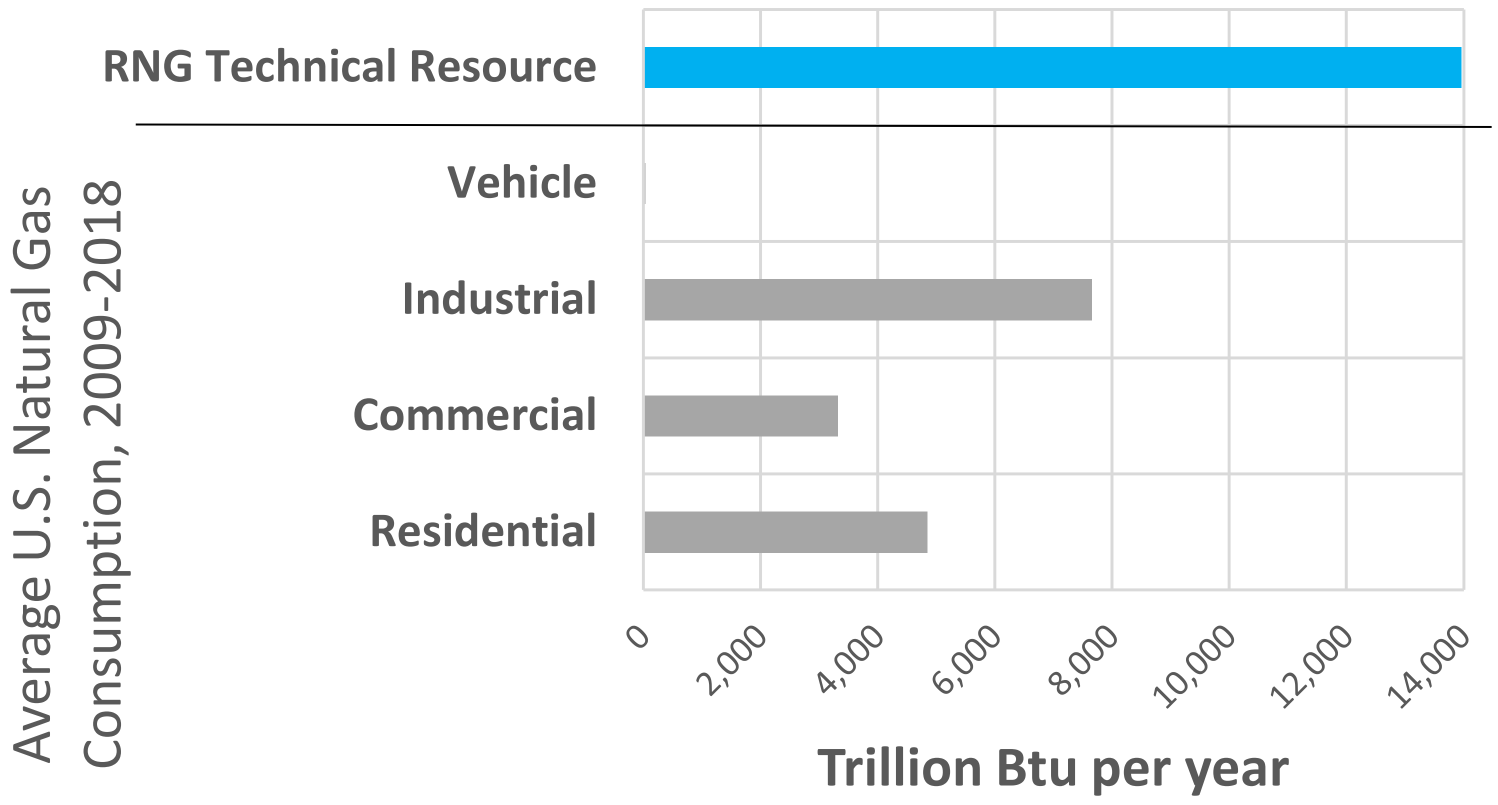
Est. Annual RNG Production, High Resource Potential Scenario



For the sake of comparison, the 10-year average (2009 to 2018) for residential natural gas consumption nationwide is 4,846 tBtu; this is shown as the black-dotted line in both figures.

Resource Assessment: Technical Resource Potential

- Technical potential: **14,000 tBtu/y**
- ICF generally finds that the potential for RNG deployment could <u>exceed</u> the estimated high resource potential scenario because we opted to employ moderately conservative assumptions regarding the expected utilization of various feedstocks.



