Topic Paper #22

Renewable Natural Gas for Transportation: An Overview of the Feedstock Capacity, Economics, and GHG Emission Reduction Benefits of RNG as a Low-Carbon Fuel

On August 1, 2012, The National Petroleum Council (NPC) in approving its report, *Advancing Technology for America's Transportation Future*, also approved the making available of certain materials used in the study process, including detailed, specific subject matter papers prepared or used by the study's Task Groups and/or Subgroups. These Topic Papers were working documents that were part of the analyses that led to development of the summary results presented in the report's Executive Summary and Chapters.

These Topic Papers represent the views and conclusions of the authors. The National Petroleum Council has not endorsed or approved the statements and conclusions contained in these documents, but approved the publication of these materials as part of the study process.

The NPC believes that these papers will be of interest to the readers of the report and will help them better understand the results. These materials are being made available in the interest of transparency.

Renewable Natural Gas for Transportation

An Overview of the Feedstock Capacity, Economics, and GHG Emission Reduction Benefits of RNG as a Low-Carbon Fuel

A White Paper for the National Petroleum Council – Future Transportation Fuels Study

March 2012

This is a working document solely for the review and use of the participants in the Future Transportation Fuels Study. Data, conclusions and recommendations contained herein are preliminary and subject to substantive change.

This draft material has not been considered by the National Petroleum Council and is neither a report nor the advice of the Council.

White Paper Authors and Contributors

Name	Organization	Title
Karen Hamberg	Westport Innovations	Vice President, Sustainable Energy Futures
Don Furseth	Acorn Solutions	Consultant
Jim Wegrzyn	Brookhaven National Labs	Senior Physicist Department of Sustainable Energy
Anthony LaRusso	National Grid	Manager, Sustainable Gas Group
Donald Chahbazpour	National Grid	Director, Sustainable Gas Group
Gail Richardson	Energy Vision	Vice President for Programs
Barry Carr	Clean Communities of Central New York	Clean Cities Coordinators
Harrison Clay	Clean Energy Fuels	Vice President, Renewable Fuels
Chris Cassidy	U.S. Department of Agriculture	Energy Advisor National Business Renewable Energy
Michael Ippoliti	Calstart	Director, Clean Transportation Solutions Group
Jack Lewnard	Gas Technology Institute	Vice President and CTO Office of Technology and Innovation
Graham Williams	GP Williams Consulting	Principal, GP Williams Consulting
Brian Chase	Chevron	General Manager

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White Paper Scope

Recent efforts to find a long-term, large-scale, and renewable alternative to petroleum fuels for the transport sector have been focused on liquid biofuels such as ethanol and biodiesel. In comparison, an analysis of renewable natural gas (RNG) has been largely omitted in the academic literature. The aim of this white paper is to provide a broad assessment of the potential for RNG as a transportation fuel in terms of feedstock capacity, cost estimates, and lifecycle greenhouse gas emission reductions. It will address three key questions:

1. What is the practical potential inventory of feedstock sources in the U.S. suitable for RNG production?
2. What are the cost estimates for RNG as a transportation fuel compared to fossil compressed natural gas (CNG) and liquefied natural gas (LNG)?
3. What are the lifecycle greenhouse gas emissions for RNG as a vehicle fuel?

For a more comprehensive overview of the RNG fuel supply chain, the technologies to produce RNG from biomass and biogas sources, barriers to deployment, findings, and recommendations, please refer to the Natural Gas chapter within the NPC-Future Transportation Fuels Study.

What is Renewable Natural Gas?

Renewable Natural Gas (RNG) is pipeline quality gas that is fully interchangeable with fossil natural gas and can be used as a 100% substitute for, or blended with, conventional gas streams for use in vehicle engines.[1] The use of RNG presents an opportunity to convert marginal and zero-value waste products into a useful transportation fuel. RNG is produced from a variety of biomass and/or biogas sources including landfill gas, solid waste, municipal wastewater, and agricultural manure via purpose-built anaerobic digesters (AD). It can also be produced from ligno-cellulosic sources such as forestry and agricultural waste via the process of thermal gasification (TG).[2]

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[1] Renewable natural gas is also referred to as renewable gas or biomethane. When compressed or liquefied it is also called bio-compressed natural gas (bio-CNG) or bio-liquefied natural gas (bio-LNG).

[2] A technical comparison of the technologies for producing RNG is beyond the scope of this white paper. Although biomass can be converted to RNG using either process, AD is generally applied to wet biomass while TG is targeted for low-moisture feedstocks. It should be recognized that both AD and TG refer to a family of technologies. Other technologies such as dry fermentation are used in Europe to digest dry wastes including energy crops and food waste.

RNG can achieve an estimated 90% reduction in greenhouse gas (GHG) emissions when used in transport applications.[3] It is a renewable fuel, easily distributed via local, regional, and national infrastructure, and is suitable for all applications from light-duty passenger vehicles to heavy-duty freight trucks. An analysis of the potential organic feedstock inventories in the U.S., one of the key questions within the scope of this white paper, indicates that approximately 4.8 trillion cubic feet (TCF) of RNG is potentially available from domestic sources.[4]

A Summary of the RNG Fuel Supply Chain

The RNG fuel supply chain includes a range of biomass feedstocks such as municipal waste streams, agricultural manure, wastewater sludge, crop residues, energy crops including switch grass and lay grass, and other ligno-cellulosic feedstocks.[5] Those feedstocks are converted to RNG using either a biochemical process such as anaerobic digestion or a thermo-chemical process such as thermal gasification. As with natural gas, RNG must be compressed or liquefied for use as a transportation fuel. The RNG can be transported to fuelling stations using the gas pipeline grid (similar to the way renewable electricity is distributed through the electrical grid), compressed or liquefied for truck or rail transport, or used at an on-site fuelling station.[6]

Anaerobic Digestion

Anaerobic digestion is the most mature and commonly used conversion technology. It is a naturally-occurring biological process in which organic material is broken down by bacteria in a low-oxygen environment resulting in the generation of methane (CH_4) and carbon dioxide (CO_2). The processes and equipment for converting biomass sources into biogas via anaerobic digesters are well known and commercially available.[7] It is currently

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[3] Pal Borjesson and Bo Mattiasson, "Biogas as a Resource Efficient Vehicle Fuel," *Trends in Biotechnology* 26, no. 1 (2008): 7-14, doi:10.1016/j.tibtech.2007.09.007; Argonne National Labs, "Well-to-Wheels Analysis of Landfill Gas-Based Pathways and Their Addition to the GREET Model," Department of Energy Report ANL/ESD/10-3 (2010): doi10.2172/951259

[4] The 4.8 TCF represents about 20% of current U.S. Natural Gas consumption.

[5] This list of feedstocks is not meant to be exhaustive.

[6] For the purpose of this white paper, the authors reference the need for pipeline quality Natural Gas. If RNG is going to be a mainstream alternative fuel, the most cost-effective and efficient means of distribution will be via existing Natural Gas infrastructure. Dedicated RNG fuelling sites near feedstock sources are suitable for captive fleets but the widespread deployment of RNG vehicles will require access to the current Natural Gas grid.

[7] Brad Rutledge, "California Biogas Industry Assessment: White Paper," WestStart-Calstart (April 2005): http://www.calstart.org/Libraries/Publications/California_Biogas_Industry_Assessment_White_Paper.sflb.ashx.

used for wet organic wastes such as municipal solid waste (MSW), livestock manure, and waste water sludge.

Approximately 500 landfills, 120 dairies, 70 wastewater treatment systems, and 10 other livestock operations recover energy from biogas.[8] Projects range from small internal combustion engines or micro-turbines using biogas to generate power for site electricity to multiple units able to export excess power to the grid. Although the majority of projects convert biogas into electricity, a few use site-generated or grid electricity to purify the gas stream, upgrade it to pipeline-quality specifications, and pressurize it for injection into the natural gas grid or use as a vehicle fuel.[9] It should be noted that AD technologies, particularly those for smaller-scale landfills, dairies, and waste water treatment plants are also under development.

Thermal Gasification

In comparison, lower moisture feedstocks such as forestry waste, energy crops, and crop residue are better candidates for thermal gasification. Thermal gasification is the conversion of solid or liquid carbon-based materials by direct internal heating provided by partial oxidation.[10] It is a mature, established industrial process that has been used mainly to convert coal into gaseous products and includes a number of different technologies and combinations of technologies.[11] While thermal gasification of coal is a mature technology, thermal gasification of woody biomass to produce RNG is at the pre-commercial stage with successful demonstration plants in Europe. Commercial-scale implementation is expected in the 2020 timeframe.[12]

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[8] Marianne Mintz and Jim Wegrzyn, "Renewable Natural Gas: Current Status, Challenges and Issues: A Discussion Paper for Clean Cities Coalitions and Stakeholders to Develop Strategies for the Future," U.S. Department of Energy (September 2009): http://www1.eere.energy.gov/cleancities/pdfs/renewable_natural_gas.pdf.

[9] The majority of biogas-to-energy projects generate electricity, largely due to state and federal incentives.

[10] The thermal gasification process uses substoichiometric air or oxygen to produce fuel gases like CO, H_2, CH_4, and lighter hydrocarbons, as well as CO_2 and N_2 depending on the process used. It relies on chemical processes at elevated temperatures of 700 to 1800 °C. The advantage of gasification is that using the syngas is more efficient than direct combustion of the original raw feedstock as more of the energy contained in the raw feedstock is extracted.

[11] Max Ahman, "Biomethane in the Transport Sector – An Appraisal of the Forgotten Option," *Energy Policy* 38, no. 1 (January 2010): 208-217, doi:10.1016/j.enpol.2009.09.007.

