The Future of Renewable Natural Gas in Massachusetts

A thesis submitted by

Shoshana Blank

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Adviser: Ann Rappaport

Reader: Penn Loh

Abstract

The Massachusetts Global Warming Solutions Act directs the Commonwealth to reduce greenhouse gas (GHG) emissions significantly by 2050. Renewable natural gas (RNG) is a low-carbon fuel that can replace natural gas in the pipeline. National Renewable Energy Laboratory data on methane potential from waste feedstocks in MA was used to calculate the percentage of gas consumption that could be replaced by RNG and the emissions reductions. Energy experts were interviewed, and case studies were written on three RNG projects in New England to identify barriers and opportunities. RNG potential equals 1.7% of current annual gas consumption. Low feedstock availability and high capital costs are barriers. Massachusetts can pass legislation directing the Department of Public Utilities to approve RNG rate recovery. Utilities can pursue voluntary RNG programs and partner with wastewater treatment plants to develop projects. The Alternative Energy Portfolio Standard could be amended to include RNG pipeline injection.

Acknowledgments

I would like start by thanking the UEP Field Projects course for introducing me to anaerobic digestion in spring 2019, and to Gretchen Carey, who brought me on a field trip to a dairy digester in Western MA. Thank you to my adviser Ann Rappaport who gave me helpful feedback and confidence in this thesis. Also, thanks to my reader Penn Loh for your insightful questions. I have gratitude for my thesis group, who motivated me towards the April deadline. Additionally, I want to thank my interviewees for sitting down with me and explaining the world of biogas, RNG, and Utilities Commissions. Last, but not least, thank you to my husband Tylor who has provided me with unending support throughout this degree program.

Abbreviations and Glossary

Term	Definition
AD	Anaerobic digestion - a natural process where organic wastes produce methane gas when in an anaerobic (without oxygen) environment
AEC	Alternative energy credit, financial incentive to develop renewable thermal technologies in the APS
APS	Alternative energy portfolio standard
Biomethane	Another term for renewable natural gas
CARB	California Air Resources Board
Carbon intensity	Emissions factor for a given fuel. The amount of carbon it emits per a given unit of energy
CH_4	Methane (a greenhouse gas)
CO	Carbon monoxide
CO_2	Carbon dioxide (a greenhouse gas)
Co-digestion	Mixing feedstocks in anaerobic digestion, such as food waste and manure
CRS	Center for Resource Solutions, a non-profit focusing on policy and market solutions to increase the use of sustainable energy
Digestate	The material remaining after the anaerobic digestion of a biodegradable feedstock, which can be used as fertilizer.
DOER	Massachusetts Department of Energy Resources
DPU	Massachusetts Department of Public Utilities
EIA	U.S. Energy Information Administration
EPA	U.S. Environmental Protection Agency
Environmental attribute	Any GHG emissions reductions and RECs associated with a renewable or alternative energy project. The entity that owns the attributes can claim the emissions reductions.
GHG	Greenhouse gas
LCFS	California Low-carbon fuel standard
LDC	Local distribution company (utility company)
MA	Massachusetts
MassDEP	Massachusetts Department of Environmental Protection
ME	Maine
N_2O	Nitrous oxide (a greenhouse gas)
NH	New Hampshire
NOx	Oxides of nitrogen, which are atmospheric pollutants
NREL	National Renewable Energy Laboratory
Organic waste	Essentially food waste. Also known as source-separated organics. Could include yard waste.
P2G	Power-to-gas, a technology that uses electrical power to produce gas fuel.

PFAS	Per- and polyfluoroalkyl substances: man-made chemicals that can be found in food, drinking water, and living organisms.
PUC	Public Utility Commission
QA/QC	Quality assurance and quality control
R&D	Research and development
Rate recovery	Utilities recover costs for providing gas (or electric) service to retail customers through monthly bills.
REC	Renewable energy certificate, specifically applied to renewable electricity, similar to "environmental attribute".
RFS	Federal Renewable Fuel Standard
RGGI	Regional Greenhouse Gas Initiative
RIN	Renewable Identification Number, an environmental attribute associated with fuels in the RFS
RNG	Renewable natural gas
RPS	Renewable portfolio standard
SNGME	Summit Natural Gas of Maine (utility company)
SSO	Source-separated organics (waste)
T&D	Transmission & distribution (of gas or electricity)
TREC	Thermal REC
VGS	Vermont Gas (utility company)
VT	Vermont
WWTP	Wastewater treatment plant

Units of Measurement

Term	Unit
atm	Standard atmosphere (unit of pressure)
Btu	British thermal unit (unit of energy)
℃	Degrees Centigrade
Dekatherm	Ten therms (unit of energy)
℉	Degrees Fahrenheit
gCO_2e	Grams of carbon dioxide equivalent emissions
m^3	Cubic meter (unit of volume)
MGD	Million gallons per day
MJ	Megajoule (unit of energy)
MMBtu	Million British thermal units (unit of energy)
MMcf	Million cubic feet (unit of volume)
MT	Metric ton (unit of weight)
$MTCO_2e$	Metric tons of carbon dioxide equivalent emissions
MWh	Megawatt-hour (unit of electricity)
SCF	Standard cubic feet (unit of volume)
tBtu	Trillion British thermal units (unit of energy)
Therm	A unit of heat equivalent to 100,000 Btu or 1.055 × 108 joules (unit of energy). Typically used for natural gas.

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The Future of Renewable Natural Gas in Massachusetts

Chapter 1: Introduction

The goal of this thesis is to explore the potential for renewable natural gas (RNG) in the state of Massachusetts (MA), as well as the steps towards implementation. The production and use of RNG for thermal heating in MA will assist the Commonwealth in reducing greenhouse gas (GHG) emissions, an important priority to the state. MA has a goal to reduce emissions at least 80% below 1990 levels by 2050. RNG, also known as 'biomethane', is methane gas that can be used interchangeably with conventional natural gas[1] (for heating, electricity, and vehicle fuel). It is produced by upgrading biogas. Biogas is created from anaerobic digestion (AD), a natural process where organic wastes produce methane gas when in an anaerobic (without oxygen) environment. Anaerobic digesters are typically located at wastewater treatment plants[2] (WWTPs) or on farms using manure (typically cow and swine). In both cases, the facilities could import food waste (source-separated organics) to the digester and co-digest with the feedstocks, producing more methane than as a single feedstock. Additionally, the AD process already happens at landfills. Landfill gas can be captured and is currently the largest source of biogas in the U.S. (US EPA, n.d.-c).

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[1] Natural gas is a fossil fuel that causes environmental damage at every stage in its lifecycle, leaking methane emissions when drilled, extracted, and transported in pipelines. When combusted, it releases CO_2 emissions (Union of Concerned Scientists, 2014).

[2] Wastewater treatment plants are also called water resource recovery facilities (WRRFs) to recognize that these facilities work to recover resources such as nutrients, organic matter, and energy, in addition to cleaning water (North East Biosolids and Residuals Association (NEBRA), 2019).

First, the thesis will quantify the untapped potential for RNG production in the state and compare that to current MA natural gas consumption, estimating potential GHG emissions mitigation from fully pursuing RNG production. This thesis will then employ interviews with experts in the RNG industry, utility companies, and project developers who have started RNG projects in New England or are familiar with the thermal energy landscape in the region. These interviews will focus on the steps to implementing an RNG project or using RNG environmental attributes at a utility company, as well as the barriers and potential solutions.

The thesis questions are (1) "What is the technical potential for RNG production in MA?", (2) "What steps would need to be taken to begin RNG pipeline injection in MA and/or use RNG environmental attributes as part of the natural gas supply?" and (3) "What are the opportunities and barriers to this implementation?"

Relevance

In the face of climate change, Massachusetts passed the Global Warming Solutions Act in 2008, requiring the state to reduce GHG emissions 80% below 1990 levels by 2050. The state has a number of policies and incentives to help it get there, including the Renewable Energy Portfolio Standard (RPS) which requires an increasing percentage of renewable energy on the electric grid each year (Beaton, 2015). In addition, the MA Department of Environmental Protection (MassDEP) enacted the Commercial Food Material Disposal ban in October 2014, banning disposal of organic waste by commercial entities that dispose of one ton or more of these materials each week. Organic waste can be composted, sent to become animal feed, or can go to an anaerobic digester to create biogas (Massachusetts Department of Environmental Protection, n.d.-a).

Massachusetts currently has around 30 operational biogas systems, some at landfills, WWTPs, dairy farms, and others just for food waste. There are still untapped feedstocks for anaerobic digestion in MA, according to the American Biogas Council and the U.S. Environmental Protection Agency (EPA), particularly at WWTPs and for food waste (American Biogas Council, 2015). There are currently no biogas upgrading to RNG projects happening in MA and the utilities are not giving customers the option to purchase RNG as a portion of their gas bills. Utility companies operating in Vermont (VT), New Hampshire (NH), and Maine (ME) are all currently pursuing projects in RNG pipeline injection. National Grid and Eversource, the two largest utility companies in MA, have expressed interest in pursuing RNG in the region. As municipalities, institutions, and residents in MA look to de-carbonize, they need innovative solutions for heating buildings and RNG is a low-carbon heating fuel. The question is, how might RNG become a reality in MA?

Why RNG? Those working on climate change mitigation, from scientists to policy makers, agree that in order to achieve long-term global climate goals and reductions in energy-use emissions, we must pursue deep electrification, of thermal heating and vehicles, powered by renewable energy. However, the U.S. has built its economy around inexpensive sources of fossil energy, primarily natural gas, which is currently the largest share of energy production in the U.S.

Center for Resource Solutions (CRS), a non-profit focusing on policy and market solutions to increase the use of sustainable energy, makes the case that “billions of dollars are invested annually in natural gas infrastructure, including more than 3 million miles of natural gas pipelines that serve 75 million customers.” RNG is a renewable fuel that can still utilize this expansive infrastructure, so as to not waste it (Green-e, n.d.). Additionally, some natural gas users in the commercial and industrial sectors cannot convert to 100% electricity for thermal energy, as they still require natural gas for uses like process heat. And lastly, some analyses show that the lifecycle GHG emissions from using RNG for residential non-electricity use are even lower than if the grid electricity were made-up of 75% renewable energy and powered those same home systems (heating, cooking) (Russell, Lowell, & Jones, 2017).

Goals of this Report

The goal of this project is to assess the future of RNG production and use in Massachusetts. It will be a roadmap that includes the technical potential of RNG produced from waste feedstocks in the state and the implementation steps needed to start producing and offering RNG as a low-carbon fuel substitute. By providing RNG case studies from neighboring states, I hope to inform those who are interested in RNG pipeline injection and RNG utility options in MA. The findings will be useful for state energy and environmental decision makers.

Chapter 2: Methodology

Literature Review

First, I conducted a literature review on anaerobic digestion, RNG, and barriers and opportunities. This literature review includes academic literature, white papers, commissioned reports, industry websites, government websites, and news articles. This enabled me to understand the background of RNG, the existing solutions being employed, and the context of energy politics in MA, which is helpful for both the quantitative and qualitative research in this project.