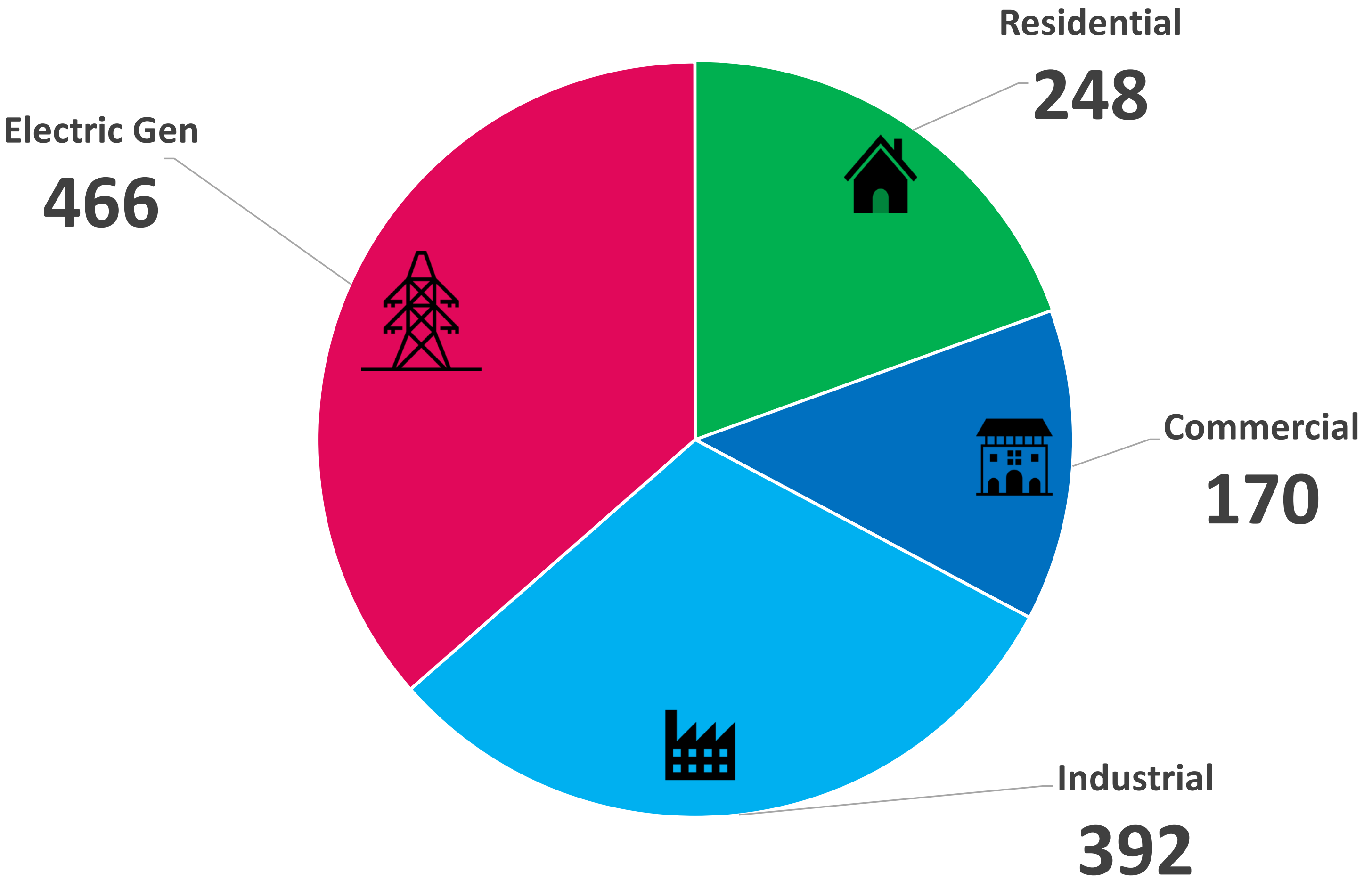
Greenhouse Gas Emissions of RNG

- RNG represents a valuable renewable energy source with a low or net negative emissions factor depending on the feedstock and the accounting framework. The GHG emission accounting method and scope employed can have a significant impact on how GHG emission factors for RNG are reported and estimated.
- GHG emissions accounting becomes complex when an assessment scope includes a diverse set of sources. This is most often seen in GHG emission inventories for agencies, corporations, and jurisdictions (e.g., community, city, county, state, country) where entities must account for a wide range of sectors (e.g., transportation, energy, agriculture).

Greenhouse Gas Emissions of RNG

- Used IPCC guidelines
- Emission factors
  - Natural gas: 53.06 kg/MMBtu
  - RNG from AD an T: 0 kg/MMBtu
  - Thermal gasification of MSW: 15 kg/MMBtu
- GHG Emission Reduction Potential
  - Low Resource Case: 101 MMT
  - High Resource Case: 235 MMT
- Equivalent to displacing 59-95% of the average GHG emissions attributable to NG consumption in residential energy sector nationwide.

Ten-Year Average Annual CO2 Emissions, Natural Gas Consumption in the U.S.