[12] Salim Abboud et al.,"Potential Production of Methane from Canadian Wastes," Canadian Gas Association (October 2010): http://www.cga.ca/publications/documents/PotentialProductionofMethanefromCanadianWastes-ARCFINALReport-Oct72010.pdf.

The gasification process can convert all organic components of the feedstock including lignin and some lignin/cellulosic materials to a resulting gas mixture called bio-syngas. The bio-syngas can then be methanated and cleaned to produce RNG.[13] Low-temperature gasification is the preferred option for biomass due to higher efficiency. Two different low-temperature gasification technologies are currently under development in Europe: i) indirect gasification, and ii) circulating fluidised bed (CFB) gasification.[14]

The processes of gas cleaning and separation of methane and CO_2 are common to both anaerobic digestion and gasification. The challenge will be to integrate existing gasification technologies for clean-up and separation into the existing RNG production process.[15] Some studies advocate that anaerobic digestion will be the main source of RNG to 2020 with thermal gasification contributing onwards.[16] This projection is based on the availability and cost of thermal gasification technologies, prior use and acceptance by industry, and the need for further technology improvements.[17]

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[13] Syngas may be burned directly in internal combustion engines, used to produce methanol and hydrogen, converted via the Fischer-Tropsch (FT) process into synthetic fuel, or converted to methane through catalytic methanation.

[14] See Ahman, "Biomethane in the Transport Sector," for a technical review of indirect gasification and CFB gasification, projections for large-scale deployment, and economic barriers.

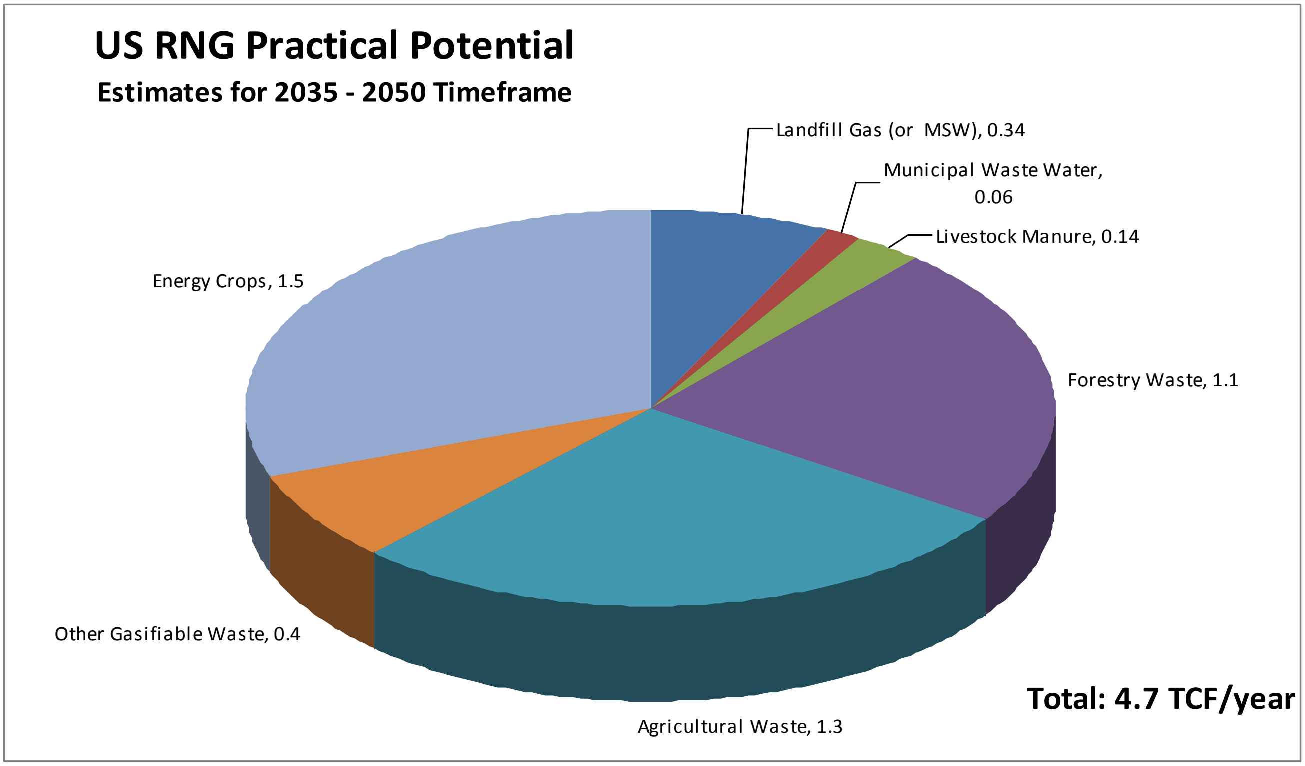
[15] Abboud et al., "Potential Production of Methane from Canadian Wastes."

[16] National Grid, "Renewable Gas – Vision for a Sustainable Gas Network," white paper (July 2010): http://www.nationalgridus.com/non_html/NG_renewable_WP.pdf.

[17] Abboud et al., "Potential Production of Methane from Canadian Wastes."

Feedstock Inventory and Practical RNG Utilization

Figure I: Practical Potential RNG Feedstock Capacity



Estimates of the potential supply of RNG are dependent on various assumptions including future waste streams, biomass availability, conversion technologies, and process yields. A review of the current literature indicates that the practical RNG potential is approximately 4.7 TCF or 40 billion gasoline gallon equivalents (GGE) per year. Table I summarizes the revised estimates for total[18] and practical[19] biogas and biomass resources, the assumed yields[20] and the resulting practical RNG potential[21] that have been derived from a recent review of the literature.

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[18] The total resource is the total available biomass resource that could, in theory, be used to produce RNG or other biofuels. It may include biomass that would be impractical to use for technical or economic reasons.

[19] The practical resource is the biomass resource (expressed in dry tons per year) that could reasonably be used based on technical and economic constraints. It is the total resource minus biomass that is not technically or economically practical to use. Each of the different feedstocks has a range of conditions related to scale, operating practices, and other limitations that define the practical resource use. Transmission criteria, such as access to the pipeline grid, have not been considered as there are alternate ways to deliver RNG.

[20] The yield is the amount RNG that can be produced from each dry ton of biomass input. It is expressed in gasoline gallon equivalents (GGE) per dry ton. The yield will depend on the biomass and the conversion processes used.

Table I Potential Feedstock Inventories and RNG Potential in the U.S.

Biomass Feedstock	Biomass Resource		Yield (gge/Dry Ton)	Practical RNG Potential	
Anaerobic Digestion	Total Resource (Million Dry Tons/yr)	Practical Resource (Million Dry Tons/yr)		Practical RNG Potential (billion gge/yr)	Practical RNG Potential (TCF/y)
Landfill Gas (or MSW)	14[a]	7[a]	400[b]	2.8	0.34
Municipal Waste Water	9	8	64	0.5	0.06
Livestock Manure	156	24	48	1.1	0.14
AD subtotal	180	39		4.5	0.5
Suitable for Thermal Gasification					
Forestry Waste	368	124	74	9	1.1
Agricultural Waste	380	148	74	11	1.3
Municipal/Other Waste	261	41	74	3	0.4
Energy Crops	530	164	74	12	1.5
Gasification subtotal	1,539	477		35	4.2
TOTAL[c]	**1,539**	**475**		**40**	**4.8**

[a] *Landfill gas resource figures are shown as millions of dry tons per year of methane produced from landfills, rather than the waste-in-place from which the methane is produced over many years.*

[b] *As the landfill gas resource data is for methane, not the original biomass, the yield shown is the energy per dry ton of methane.*

[c] *The total has been adjusted to avoid double-counting of biomass that contributes to both AD and gasification subtotals.*

To facilitate comparison with liquid biofuel analyses that may compete for the same feedstock, the biomass resources are cited in millions of dry tons per year, yields are in GGE per dry ton, and the RNG potential is shown in billions of GGE per year. For comparison with natural gas figures, the practical RNG potential is also shown in TCF per year.[22] The sources, assumptions, and methodology used to produce this table are discussed in Appendix One.

The key data points from Table I are as follows:

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[21] The practical potential is the quantity of RNG that could be produced each year from the practical resource based on expected yields.

[22] The determination of a practical resource and practical potential is dependent upon numerous technical and economic assumptions including at what scales conversion plants are practical.

- The total resource is estimated to be 1.5 billion dry tons per year of biomass. Of that total, approximately 180 million dry tons per year (or approximately 12 percent) of landfill gas and biomass is suitable for current AD conversion technologies with the balance assumed more suitable for TG.
- The current yields for AD are approximately 50 GGE per dry ton depending on feedstock. In comparison, the IEA forecasts for RNG from gasification yields approximately 74 GGE per dry ton. These yields assist with the estimation of a total practical resource:

    - 4.5 billion GGE or 0.5 TCF of RNG per year is the practical potential from feedstock sources suitable for anaerobic digestion,
    - 35 billion GGE or 4 TCF of RNG is the practical potential from feedstock sources suitable for thermal gasification, thereby
    - A total practical potential of approximately 40 billion GGE or 4.8 TCF of RNG per year is available.[23]

The Economics of RNG Projects

The actual cost of RNG within the time frame of the NPC-Future Transportation Fuels Study will depend on many factors including biomass availability and cost, conversion processes, conversion yield, the costs of capital, delivery costs, distribution infrastructure, and others. Table II illustrates cost ranges and variables for the different feedstock pathways.

Table II RNG Cost Summary

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[23] Note that this practical potential does not account for competition for biomass, nor is it a recommendation that all this feedstock should be used for RNG generation. Recommendations regarding allocation of biomass to competing applications and pathways are subject to a broader analysis likely to include net energy ratios, lifecycle emissions analysis, economics, resource considerations, and other factors.