Quantitative Methods

I conducted the quantitative methods to find out: (1) the technical potential of RNG production in MA as a percentage of natural gas consumption for non-electricity use and (2) the potential for GHG emissions reductions from harnessing 100% of this RNG. I took the methane potential for MA that the National Renewable Energy Laboratory (NREL) has calculated, and exported this data from their BioPower Atlas tool (National Renewable Energy Laboratory, n.d.). The data is broken down as technical potential of methane from four sources in the state: landfills, animal manure, organic waste, and WWTPs. Figure 1 presents estimated biogas potential in the U.S. from these sources and Figure 2 indicates that MA has a comparative advantage in biogas potential. Milbrandt (2005) discusses the methodology used to calculate this methane potential by state and this same methodology was used when the data was updated in 2014. The data is given in metric tons (MT) of methane potential per year. Since RNG is essentially 95-99% methane, the methane potential was used as a proxy for the RNG technical potential in the state. Conversion factors were employed to convert RNG from weight (MT) to volume (MMcf). Million cubic feet (MMcf) is a unit of volume that is commonly used for natural gas. For methane, at 60°F and 1 atm, 0.678 kg = 1 m^3 (National Institute of Standards and Technology, 2018).

Equation 1

Total RNG technical potential from MA annually (MMcf) = *Sum of methane potential from each county from all feedstocks types (MT) * 1,000 kg/MT * 1.475* m^3*/kg methane * 35.31 SCF/* m^3 ** 1 MMcf/1,000,000 SCF*

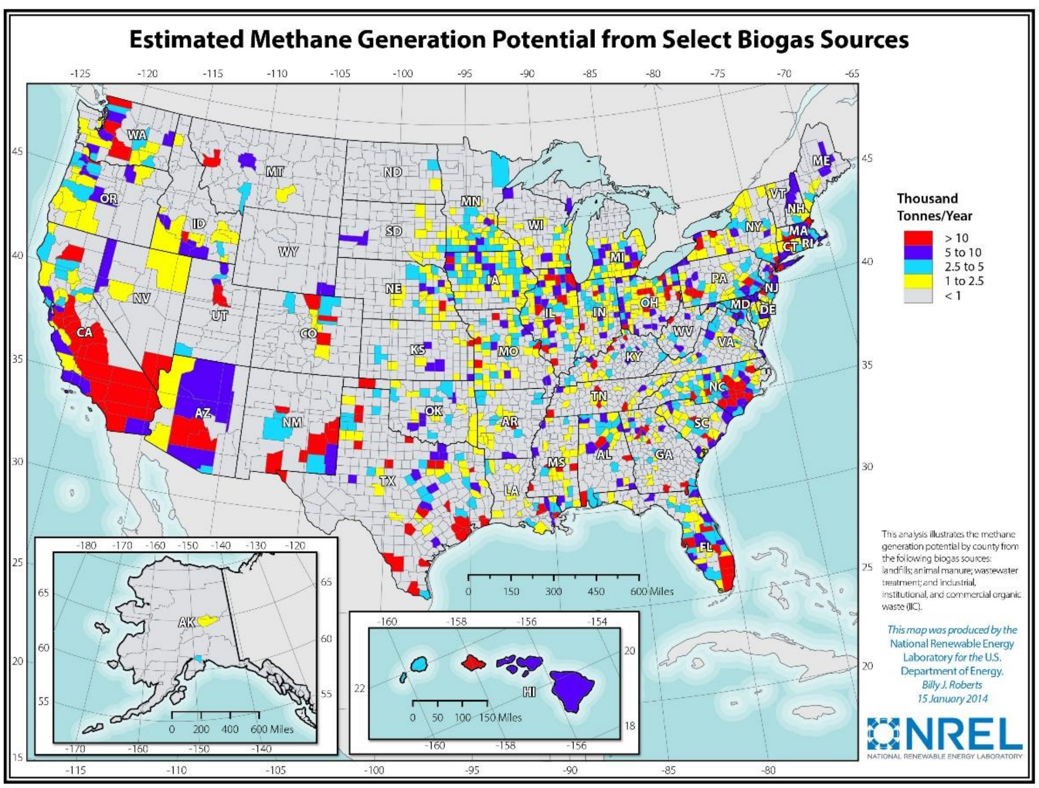

Figure 1 – Biogas-Methane Resources from waste feedstocks in the U.S. (National Renewable Energy Laboratory, 2014)

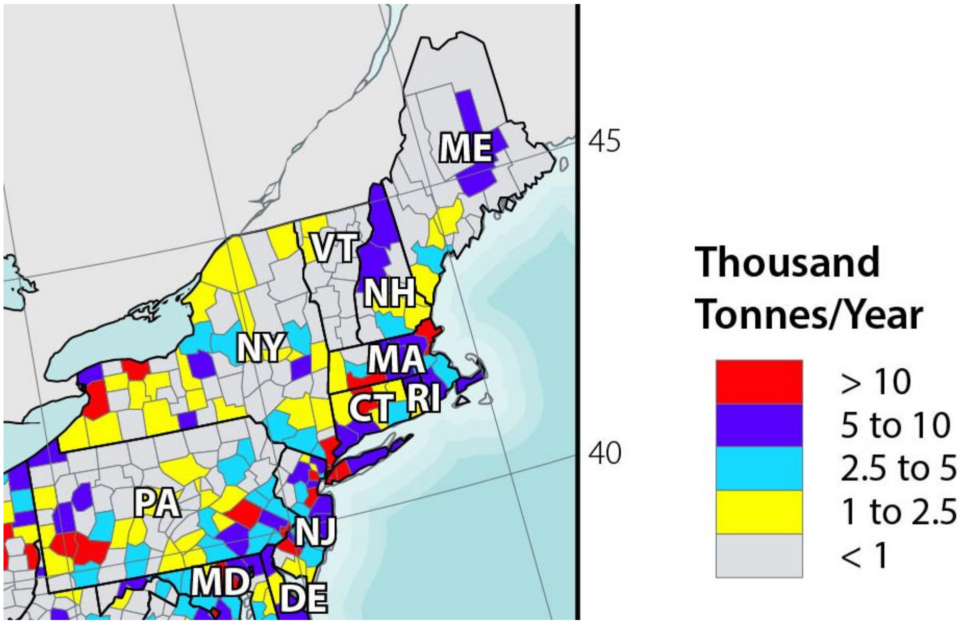

Figure 2 – Biogas-Methane Resources map - New England states (National Renewable Energy Laboratory, 2014)

I used U.S Energy Information Administration (EIA) data on natural gas consumption by End Use for calendar year 2018 for MA, adding up volumes delivered to residential, commercial, and industrial consumers for non-electricity/non-vehicle use (U.S. Energy Information Administration, 2020). Next, I compared the total volume of RNG technical potential to this total natural gas consumption figure.

Equation 2

RNG potential as a percentage of natural gas consumption in MA (%) = [*Total RNG technical potential from MA (MMcf)*] ÷ [*Sum of natural gas consumption from residential, commercial, and industrial end uses (MMcf)*]

I calculated estimated GHG emissions reductions if 100% of this RNG were produced and injected into the pipeline. I used lifecycle carbon intensity values for traditional natural gas and for RNG from landfill gas, animal manure, wastewater sludge, and food and green waste (organic waste), sourced from the California Air Resources Board (CARB) Low-Carbon Fuel Standard (LCFS) certified fuel pathways (California Air Resources Board, 2020). Table 1 shows the carbon intensity of each fuel and Figure 3 compares these carbon intensities graphically. While these carbon intensity values are meant for natural gas and RNG for vehicle fuel and include the “tank to wheels” combustion of the fuel in vehicle segment of the lifecycle, there are no certified lifecycle carbon intensities that exist for RNG injected into the pipeline for thermal use. These carbon intensity values account for methane leaks throughout the lifecycle of the fuel, including pipeline leaks since RNG used as vehicle fuel is also injected into the pipeline.

Table 1 – Carbon intensities of natural gas and RNG from various feedstocks (California Air Resources Board, 2020; Russell et al., 2017)

Gas Source	***Carbon Intensity (gCO_2e/MJ)***
California Natural Gas (Traditional)	78.37
Landfill Gas	46.42
Dairy Manure	-276.24
Wastewater Treatment Plant	19.34
Food and Green Waste	-22.93

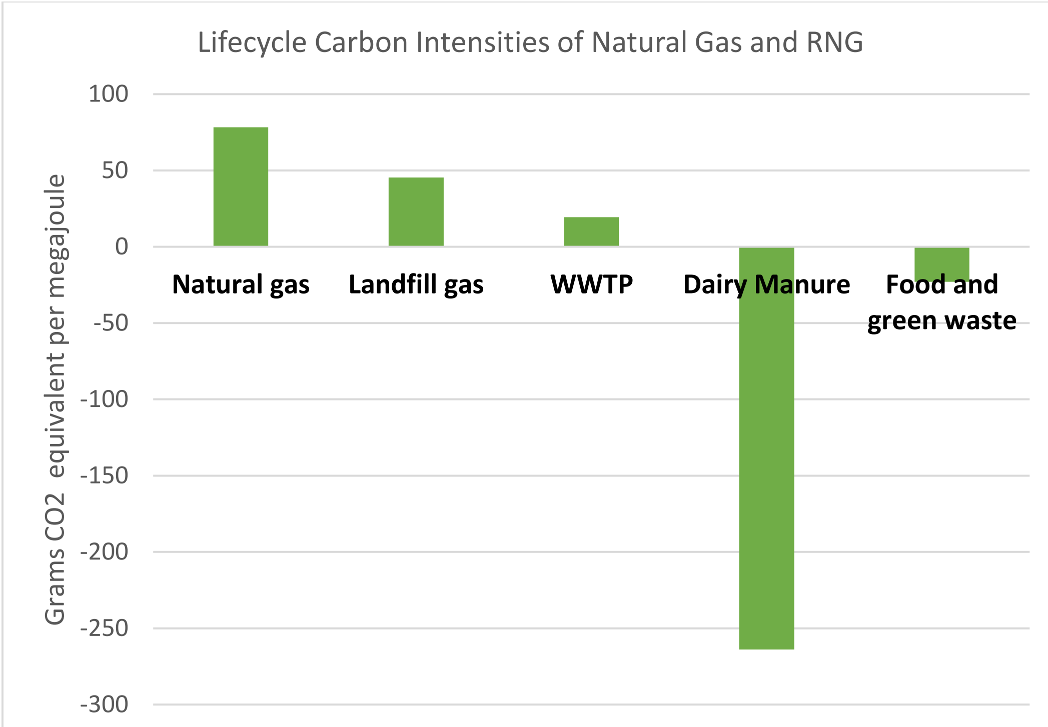

Figure 3 – Carbon intensities of natural gas and RNG from various feedstocks (California Air Resources Board, 2020; Russell et al., 2017)

In order to calculate the potential GHG emissions mitigated by injecting 100% of the RNG available in the state into the natural gas pipeline, thus displacing natural gas, a Reference Case (business-as-usual) and an RNG Scenario were created. The difference between the Reference Case and the RNG Scenario is the potential GHG emissions mitigated from RNG use. This number can be compared to gross GHG emissions for the state of MA to determine whether RNG would have a significant impact on the state's GHG emissions. 2017 is the last year that the MassDEP has completed GHG data. The MA gross GHG emissions include the following categories: fossil fuel combustion, natural gas systems (leakage), industrial processes, agriculture & land use, and waste (Massachusetts Department of Environmental Protection, 2020).