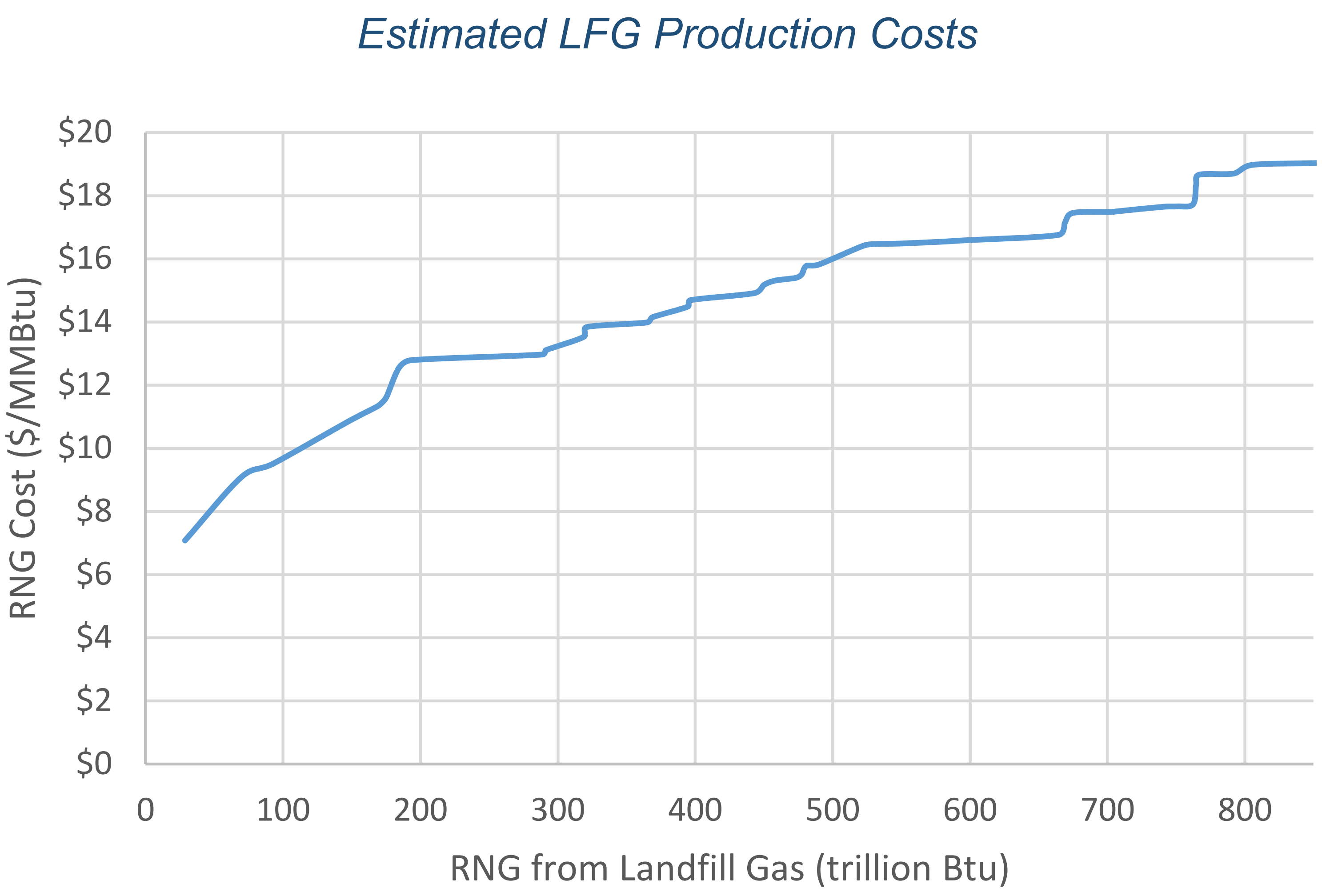
RNG Cost Assessment

- ICF notes that our cost estimates are not intended to replicate a developer's estimate when deploying a project.
  - Conditioning and upgrading represents a series of no less than a half-dozen issues that must be dealt with at the project level
  - Interconnect: Varies considerably between jurisdictions

Cost Parameter	ICF Cost Assumptions
Facility Sizing	• Differentiate by feedstock and technology type: AD and TG • Prioritize larger facilities to the extent feasible, but driven by resource estimate
Gas Conditioning and Upgrade	• These costs depend on the feedstock and the technology required.
Compression	• Capital costs for compressing the conditioned/upgraded gas for pipeline injection.
Operational Costs	• Costs for each equipment type–digesters, conditioning equipment, collection equipment, and compressors–as well as utility charges for estimated electricity consumption.
Feedstock	• Feedstock costs (for thermal gasification), ranging from $30 to $100 per dry ton.
Financing	• Financing costs, including carrying costs of capital (assuming a 60/40 debt/equity ratio and an interest rate of 7%), an expected rate of return on investment (set at 10%), and a 15 year repayment period.
Interconnection	• Costs of interconnection—representing the point of receipt and any pipeline extension. This cost is in line with financing, constructing, and maintaining a pipeline of about 1-mile in length. The costs of delivering the same volumes of RNG that require pipeline construction greater than 1-mile will increase, depending on feedstock/technology type, with a typical range of $1-5/MMBtu.
Project lifetimes	• 20 years. The levelized cost of gas was calculated based on the initial capital costs in Year 1, annual operational costs discounted at an annual rate of 5% over 20 years, and biogas production discounted at an annual rate of 5% for 20 years.

RNG Cost Assessment: Landfill Gas

- Four types of landfills: candidate landfills without collection systems in place, candidate landfills with collection systems in place, landfills without collection systems in place, and landfills with collections systems in place.
- For each region, ICF further characterized the number of landfills across these four types of landfills, distinguishing facilities by estimated biogas throughput



RNG Cost Assessment: Animal Manure

- Developed assumptions for each region
  - Based on a combination of the size of the farms
  - Assumptions that certain areas would need to aggregate or cluster resources.
- There is some uncertainty associated with this approach because an explicit geospatial analysis was not conducted.
- Animal manure production costs: \$18.4/MMBtu to \$32.6/MMBtu.