RNG Cost Summary	Biomass	Conversion (to pipeline quality RNG)			Delivery	Other / Co-Products	RNG Cost Estimates (Delivered to Pipeline)	
Biomass / Case	Biomass Cost ($/dry ton)	Digestion / Gasification ($/MMBTU/d input)	Upgrading and Cleanup ($/mmcfd input)	Yield (gge/dry ton and % of Energy Input)	Pipeline Injection ($/MMBTU delivered)	Any other costs or co-product credits.	$/MMBTU	$/gge
Landfill Gas	Waste already collected. MSW may require sorting or cleaning.	LFG collection system costs ($0.9 average, range: $0.6 - $1.2)	Biogas Upgrading and Cleanup ($0.5 - $25). Costs depend on scale.	~ 85% of Energy Content in collected Landfill Gas	Requires compressors, connection and monitoring equipment, and pipe (typically $50/ft installed) to the pipeline injection point. ($0.2 - $30 depending on scale) For longer distances to pipeline multiply by approx (1 + miles/2). Urban costs per mile can be much higher than in agricultural areas.	Could get credits for tipping fees, carbon credits for avoided emissions, value of co-products including digestate, other non-RNG outputs, heat for district heating, excess power delivered to grid.	$5 - $9	$0.6 - $1.1
Livestock Manure - Large Dairy		Covered lagoon ($1-$7) or Anaerobic Digester ($2 - $25)		Typically 48 - 64 (35% - 46%)			$5 - $9	$0.6 - $1.1
Livestock Manure - Medium							$7 - $13	$0.8 - $1.6
MSW - Digestable - Large		Anaerobic Digester ($2 - $25) Costs depend on scale and type.					$4 - $12	$0.5 - $1.5
Wastewater Sludge							$5 - $11	$0.6 - $1.4
Large Plant (ag waste, energy crops, &/or forest waste)	$30 - $150	Thermo-Chemical Conversion (e.g., Gasification and Methanation with Clean up) ($5 - $40/MMBTU) Costs depend on scale.		Typically 70 - 95 (50% - 70%)			$8 - $20	$1.0 - $2.5
Medium Plant (ag waste, energy crops, &/or forest waste)	$10 - $50						$15 - $25	$1.9 - $3.1

Utilizing the data ranges identified above, Figure II depicts RNG cost estimates for the fuel delivered to the natural gas pipeline. The delivered cost of RNG is composed of four components: i) biomass costs as delivered to the conversion facility; ii) conversion costs to convert biogas or biomass feedstocks to pipeline quality natural gas; iii) delivery costs associated with transporting the fuel to point of consumption including compressors, monitoring equipment, and interconnects to pipelines; and iv) other costs and co-product credits if applicable.[24]

The costs summarized in Table II do not include credits for co-products, tipping fees, or carbon credits. These credits can have an important impact on the economics of projects, yet in many cases the value of these credits and the markets for co-products are not well established.

Figure II includes an illustrative example, showing a $50 per wet ton tipping fee for a MSW project. In this case, the facility is paid the tipping fee to dispose of the waste. The orange bar shows the magnitude of this revenue relative to RNG costs and the diamond indicates the resulting net cost. The error bars in black show the cost range when tipping fee revenues are not included.[25]

In contrast to waste disposal cases where the facility may be paid to dispose of waste biomass, the three thermal gasification plant examples in Figure II show a cost for the biomass. The costs for the biomass depend on a number of factors including how far it must be transported. This is illustrated by two cases for 3,000 ton per day thermal

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[24] Other costs and co-product credits could include carbon credits for avoided emissions, the economic value of any co-products (such as digestate, excess usable heat/power etc.), and any additional costs. This model does not assume any value for co-products or carbon credits for this analysis and the category is primarily for future scenarios.

[25] The examples in Figure II do not include tipping fees, co-product credits, or carbon credits.

gasification plants. The one with the lower ($35/dry ton) biomass cost has a lower RNG cost than the $75/dry ton case. Large conversion plants require large volumes of biomass, generally requiring that it be collected from a wider geographic region. The final thermal gasification example in Figure II shows a smaller (500 ton per day) plant. Its conversion costs don't have the benefits of scale of the larger plants; however, it makes use of local biomass, reducing the biomass component of the overall cost. Selecting conversion plant locations and sizes typically includes tradeoffs between economies of scale and the cost of delivered biomass.

Figure II **RNG Cost Estimates by Feedstock (Delivered to the Pipeline)**[26]

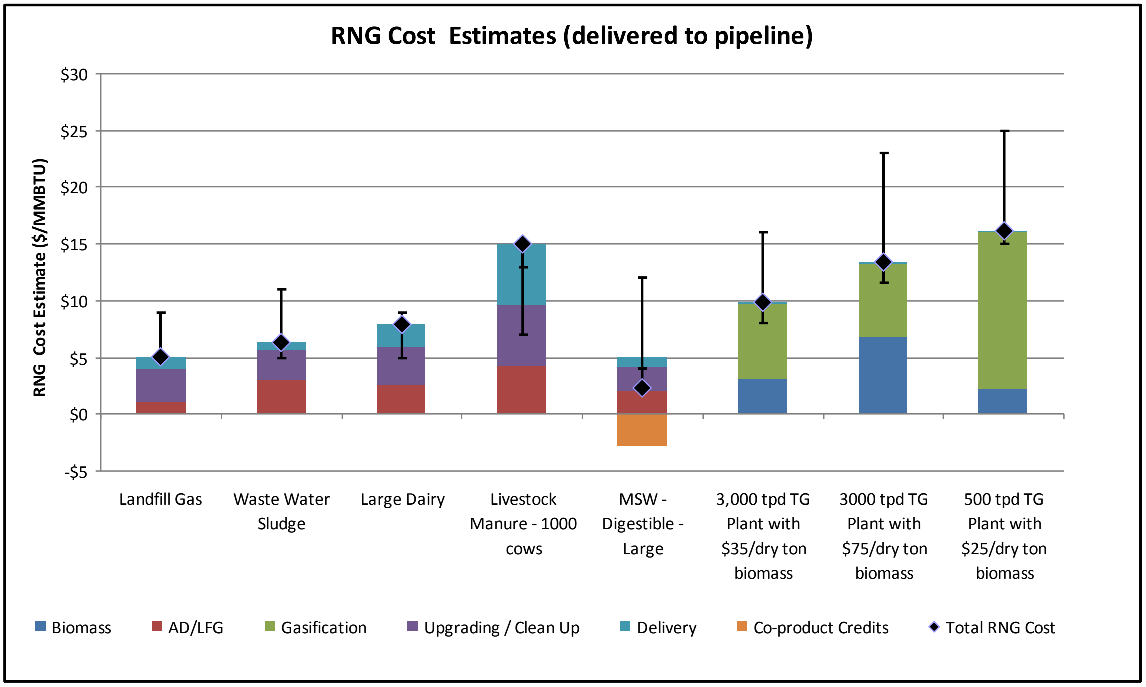

Figure III illustrates the retail price of RNG compared to gasoline, diesel, and fossil natural gas. While RNG is competitive with gasoline and diesel, project developers are more likely to compare it to the retail price of fossil natural gas. The lack of financial incentives for RNG makes it difficult to compete with lower-priced fossil natural gas.[27]

Figure III Retail Price of RNG

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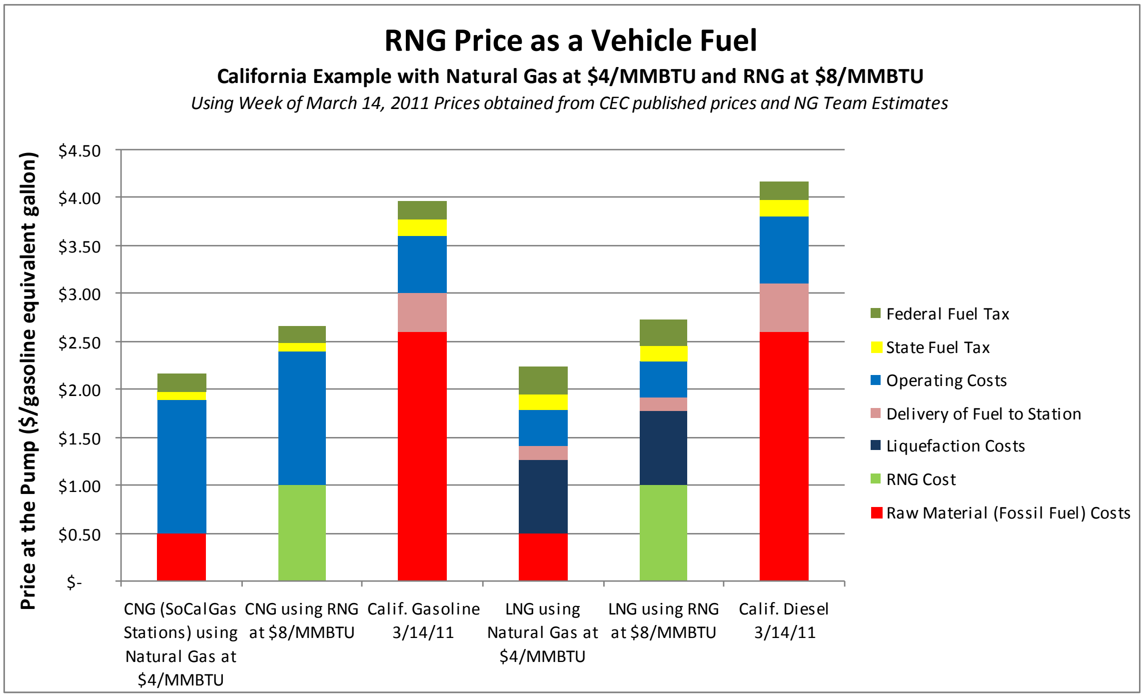
[26] Gas clean-up costs are also included within the thermal gasification scenarios.