Equation 3 - Reference Case Emissions

Total emissions from natural gas consumption business-as-usual ($MTCO_2e$) = *Sum of natural gas consumption from residential, commercial, and industrial end uses (MMcf) * 1,000,000 SCF/MMcf * 1,036 Btu/SCF * 1 MJ/947.82 Btu * Traditional natural gas carbon intensity (gCO_2e/MJ) * 1 metric MT/1,000,000 g*

Equation 4 - RNG Scenario Emissions

Total emissions from natural gas consumption if RNG utilized ($MTCO_2e$) = [*RNG potential from organic waste (MMcf) * RNG food and green waste carbon intensity (gCO_2e/MJ)*] + [*RNG potential from animal manure (MMcf) * RNG dairy manure carbon intensity (gCO_2e /MJ)*] + [*RNG potential from WWTP (MMcf) * RNG WWTP carbon intensity (gCO_2e/MJ)*] + [*RNG potential from landfill gas (MMcf) * RNG landfill gas carbon intensity (gCO_2e/MJ*)] + [*New total volume of natural gas after having displacement from RNG (MMcf) * Traditional natural gas carbon intensity (gCO_2e/MJ*)]

Equation 5 - GHG Emissions Mitigated

GHG emissions mitigated from RNG use ($MTCO_2e$) = *Reference Case Emissions – RNG Scenario Emissions*

Equation 6 - GHG Emissions Mitigated as a percentage of 2017 MA Gross Emissions

GHG emissions mitigated as a percentage of 2017 MA Gross Emissions = *GHG emissions mitigated from RNG use ÷ 2017 MA Gross Emissions*

Qualitative Methods

I prepared interview questions and interviewed experts in the RNG industry in New England (see Appendix A and B). The interviews were designed to reveal the steps needed to implement an RNG project or use RNG environmental attributes as part of a utility's gas supply. Some of the interviewees are involved in developing RNG projects in neighboring states: VT, NH, and ME. I wrote short case studies on the New England projects, and then used cross-case analysis to identify a decision pathway for MA. In addition, I used websites and news articles to gather data to complete the case studies. In all the interviews, I employed the snowball method to find other people to interview who were relevant for this thesis.

Chapter 3: Literature Review and Background

Anaerobic Digestion and Biogas

Technology and Feedstocks

Anaerobic digestion (AD) is a process that uses microorganisms to convert organic matter into methane (CH_4) and carbon dioxide (CO_2) gases (Kougias & Angelidaki, 2018). The resulting gas is called biogas and is composed of 60-70% methane (US EPA, 2018). Biogas can be used as a renewable fuel to create energy.

There are four phases of methane fermentation: hydrolysis, acidogenesis, acetogenesis/dehydrogenation, and methanation. Each phase utilizes a different set of microorganisms (methanogenic bacteria) that can survive under anaerobic (without oxygen) conditions. The digestion process could take place at either mesophilic (35-42 °C) or thermophilic (45-60 °C) temperatures and methane formation needs a pH level between 6.5 to 8.5 (Weiland, 2010). Wet digestion has a total solids content of 20% or less, and dry digestion has a solids content of 25-45%. Animal manure, wastewater sludge, and food waste are ideal for wet digestion (Pike, 2014; Russell et al., 2017).

Organic material is the feedstock for AD and these feedstocks include: livestock manure (dairy, beef, poultry, and swine); food waste; fats, oils, and greases; wastewater biosolids and primary sludge; and municipal solid waste in landfills (Pike, 2014; USDA, US EPA, & US Department of Energy, 2014). Additionally, crop residues, logging residues, forest thinnings, and energy crops (such as maize, sorghum, and grass) are used in dry digestion (ICF, 2019; Weiland, 2010). These dry crops are often processed through thermal gasification rather than AD, and there is a high potential for thermal gasification in New England, however this study will only focus on wet AD (National Grid, 2010). This study focuses on AD rather than thermal gasification because AD uses readily available waste as a feedstock, and does not require dedicated uses of land for crop growth, therefore reducing emissions from current methane-producing processes (Gasper & Searchinger, 2018). There are certain feedstocks for thermal gasification that are also waste products, such as logging residue and forest thinnings, but those remain outside the scope of this study.

Studies show that co-digesting various types of organic matter together yields higher rates of biogas than AD with a single feedstock. Banks et al. found an increase in electrical energy potential and biogas production from increasing the ratio of food waste to cattle manure (2011). Adding pretreated meadow grass was shown to increase methane production from manure by 114% (Søndergaard, Fotidis, Kovalovszki, & Angelidaki, 2015). Digestion of cow manure alone vs co-digestion with organic waste resulted in a 277% increase in methane production (Macias-Corral et al., 2008). Co-digestion of source separated organic waste (SSO) with and industrial waste and with sewage sludge was shown to achieve the highest GHG reductions over windrow composting and single substrate anaerobic digestion of SSO (Yoshida, Gable, & Park, 2012).

In addition to biogas, AD with biosolid feedstocks (WWTP and manure) also produces a digestate byproduct. This can be used and sold as a fertilizer or as a soil amendment. AD on dairy farms produces a third byproduct, livestock bedding, which can also be sold (US EPA, 2018).

Biogas utilization pathways

Biogas can be used in a combined heat and power (CHP) plant to heat buildings at the digester site and provide electricity. Assuming there is more electricity produced than needed on-site, the electricity can serve the grid. While CHP is a more efficient use of biogas, since it provides both heat and power, the biogas could simply be combusted to send electricity to the grid or to produce electricity used behind the meter (Pennington, 2019). Alternatively, biogas can be upgraded to renewable natural gas (RNG) and injected into the natural gas grid, where it can have an end-use as a vehicle fuel or used for heating purposes (USDA et al., 2014). RNG could also be used directly as a vehicle fuel from the RNG plant, without being transported via pipeline.

RNG Specifications for Pipeline Injection

Upgrading biogas to RNG involves removing all gas contaminants and CO_2 so the resulting gas has a methane content of more than 95% (Weiland, 2010). First, hydrogen sulfide (H_2S) is removed, followed by moisture removal to get the gas down to just 4-13% water. Then, other trace constituents are removed, such as siloxanes and volatile organic compounds (VOCs). These trace constituents can pose health risks and damage pipelines and end-use equipment (Russell et al., 2017). And last of all, CO_2 is removed. While there are specifications for how much CO_2 is allowed in RNG being used as vehicle fuel, there is no federal standard for RNG being injected into the natural gas pipeline (Rodgers, 2019). The specifications are up to the pipeline operator, typically either a utility company, local distribution company (LDC), or interstate pipeline distribution company (Northeast Gas Association, 2019). RNG is upgraded to a point where it is virtually identical to conventional natural gas. It is important for the RNG to have a similar heating value and Wobbe index to natural gas, so that it can be used interchangeably in appliances that typically use natural gas. Heating value is the amount of heat produced by complete combustion of fuel, expressed in energy per unit volume of natural gas. The Wobbe index measures the rate of energy delivered through a fixed orifice at a constant pressure, and is essentially density-corrected energy content (Von Wald, Stanion, Rajagopal, & Brandt, 2019).

RNG Future Technologies for Thermal Energy

RNG can be produced by two methods other than AD and thermal gasification, power-to-gas (P2G) and artificial photosynthesis, but these technologies are still under development (Russell et al., 2017). P2G is an energy technology where electricity is converted into a gaseous fuel (RNG). Electricity can be used to separate water (H_2O) into hydrogen and oxygen, through electrolysis. The hydrogen can be combined with CO_2 to create CH_4 (methane) through a process called methanation and used as RNG (also called syn-gas). When the electricity in P2G is sourced from renewable energy, the production of RNG is carbon neutral. This is a good alternative use for wind and solar electricity, which are often curtailed when there is a system-wide oversupply and local transmission constraints. Additionally, CO_2 is emitted from biogas plants upgrading to RNG, or from other sources like natural gas power plants, and methanation would capture this CO_2, turning it into useful energy as RNG.

The hydrogen produced from electrolysis of water can be used in other ways: a fuel cell to store renewable electricity for use at a later time or injected as hydrogen into the natural gas pipeline to augment the natural gas supply. Hydrogen can be blended with natural gas in the pipeline and has zero carbon emissions. ITM Power in the United Kingdom started a pilot project to inject hydrogen into Keele University's natural gas network (20% hydrogen blend) in January 2020 (Clark & Montgomery, 2020; ICF, 2019; ITM Power, 2020).

Much of the current research estimating the impact RNG could have on our thermal energy supply also projects into the future with P2G and hydrogen technologies, noting that AD alone will not produce enough RNG to meet 100% of natural gas demand. One future projection is a study conducted by ICF for the American Gas Foundation. The high resource scenario estimates 4,510 tBtu/yr of RNG production by 2040. The U.S. consumes 15,850 tBtu/yr on average between the residential, commercial, industrial, and transportation sectors (ICF, 2019) (see Figure 4).

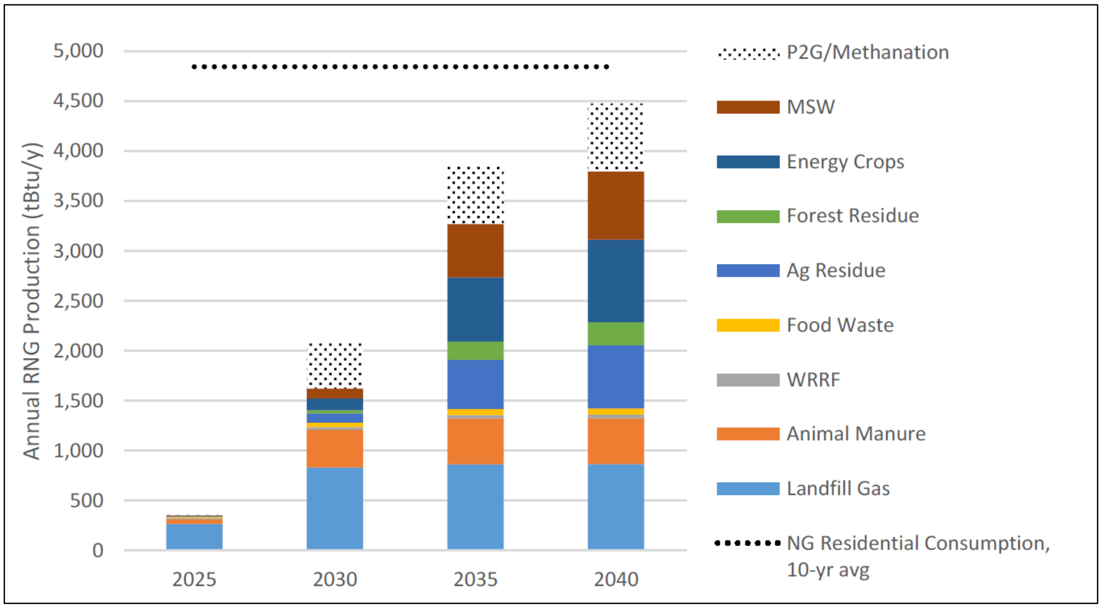

Figure 4 – Estimated annual RNG production (ICF, 2019)[3]

RNG in European Countries

Biogas is a national priority in Denmark since it is an agricultural country with hogs outnumbering people five to one. Animal manure from cows and pigs are the most abundant feedstock for AD in the country. There are biogas plants spaced out evenly in agricultural regions, each serving about 100 to 250 farms in the region surrounding it (12 to 19-mile radius). These plants are located close to the natural gas pipeline so they can be injected as RNG. RNG first started being injected into Denmark pipelines in 2013, and by 2018 it equaled 11% of the natural gas consumption. There are numerous policies that support biogas production in Denmark: a goal to turn 50% of manure into biogas by 2020,

[3] MSW refers to municipal solid waste, specifically 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. (ICF, 2019).

investment grants, and electricity and gas injection feed-in tariffs for biogas and RNG (Hansen, Spencer, & Barbagallo, 2019).

