Renewable Natural Gas

Renewable Thermal Technology

RENEWABLE THERMAL COLLABORATIVE

Technology Overview

Description of technology

- Renewable natural gas (RNG), also known as biogas or biomethane is virtually identical in composition with fossil natural gas.
- RNG comes from the processing of gases captured from landfills, agricultural or food waste, wastewater treatment plants, and other sources. These facilities primarily produce methane through anaerobic digestion.
- Alternatively, synthetic natural gas, also known as power-to-gas (P2G), uses electrolysis to produce hydrogen that is then combined with CO_2 to produce methane (CH_4). P2G is not covered in this fact base due to the large differences between P2G and other RNG in terms of feedstock and economic viability.

Types of equipment

- All existing fossil natural gas equipment are compatible with RNG fuel.

Gas fired heater[1]

Gas furnaces[2]

Gas boilers[3]

Gas air heaters[4]

Note: Example equipment not exhaustive

1. Sigma Thermal Direct Fired Heater; 2. Thermcraft gas fired industrial furnace; 3. Hurst Boiler industrial boiler systems; 4. Ambirad natural gas air heater unit

Technical characteristics

- **Temperature range:** Up to 1,950 ºC
  - Meets all industrial heating temperature requirements aside from very highest temperature applications (i.e., steelmaking)
- **Heat flux:** High
  - Dependent on burner configuration, able to deliver high quantities of heat; identical to fossil natural gas combustion
- **Heated materials:** Most materials are applicable
- **Emissions:** Theoretically net-zero, but methane leakage and energy use during processing could lead to non-zero emissions
- **Technical maturity:** High maturity
  - RNG is produced at large scales across the US, but supply still only constitutes <0.2% of total natural gas demand

Since RNG is a direct substitute for fossil natural gas, it can serve nearly all industrial applications where natural gas is currently deployed

Key properties of RNG combustion heating include:

- 1,950 ºC max. temp.
- High heat flux
- Heats all materials

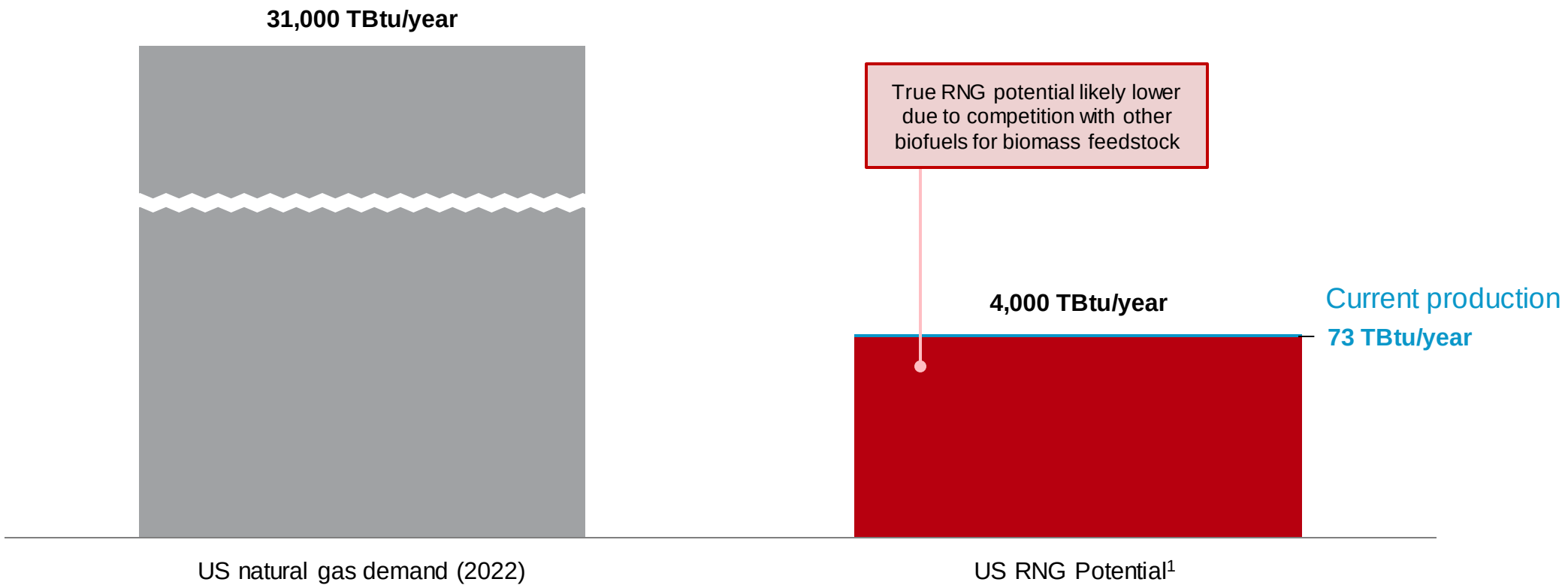
These properties align with requirements for several process heating applications.