Factor	Cost Elements Considered	Costs
Performance	• Capacity factor	• 95%
Installation Costs	• Construction / Engineering • Owner's Cost	• 25% of uninstalled costs of equipment • 10% of uninstalled costs of equipment
Gas Upgrading	• CO2 separation • H2S removal • N2/O2 removal	• \$2.3 to \$7.0 million depending on facility • \$0.3 to \$1.0 million depending on facility • \$1.0 to \$2.5 million depending on facility
Utility Costs	• Electricity: 30 kWh/MMBtu • Natural Gas: 6% of product	• 4.6—13.7 ¢/kWh • \$3.00-\$8.25/MMBtu
Operations & Maintenance	• 1 FTE for maintenance • Miscellany	• 15% of installed capital costs
For Injection	• Interconnect • Pipeline • Compressor	• \$2.0 million • \$1.5 million • \$0.2-0.5 million
Other	• Value of digestate • Tipping fee	• Valued for dairy at about \$100/cow/y • Excluded from analysis
Financial Parameters	• Rate of Return • Discount Rate	• 10% • 7%

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RNG Cost Assessment: Water Resource Recovery Facilities

- ICF developed assumptions for each region by distinguishing between water resource recovery facilities based on the throughput of the facilities.
- WRRFs production costs: $7.4/MMBtu to $26.1/MMBtu

Factor	Cost Elements Considered	Costs
Performance	• Capacity factor	• 95%
Installation Costs	• Construction / Engineering • Owner's Cost	• 25% of uninstalled costs of equipment • 10% of uninstalled costs of equipment
Gas Upgrading	• CO_2 separation • H_2S removal • N_2/O_2 removal	• $2.3 to $7.0 million depending on facility • $0.3 to $1.0 million depending on facility • $1.0 to $2.5 million depending on facility
Utility Costs	• Electricity: 26 kWh/MMBtu • Natural Gas: 6% of product	• 4.6—13.7 ¢/kWh • $3.00-$8.25/MMBtu
Operations & Maintenance	• 1 FTE for maintenance • Miscellany	• 10% of installed capital costs
For Injection	• Interconnect • Pipeline • Compressor	• $2.0 million • $1.5 million • $0.2-0.5 million
Financial Parameters	• Rate of Return • Discount Rate	• 10% • 7%

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RNG Cost Assessment: Food Waste

- ICF made the simplifying assumption that food waste processing facilities would be purpose built, and be capable of processing 60,000 tons of waste per year
- Assumed that food waste facilities would be able to offset costs with tipping fees.
- AD of food waste $19.4/MMBtu to $28.3/MMBtu.

Factor	Cost Elements Considered	Costs
Performance	• Capacity factor • Processing Capability	• 95% • 60,000 tons per year
Dedicated Equipment	• Organics Processing • Digester	• $10.0 million • $12.0 million
Installation Costs	• Construction / Engineering • Owner's Cost	• 25% of uninstalled costs of equipment • 10% of uninstalled costs of equipment
Gas Upgrading	• CO2 separation • H2S removal • N2/O2 removal	• $2.3 to $7.0 million depending on facility • $0.3 million • $1.0 million
Utility Costs	• Electricity: 28 kWh/MMBtu • Natural Gas: 5% of product	• 4.6—13.7 ¢/kWh • $3.00-$8.25/MMBtu
Operations & Maintenance	• 1.5 FTE for maintenance • Miscellany	• 15% of installed capital costs
Other	• Tipping fees	• Varied by region;
For Injection	• Interconnect • Pipeline • Compressor	• $2.0 million • $1.5 million • $0.2-0.5 million
Financial Parameters	• Rate of Return • Discount Rate	• 10% • 7%

Region	Tipping Fee, 2018
Pacific: AK, AZ, CA, HI, ID, NV, OR, WA	$68.46
Northeast: CT, DE, ME, MD, MA, NH, NJ, NY, PA, RI, VA, WV	$67.39
Midwest: IL, IN, IA, KS, : MI, MN, MO, NE, OH, OH, WI	$46.89
Mountains / Plains: CO, MT, ND, SD, UT, WY	$43.57
Southeast: AL, FL, GA, KY, MS, NC, SC, TN	$43.32
South Central: AR, LA, NM, OK, TX	$34.80
National Average	$55.11

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RNG Cost Assessment: Thermal Gasification

- ICF used similar assumptions across the thermal gasification of feedstocks, including agricultural residue, forestry residue, energy crops, and municipal solid waste (MSW).
  - Agricultural residues: $18.3/MMBtu to $27.4/MMBtu
  - Forestry and forest residues: $17.3/MMBtu to $29.2/MMBtu
  - Energy crops: $18.3/MMBtu to $31.2/MMBtu
  - MSW: $17.3/MMBtu to $44.2/MMBtu

Factor	Cost Elements Considered	Costs
Performance	• Capacity factor • Processing Capability	• 90% • 1,000-2,000 tpd
Dedicated Equipment & Installation Costs	• Feedstock Handling (drying, storage) • Gasifier • CO2 removal • Syngas Reformer • Methanation • Other (cooling tower, water treatment) • Miscellany (site work, etc.) • Construction/ engineering	• $20-22 million • $60 million • $25 million • $10 million • $20 million • $10 million • • • All-in: $335 million for 1,000 tpd
Utility Costs	• Electricity: 30 kWh/MMBtu • Natural Gas: 6% of product	• 4.6—13.7 ¢/kWh • $3.00-$8.25/MMBtu
Operations & Maintenance	• Feedstock • 3 FTE for maintenance • Miscellany: water sourcing, treatment/disposal	• $30-$100/dry ton • 12% of installed capital costs
For Injection	• Interconnect • Pipeline • Compressor	• $2.0 million • $1.5 million • $0.2-0.5 million
Financial Parameters	• Rate of Return • Discount Rate	• 10% • 7%

RNG Cost Assessment: Power-to-Gas

- ICF developed the levelized cost of energy for P2G systems using a combination of an electrolyzer and a methanator to produce RNG for pipeline injection. The main cost considerations include:
  - installed cost of electrolyzers on a dollar per kW basis ($/kW)
  - the installed cost of a methanation system on a $/kW basis
  - the cost of RNG compression and interconnect for pipeline injection
  - the cost of electricity used to run the P2G system