Germany has approximately 8,700 biogas plants, which are primarily used for electricity and CHP. As of 2016 there were 196 biogas plant upgrading to RNG in the country. These tend to be larger volume biogas plants that use energy crops as a feedstock (Daniel-Gromke et al., 2018).

State of RNG in the U.S.

The majority of AD projects in the United States use the biogas to generate electricity, largely due to state and federal incentives (Hamberg et al., 2012). Of the biogas that is currently being upgraded to RNG, almost all of it is being used as vehicle fuel. These two uses of biogas, for electricity and for RNG-vehicle fuel, are influenced by states' RPS, requiring an increase in renewable electricity, as well as low-carbon vehicle fuel policies (Gasper & Searchinger, 2018). The low-carbon fuel policies include the EPA's Renewable Fuel Standard (RFS) and the CARB Low Carbon Fuel Standard (LCFS). The RFS allows for the issuance of Renewable Identification Numbers (RINs), which renewable fuel earns when sold into the transportation sector. RINs apply a monetary environmental attribute to each unit of RNG used as vehicle fuel, giving RNG producers an economic incentive to sell their fuel. Similarly, RINs in the LCFS program are called LCFS credits (Center for Resource Solutions, 2019). The LCFS requires refineries and fuels suppliers in California to reduce the carbon intensity of their fuels, and they can purchase credits to meet these targets (Russell et al., 2017). The monetary value of the LCFS credits generated by RNG from various feedstocks is shown in Figure 5. RNG produced from dairy manure has the highest credit value, but if it were mixed with a food waste feedstock, the credit value is reduced.

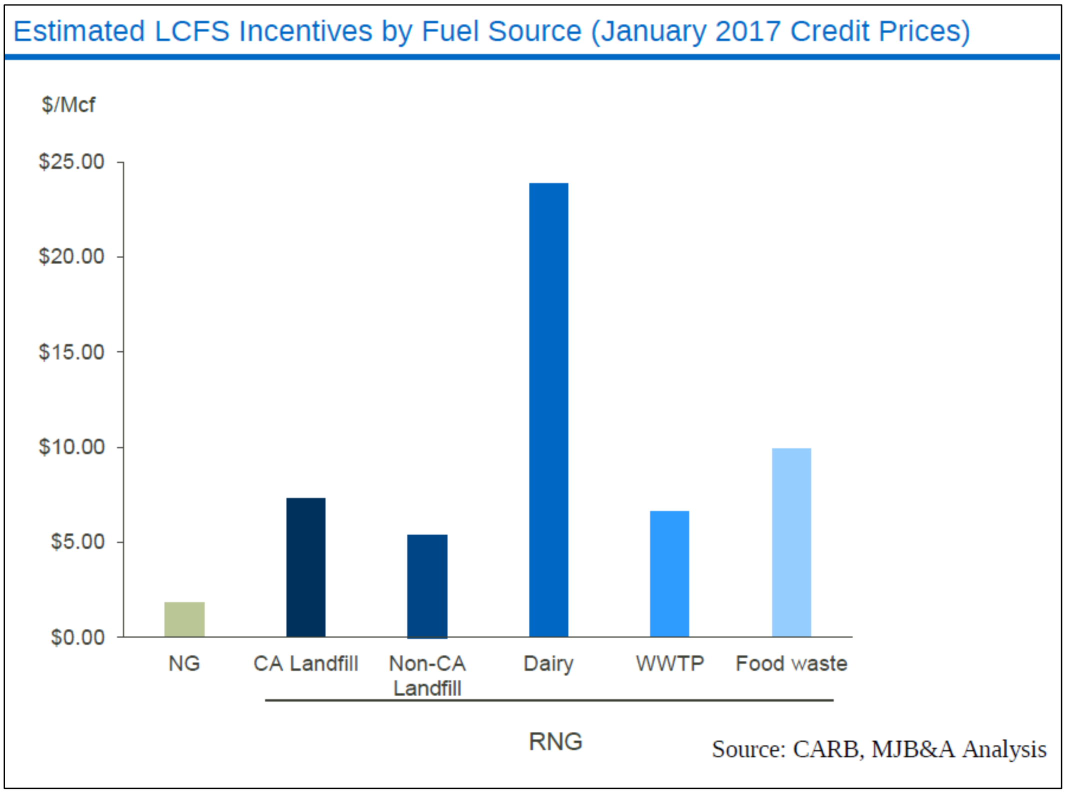

Figure 5 – Monetary value of LCFS credits generated from various fuels (Russell et al., 2017).

RNG for vehicle fuel has built a market in the U.S. largely from the incentives created by the RFS and LCFS policies, with their associated credits. Similarly, when CRS created the *Green-e* standard for renewable energy certificates (RECs) in 1997, this new certification helped launch the voluntary green power market (US EPA, n.d.-b). RECs enable consumers to purchase renewable energy attributes, and drive demand for more renewable electricity, while ensuring that each megawatt-hour (MWh) of renewable power is not double counted (T. Jones, 2016). While RECs have standardized a high-quality attribute for renewable electricity that can be purchased on a voluntary market, for low-carbon fuels for thermal applications, like RNG, there is no standardized environmental attribute to drive a market. Each MMBtu of methane fuel produced from an RNG facility has an associated environmental attribute, an intangible benefit that can be sold separately from the physical methane commodity. The company, institution, or person that purchases the environmental attribute gets to claim the GHG emissions reductions (Summit Natural Gas of Maine, n.d.). In Figure 6, even though the house is purchasing a mixture of fuel (natural gas and identical RNG) from the pipeline, they did not purchase the environmental attribute and cannot claim the GHG emissions reductions.

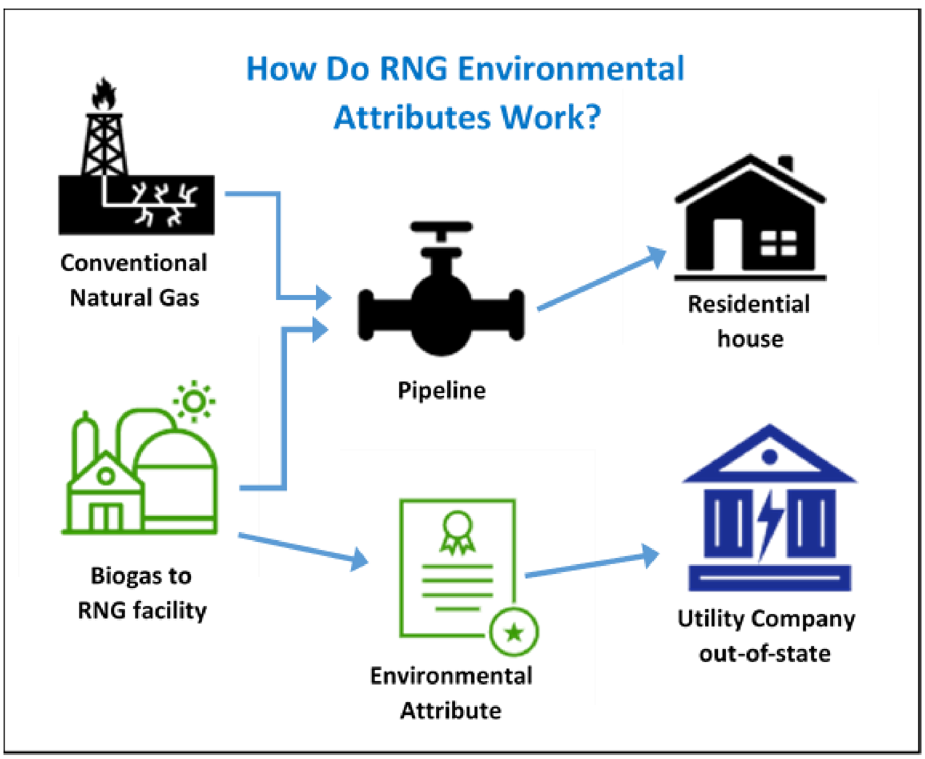

Figure 6 – How do RNG environmental attributes work? (Created by author)

The RNG market for use in thermal heating is still in its infancy in North America, therefore there is no verification in many RNG supply contracts and there are no standards or rules to give voluntary purchasers assurance that these are environmental beneficial purchases. RNG fuel producers are not able to produce a guaranteed attribute when selling for thermal end-uses, only for vehicle fuel end-uses. CRS is currently creating a Renewable Fuels Standard for Canada and the U.S. to address mainly RNG, for non-electricity use, with the goal of publishing in late 2020 (Center for Resource Solutions, 2019). Once *Green-e*'s consumer protection and product disclosure rules, as well as environmental criteria, are put into place, there will be more trust in the market, and more investor confidence (Green-e, n.d.).

Today, there is no central marketplace for RNG suppliers and buyers to trade RNG supply contracts. RNG buyers, such as a utility company, transact with individual producers/projects or work through RNG brokers, to acquire RNG supply or the environmental attributes associated with RNG in bilateral transactions (Kane & Murray, 2019). As of April 2020, there are around 15 operational landfill and AD projects in Canada and the U.S. that are exporting RNG to the gas grid for thermal use, with 15 other projects under development (The Coalition For Renewable Natural Gas, 2020).

The most abundant source of biogas in the U.S. is from landfills, with 578 operational projects as of December 2019, 56 upgrading to RNG. 47 of the RNG projects are used as vehicle fuel, while the remaining 9 projects have an end-use that is not vehicle fuel (presumably for thermal heating). The EPA has identified an additional 478 candidate landfills for biogas collection (US EPA, n.d.-c).

The second source of biogas in the U.S. is from manure. There are 286 operational and under construction manure digesters in the U.S. as of October 2019, and just 15 of those projects listed pipeline injection as the end-use (US EPA, n.d.-d). EPA's AgSTAR program estimates just over 2,000 swine and dairy farms as candidates for biogas AD systems. These candidate farms are large, defined by the EPA as dairy farms with over 500 head of cattle and hog farms with over 2,000 swine. These numbers were determined based on AgSTAR's evaluations of successful AD systems, from their technical and economic performance. If all these farms pursued biogas and converted it all to RNG, there would be enough energy to heat over 2.7 million homes per year. The top ten states for candidate dairy and swine farms only include one state in the Northeast. New York State is rated number nine in terms of dairy farm candidates. The states at the top of the list have much more biogas potential than most states in America. For example, California alone has the potential to generate 32.6 billion cubic feet (BCF) of methane per year from its dairy farms, while the rest of the 49 states combined have the potential capacity for 75.9 BCF (US EPA, 2018).

The third source of biogas in the U.S. is WWTPs. There are an estimated 1,268 WWTPs using AD to produce biogas, out of 16,000 WWTPs in the U.S. Many WWTPs have excess capacity to add source-separated organics as a feedstock, which will increase biogas production (Russell et al., 2017).

Food waste is typically co-digested at WWTPs or farm digesters listed above. However, there are also stand-alone food waste digesters, some collecting food waste from many sources, and others as industry-dedicated digesters for a single business, such as a grocery store chain. There were 50 stand-alone food waste digesters in operation in the U.S. as of 2018, 16 on-farm digesters co-digesting food waste, and 72 WWTP digesters co-digesting food waste (Pennington, 2019).