Industry Sector	Process Heating Applications						Relevant Equipment
Refineries	Distillation	Reactors					Boiler, process heater
Chemicals	Distillation	Drying	Reactors				Boiler, process heater, furnace, air heater
Iron & steel	Pelletization	Hot rolling	Basic oxygen furnace	Blast furnace			Boiler, furnace
Food	Drying	Pasteurizing	Boiling	Sterilizing	Washing	Cooking	Air heater, boiler, oven
Paper	Stock steaming	Drying	Wood processing	Evap. & chem. prep.	Lime calcination		Air heater, boiler, oven, furnace
Cement	Pre-heating & treating	Melting furnace	Forming	Annealing	Kiln combustion		Furnace

Not applicable | Potentially applicable | Currently deployed

Note: Since RNG has been blended into the existing natural gas distribution network, all potentially applicable process heating applications are denoted as "currently deployed"

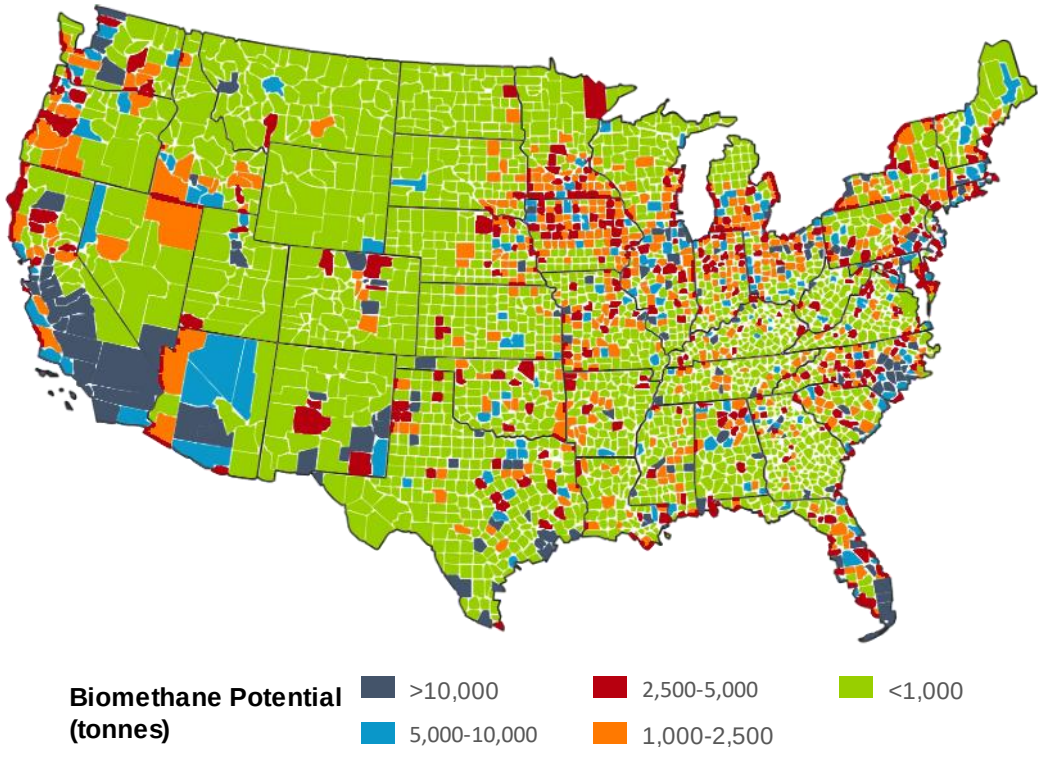
Potential long-term RNG supply can meet up to 13% of US total natural gas demand, while <2% of potential supply is currently in production