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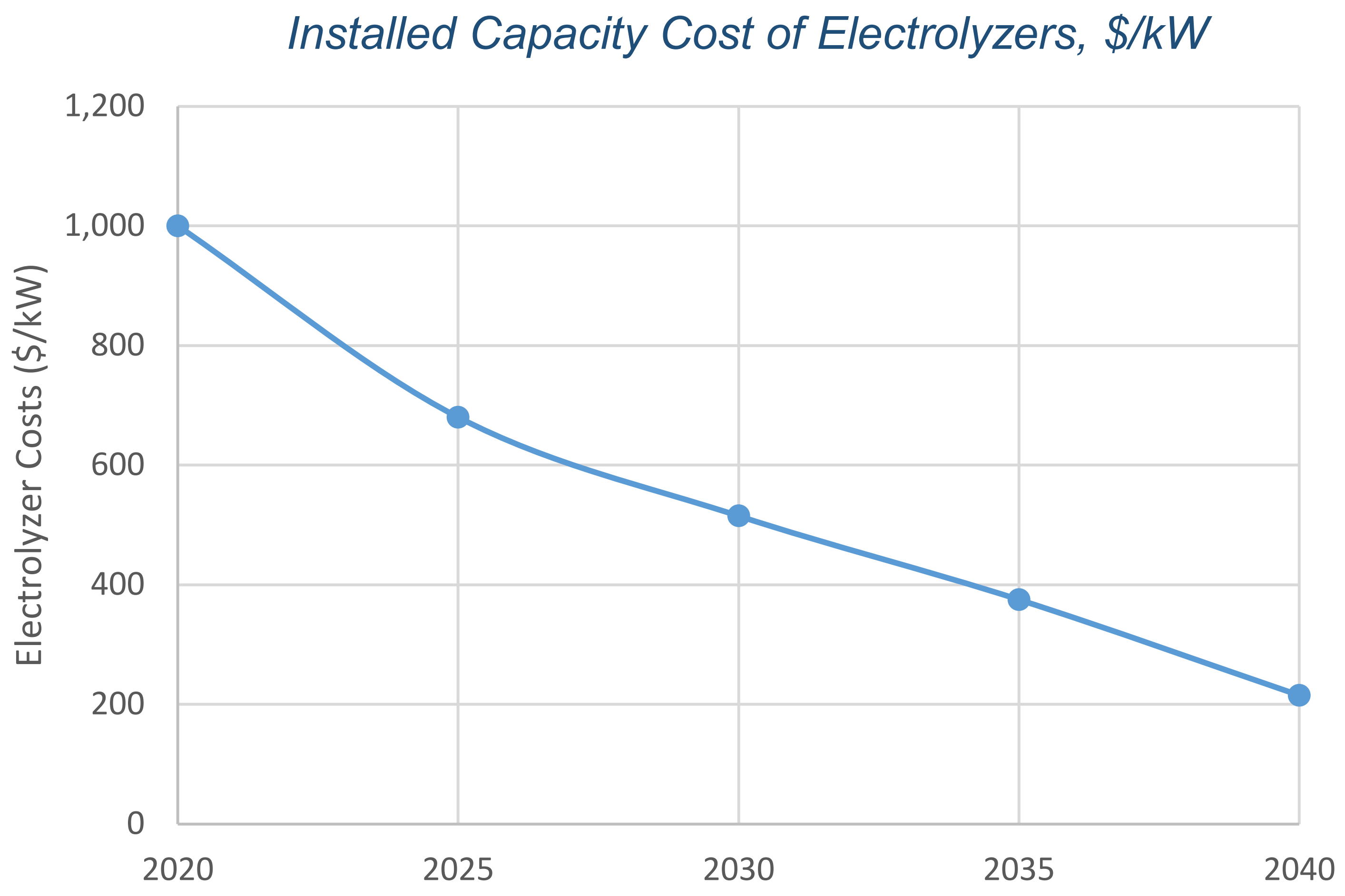
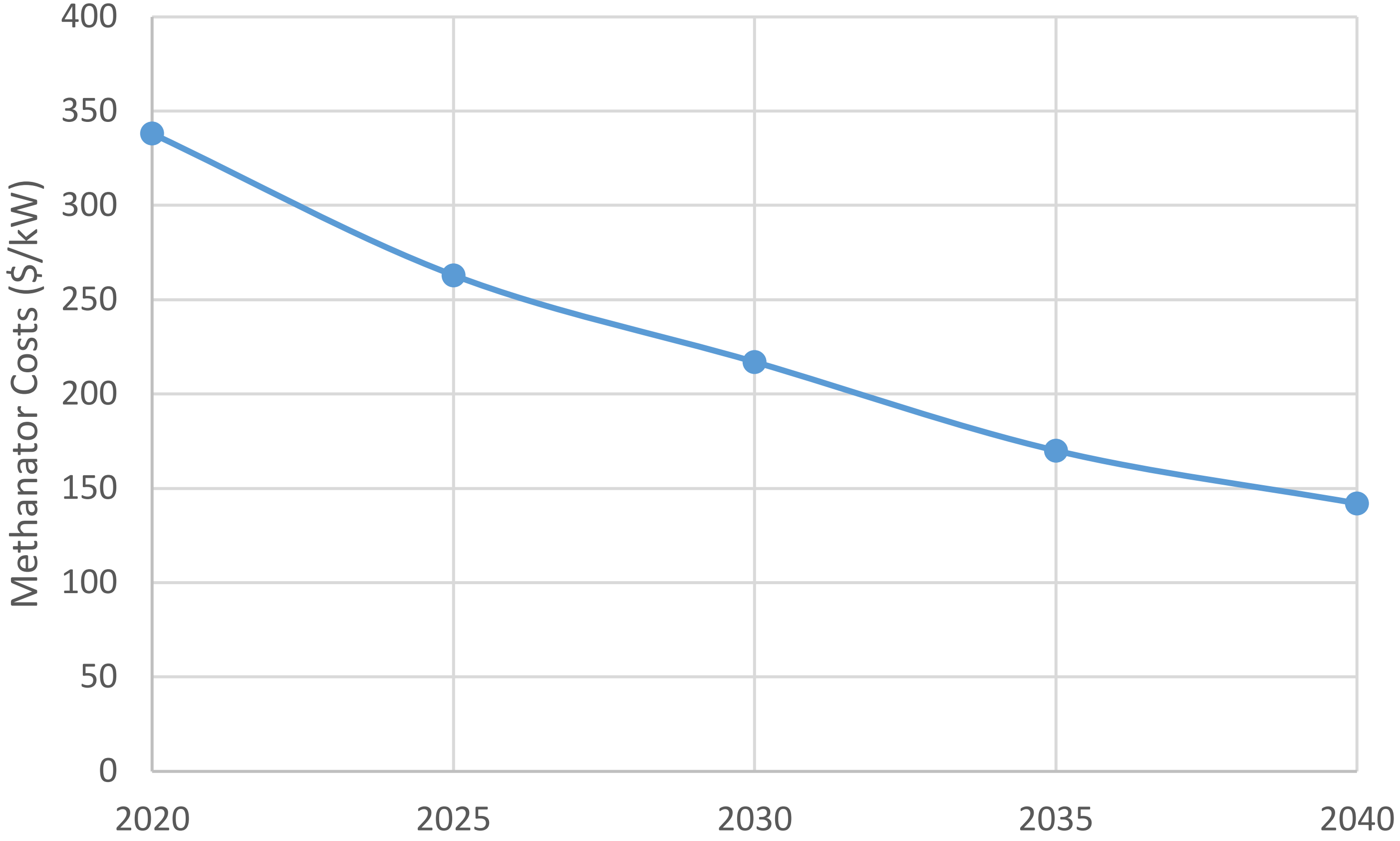
RNG Cost Assessment: Electrolyzers for P2G