Lifecycle GHG emissions of RNG

RNG is a low-carbon alternative to conventional natural gas because its production and use prevents release to the atmosphere of methane emissions from business-as-usual landfill, manure, food, and other wet waste management (Hamberg et al., 2012). Landfills, farms, and WWTP contributed 30% of all methane emissions in the U.S. in 2015, which makes up 3% of total GHG emissions. Greenhouse gases (GHG) include CO_2, methane, nitrous oxide (N_2O), as well as fluorinated gases, found in refrigerants. GHG benefits between the RNG and conventional natural gas pathway only differ in the upstream and downstream emissions, where RNG captures methane from feedstocks that would have been emitted into the atmosphere (upstream). RNG from WWTPs and farms may avoid additional emissions if byproducts of biogas are used in lieu of synthetic fertilizers. The direct emissions from combusting RNG and natural gas are the same (Gasper & Searchinger, 2018).

In order to calculate GHG emissions reductions from RNG, it is necessary to calculate GHG emissions from a reference case scenario as well as the RNG scenario. If the lifecycle RNG pathway has fewer emissions than the lifecycle reference case, RNG reduces GHG emissions. It is important to consider methane leaks in both the reference case and the RNG scenario. Each RNG project has different lifecycle GHG emissions and should be evaluated on a case-by-case basis (Gasper & Searchinger, 2018).

Ebner et al. performed a lifecycle analysis using data from a farm digester in New York State, utilizing co-digestion of dairy manure and industrial food waste. Conventional manure management includes factors such as volatile solids content, biomethane potential of manure, nitrous oxide emissions from nitrification and denitrification, biodegradation emissions, fertilizer displacement emissions, long-term carbon sequestration factors, and direct nitrous oxide emissions. For reference case food waste disposal, there are many variables associated depending on where the food would have gone: landfill, incinerator, or compost. In the co-digestion case, the food waste would no longer emit GHGs from its disposal process and the manure would no longer emit GHGs from storage and land application. In addition, the digestate (fertilizer) byproduct displaces inorganic fertilizer and sequesters carbon when land applied. All these factors lead to co-digestion having reduced GHG emissions when compared to conventional management of these feedstocks. One ton of food waste and manure had lifecycle emissions of 52.8 kgCO_2e (CO_2 equivalent emissions) in the reference case and -2.2 kgCO_2e in the co-digestion case (2015).

There are many variables to consider when building a model to measure the lifecycle GHG emissions from biogas production. Feedstock type, single feedstock or co-digestion, size of biogas plant (kW electricity load), biogas utilization pathway, and digestate processing and handling. There is also transport to consider between feedstock supply and biogas production and during digestate spreading (Poeschl, Ward, & Owende, 2010, 2012).

Few studies conducted in the US examine the lifecycle GHG emissions of AD and biogas production upgrading to RNG. European analyses of RNG for injection in the natural gas grid use dry feedstock and thus result in higher per unit carbon emissions than would be expected using wet wastes (Adelt, Wolf, & Vogel, 2011).

The lifecycle environmental impact of taking biogas from grass/corn silage and manure co-digestion, upgrading it to RNG, and injecting it into the gas grid for heating, was analyzed by a study in 2019. The biogas was upgraded using membrane separation technology and used electricity for the upgrading from a CHP plant powered by biogas. The production and utilization of 1 MWh equivalent of biomethane generated 259 $kgCO_2e$, whereas the natural gas pathway emissions were 450 $kgCO_2e$ (Natividad Pérez-Camacho, Curry, & Cromie, 2019). Similarly, biomethane injected into the pipeline had a lower lifecycle GHG footprint than natural gas in a separate lifecycle analysis (Morero, Groppelli, & Campanella, 2015).

When making a decision for the future on energy infrastructure, or other large planning projects, it is important to use lifecycle rather than tailpipe emission factors, where the whole picture cannot be captured (Mohareb, Maclean,

& Kennedy, 2011). However, many estimations today analyze the future GHG reduction potential from RNG with a combustion GHG accounting framework. ICF conducted a large research study on the future potential for RNG in the U.S. for the American Gas Foundation, published in December 2019. They analyzed RNG from AD, as well as from thermal gasification and P2G technologies. They chose to use the combustion GHG accounting framework, consistent with Intergovernmental Panel on Climate Change (IPCC) guidelines, developed in 2006. These guidelines state that any CO_2 emissions from combusting biogenic fuel sources, such as biogas from food, manure, and WWTP fuels, should not be included in the inventory. Therefore, RNG from these sources is assumed to have zero emissions when combusted. It's also common in other approaches to exclude biogenic CO_2 emissions from combustion because it is assumed that the equivalent amount of CO_2 is sequestered by that biomass source during its lifetime.

A lifecycle approach instead calculates all CO_2, CH_4, and N_2O emissions avoided or emitted at all phases of the lifecycle, from collection and processing, pipeline transmission, and combustion. A comparison of the lifecycle vs. the combustion approach is in Figure 7. Additionally, ICF calculated the potential GHG reductions from RNG with a lifecycle approach in their appendix (ICF, 2019). For New England, RNG from animal manure and food waste has larger estimated emissions reductions for the high resource scenario in the lifecycle approach than in the combustion accounting approach. See Figure 8 and Figure 9.

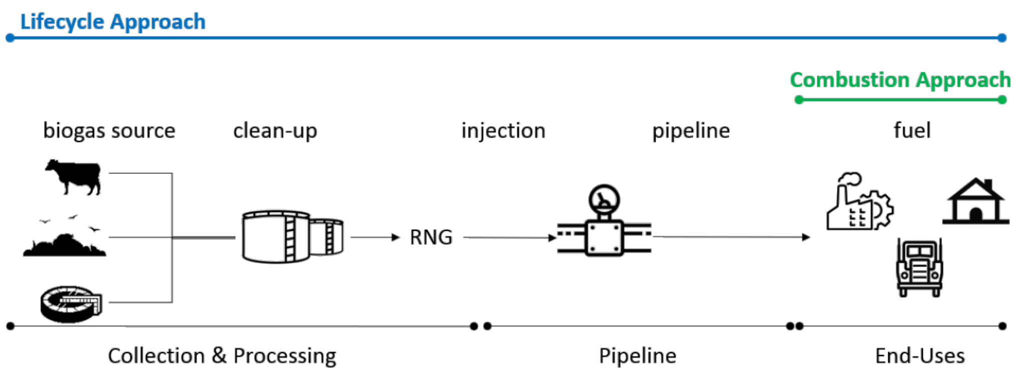

Figure 7 – RNG GHG accounting: lifecycle vs. combustion approach (ICF, 2019)

Feedstock	High RNG Resource Case | GHG Emission Reduction Potential, MMT									
	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	1.2	5.0	9.2	2.5	7.7	3.1	5.6	3.3	8.2	45.9
Animal Manure	0.8	1.3	3.2	4.7	3.4	2.0	3.8	3.1	2.2	24.5
WRRF	0.1	0.3	0.4	0.1	0.3	0.1	0.2	0.1	0.3	1.8
Food Waste	0.2	0.5	0.5	0.2	0.7	0.2	0.4	0.2	0.5	3.4
Ag Residue	0.0	0.5	7.6	19.2	1.4	0.4	1.5	1.4	2.0	34.0
Forestry and Forest Residue	0.4	0.5	1.0	0.7	4.0	2.2	2.0	1.0	0.7	12.5
Energy Crops	0.0	0.5	3.4	13.8	4.1	4.9	17.5	0.2	0.0	44.4
Sub-Total	***2.7***	***8.6***	***25.3***	***41.2***	***21.5***	***12.9***	***31.1***	***9.3***	***14.0***	***166.6***
Renewable gas from MSW										
MSW	1.2	3.5	3.9	1.8	5.2	1.6	3.2	1.9	4.1	26.4
RNG from P2G / Methanation										
P2G / Methanation										42.3
Totals	**3.9**	**12.1**	**29.3**	**42.9**	**26.7**	**14.5**	**34.2**	**11.2**	**18.1**	**235.3**

Figure 8 – Potential GHG emissions reductions for the U.S. using combustion accounting (ICF, 2019)

Feedstock	High RNG Resource Case | GHG Emission Reduction Potential, MMT									
	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	0.8 - 0.9	3.8 - 4.3	5.1 - 6	1.5 - 1.7	5.3 - 5.8	2.2 - 2.3	3.4 - 3.9	1.9 - 2.6	5 - 7.4	28.9 - 35
Animal Manure	3.2 - 3.3	6.4 - 6.6	14.5 - 14.8	12.1 - 12.2	5.9 - 5.9	1.8 - 1.8	5.3 - 5.3	9.8 - 10.2	10.8 - 11.4	69.7 - 71.5
WRRF	0.1 - 0.1	0.3 - 0.3	0.2 - 0.2	0.1 - 0.1	0.2 - 0.2	0.1 - 0.1	0.1 - 0.1	0.1 - 0.1	0.2 - 0.3	1.2 - 1.4
Food Waste	0.3 - 0.3	0.7 - 0.8	0.7 - 0.8	0.2 - 0.3	0.8 - 0.9	0.1 - 0.1	0.2 - 0.2	0.1 - 0.1	0.8 - 0.9	4 - 4.4
Ag Residue	0 - 0	0.1 - 0.4	1.4 - 5.5	3.6 - 13.9	0.3 - 1	0.1 - 0.3	0.3 - 1.1	0.3 - 1.1	0.4 - 1.4	6.4 - 24.7
Forestry and Forest Residue	0.1 - 0.3	0.1 - 0.4	0.2 - 0.7	0.1 - 0.5	0.7 - 2.9	0.4 - 1.6	0.4 - 1.4	0.2 - 0.7	0.1 - 0.5	2.3 - 9.1
Energy Crops	0 - 0	0.1 - 0.4	0.6 - 2.5	2.6 - 10	0.8 - 3	0.9 - 3.5	3.3 - 12.7	0 - 0.2	0 - 0	8.3 - 32.3
Sub-Total	*4.4 - 4.9*	*11.5 - 13.1*	*22.7 - 30.5*	*20.1 - 38.6*	*14 - 19.8*	*5.5 - 9.7*	*12.8 - 24.8*	*12.4 - 14.9*	*17.3 - 21.9*	*120.8-178.2*
Renewable gas from MSW										
MSW	0.3 - 1.2	0.9 - 3.5	1 - 4	0.5 - 1.8	1.4 - 5.2	0.4 - 1.7	0.8 - 3.2	0.5 - 1.9	1.1 - 4.2	6.9 - 26.8
RNG from P2G / Methanation										
P2G / Methanation										42.3
Totals	4.7 - 6.2	12.4 - 16.6	23.7 - 34.5	20.6 - 40.4	15.4 - 25	6 - 11.3	13.7 - 28	12.9 - 16.9	18.3 - 26.1	170.0-247.3

Figure 9 – Potential GHG emissions reductions for the U.S. using lifecycle accounting (ICF, 2019)

RNG Benefits and Criticisms

RNG Benefits

Biogas/RNG has many benefits, other than being a renewable fuel that reduces business-as-usual methane emissions from manure management, WWTPs, food waste, and landfills. Biogas production through AD on dairy (or swine) farms assists the farms with manure management and gives them added revenue streams, either through selling environmental attributes, receiving tipping fees from food waste producing entities, selling animal bedding, and selling digestate as a fertilizer. Farms producing biogas on-site also get to use the digestate byproduct as a soil additive, improving their soil health and plant growth and reducing the need for chemical fertilizers. AD has other environmental benefits, such as reducing pathogens in manures and food waste and reducing odors from manure management. Dairy farms with an anaerobic digester also benefit from positive public image with reduced odors and improved water quality (US EPA, 2018).