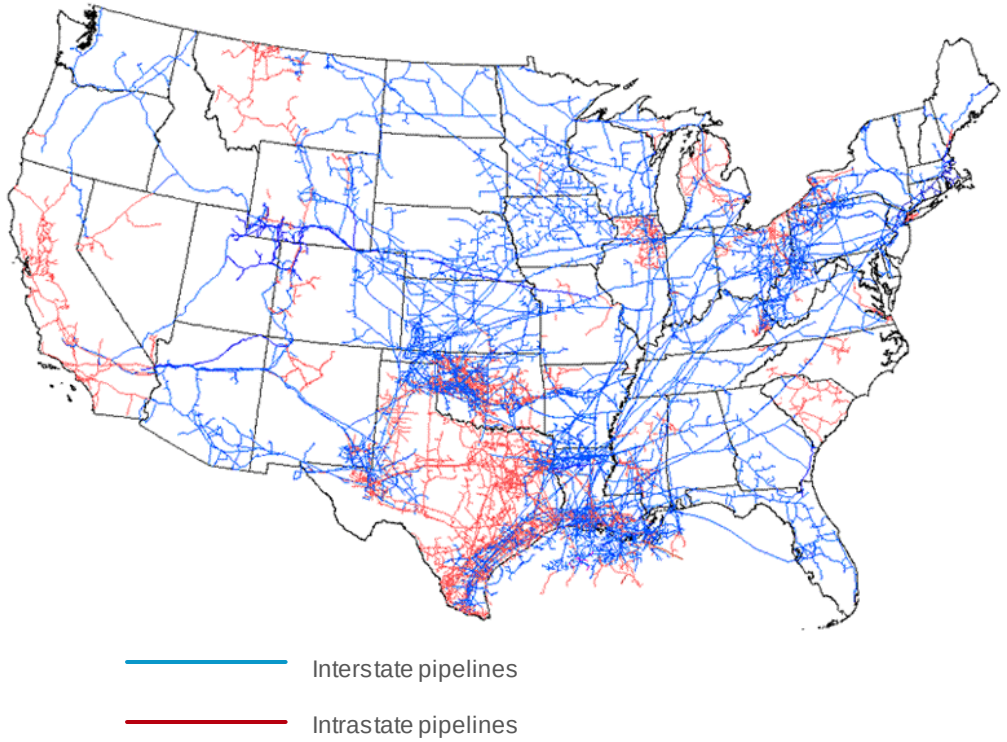
1. Assumes lignocellulosic biomass resources are used, does not account for competing uses (e.g., other fuels, power generation)
Source: EIA, IEA, EPA, Argonne National Laboratory, MJB&A, California Bioenergy, BCG analysis

RNG is likely to be consumed locally or regionally since RNG supply potentially does not directly align with existing gas pipeline infrastructure

Biomethane supply potential



Interstate and intrastate natural gas pipelines



Source: NREL, US EIA

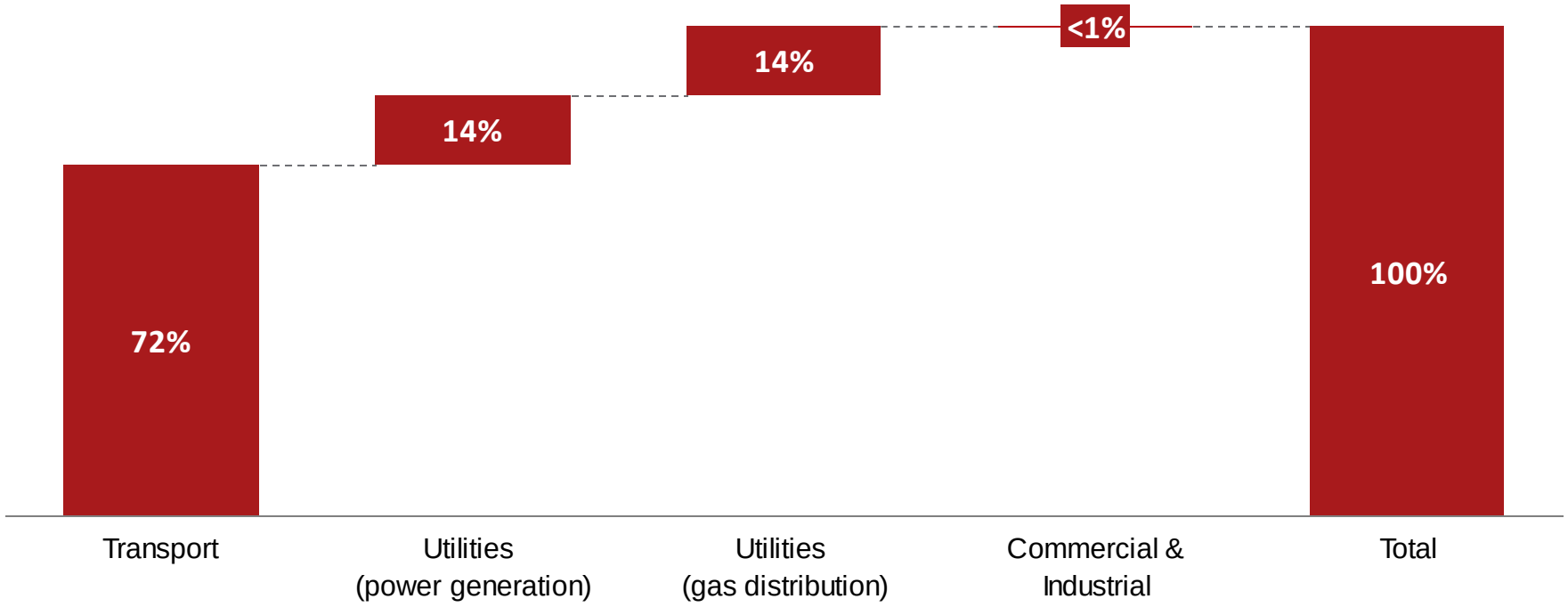
2022 production for RNG was ~73 TBtu/year with vast majority allocated to transportation demand and nearly zero to industrial applications