[27] The Linde-Waste Management project at the Altamont Landfill is the largest RNG for transportation project in the U.S. It is unique in that the market for the RNG fuel is built into the project as nearly 400 refuse haulers are fuelled with RNG.



A review of the literature highlighted the following key findings specific to RNG costs:

Cost Variability and Infrastructure:

- RNG costs vary from project to project and future costs are dependent upon numerous assumptions.
- In addition to the infrastructure required to convert biomass into RNG, build-out is also required for the fuelling station infrastructure.
- Depending on the feedstock and production location, there may be several options for distribution to the point of consumption. Each of these options introduces additional cost and technical considerations.[28]
- The delivered cost of biomass is highly dependent upon the distance it must be transported. Some RNG feedstocks such as landfill gas, livestock manure, and municipal waste are already collected. The collection and transportation of forestry and/or agricultural wastes can introduce costs on the order of $50/dry ton or more.[29]

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[28] According to Mintz and Wegrzyn, "Renewable Natural Gas," pipelines are most applicable to projects injecting RNG into the natural gas grid. For projects providing fuel for natural gas vehicle fleets at a location other than the landfill or digester site, over-the-road transport is the norm.

[29] Collection and transportation costs vary depending upon distance and other factors. The EIA has a table of biomass quantities available at different cost levels at http://www.eia.doe.gov/oiaf/analysispaper/biomass/table3.html. Some studies use a GIS-based approach to model costs of delivered biomass to a particular site based, for example, on national biomass spatial distribution information at http://www.nrel.gov/gis/biomass.html.

- The injection of RNG into the natural gas grid can be expensive for small facilities or where the facility is far from the pipeline. For some facilities, the local use of biogas and RNG or other means of distribution may be more affordable.

Feedstocks Suitable for Anaerobic Digestion:

- RNG is expected to cost in the range of $3-20/MMBTU from landfill gas, wastewater treatment plants, municipal solid waste, and livestock manure from reasonably sized farms. Higher costs are expected from smaller feedstock sources.[30]
- RNG from large landfill sites is a low cost source of RNG as the biogas is generated naturally with no need for investment in an anaerobic digester. The capital cost requirements to build-out RNG capacity are low for landfill sites.
- RNG from large dairy farms can be produced using covered lagoons rather than a more expensive digester. For small farms the costs of cleaning, upgrading, and pipeline injection can be prohibitive.[31]

Feedstocks Suitable for Thermal Gasification:

- Thermal gasification is expected to produce RNG in the range of $13/MMBTU for large plants (5,000 dry tons per day) to $40+/MMBTU for small plants (50 dry tons per day).[32]
- Conversion plants are capital intensive and the cost of capital is a dominant component in conversion costs. Larger plants benefit from economies of scale. Capital cost assumptions such as debt-equity ratio, amortization period and required IRR have a significant impact on RNG costs.
- Thermal gasification plants are expected to be in the range of in the range of $40,000/daily barrel for a large (5,000 dry tons per day) plant to $225,000/daily barrel for a small (50 dry tons per day) plant.[33]
- Installed capital costs could drop significantly as technologies and supply chains mature and as volume increases. The costs of capital could also drop as plants

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[30] An extremely small-scale technology for use with biogas flows of 20 - 100 scfm is being developed in Wisconsin for use at smaller landfills and wastewater plants. Project costs are not available but newly emerging technologies for biogas clean-up and anaerobic digestion may make smaller biomass sources more economically feasible, thereby expanding the practical potential.

[32] Zwart et al., “Production of Synthetic Natural Gas (SNG) from Biomass: Development and Operation of an Integrated Bio-SNG System,” Energy Research Centre of the Netherlands, ECN-E--06-018 (30 October 2006): http://www.ecn.nl/docs/library/report/2006/e06018.pdf. Table 5.5 reports costs of 9 to 31 Euros per GJ. These figures have been converted to $/MMBTU.

[33] Based on capital cost estimates from Zwart et al., “Production of Synthetic Natural Gas.”

become more suitable for debt financing. These potential cost reductions have not been applied.

Greenhouse Gas Life-Cycle Analysis

Renewable natural gas can offer significant greenhouse gas reductions compared to diesel, gasoline, natural gas, and some liquid biofuels. These key points are critical to an understanding of the GHG emission reduction benefits of RNG as a transportation fuel:

i) There is the potential for emission reductions upstream or tank-to-wheels (TTW) from the capture of methane emissions from landfills or dairies and well-to-tank (WTT) via the use of RNG as a substitute to replace petroleum or in blended mixtures with fossil natural gas.
ii) The GHG emissions reduction benefit is dependent on the feedstock and conversion pathway and is not inherent in the fuel itself.

The GHG benefits for RNG derived from landfill gas, dairy digester biogas, and manure have been well-documented.[34] For example, RNG from landfill gas liquefied into LNG for heavy duty transport applications has WTW GHG savings of approximately 72-97% compared to diesel fuel pathways.[35]

Thermo-chemical processes such as thermal gasification with methanation to produce RNG are less mature but are seen to have the potential for GHG emission reductions. A life-cycle analysis of greenhouse gas emissions for biomass to renewable LNG or CNG via thermal gasification is not readily available in the literature. Given this gap, we are not able to comment on the emissions reduction benefits of anaerobic digestion versus thermal gasification.

Table III depicts the emissions reductions identified in the literature to better reflect the range of cases and uncertainties. These ranges are also plotted in Figure IV.

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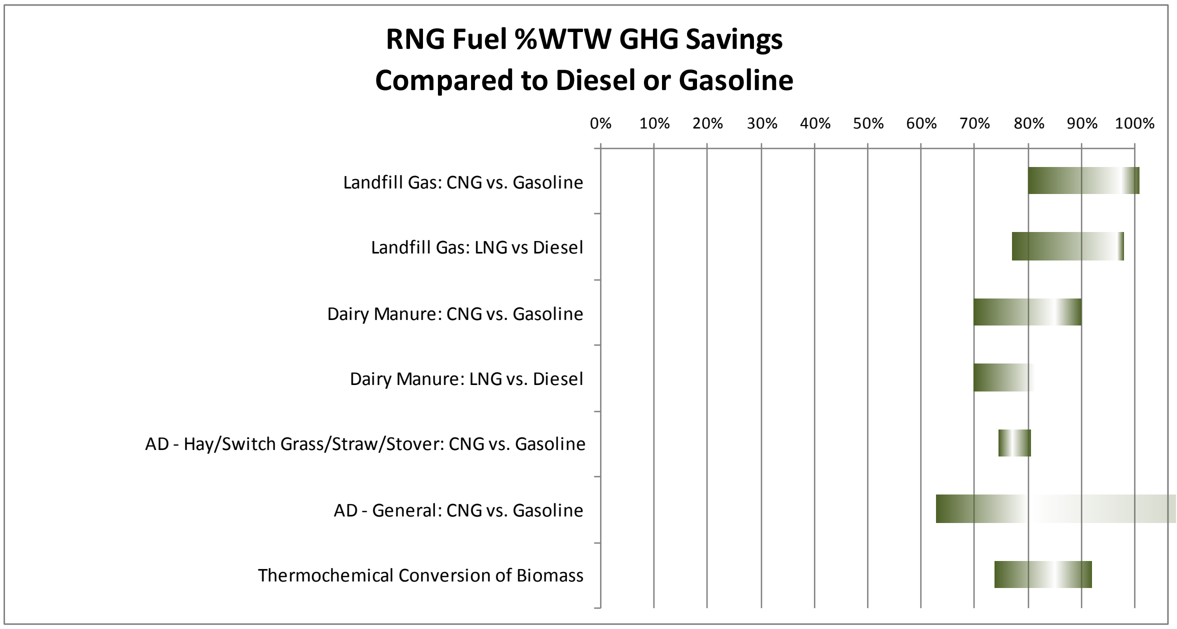
[34] Argonne National Labs has published models derived from GREET for CNG and LNG from landfill gas for a range of cases including different electricity sources, on-site compression or liquefaction, and off-site compression or liquefaction. CARB has carbon intensities for CNG and LNG from landfill gas and dairy digester biogas with differing cases of liquefaction efficiency. GHGenius biomethane results are available for CNG from not only landfill gas and manure but also for the anaerobic digestion of hay, switch grass, wheat straw and corn stover.

[35] Argonne National Labs, "Well-to-Wheels."

Table III: Greenhouse Gas Emissions Reductions Associated with Different Feedstock Pathways

Source	RNG Fuel	Fuel %WTW GHG Savings	Notes
Landfill Gas	CNG vs. Gasoline	80% - 101%	Argonne 2010 GREET analysis of various LFG cases. GREET 1.8d.1 default is 98%
	LNG vs Diesel	77% - 98%	Argonne 2010 GREET analysis of various LFG cases. GREET 1.8d.1 default is 97%
Dairy Manure	CNG vs. Gasoline	70% - 90%	CARB 2009 GREET analysis: 85% better than gasoline.
	LNG vs. Disel	70% - 81%	CARB CI data March 2011. 81% with 90% efficienct liquefaction.
AD - Hay/Switch Grass/Straw/Stover	CNG vs. Gasoline	75% - 81%	GHGenius 2009 Biomethane results.
AD - General	CNG vs. Gasoline	63% - 200%	UK study range. High end is liquid manure.
Thermochemical Conversion of Biomass		74% - 92%	Lacking solid studies. UC Davis 2006 has this range using LEM. CEC demonstration project cites 85%.

Figure IV: Greenhouse Gas Emissions Reductions of RNG Feedstocks



The WTW greenhouse gas reductions of fuels are calculated based on grams of CO_2-equivalent per MJ of fuel energy. These values can then be used to calculate the WTW emissions reduction of different natural gas vehicles. Fuel blends and differences in relative efficiency, if any, must be considered when calculating the emission reduction benefits of specific vehicles. This exercise was beyond the scope of this white paper.