AD is a positive end-use for food waste from food manufacturing and distribution companies, commercial facilities, or even residential houses in cities. Traditionally, food waste is sent to landfills, where it produces methane emissions. Food waste sent to an anaerobic digester or a compost farm avoids these methane emissions, and AD has a smaller physical footprint than composting (USDA, EPA, DOE, 2014).

AD at WWTPs reduces sludge volumes. WWTPs must pay for disposal of their sludge at landfills, incinerators, through direct land application, or for processing to produce fertilizer products, so by reducing it they save money on tipping fees. This also means reduced trucking of sludge, which is beneficial for the surrounding communities (Wong, 2011).

RNG may have higher benefits than biogas for a few reasons. It is often more energy efficient to use RNG in the natural gas grid than in smaller, on-site combustion equipment (Poeschl et al., 2010). Additionally, there is already a lot of expensive gas transmission infrastructure in the U.S. (pipelines) that will become stranded assets if natural gas no longer flows through them. Meanwhile, states and utility companies are currently spending money to upgrade and patch leaking pipelines. RNG fills a gap for certain energy end-uses that have limited low-carbon alternatives, such as high-heat industrial processes that cannot rely on electrification (Von Wald et al., 2019). RNG is also a reliable fuel during all seasons and times of day, and could be used to assist natural gas utilities in times of high need, such as during extremely cold weather patterns (Clark & Montgomery, 2020). When there are cold snaps in the winter, there is a higher demand for natural gas for heating, which reduces the natural gas available for the electric sector. This results in liquefied natural gas (LNG) and oil reserves being used to meet this demand, which spikes the GHG emissions and increases costs for customers (Massachusetts Department of Energy Resources, 2018). Instead, RNG storage could be used to meet this increased demand. Consolidated Edison, one of the largest utility companies in the U.S., is constructing three RNG facilities to supply 7,100 dekatherms of fuel during times of peak demand, in addition to funding other solutions: energy efficiency, electrification of space heating, and increased natural gas storage (Consolidated Edison, 2019).

RNG Criticisms

RNG from waste feedstocks has lower upstream emissions than natural gas because it captures methane from feedstocks that would otherwise have emitted methane into the atmosphere. It's important to create RNG from feedstocks that are currently emitting methane, rather than taking a feedstock that is emitting CO_2 (such as a landfill flaring gas) and turning that into RNG. This is because methane emissions are 28 times worse for global warming than CO_2, over a 100-year time horizon (Myhre et al., 2013). Taking a landfill flaring CO_2 and instead creating methane could end up leaking methane into the atmosphere if there are leaks in the system, which would not improve the business-as-usual case. Additionally, creating RNG from an energy crop, rather than a waste feedstock, introduces negatives such as land-use change, which could result in less ecosystem carbon storage. Crops as feedstocks also compete with food production (Gasper & Searchinger, 2018).

RNG production needs to have the same or fewer methane leaks as natural gas production in order to reduce lifecycle GHG emissions. During the RNG production process, there could be anywhere from 2-10% of methane leakage (as a percentage of the total fuel produced), from leaks in the seals of the digesters or venting and offgassing when upgrading to RNG. During transmission and distribution (T&D) , RNG could have another 0.4 – 0.9% leakage, but this would be using the same infrastructure and methane leakage rates experienced in the T&D of conventional natural gas (Gasper & Searchinger, 2018).

One criticism of RNG is that it reduces GHG emissions by using methane from operations that are not environmentally friendly and should cease to exist. Landfill gas is a major source of RNG, but as many municipalities, states, and institutions work to reduce their waste, and corporations move towards providing more recyclable and compostable packaging, landfill volumes across the nation will be reduced and landfills will close. Landfill gas production declines over time after a landfill closes, although waste decomposition in a landfill continues to produce high concentrations of methane for 20-25 years (ICF, 2019). Additionally, factory farms with thousands of head of cattle are the most economic for producing RNG, and Lauer, Hansen, Lamers, & Thrän (2018) found that there would need to be at least 3,000 head of cattle to make it economically viable to produce RNG on a dairy farm. A dairy farm of this size has a large negative environmental footprint, however, dairy farms in MA are much smaller (Ucciani, 2020).

A second criticism of RNG is that there is not a large enough supply in the U.S. compared to our demand for natural gas. Figure 10 shows the California and U.S. RNG potential from waste feedstocks. California's RNG potential is equal to 3% of its total natural gas use. Roughly a third of its natural gas use comes from electricity (Union of Concerned Scientists, 2017). A study commissioned by the American Gas Foundation and conducted by ICF found that the U.S. could supply between 10 – 24% of its natural gas consumption (excluding electricity) from

RNG, both from waste feedstocks and thermal gasification, by 2040. See Figure 4 (ICF, 2019).

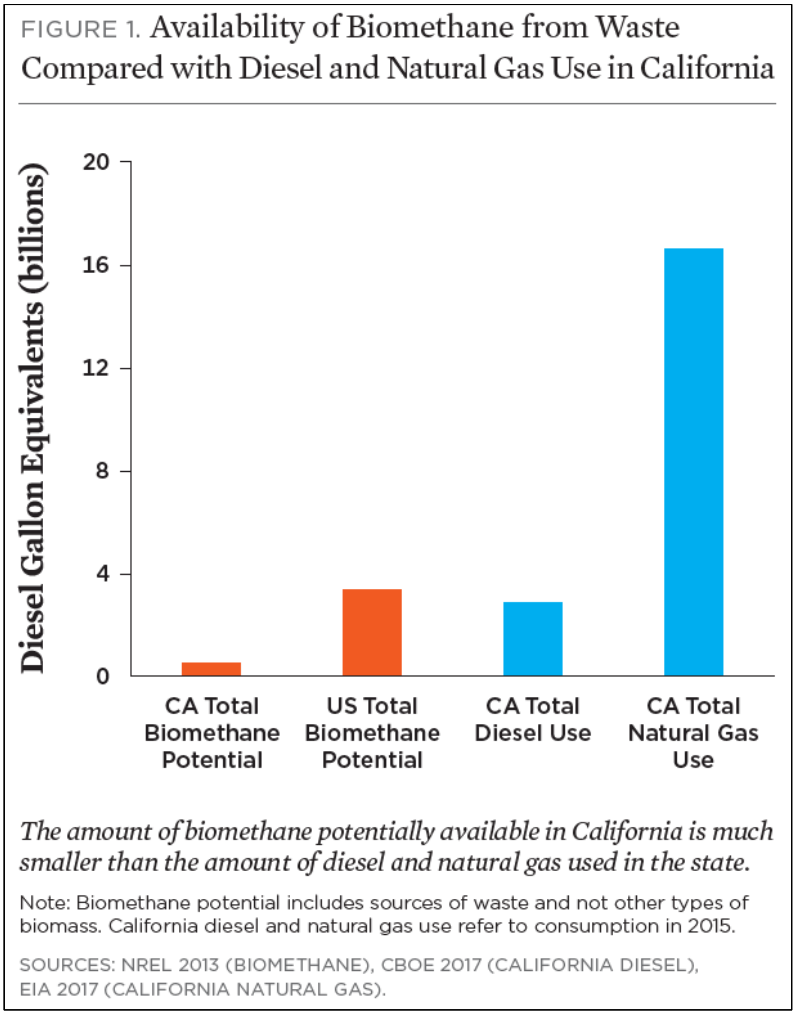

Figure 10 – Availability of biomethane in California (Union of Concerned Scientists, 2017)

Ultimately, RNG's direct competition is electrification, of both buildings and of vehicles. Analysts have not arrived at an overall consensus on whether using RNG in existing gas infrastructure is more or less costly than electrification (ICF, 2019; B. Jones, 2020; Roberts, 2020). Additionally, RNG still requires the combustion of a fuel, resulting in particulate matter emissions and other products of incomplete combustion, which have negative effects on human health. Meanwhile, renewable electricity provides energy without combustion. While renewable electricity can theoretically create zero-carbon energy for most of our energy needs, some RNG is carbon negative (manure and food waste), while other RNG is low-carbon (landfills and WWTP). Thus, RNG can help reduce the carbon intensity of natural gas when used in the pipeline at the present time, when pipelines are still flowing with methane, while we transition to lower-carbon energy supplies. “Make no mistake, the natural gas industry opposes electrification because it wants to expand pipeline infrastructure,” David Roberts wrote in a February, 2020 article in Vox entitled “The False Promise of ‘Renewable Natural Gas’” (Roberts, 2020).

RNG Barriers and Opportunities

RNG Barriers

High Capital Costs

There are many costs associated with the installation, operation, and maintenance of digesters as well as the conditioning equipment to upgrade to RNG. Injecting RNG into the natural gas pipeline could be a large capital investment, especially for small facilities, or ones that are not located close to a pipeline (Von Wald et al., 2019; Wong, 2011). For small dairy farms, it is best to aggregate waste with other farms to achieve economies of scale. RNG from landfill sites comes at a lower production cost since AD is a natural landfill process and does not require the construction of a digester. At the same time, it is difficult to compete with the low cost of natural gas, due to fossil fuel subsidies and the absence of a federal carbon price. Estimates for RNG costs range from $3-30/MMBtu, depending on the sources of the RNG. Conventional natural gas's average price has been $3.50/MMBtu since 2010, and is projected to stay below $5/MMBtu through 2030, assuming no policy changes (Gasper & Searchinger, 2018; Hamberg et al., 2012).

The total cost of upgrading to RNG and monitoring gas quality as well as pipeline interconnection for biogas producers and are $1.5 – 3.5 million per site in California, but interconnection cost estimates for other states are between $75,000 and $500,000 per site (Russell et al., 2017). If the biogas/RNG plant is not located next to an existing pipeline, cost estimates are $1 million to build each mile of pipe. The extension has to be designed to handle the flow, so a remote RNG plant may have to build a pipe to go to a larger distribution node regulator pit or take station (O'Rourke, 2020).

Biogas Policies

Current policies, standards, and incentives are focused on using biogas for on-site electrical power generation or as a vehicle fuel rather than upgrading it to RNG. These are policies such as the Federal Renewable Energy Production Tax Credit and the Federal RFS.

Until a standard is in place and buyers and sellers of RNG can accurately verify and transfer the environmental attributes, there is a risk of double-counting emissions reductions from these projects. There is also a risk of double counting when projects shift between the voluntary and compliance sectors (Center for

Resource Solutions, 2019). For example, an RNG project could be in a state where there are no mandatory policies for renewable fuels, as most states in the U.S. currently are, able to sell environmental attributes on the voluntary market. However, if that state, or if the country, introduces mandatory minimum requirements for RNG inclusion in thermal energy supply, this project could be switched to the compliance sector and can no longer sell the attributes on the voluntary market.

There is a lack of awareness of the benefits from biogas by the public, investors, and policy makers (Wong, 2011). Additionally, there is a lack of market maturity for valuing GHG emission reductions and for the non-energy byproducts, like digestate fertilizer (USDA, EPA, DOE, 2014). If there were a U.S. climate stabilization policy to provide financial credits for methane mitigation and increasing the price of fossil fuels, biogas (and RNG) would become more competitive (Zaks et al., 2011).

Opportunities in Policy

With RNG for pipeline injection, cost is the biggest barrier. However, with the immediate need for climate change solutions that can reduce GHG emissions in energy use, there is a desire for this type of technology to flourish from policymakers and their constituents (natural gas customers). Because of this desire for climate mitigation, there are numerous potential policy solutions, many of which are being employed in limited cases.