Estimated current RNG consumption in 2022

73
TBtu/year

<0.2% of total US natural gas demand

Estimated US RNG customer segment share (% of capacity allocated)

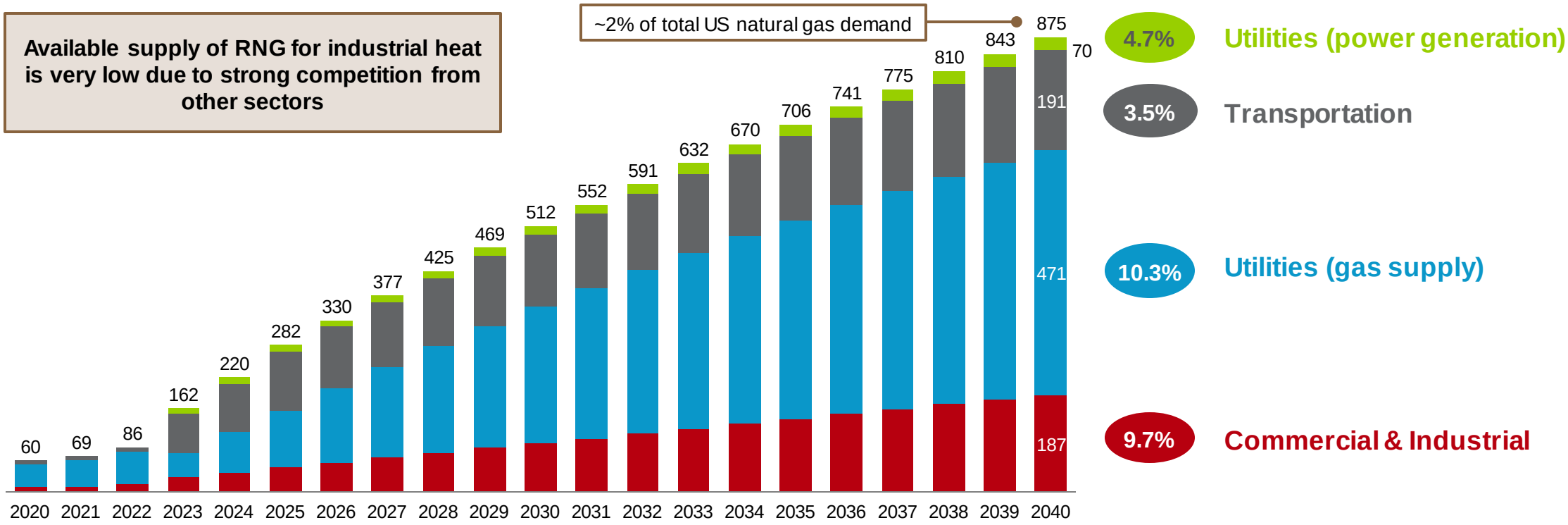


Includes LFG to RNG, agriculture sourced RNG, and wastewater sourced RNG; Projects without reported capacity estimated using benchmarks from the EPA and other sources listed below
Source: IEA, EPA, Argonne National Laboratory, MJB&A, California Bioenergy, BCG analysis