- The graph illustrates ICF's assumptions regarding the installed costs of electrolyzers
  - assumed that the resource base for electrolyzers would be some blend of proton exchange membrane (PEM), alkaline systems, and solid oxide systems.
  - Rather than be deterministic about which technology will be the preferred technology, we present the cost as a blended average of the $/kW installed.
- This is based on ICF's review of literature and review of assumptions developed by UC Irvine.



RNG Cost Assessment: Methanation as part of P2G System

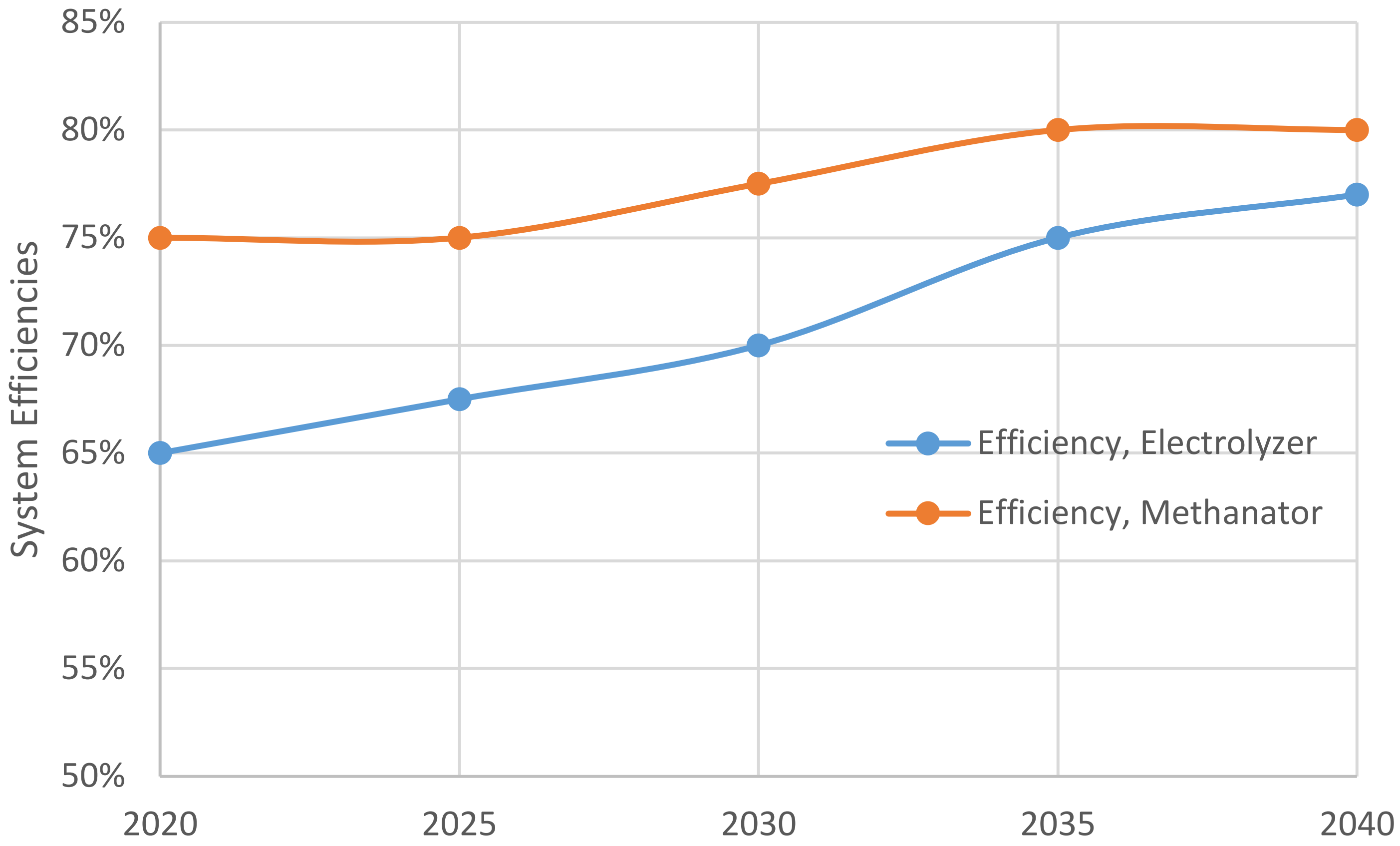
- The graph illustrates ICF assumptions regarding a a decreasing cost of methanation technology consistent with the figure below, presented in units of $/kW.