In one study, researchers in Germany created a dynamic market model to determine how different policies and regulations would affect RNG production. They found that if the government financial incentives for RNG went away in 20 years, most of the RNG used in Germany could no longer be produced economically (Horschig, Adams, Gawel, & Thrän, 2018). In 2013, Italy created a feed-in tariff to support RNG injection, with different incentive levels depending on how much manure was used in the biomethane, incentivizing a higher manure percentage (resulting in more negative GHG emissions) (Patrizio & Chinese, 2016). These feed-in tariffs in Italy are financed by consumers through their utility bills (Renewable Energy World, 2012). Once California created gas quality standards and calculated the costs associated with cleaning, upgrading, and injecting RNG into the pipeline in 2015, the Public Utility Commission (PUC) created an incentive program with $40 million available annually for biogas producers. As with the CA LCFS, larger incentives are given to dairy farm projects than to other types of RNG, since these projects are carbon negative (Russell et al., 2017).

Previous studies show that RNG requires subsidies of $3.75 - $26.00/MMBTU to be economically viable. (Von Wald et al., 2019). State tax incentives for RNG developers and utility companies could be another route, since these incentives helped jump-start electric vehicle technology. Additionally, since the high cost of RNG upgrading comes from equipment and operation of the upgrading equipment, the PUC could approve tariffs where utilities pay for the up-front costs of the upgrading and interconnection facility, while project developers pay them back over time at a set rate of $/volume of RNG injected into the pipeline (M.J. Bradley & Associates, 2019b).

If there were a policy change and there were a federal or state-level price on carbon, a low-carbon RNG would become the inexpensive option, when compared with conventional natural gas (Mingle, 2019a).

Financial aspects aside, if a state has certain climate and GHG mitigation goals, one could assume there would be political will to support RNG. Legislation to support RNG could take several forms, including adding a thermal carve-out to an existing RPS. This allows thermal energy to qualify for RECs under the RPS, and electric utilities are obligated to purchase a set number of RECs each year. NH is currently the only state in the U.S. with a thermal carve out in their RPS (Clark & Montgomery, 2020). An Alternative Energy Portfolio Standard (APS), distinct from an RPS, is another mechanism that allows thermal energy to qualify for RECs, known as Alternative Energy Credits (AECs).

Another policy option is requiring a percentage quota of the state's natural gas supply to come from RNG, called a Renewable Natural Gas Standard. Examples of Renewable Natural Gas Standard are in Table 2. Nevada's State Senate passed a bill (SB 154) in May 2019 that directs the PUC to create regulations that will require utilities in state to start RNG projects, and asks that these companies have at least 1% of RNG in their gas supplies by 2025, 2% by 2030, and 3% by 2035 (M.J. Bradley & Associates, 2019b). California's State Senate passed a bill in September 2018 (SB 1440) that requires the PUC "to consider adopting specific biomethane procurement targets or goals for each gas corporation…[requiring] if the PUC adopts these targets or goals, to take certain actions in regards to the development of …and the procurement of the biomethane," (Hueso, 2018, chapter 739).

Table 2 – RNG legislation in various states (Cancela, 2019; Energy and Technology Committee, n.d.; Grayson, 2018; House Appropriations, 2019; Hueso, 2018; B. Jones, 2020; Senate Interim Committee on Environment and Natural Resources, 2019)

State	***Title***	***Status***	***Description***
California	AB-3187	Signed by Governor 9/20/18	Directs the PUC to consider whether to allow rate recovery for RNG projects to reduce GHG emissions.
California	SB-1440	Signed by Governor 9/23/18	Requires the PUC to consider adopting specific RNG procurement targets
Connecticut	HB-5350	Public Hearing 3/5/20	Allows the Commissioner of Energy to solicit proposals for the supply of RNG for injection into the pipeline. Requires the PUC to open dockets to evaluate if gas companies should accelerate pipeline repair schedules.
Nevada	SB-154	Signed by Governor 5/14/19 *Effective 10/19*	Requires the PUC to authorize public utilities engaging in RNG activities and to recover reasonable costs. Requires utilities to attempt to reach at least 3% RNG by 2035.
Oregon	SB-98	Signed by Governor 7/15/19 *Effective 9/19*	Requires the PUC to adopt an RNG program for both large and small natural gas utilities. Large utilities will be able to supply 5% RNG starting 2020, 10% by 2030 and increasing percentages over time.
Washington	HB-1257	Signed by Governor 5/7/19 *Effective 7/19*	Requires utilities to offer voluntary RNG programs with a tariff. Allows utilities to supply RNG to all retail customers as a portion of their gas supply, as long as it costs no more than 5% of natural gas.

Without these policies, a state's PUC requires that utility companies offer the lowest price energy product to their customers, to not put an added burden on the public. However, if the customers are demanding the RNG options and willing to pay extra for it, then the PUC may allow customers to pay for the renewable option on their bills. In 2011, the British Columbia Utilities Commission allowed the FortisBC utility company to offer a voluntary opt-in program for customers to pay a premium to add RNG to their gas supply (Russell et al., 2017). In addition, the commission allows the utility company to spread this increased gas cost to all non-participating customers, essentially making ratepayers assist with building a more sustainable natural gas system (rate recovery). Spreading this cost to customers outside of the voluntary program shows the impact of the state or province's climate goals on the PUC (M.J. Bradley & Associates, 2019a).

Clear gas quality and interconnection standards make it easier for project developers to model out their finances and project at the beginning (Russell et al., 2017). In fall 2019, the Northeast Gas Association and the Gas Technology Institute released the "Interconnect Guide for Renewable Natural Gas in New York State" for this exact purpose, and it was sponsored by utility companies, such as National Grid and Con Edison (Northeast Gas Association, 2019). Some regions of California have also started to regulate the quality of the RNG that can be injected into the pipeline, focusing on the Wobbe index and the siloxane concentration of the RNG, to ensure gas interchangeability (Von Wald et al., 2019).

States can start investigating the potential for RNG within state boundaries if they plan to use it as a strategy in their GHG mitigation goals. They can even assess RNG potential from woody biomass and P2G and weigh the benefits and costs with pursuing all RNG options. Oregon, Washington, and California have all recently passed state bills for this research (M.J. Bradley & Associates, 2019b).

Opportunities in the Private Sector

While state and federal policies offer the most potential to incentivize RNG, utility companies can also make bold commitments. However, they often still need final approval from the state's PUC. For example, in spring 2019 Southern California Gas Company (SoCalGas) committed to replacing 20% of their natural gas supply with RNG by 2030. They are still awaiting the regulatory authority to purchase 5% of their supply as RNG by 2022 and approval from the PUC for a voluntary program for customers to purchase RNG (Southern California Gas Company, 2019). Utility companies can also support demonstration projects, such as SoCalGas is currently doing with two P2G projects to pilot the technology (M.J. Bradley & Associates, 2019a).

Private companies and institutions have climate goals, just like cities and states. RNG environmental attributes are starting to be a viable option for these institutions in their pathway towards carbon neutrality. In 2018, L'Oréal USA underwent a 15-year Power Purchase Agreement (PPA) to purchase 40% of the RNG produced at a Kentucky landfill. L'Oréal will sell the attributes for five years as they have a high price, and will use the attributes for the remaining ten years, enabling them to be carbon neutral at that time (Stark, 2018).

Chapter 4: Massachusetts context

State of Biogas Production

There are currently six anaerobic digesters in MA at WWTPs, and one of them, the Greater Lawrence Sanitary District, co-digests with food waste from a nearby organics processor (see Figure 11) (Massachusetts Department of Environmental Protection, 2018). There are 133 WWTPs in MA and about three-quarters of them are small facilities with a flow rate below 5 million gallons per day (MGD) (Wong, 2011).

Wastewater Biogas Facilities in Massachusetts

Facility	Actual Flow	Use of biogas	Age	Savings
Boston/MWRA	360 MGD	Heat to maintain digester temperatures & generating electricity with steam turbine	~ 20 yrs	$15 mil in saved fuel costs from biogas and CHP (modifications are planned to save $500,000 more); $1 mil in revenue from FY 2008 from Renewable Energy Certificate sales[2]
Pittsfield	13 MGD (2008)	Heat to maintain digester temps.	Flare excess originally built in 1963; later rehab	
Rockland	2.5 MGD	Heat to maintain digester temps .Flare excess	~ 20 yrs	
Greater Lawrence Sanitary District	30 MGD	Heat to maintain digester temps. Flare excess	Tanks installed ~ 2002	Cost savings through sludge treatment/digestion $600,000 /year
Clinton	2-4 MGD	Heat to maintain digester temps. Flare excess	~ 20 yrs	
Fairhaven Water Pollution Control Facility	2.7 MGD	Heat recovery for digesting operation & electric power generation	New installation (2010-2011)	Anticipated energy cost & sludge disposal savings of approximately $300,000/year

Figure 11 – WWTPs in MA using anaerobic digestion (Massachusetts Department of Environmental Protection, 2018).

There are 12 landfills capturing the landfill gas, using it to run a reciprocating engine to create electricity. Additionally, there are four “candidate” landfills in the state. The EPA defines a “candidate” landfill as one that is actively accepting waste or has been closed for five years or less, has at least one million tons of waste, and does not currently have a landfill gas project in operation or planned. These landfills would be good choices to build a new landfill gas plant, presumably because they would be able to generate enough methane to make the project economically viable (US EPA, 2020). There are eight digesters on dairy farms that also accept food waste, for co-digestion. These digesters either use the biogas to directly create electricity for the grid, or they have co-generation, so they heat the buildings at the farm while also providing grid electricity (US EPA, n.d.-d). One digester just accepts food waste (Cook, 2020). A few other digesters in the state are privately owned and are used at food manufacturing or distribution sites, such as Ken's Foods and Stop & Shop's distribution warehouse in Freetown (Evoqua Water Technologies LLC, 2019; Skahill, 2017). There are no biogas plants in MA upgrading the gas to RNG as of spring 2020.

Relevant Policies in MA

Many of the renewable energy policies in place or being proposed in MA are related to renewable electricity rather than renewable fuels or reducing the carbon intensity of heating. These include policies like the Renewable Portfolio Standard and the Regional Greenhouse Gas Initiative (RGGI). RGGI is a regional program with ten Northeastern states that uses a cap-and-trade system to reduce GHG emissions from power plants. MA is able to sell its "allowances" in auctions and use the revenue to fund energy efficiency (Beaton, 2015).

Renewable Portfolio Standard

The MA RPS was originally created in 1997 and was expanded in the Green Communities Act of 2008 as well as modified in 2012 in the Competitively Priced Electricity Act of 2012. This policy requires retail electricity suppliers to supply a percentage of renewable electricity in their portfolio, increasing by one percent annually, with no end date. In 2020, 15% of the electricity supply must be from Class I renewable resources such as wind, solar, small hydro, and biogas from landfills or anaerobic digesters.

MA is one of eleven states and the District of Columbia that have included renewable thermal technologies in their RPS. This was added into the RPS in 2014 with "The Act Relative to Credit for Thermal Energy Generated with Renewable Fuels of 2014". In 2017, the MA Department of Energy Resources (DOER) filed Regulation 225 CMF 16.00 to add renewable thermal to the RPS. Renewable thermal falls under the Alternative Energy Portfolio Standard (APS), which is a separate tier of the RPS. Rather than issue RECs for renewable thermal, the APS issues alternative energy credits (AECs), where 1 MWh of electricity is earned for every 3,412,000 British thermal units (BTUs) of useful thermal energy produced, essentially converting renewable thermal energy into the familiar REC unit (Donalds, 2018). Biogas used for thermal energy with a dedicated pipeline qualifies for AECs under the APS, but RNG injected into the broader gas pipeline does not qualify. For example, the Turnkey landfill in Rochester, NH purifies and pipes its biogas via a 12-mile pipeline directly to the co-generation plant at the University of New Hampshire. If this project were in MA, it would qualify for AECs (Steltzer, 2020; University of New Hampshire Sustainability Institute, n.d.).