RNG for Transportation in the United States

The largest commercial-scale landfill gas (LFG) to RNG plant is located at the Altamont Landfill near Livermore, California. Operated by Waste Management-Linde, the plant has a daily capacity of 13,000 LNG gallons and fuels 400 refuse haulers powered by Cummins Westport (CWI) ISL G engines. By displacing 2.5 million gallons of diesel, the RNG produced at Altamont eliminates over 30,000 tons of GHG emissions, 200 tons of nitrogen oxides (NOx), and four tons of particulate matter (PM) per year.[36] The Frank R. Bowerman Landfill in Irvine, California is another commercial-scale LFG to RNG plant, generating nearly 5,000 gallons of LNG per day. The fuel is used by the Orange County Transit Authority's (OCTA) fleet of LNG-powered buses and refuse trucks[37].

A notable a RNG for transportation project is Hilarides Dairy in Lindsay, California. The dairy received a $600,000 grant from the California Air Resources Board's Alternative Fuel Incentive Program, which subsidizes projects facilitating a greater use of non-petroleum fuels. Using an anaerobic-lagoon digester that processes the manure of nearly 10,000 cows, the project generates 226,000 cubic feet of biogas per day for electrical power and enough fuel to run two heavy-duty milk delivery trucks and five pick-up trucks.[38]

Key Findings

1. RNG has the potential to provide approximately 40 billion GGE per year.

2. RNG for transportation must overcome the economic, scale, and efficiency challenges of other competing pathways.[39]

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[36] "Linde and Waste Management Receive California Governor's Award for Sustainable Facility," Linde Group press release (November 16, 2010): available at http://www.the-linde-group.com/en/news_and_media/press_releases/news_2010_1117_2.html.

[37] In comparison, very small-scale projects like the Dane County Landfill BioCNG Project in Madison, Wisconsin generate 20 scfm of RNG or approximately 100 GGE of gasoline to fuel the County's fleet vehicles.

[38] "Dairy Trucks Powered by Cow Waste," California Environmental Protection Agency press release 09-11, February 11 2009, on the Air Resource Board website, http://www.arb.ca.gov/newsrel/2009/nr021109b.htm.

[39] A more comprehensive discussion about why RNG is best suited to transportation applications is available in the Natural Gas chapter of the Future Transportation Fuels Study. Ahman, "Biomethane in the Transport Sector," notes that in countries with high biomass utilization rates such as Sweden, only 3-4% of the supplied bio-energy is used in the transport sector and approximately 80% is used for heating and electrical power generation. Given the development of alternative non bio-energy sources for heating and electricity

3. Current standards and incentives favour the use of biogas for on-site electrical power generation, not upgrading to RNG for transportation.[40]

4. Woody biomass, agricultural crop waste, and energy crops which comprise more than 80% of the current potential RNG inventory are subject to competition with liquid biofuel production.

5. The majority of the biomass feedstocks will require thermal gasification.

6. Economies of scale are critical to the feasibility of thermal gasification projects.

7. The development of a market for biogas and RNG is driven by differing policy objectives that have to address the inherent uncertainty of both long-term emission reduction ambitions and the deployment of other renewable technologies in all sectors.

8. RNG costs are dependent on the scale of operation. Large processing facilities can benefit from economies of scale, thereby reducing the costs per MMBTU. Practical plant size may be limited by the supply of nearby feedstocks, as transporting the biomass over long distances can increase its delivered cost. For small sites such as small dairies, the capital costs associated with cleaning, upgrading, and pipeline injection may be prohibitive. Aggregating feedstocks from many small sites may be a more economic approach.

9. A rigorous economic and environmental life-cycle assessment is needed to determine the best pathway for biogas and biomass feedstocks.[41]

10. Biogas and biomass feedstock inventories are fragmented and regional in scope, thereby adding to the challenge of a national RNG for transportation strategy.

11. Recent discoveries of natural gas shale reserves and the softening of natural gas prices have impacted the economics of RNG projects. Anaerobic digesters, biogas upgrading facilities, and liquefaction units require up-front capital investments that

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such as solar and wind, biomass derived fuels such as RNG may be the only carbon neutral option for the transport sector.

[40] At present, the most significant demand for RNG is from power producers in Renewable Portfolio Standard (RPS) states that use the fuel in combined cycle plants to generate renewable electricity to satisfy RPS compliance requirements.

[41] All biomass will not be available for the transport sector as other sectors also need to phase out fossil fuels and will thus be competing for the limited biomass resources.

are difficult to align with the economics of an abundant, long-term supply of low-cost fossil natural gas.

12. Developers of RNG projects must negotiate with gas utilities for access to pipelines, thereby adding time and cost.[42] Each state faces a different mix of regulatory barriers making it difficult to generalize opportunities and constraints from a national perspective.

13. Gas quality considerations are not a barrier for introducing RNG to the natural gas pipeline system as various technologies exist today to process biogas to a product that is indistinguishable from a constituent perspective to natural gas.[43]

14. In contrast to the demand for renewable electricity, a similar robust market for lower-carbon or renewable natural gas does not currently exist. An established market, preferably with long term price commitments, may encourage the capital investment required to build RNG capacity.

15. It is important to introduce other economic benefits such as the capacity of the producer or feedstock owner to convert a waste problem into a supplementary revenue source, the ability to avoid costs associated with the disposal of the waste stream, and the job creation potential at all stages of the supply chain.

16. Carbon finance can further improve project economics as carbon offsets can be earned via the capture of the methane from feedstock sources and switching vehicle fuel from diesel to RNG.

17. A significant barrier to the increased use of RNG in transportation applications is the Investment Tax Credit (ITC) which incentivizes on-site power generation from RNG but does not provide any incentive to produce RNG for pipeline injection and transport applications.

18. RNG can achieve an estimated 90% reduction in greenhouse gas (GHG) emissions when used in transport applications.[44]

19. A life-cycle analysis of greenhouse gas emissions for biomass to renewable LNG or CNG via thermal gasification is not readily available in the literature.

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[42] Mintz and Wegrzyn, “Renewable Natural Gas.”

[43] National Grid, “Renewable Gas.”

[44] Borjesson and Mattiasson, “Biogas as a Resource Efficient Vehicle Fuel,” and Argonne National Labs “Well-to-Wheels Analysis.”

20. The case studies profiled in this white paper demonstrate the suitability of RNG for transportation.

21. The technologies for anaerobic digestion and biogas clean-up are maturing and evolving. It is likely that smaller landfills, dairies, waste water treatment plants etc. may become more economically feasible. An analysis of these technologies is beyond the scope of this white paper.

List of Terms

Anaerobic Digestion	A naturally occurring biochemical process in which organic material is broken down by bacteria in a low-oxygen environment resulting in the generation of methane gas and carbon dioxide.
Anaerobic Digester	Equipment for optimizing the anaerobic digestion of biomass and/or liquid waste to produce biogas.
Biofuels	Renewable liquid or gaseous transportation fuels that are made from organic matter.
Biogas	A renewable energy source similar to natural gas but with a lower heat content. It is derived from renewable biomass sources via anaerobic digestion. In its unpurified state, the major components of biogas are methane (~60 – 70%), carbon dioxide (~30 – 40%) and additional smaller components of hydrogen sulphide (50 – 2000 ppm), water vapour, oxygen and various trace hydrocarbons.
Biogas Upgrading	A process whereby a significant portion of the carbon dioxide, water, hydrogen sulphide and other impurities are removed from raw biogas. The major technologies include water scrubbing, membrane separation, pressure swing adsorption (PSA) and mixing with higher quality gases.
Biomass	A renewable organic biological material that can be used to produce energy. It includes materials such as wood, grasses, energy crops, residues from agriculture and forestry, organic components of municipal and industrial wastes.
Biomethane	Biogas which has been purified via a process to remove the bulk of the carbon dioxide, water, hydrogen sulphide and other impurities. Generally referred to as renewable natural gas.
Co-digestion	Refers to anaerobic digestion of two or more biomass sources simultaneously to improve overall biogas yield.
Combined Heat and Power (CHP)	A group of technologies that produce electricity and heat (also known as co-generation) in a single, integrated system. It converts as much as 90% of the fuel into usable energy.
Feedstock	A raw material that can be converted into one or more useful products including renewable natural gas.
Landfill Gas (LFG)	Landfill gas (LFG) is biogas produced via organic decomposition at landfills. It is typically comprised of ~50% methane, ~50% carbon dioxide and smaller amounts of siloxanes, sulphur compounds, various trace hydrocarbons, and other impurities. The percentage of methane can vary from 40%-60% depending on waste composition. The methane may be vented, flared, combusted to generate electricity or thermal energy on-site or upgraded to renewable natural gas.

Methane	A colorless, flammable, odorless hydrocarbon gas and the major component of natural gas.
Practical Resource	The practical resource is the biomass resource expressed in dry tons per year that could reasonably be used based on technical and economic constraints. It is the total resource minus biomass that is not technically or economically practical to use. Each of the different feedstocks (forestry waste, livestock manure, waste water sludge etc.) has a range of conditions related to scale, operating practices and other limitations that define the practical resource use.
Practical RNG Potential	The practical potential is the quantity of RNG that could be produced each year from the practical resource based on expected yields.
Renewable Natural Gas	Renewable natural gas is pipeline quality gas that is fully interchangeable with natural gas, but produced from renewable biomass or biogas. Also referred to as biomethane or renewable gas.
Tank-to-Wheels	A measurement of greenhouse gas emissions during vehicle operation. This is one component of a Well-to-Wheels analysis.
Thermal Gasification	A chemical process whereby biomass is converted to synthetic gas by mixing with reactants at very high temperatures. The syngas can then be methanated to produce RNG.
Total Resource	The total resource is total available biomass resource that could, in theory, be used to produce RNG, or other bio-fuels. It may include biomass that would be impractical to use for technical or economic reasons.
Well-to-Wheels	A measurement of greenhouse gas emissions that takes into account fuel production and distribution as well as end-use emissions in transportation applications.
Wheeling	The movement of natural gas from one system to another over transmission facilities of intervening systems.
Yield	The yield is the amount RNG that can be produced from each dry ton of biomass input. It is expressed in gasoline gallon equivalents (GGE) per dry ton. The yield will depend on the biomass and the conversion processes used.