Installed Capacity Cost of Methanator, $/kW

RNG Cost Assessment: Conversion Efficiencies

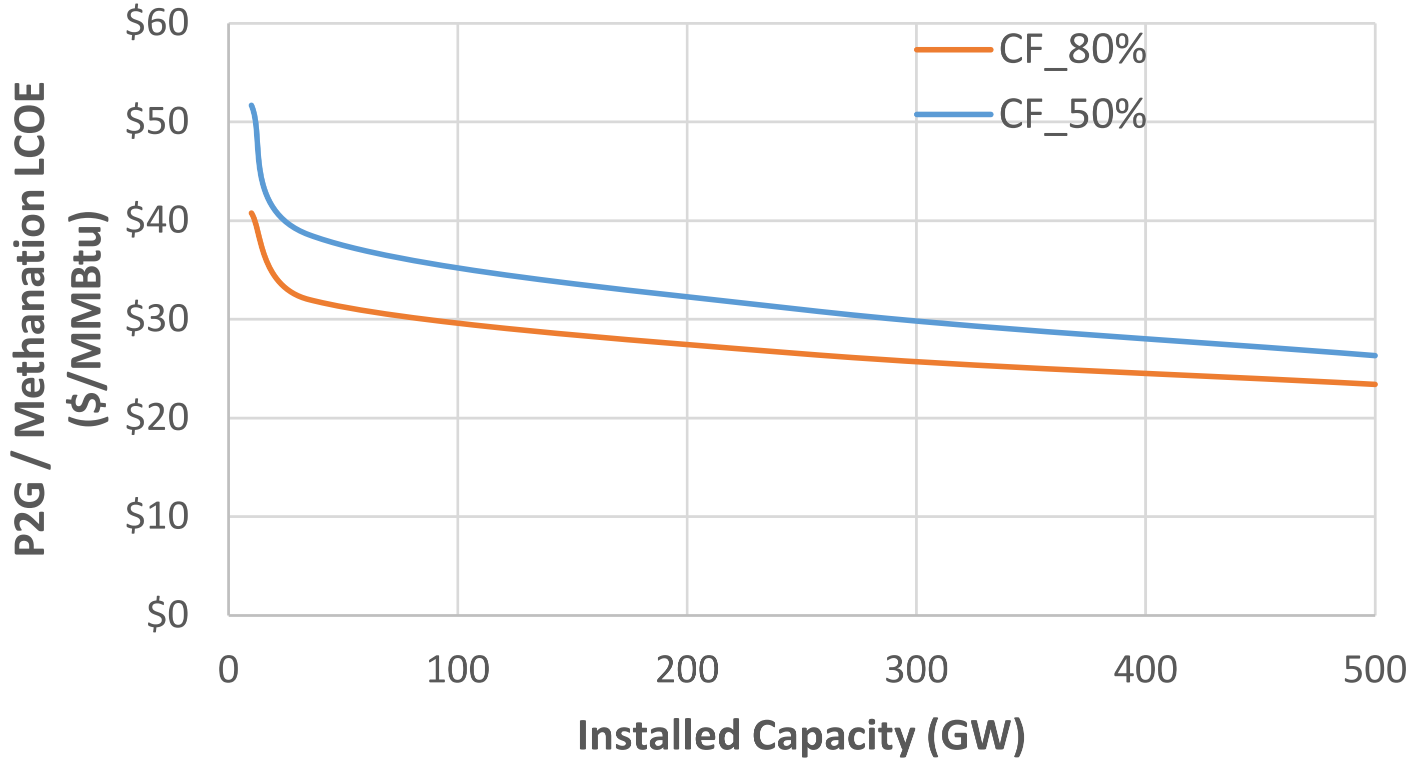
- The figure illustrates the assumed conversion efficiencies for hydrogen production from electrolyzers (**blue**) and for the methanation reaction to produce RNG for injection (**orange**).