Significant demand growth across sectors expected for RNG, with largest share from gas utilities and <10% share for industrial applications by 2040

Total expected demand by sector (TBtu/year)

Available supply of RNG for industrial heat is very low due to strong competition from other sectors



CAGR
('25 – '40)

4.7% **Utilities (power generation)**

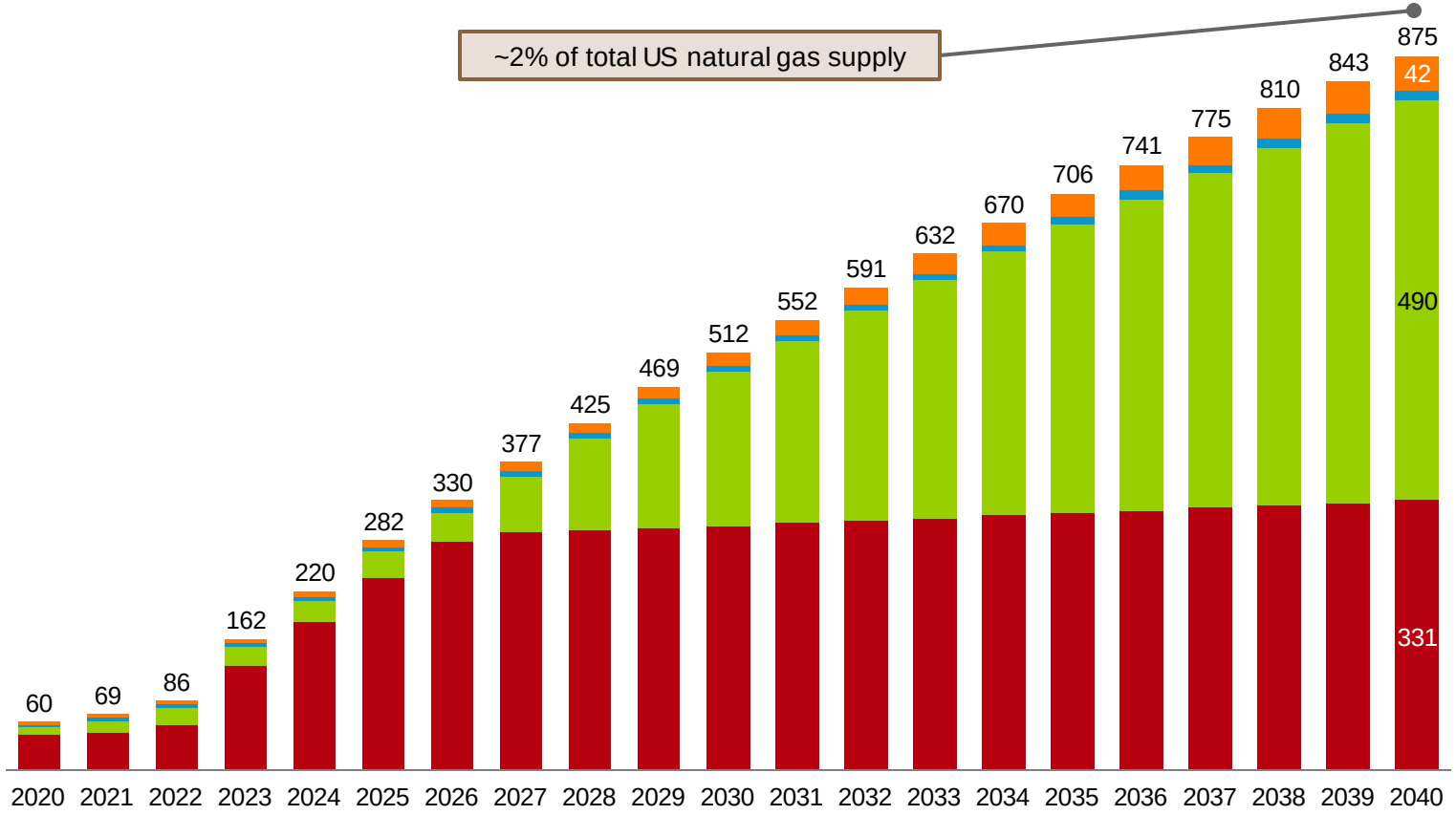
3.5% **Transportation**

10.3% **Utilities (gas supply)**

9.7% **Commercial & Industrial**

Source: BCG Analysis

RNG supply is expected to grow, with agricultural waste being the largest source of growth beyond 2026