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List of Acronyms

BCF	Billion cubic feet
BTU	British thermal unit
CARB	California Air Resources Board
CFB	Circulating fluidized bed gasification
CH_4	Methane
CNG	Compressed natural gas
CO_2	Carbon dioxide
DGE	Diesel gallon equivalents
EPA	Environmental Protection Agency
GGE	Gasoline gallon equivalents
GHG	Greenhouse gas
GJ	Gigajoule
GREET	Greenhouse Gases, Regulated Emissions and Energy Use in Transportation Model
ICE	Internal combustion engine
LCA	Life cycle assessment
LFG	Landfill gas
LMOP	Landfill Methane Outreach Program
LNG	Liquefied natural gas
MJ	Megajoule
MSW	Municipal solid waste
NOx	Nitrogen oxides
OEM	Original equipment manufacturer
PM	Particulate matter
RNG	Renewable natural gas
RPS	Renewable portfolio standard
SOx	Sulphur oxides
tCO_2e	Tonne of carbon dioxide equivalent
TCF	Trillion cubic feet
TTW	Tank to wheels
WIP	Waste-in-place
WTT	Well to tank
WTW	Well to wheels

Appendix One: Feedstock Inventory Methodology and Assumptions

This appendix details the methodology, assumptions and reference studies used to arrive at estimates for the total and practical potential biomass resources available in the study timeframe and the resulting practical RNG potential.

The table below summarizes the estimate for the practical RNG potential in the U.S. in the 2035 to 2050 timeframe. It is important to note that this does not represent a theoretical maximum but rather an estimate of the potential that could be practically achieved if there is a strong mandate to reduce GHG emissions using RNG.

The practical potential is based on a set of assumptions and criteria. Changing those assumptions and criteria would produce a different estimate as what is practical is dependent upon evolving technology, associated costs, and site-specific considerations. The available quantity of biomass is also dependent upon assumptions about future management practices for waste, land, agriculture, and forests.

There are competing uses for the feedstocks and this table does not subtract amounts based on assumptions about outcomes of competing biomass uses or future policy. For example, many of the feedstocks could be used instead for electrical power generation or to produce liquid biofuels. This table estimates the amount of RNG that could be produced if all the listed feedstocks are converted.

Biomass Feedstock	Biomass Resource		Yield (GGE/Dry Ton)	Practical RNG Potential	
	Total Resource (Million Dry Tons/yr)	Practical Resource (Million Dry Tons/yr)		Practical RNG Potential (billion GGE/yr)	Practical RNG Potential (TCF/yr)
Anaerobic Digestion					
Landfill Gas (or MSW)	14[a]	7[a]	400[b]	2.8	0.34
Municipal Waste Water	9	8	64	0.5	0.06
Livestock Manure	156	24	48	1.1	0.14
AD subtotal	180	39		4.5	0.5
Suitable for Thermal Gasification					
Forestry Waste	368	124	74	9	1.1
Agricultural Waste	380	148	74	11	1.3
Municipal/Other Waste	261	41	74	3	0.4
Energy Crops	530	164	74	12	1.5

Gasification subtotal	1,539	477		35	4.2
TOTAL[c]	**1,539**	**475**		**40**	**4.8**

[a]Landfill gas resource figures are shown as millions of dry tons per year of methane produced from landfills, rather than the waste-in-place from which the methane is produced over many years.
[b]As the landfill gas resource data is for methane, not the original biomass, the yield shown is the energy per dry ton of methane.
[c]The total has been adjusted to avoid double-counting of biomass that contributes to both AD and gasification subtotals.

Introduction to Relevant Studies

QSS Group (1998) found that 1.25 quads (10 billion GGE or 1.2 TCF) could be produced annually in the U.S. by using approximately 33% of the biogas potential from landfills, animal waste, and sewage.[45] Oak Ridge National Laboratory (2005) determined that the U.S. has a potential biomass feedstock from forestry and agricultural resources exceeding 1 billion dry tons per year.[46] More recently, the National Academy of Sciences concluded that over 550 million dry tons per year of biomass could be available for bioenergy by 2020 using idle agricultural land under the Conservation Research Program, as well as wastes from forestry, agriculture, and municipalities.[47] IEA (2010) cited higher potential energy yields from biomass for RNG (derived via bio-SNG from gasification) for transportation than for either cellulosic ethanol or biomass-to-liquids diesel.[48]

One of the challenges of assessing a potential feedstock inventory is differentiating between published academic or institutional studies versus assessments or calculations provided in conference presentations, press releases, and other industry materials. Please access the bibliography for all sources used in this analysis.

A recently published American Gas Foundation study provides a state-by-state analysis of the RNG potential from currently available feedstocks and discounts some of the potential based on assumptions about feedstocks currently targeted for other applications such as

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[45] QSS Group Inc., “Biogas for Transportation Use: A 1998 Perspective,” Fairfax VA,(July 1998).

[46] Oak Ridge National Laboratory, “Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply,” Report DOE/GO-102005-2135 (2005): available at U.S. DOE Energy Efficiency & Renewable Energy website at http://www1.eere.energy.gov/biomass/pdfs/final_billionton_vision_report2.pdf.

[47] National Academy of Sciences, *Liquid Transportation Fuels from Coal and Biomass: Technological Status, Costs and Environmental Impacts*, Washington DC: National Academies Press (2009): available at http://www.nap.edu/catalog.php?record_id=12620.

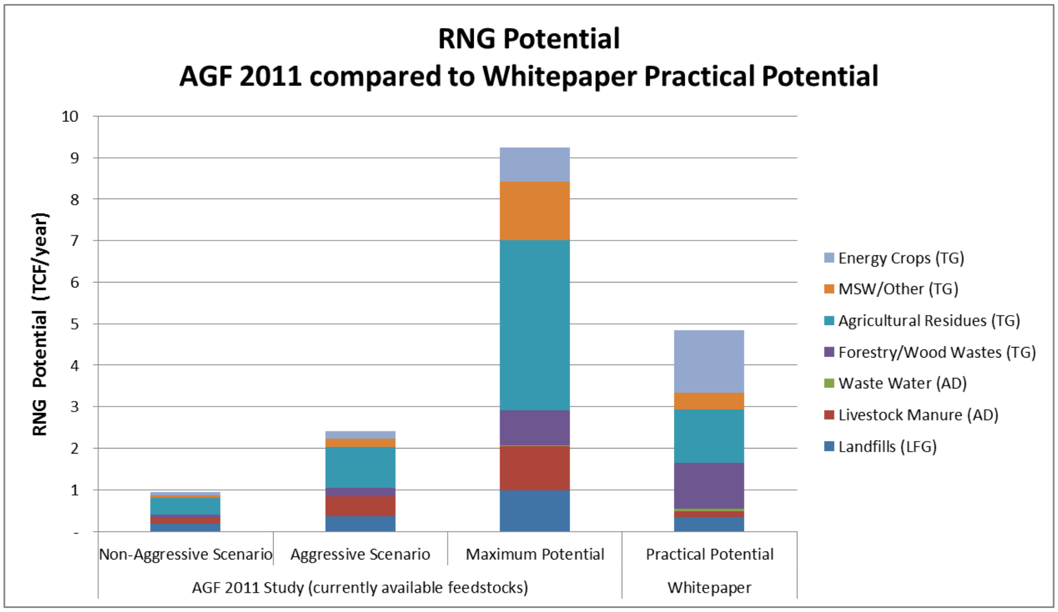
[48] International Energy Agency, “Sustainable Production of Second Generation Biofuels,” information paper by Anselm Eisentraut (OECD Publishing 2010): available at http://www.iea.org/papers/2010/second generation biofuels.pdf.

electricity generation.[49] It estimates over 9 TCF (76 billion GGE) per year as the maximum potential, comprised of 2 TCF (17 billion GGE) from anaerobic digestion and 7 TCF (59 billion GGE) from thermal gasification.

It analyzes two potential scenarios that they considered to be reasonable, representative long term cases.

- The non-aggressive scenario provided 0.9 TCF/year (0.3 TCF/year from AD; 0.6 TCF/year from TG) or 7.8 (2.7 AD + 5.1 TG) billion GGE.
- The aggressive scenario estimated 2.4 (0.8 AD + 1.6 TG) TCF/year or 20 (7 AD + 13 TG) billion GGE/year.
- The practical RNG potential estimate in this white paper is higher than the aggressive case but well below the maximum potential.
- The main differences are that the AGF study considered only currently available biomass and not the timeline of the NPC-Future Transportation Fuels study. It also discounted some biomass based on assumed other uses and tempered assumptions about technology adoption based on historical experience with reference cases.

The diagram below compares the AGF RNG scenarios to the practical potential in this whitepaper.



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[49] American Gas Foundation, "The Potential for Renewable Gas: Biogas Derived from Biomass Feedstocks and Upgraded to Pipeline Quality," Stephen Takach et al (Gas Technology Institute, Des Plaines, Illinois, September 2011): available at http://www.gasfoundation.org/ResearchStudies/agf-renewable-gas-assessment-report-110901.pdf.