Assumed Efficiency for Electrolysis & Methanation

RNG Cost Assessment: P2G

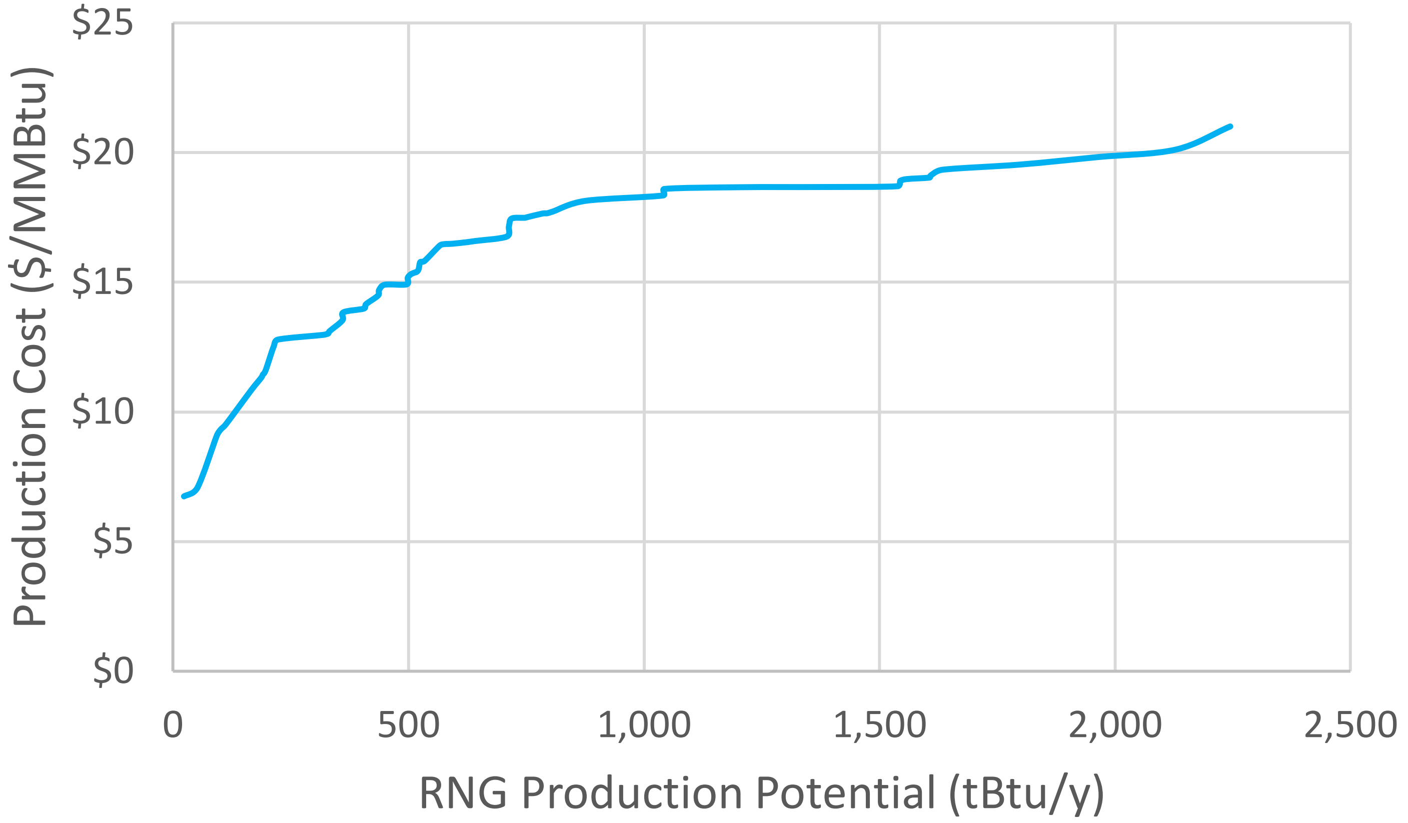
- ICF developed cost estimates assuming a 50 MW system for P2G co-located with methanation capabilities, and included the costs of compression for pipeline injection, interconnection costs, and pipeline costs.
- We assumed an electricity cost of $42/MWh based on the supply curve for dedicated renewables that we developed using IPM.
- We assumed operational costs of 10% and 7% of capex, respectively for the electrolyzer and the methanator; and we assumed operational costs of 5% of capex for pipeline and interconnect systems.



Estimated RNG costs from P2G / Methanation ($/MMBtu) as a function of installed capacity of P2G systems

RNG Cost Assessment: Combined Supply

- ICF estimates that more than half of the RNG production potential in the high resource potential scenario would be available at less than $20/MMBtu, as shown in the figure.
- Front end of the supply curve to be landfill gas projects and WRRFs that are poised to move towards RNG production.
- Higher costs are associated with some of the larger animal manure projects and the well-positioned food waste projects.
- Upward sloping captures the first tranche of thermal gasification projects.



Combined RNG Supply-Cost Curve, less than $20/MMBtu in 2040

RNG Cost Assessment: Cost-Effectiveness

- The GHG cost-effectiveness is reported on a dollar per ton basis, and is calculated as the difference between the emissions attributable to RNG and fossil natural gas.
  - Assumed fossil natural gas price: $3.89/MMBtu (from EIA).
- GHG Cost-Effectiveness of RNG: $55-300/ton.
- The GHG cost-effectiveness of RNG as a mitigation strategy is competitive with and in many cases lower than the costs per ton that are associated with other strategies to reduce GHG emissions, such as electrification at $572-806/ton and atmospheric removal of CO_2 at $94-232/ton.

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