Food waste

Expected to grow to account for increasing organic waste diversion

Wastewater

Expected to grow 5% per annum to serve nominal voluntary demand

Agricultural waste

Once economic limit for landfill gas is reached, agricultural waste RNG will be used to meet voluntary demand

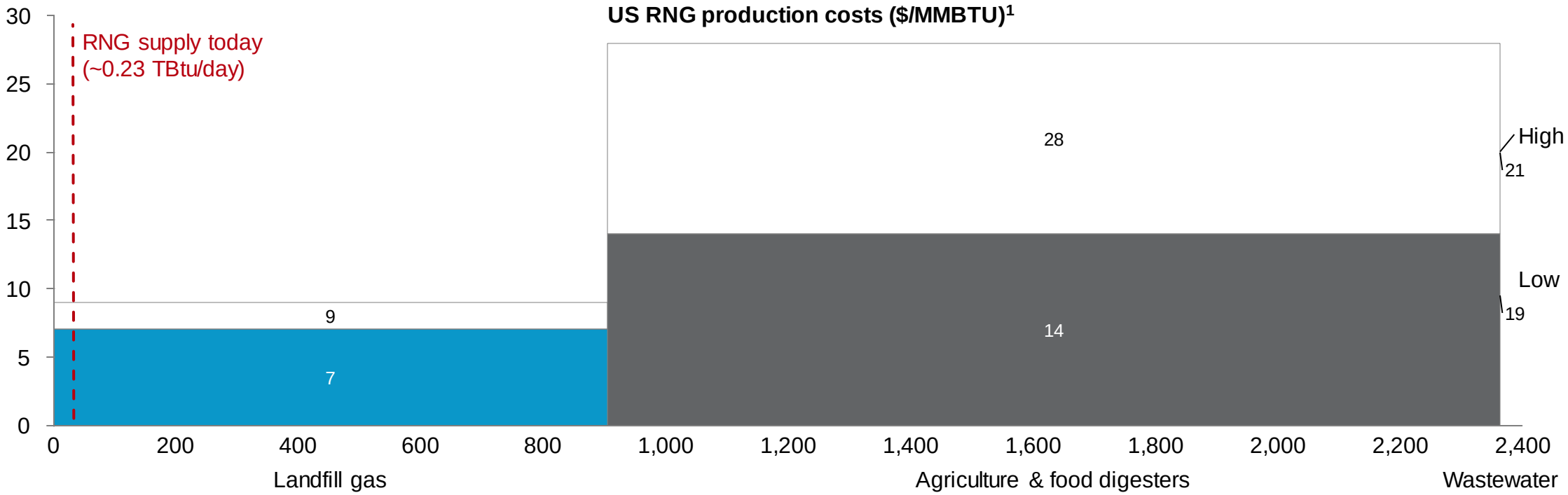
Landfill gas

Supply to grow to meet voluntary demand until economic limit is hit, after which supply expected to plateau

Source: BCG Analysis

Potential US RNG supply sources have varying cost ranges due to site-specific requirements, and differences in capital and operating costs