Methodology

The methodology used to transform the results of various studies to an estimate for the practical RNG potential in the study time frame can be summarized as followed:

- Identify the total U.S. resource for the different feedstocks, preferably in the study timeframe, based on the relevant references. This is captured in the total resource column, generally in millions of dry tons per year.
- Identify the fraction of that resource that is practical based on a set of assumptions and criteria intended to reflect a practical limit in the study timeframe based on the reference studies.
- Determine a yield (expressed in GGE/Dry Ton) based on relevant studies for the feedstock and a process assumed for that feedstock.
- Calculate the resulting practical RNG potential with the results in billions of GGE per year and TCF of RNG per year.
- Compare the results to relevant studies for alignment.

The following terminology has been used:

- Total Resource: The total available biomass resource that could in theory be used to produce RNG or other biofuels. It may include biomass that would be impractical to use for technical or economic reasons.

- Practical Resource: The biomass resources expressed in dry tons per year that could reasonably be used based on technical and economic constraints. It is the total resource minus biomass that is not technically or economically practical to use. The economic constraint does not require that the RNG compete with current natural gas prices but rather that it be reasonable in a scenario where there is policy support for RNG thus making it comparable with other renewable fuels. Each of the different feedstock sources has a range of conditions related to scale, operating practices, and other limitations that define the practical resource use.

- Yield: The amount of RNG that can be produced from each dry ton of biomass input expressed in GGE per dry ton. The yield will depend on the biomass and the conversion processes used.

- Practical RNG Potential: The quantity of RNG that could be produced each year from the practical resource based on expected yields.

Feedstocks Considered and Conversion Processes

Currently the most commonly used feedstocks for RNG production are landfill gas (from the natural digestion of the organic fraction of municipal solid waste and industrial waste), livestock manure, and waste water sludge. These are produced using anaerobic digestion.

Other potential feedstocks include forestry waste (wood residues from processing, fuel treatment removals from timberland and other forestland, logging residues, other removable residue, and urban wood waste), agricultural waste (crop residues, small grain residues, wheat straw, and corn stover), and energy crops (dedicated fuel crops such as switch grass). A separate municipal/other wastes category was added to include organic municipal wastes that are not suitable for digestion. These are generally low-moisture ligno-cellulosic feedstocks well-suited for thermal gasification. It should be noted that some of these wastes are currently co-digested in anaerobic digesters, and that many of these feedstocks could also be converted using anaerobic digestion technology. Similarly, feedstocks in the AD section could also be converted using TG technology.

This list of feedstocks was based on reference studies, and the AD/TG categorization generally matches other studies, putting wet digestible wastes in the AD category and lower moisture ligno-cellulosic feedstock in the TG category. [50]

Landfill Gas or Digestible Municipal Solid Waste

Landfill gas (LFG) is produced from the natural anaerobic digestion of the organic fraction of the municipal solid waste (MSW) at landfill sites. The EPA Landfill Methane Outreach Program (LMOP)[51] maintains a detailed database of landfills, their waste-in-place (WIP), LFG use, and flows and emission reductions.[52] The EPA also provides software for estimating methane emissions from landfills. [53]

Approximately 0.7 TCF of methane is generated per year from MSW and industrial landfills. About 0.2 TCF is recovered in gas-to-energy projects, about 0.2 TCF is flared, a small amount is oxidized and the balance remains as methane emissions. The EPA total

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[50] There may be additional potential RNG feedstocks that have not been captured. For example, there may be potential for RNG as a co-product from biomass processing streams, or the potential to produce RNG from ethanol processing residues. There may also be waste streams or feedstocks not included in the reference studies.

[51] U.S. Environmental Protection Agency, “Landfill Methane Outreach Program,” last updated February 14, 2012: available at http://www.epa.gov/lmop/.

[52] There are more than 700 landfills excluded by the EPA as candidates because their gas flow falls below 2000 scfm. If AD/biogas cleanup can be economically developed for lower volumes, the practical RNG fuel potential would expand.

[53] LandGEM available at http://www.epa.gov/ttn/catc/products.html#software

methane emissions are used as the total resource and the fraction that is captured in gas-to-energy projects or currently flared is treated as the practical resource. Gas-to-energy projects compete for landfill gas and current policy rewards electrical power generation. No assumptions have been made that LFG currently being used for power generation would be unavailable for RNG production.

As methane is produced naturally from waste-in-place landfills, the renewable biomass for LFG is shown as millions of dry tons/year of methane rather than MSW which is not reported in dry figures. In 2008, the EPA estimated 14.5 million dry tons of methane generated from landfills and the amount recovered through gas-to-energy and flaring totalled about half that or 7.1 million dry tons of methane. The yield shown is the GGE/dry ton of methane not biomass.

The resulting practical RNG potential is 0.34 TCF for landfill gas. Future waste management practices could include separation of organic wastes from other components. In particular, food wastes and yard trimmings could be sent to anaerobic digesters rather than to landfill.[54] If waste is converted or recycled rather than landfilled, this will reduce the amount of waste-in-place and will reduce LFG production.

Waste Water Sludge

An EPA document "Opportunities for and Benefits of Combined Heat and Power at Wastewater Treatment Facilities" serves a useful introductory reference for scoping the RNG potential.[55] In short:

- 600 BTU of methane can be produced per person per day from waste water. That is equivalent to 1.8 GGE per year per person or 0.5 billion GGE (0.06 TCF) in the U.S. per year.
- Data on liquid waste volumes, densities, solids content and volatile solids content can be used to work back to dry ton based units.
- Given the relatively small potential, further discussion and analysis is omitted.

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[54] If we project EPA 2009 MSW per capita to 2035 and assume a U.S. population of 390 million, an additional 27 million dry tons per year could be produced if 90% of food scraps and yard trimmings are collected. If 170 m^3 CH_4 could be produced from each wet metric ton, the practical RNG potential for the 2035 population would be 0.43 TCF compared to 0.34 TCF for the 2008 U.S. population. This closely aligns with the 2008 LFG quantity. The 170 m3 CH_4/wet tonne is the approximate theoretical maximum yield. If we utilize a more conservative yield (100 m^3 of biogas, 60% CH_4 per wet metric ton) that would result in a practical RNG potential of 0.15 TCF with an equivalent yield of 46.4 GGE/dry ton of food scraps and yard trimmings.

[55] Environmental Protection Agency, "Opportunities for and Benefits of Combined Heat and Power at Wastewater Treatment Facilities," U.S. Environmental Protection Agency Combined Heat and Power Partnership (October 2011): available at http://www.epa.gov/chp/documents/wwtf_opportunities.pdf.

Agricultural Manure

In *"Cow Power: The Energy and Emissions Benefits of Converting Manure to Biogas"*, Cuellar and Webber (2008) analyzed U.S. livestock data to estimate the amount of livestock manure and its biogas energy potential.[56] Their estimate serves as a useful reference for the total resource:

- Using United States Department of Agriculture (USDA) data[57] on moisture content (typically 87% as excreted) the total resource can be estimated at 156 million dry tons per year.
- Cuellar and Webber calculated over 900 trillion BTU (7.5 billion GGE or 0.9 TCF) in biogas energy potential.
- This calculates to an average yield of about 48 GGE/dry ton.

EPA's AgSTAR program produced an opportunities document that serves as a useful reference for scoping the practical resource and its RNG potential:[58]

- AgSTAR considered only livestock manure from reasonably sized farms with appropriate manure management practices[59],
- Their estimates of 154 billion cubic feet (BCF) of methane at 923 BTU per cubic foot works out to 1.1 billion GGE or 0.14 TCF using 24 million dry tons per year. This is only 15% of the total resource potential.
- Note that conversions to dry ton based units are dependent upon assumed moisture content or the ratio of volatile solids to total solids. These conversions should be treated as approximate. Detailed methane emission data and models are available if necessary.

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[56] Amanda Cuellar and Michael Webber, "Cow Power: The Energy and Emissions Benefits of Converting Manure to Biogas," *Environmental Research Letters* 3, no. 3 (July 2008): doi:10:1088/1748-9326/3/3/034002.

[57] U.S. Department of Agriculture, "Agricultural Waste Management Field Handbook: Chapter 4: Agricultural Waste Characteristics," National Resources Conservation Service publication number 210–VI–AWMFH (March 2008): available at http://directives.sc.egov.usda.gov/OpenNonWebContent.aspx?content=17768.wba.

[58] EPA AgSTAR, "Market Opportunities for Biogas Recovery Systems at U.S. Livestock Facilities," (November 2011): available at http://www.epa.gov/agstar/documents/biogas_recovery_systems_screenres.pdf.

[59] This includes dairy farms with more than 500 head with flushed or scraped freestall barns and open lots with total solids content < 15% and at least weekly manure collection, or farms with over 2,000 swine with flush, pit recharge, or pull-plug pit systems.

The practical resource is dependent on manure management practices and on the size of the farm needed for anaerobic digestion to be practical. It is possible that more farms could use liquid/slurry waste management suitable for AD in the 2035 to 2050 time frame thereby increasing the practical resource or that technology advances make RNG practical at smaller farms or for drier manure management practices. Changes in population and per capita meat and dairy consumption could also impact both the total resource and practical resource.

Feedstock Sources Suitable for Thermal Gasification

The IEA recently cited higher energy yields of 74 GGE/dry ton for bio-SNG (RNG from gasification and methanation) than for biomass-to-liquids diesel (57 GGE/dry ton) or cellulosic ethanol (51 GGE/dry ton), resulting in better yield from biomass resources.[60] Although other sources have forecast higher yields, the IEA bio-SNG yield forecast was used as an objective reference to estimate the RNG potential from the gasification of biomass.