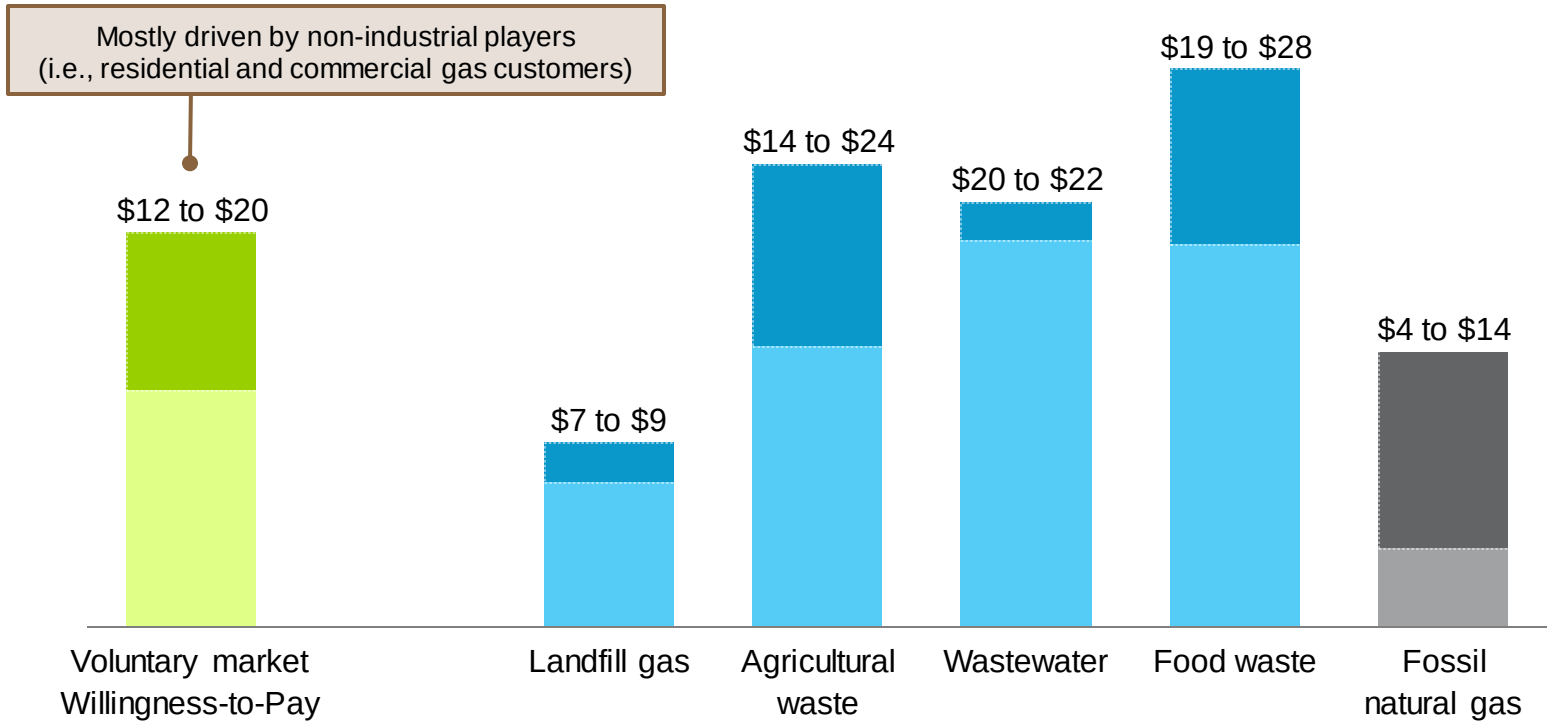
Estimated technical potential US RNG in 20 years vs. estimated supply costs



1. Cost ranges include biogas production, upgrading, and interconnection; Derived from IEA averages. 2. Includes LFG to RNG, agriculture sourced RNG, and wastewater sourced RNG; Projects without reported capacity estimated using benchmarks from the EPA and other sources listed below.
Source: IEA, EPA, ICF, BCG analysis, CBC, Federal environmental webpages

RNG from landfill gas has the lowest cost, and often falls within the voluntary market Willingness-to-Pay

RNG production costs by feedstock vs voluntary market Willingness-to-Pay ($/MMBTU) in 2020

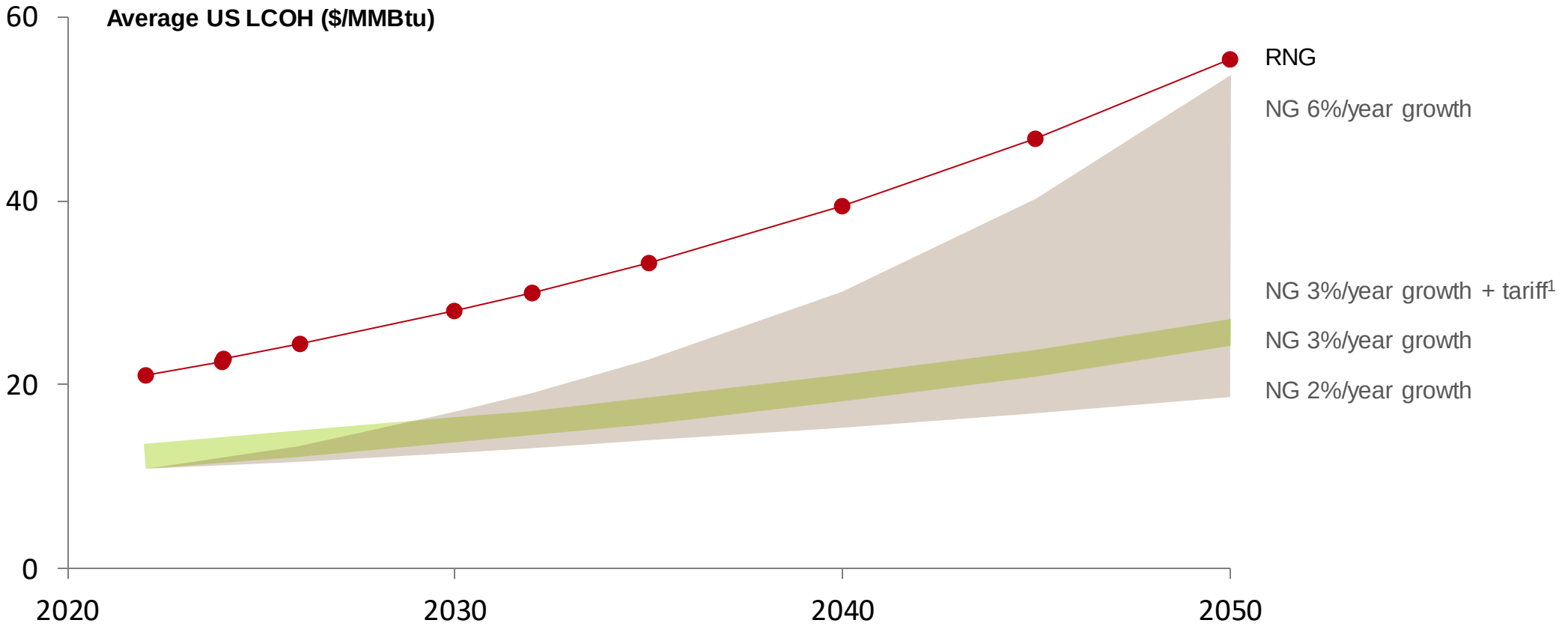


Policymakers can make RNG more cost competitive by

- Providing incentives for RNG producers and purchasers
- Implementing tariffs on ambient releases of methane

Source: ICF, EPA, USDA

RNG costs are expected to be higher than fossil natural gas in the next 30 years, especially as RNG production expands into more costly feedstocks



1. Based on $51/tonne CO2 social cost of carbon
Notes: Subsidized are shown in plots, subsidized and unsubsidized LCOHs are within 5%. Subsidies may further reduce RNG producer costs and consequently LCOH by <10%.

RNG industrial heating has many advantages, but faces supply constraints and other key barriers in gaining widespread adoption

Advantages

Can continue using existing gas combustion equipment

Costs for landfill RNG in some locations are in range of fossil NG

Reduces waste and captures methane emissions

Can continue using most existing pipeline infrastructure

Barriers

Higher operating costs compared to fossil natural gas systems

Limited total supply due to feedstock constraints

Competitive supply environment (i.e., transportation, power generation)

Gas infrastructure may require reconfiguration RNG supply locations

Disclaimer

This document has been prepared in good faith on the basis of information available at the date of publication without any independent verification. The drafters do not guarantee or make any representation or warranty as to the accuracy, reliability, completeness, or currency of the information in this document nor its usefulness in achieving any purpose. Readers are responsible for assessing the relevance and accuracy of the content of this document. It is unreasonable for any party to rely on this document for any purpose and the drafters will not be liable for any loss, damage, cost, or expense incurred or arising by reason of any person using or relying on information in this document. To the fullest extent permitted by law, the drafters shall have no liability whatsoever to any party, and any person using this document hereby waives any rights and claims it may have at any time against BCG with regard to the document. Receipt and review of this document shall be deemed agreement with and consideration for the foregoing.

This document is based on a primary qualitative and quantitative research. It does not provide legal, accounting, or tax advice. Parties responsible for obtaining independent advice concerning these matters. This advice may affect the guidance in the document. Further, the drafters have made no undertaking to update the document after the date hereof, notwithstanding that such information may become outdated or inaccurate. The drafters have used data from various sources and assumptions provided to the drafters from other sources. The drafters have not independently verified the data and assumptions from these sources used in these analyses. Changes in the underlying data or operating assumptions will clearly impact the analyses and conclusions.

This document is not intended to make or influence any recommendation and should not be construed as such by the reader or any other entity.