To estimate the total resource of sustainable biomass that could be used for bioenergy, the Oak Ridge National Laboratory (2005) "*Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply*" report served as the primary reference. It focuses on the potential biomass feedstock from agricultural and forestry source by the mid-21st century and examined several scenarios for land use management, crop selection, and technological change. It identified nearly:

- 368 million dry tons per year of potentially available forest resources,
- 597 million dry tons per year of potentially available agricultural resources without including any perennial crops,
- Or 997 million dry tons per year of potentially available agricultural resources including perennial crops, and
- For a total of over 1.4 billion dry tons of total potential in the high crop yield, with land use and technology changes, including perennial crops or almost 1 billion dry tons without perennial crops.

The National Academy of Sciences (2009) report served as the basis for the practical resource analysis[61]:

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[60] Their yield forecasts were 307 lge/tdm for bio-SNG, 217 for BTL diesel and 214 for cellulosic ethanol. See IEA, "Sustainable Production of Second-Generation Biofuels: Potential and perspectives in major economies and developing countries," Anself Eisentraut, OECD Publishing, IEA Energy Papers series no. 2010/1 (February 2010): doi:10.1787/5kmh3njpt6r0-en.

[61] National Academy of Sciences, "Liquid Transportation Fuels."

- 416 million dry tons per year of ligno-cellulosic feedstock could be produced for biofuel using 2008 technologies.
- 548 million dry tons per year of ligno-cellulosic feedstock could be produced using expected 2020 technologies, including 164 million dry tons per year of dedicated fuel crops grown on idle agricultural lands.

Gasification of Forestry Waste

The total resource was based on the Oak Ridge National Laboratory (2005) study. Units are expressed in million dry tons per year.

- 141 available based on existing use (wood residues from wood processing mills and pulp and paper mills, pulping liquors, fuelwood, and urban wood residue including construction and demolition debris);
- 137 from unexploited resources (residues from logging and site clearing operations, fuel treatments in timberland and other forest land to reduce fire hazards, and unexploited wood and urban residues); and
- 89 more forecast based on growth in demand for forest products, and increased forest yields tempered by improved efficiencies, increased recycling and more efficient manufacturing processes.
- Total resource: 368 million dry tons per year of forest wastes available by 2050

NAS (2009) projected that 124 million dry tons per year of woody biomass could potentially be developed by 2020. That projection is based on significant recovery losses, and intentionally leaving nutrient-rich residues in the forest to maintain soil fertility. This study was used for the practical resource estimate. Note that urban wood residues from construction and demolition have not been included in the MSW resources suitable for anaerobic digestion, thus avoiding the double counting of this resource.

Gasification of Agricultural Waste

The Oak Ridge National Laboratory (2005) study was used as the basis for the total resource for agricultural biomass sources. It is focused on potential resources available by 2050 under a number of scenarios. The most optimistic yet reasonable scenario (Scenario Three) involves modest land use changes as well as improvements in crop management, crop yields and technology.

The following waste streams (expressed in millions of dry tons per year) are included as agricultural waste suitable for gasification:

- Corn stover (256)
- Wheat straw (52)
- Small grain residues (25)
- Other crop residues (47)
- Total resource: 380 million dry tons per year

Manures and other residues have been excluded to avoid double counting with anaerobic digestion resources. Dry manure, in comparison, may be better suited for gasification rather than AD.

The 2020 Technologies scenario of NAS (2009) was used as the basis for the practical resource. The following waste streams expressed in millions of dry tons per year are included as agricultural waste suitable for gasification:

- Corn stover (112)
- Wheat and grass straw (18)
- Hay (18)
- Practical resource: 148 million dry tons per year

Gasification of Energy Crops

Scenario Three from the Oak Ridge National Laboratory (2005) study has been used as the basis for the total resource for agricultural biomass sources. The following energy crops are included in millions of dry tons per year as energy crops suitable for gasification:

- Biomass grown on CRP land (18)
- Grains for biofuels (87)
- Soybeans (48)
- Perennial crops (additional energy crops not included above) (377)
- Total resource: 530 million dry tons per year

The practical resource for energy crops is based on the 2020 Technologies scenario of NAS (2009):

- 24 million acres (2/3 of the CRP land) used for dedicated fuel crops
- 80 million dry tons per year of normal yielding energy crops (5 tons/acre) on 16 million acres of CRP
- 84 million dry tons per year of high yielding energy crops (10.5 tons/acre) on the 8 million acres of CRP.

- Practical resource: 164 million dry tons per year of dedicated fuel crops grown on 2/3rds of the CRP land.

Note that this practical resource does not require any land currently used for food crops. It does however need high yield dedicated energy crops requiring improved technology and management practices.

Gasification of Municipal and Other Wastes

The total and practical resource and RNG potential for this category is based on organic waste, including some feedstocks that could have been digested instead. The relevant AD numbers have been subtracted to avoid double counting.

EPA 2009 waste data has been used for the MSW analysis.

- 4.34 lbs per day per person of waste generated.
- 76.6% included in the total resource (paper and paper board, food scraps, yard trimmings, textiles, rubber and leather, plastics).[62]
- 11.1% is the Practical Resource (only 10% of the paper and paperboard generated assuming increased recycling, plus textiles, rubber, and leather). Food scraps and yard trimmings are assumed better suited for AD. Increased recycling is also expected, so only 10% of the paper and paperboard waste generated are assumed to be available.
- 90% of the relevant waste generated can be collected.
- 60% moisture content (estimate only, not validated).
- 390 Million U.S. population (AEO 2010 Reference case for 2035).

This yields 95 million dry tons as the total resource which is approximately the same as the NAS (2009) findings and 12 million dry tons of suitable MSW for the practical resource.

Municipal waste water is a smaller resource and preliminary calculations removed it from the list of potential feedstock sources.[63]

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[62] Wood is included in the forestry section.

[63] Assuming 0.15 dry lbs per day of volatile solids per person and a population of 390 million in 2035, that calculates to a total resource of approximately 11 million dry tons per year. If we assume 90% of this is collected in waste water treatment facilities of a reasonable size and 50% of the energy content remains after AD, there are 5 million dry tons per year of volatile solids suitable for gasification.

Livestock manure, including and preferring dry manure, can also be gasified. The total resource of livestock manure is 156 million dry tons per year. Based on farm size and liquid/slurry manure management criteria set by AgSTAR, the practical resource for AD was determined to be 24 million dry tons per year. In comparison, NAS (2009) cited a USDA study that found 60.6 million dry tons per year of dry manure that could be made available. The difference between these two figures, or about 37 million dry tons, could remain for gasification. This amount could come from suitably sized farms using drier manure management practices or even be combined with the dried digestate from AD. This number has not been validated against USDA farm size manure management data but is provided as a simple analysis.

Appendix Two: The Economics of RNG Projects

This appendix provides a summary of the literature on RNG production costs from existing projects in the U.S.:

- The California Energy Commission[64] estimated the costs of producing pipeline quality RNG from landfill gas to be $1.7 - $2.2/MMBTU[65].
- CALSTART estimated current (2010) RNG production costs of $5.9/MMBTU from livestock manure for a medium sized facility and $9/MMBTU for a smaller one.[66] The dominant cost was upgrading the biogas to RNG: $4/MMBTU for a medium sized facility and $7/MMBTU for a small one. Biogas production was typically $2 per 1000 ft^3 of biogas, with covered lagoons being the lowest cost and the large, covered lagoon system at Hilarides only $0.38.
- A 2009 California Energy Commission study did a detailed economic analysis of RNG from dairies injected into the pipeline using current technology and costs.[67]. They found that the cost of pipeline injection could be significant, especially for

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[64] California Energy Commission, "Economic and Financial Aspects of Landfill Gas to Energy Project Development in California," consultant report for Public Interest Energy Research no. 500-02-020F (April 2002): available at http://www.energy.ca.gov/reports/2002-04-08_500-02-020F.PDF.

[65] Results summarized on page 29 of the CEC study are per mcf of pipeline quality gas. They are stated here per MMBTU.

[66] Calstart, "Economic Assessment of Biogas and Biomethane Production from Manure," white paper by Patrick Chen et al. (March 2010): available at http://www.calstart.org/Libraries/Publications/Economic_Assessment_of_Biogas_and_Biomethane_Production_from_Manure_2010.sflb.ashx.

[67] California Energy Commission, "Economic Study of Bioenergy Production from Digesters at California Dairies," Nicholas Cheremisinoff, Kathryn George, Joseph Cohen, publication no. CEC-500-2009-058 (October 2009): available at http://www.energy.ca.gov/publications/displayOneReport.php?pubNum=CEC-500-2009-058.

dairies miles from an interconnection to the natural gas grid. For example, the cost of pipeline injected RNG would be $12/MMBTU for the Hilarides Dairy compared to $42/MMBTU for the Castelanelli Dairy which would require 5 miles of pipeline..[68] Capital costs, including the costs to pipeline interconnect, were the cost drivers.

- NREL's case study for biogas from dairy farms resulted in a RNG cost of $11/MMBTU delivered into the pipeline.[69] This consisted of $6 paid to the farmers, $2.5 for RNG production and $3 for delivery (10 miles) into the pipeline.
- ECN in the Netherlands estimated costs of RNG production from biomass using the MILENA gasification technology ranging from $13/MMBTU at a large facility to $42/MMBTU at a smaller one, including biomass costs of $3.7 to $7.7/MMBTU[70] of RNG.[71]

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[68] The study used costs per therm. These have been converted to costs per MMBTU.

[69] Saur, G. and Jalalzadeh, A., "H2A Biomethane Model Documentation and a Case Study for Biogas from Dairy Farms," technical report for National Renewable Energy Laboratory no. NREL/TP-5600-49009 (December 2010): doi: 10.2172/1000098

[70] Table 5.5 reports the costs of 9 to 31 euros per GJ. These figures have been converted to $/MMBTU.

[71] Zwart et al. (2006) "Production of Synthetic Natural Gas"