Eliminating gas leaks

A study commissioned by the MA Department of Public Utilities (DPU) estimated gas leaks from distribution infrastructure (pipelines) of 0.6 to 1.1%. In

2014, almost all of the utility companies in MA filed plans to replace their pipelines over a 20 to 25 year timeframe. *An Act Relative to Natural Gas Leaks*, which passed the MA State Legislature in 2014, requires the gas utilities in the state to submit Gas System Enhancement Plans (GSEPs) annually, to show their plans to replace aging pipelines over the coming year (Massachusetts Department of Public Utilities, 2018). To pay for these repairs, they can pass the costs onto the ratepayers. After research was published in 2016 showing that 7% of the most extreme pipe leaks in the state were responsible for 50% of the methane emissions, a law passed to require utilities to prioritize repairing the most extreme leaks ("General Law - Part I, Title XXII, Chapter 164, Section 144," n.d.). While replacing 25% of the state's aging pipelines would cost around $9 billion, it would cost $100,000 to triage the 7% of leaks that are most extreme (Egg, 2020; Phillips, 2020).

Leading by Example

The Leading by Example program works on GHG reductions at all Executive branch agencies within the state as well as 29 public institutions of higher education and several quasi-public institutions. The program provides grants for feasibility studies, such as for renewable energy (Beaton, 2015).

Commercial Food Material Disposal Ban

The Commercial Food Materials Disposal Ban took effect in October 2014 and bans disposal for food and other organic wastes for businesses and institutions that produce more than one ton of organic waste per week. There are resources to help these businesses find an alternative destination for their food waste, including contact information for all compost and AD facilities in the state (Massachusetts Department of Energy Resources, n.d.). As of spring 2020, the MassDEP is considering reducing the threshold of waste to include businesses that generate over half a ton of organic waste per week, which will increase food waste diversion. This disposal ban has increased the amount of food waste being diverted over time, as the state diverted 100,000 tons in 2008 and 280,000 in 2018 (Massachusetts Department of Environmental Protection, 2019). There is an estimated 1,000,618 tons per year of food waste generated from businesses that have over one ton of waste per week, and an additional 94,547 tons per year from businesses that generate between half to one ton of food waste each week (Fischer, 2020). Lack of enforcement is an impediment to getting all this food waste diverted to composters and anaerobic digesters. Since the law went into effect in 2014, the state has fined violators less than $20,000 (Donnelly & Haddadin, 2020). However, the MassDEP is focusing on increasing its outreach to businesses, as well as inspections and enforcement, and prefers to issue notices of noncompliance, which generally get a company to start complying before needing to issue a penalty (Fischer, 2019).

Financial and Technical Assistance for AD Projects

The state offers numerous grants and resources to help start AD projects, ranging from site assessment and feasibility studies to construction financing assistance and design assistance. The Massachusetts Clean Energy Center is one of the main resources in this area and has been supporting AD projects in the state since 2011 (Barad, 2020; Massachusetts Department of Environmental Protection, n.d.-b).

Next-Generation Climate Bill

On January 23, 2020, the MA State Senate released the "Senate Climate Package", made up of three bills with "An Act setting next-generation climate policy" (S.2477) being the main bill. The bill proposes economy-wide carbon pricing for the state and sets new near-term goals for GHG reduction for years 2025 and every five years after that until hitting net-zero by 2050. The bill also calls on the state's DPU to shift priorities when making energy decisions, moving away from the least-cost acquisition rule, above all other factors. The DPU would be forced to have a new mission statement that would "require the agency to balance five priorities: reliability of supply, affordability, public safety, physical and cyber security, and reductions in greenhouse gas emissions," (Cronin, 2020a). These bills were passed in the Senate on January 30, 2020 and go to the House, where the bills could be passed, or new bills could be created and both scenarios would bring the climate bills to a special conference committee to negotiate final language before being sent to the Governor (Cronin, 2020b).

FUTURE Bill

In order to help gas utilities transition to renewable thermal technologies, MA environmental advocates from Gas Leaks Allies have teamed up with state legislators to write "For a Utility Transition to Using Renewable Energy" legislation, or the FUTURE bill (H.2849/S.1940), currently active in the state house as of spring 2020. "The FUTURE bill would create a renewable thermal credit market for gas utilities, allows them to bill for BTUs, and gives them a path to evolve into renewable energy companies," (Egg, 2020). The bill's text does not specify all the renewable thermal technologies: "heat pumps, solar thermal, or other heating or cooling technologies using renewable sources of energy that do not emit greenhouse gases," (Ehrlich et al., 2019).

Relevant Utility Companies

There are seven privately owned gas utilities in MA and four municipal gas companies, shown in Figure 12. Two of the larger gas companies are National Grid and Eversource, covering a significant service area of the state. As of February 2020, Eversource is purchasing Columbia Gas, the company that has the next highest number of gas customers (MA Gas Division, n.d.; Young, 2020).

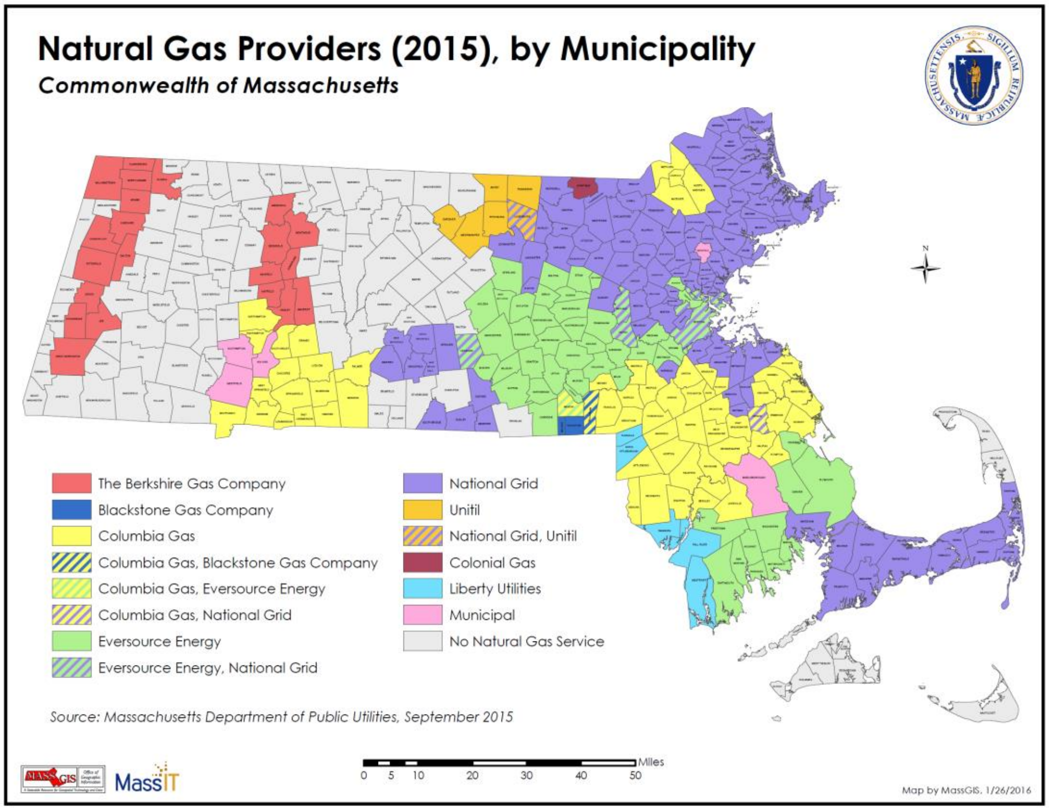

Figure 12 – Natural gas utilities in Massachusetts (MA Gas Division, n.d.)

Eversource gave testimony to the DPU in November 2019 as part of a petition for approval of an increase in base distribution rates and performance-based regulatory plan for gas service. In the docket, Eversource's President and Vice President describe a new position they are creating as Director of Clean Gas Technologies, someone who will advance their work in RNG, P2G, operational methane reduction, LNG strategy coordination, and gas efficiencies. They also propose a few geothermal pilot projects. Eversource describes that they are "seeking opportunities to add renewable natural gas to its resource portfolio", explain what RNG is, and how it is being used in local gas distribution systems in other states. They mentioned that although they are not pursuing RNG at the present time, they see it as something they want to procure in the future, but realize that it will come at a higher cost than natural gas. Eversource's President, William Akley, said:

> *As with other market transformation initiatives, RNG will need to be evaluated differently due to the fact that it creates substantial environmental benefit but will require a level of capital investment not typical for gas-supply contracts. This will mean that long-term contracts will be necessary to support the development of these types of resources similar to the experience with wind power and other renewable resources…. The Company anticipates that, ultimately, it may be possible to factor in proceeds from renewable gas attributes or other offsetting revenues that may lower the ultimate cost to customers. In any event, any contract that the Company may decide to enter into will require the Department's pre-approval with consideration of the environmental benefits that are attendant to the agreement* (Crane, 2019).

National Grid has not proposed an RNG project in MA but did propose one in the downstate New York region in April 2019. The filing with the New York State Public Service Commission is to update their delivery rates and includes a proposal for a "green gas tariff", essentially a voluntary opt-in program for customers to choose to pay a premium for RNG. Additionally, they proposed a P2G pilot project, a hydrogen blending study, a geothermal pilot, and a program to lower the cost of RNG interconnections to the gas network (National Grid, 2019).

Liberty Utilities is a small company operating in MA, but also featured in the case study presented in this report on NH. Since Liberty is already working on sourcing RNG in NH, they are interested in developing two RNG projects in MA soon. They are already working with two developers, and they hope to put both projects in one docket for the MA DPU in summer 2020 (Clark & Montgomery, 2020).

Barriers and Opportunities

There are several barriers to accessing organic feedstocks in MA. Dairy farms in the state are small, not producing a lot of manure. Small dairy farms are acceptable at the existing digesters in the state that create biogas for electricity production, but since upgrading to RNG increases a project's costs, these small farms would not make RNG production financially viable (Ucciani, 2020). Food waste feedstocks are going to digesters, but compost farms and animal farms are competing end-users for this feedstock. For WWTPs, most sewage treatment plants in the state are relatively small and would not have enough sludge to make a digester financially viable, even though AD would be a great solution to manage the sewage sludge. The North East Biosolids and Residuals Association (NEBRA) conducted a survey of all WWTPs in MA in 2019, concluding that three regional facilities should be built to consolidate sludge from small community facilities, making resource recovery more cost-efficient (2019). There is also concern about the presence of PFAS[4] in the fertilizer that can be produced from digested sewage sludge, so more research needs to be done to see whether and how PFAS in these fertilizers should be regulated to protect human health and

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[4] Per- and polyfluoroalkyl substances (PFAS) are man-made chemicals that have been used since the 1940s in many commercial products such as water-resistant fabrics, nonstick products (e.g. Teflon), cleaning products, and pesticides, and therefore they can be found in food, drinking water, and living organisms. PFAS are often detected in sewage sludge, the influent to WWTPs, but typical wastewater treatment processes cannot remove PFAs from the final effluent, biosolid fertilizer (Coggan et al., 2019; US EPA, n.d.-a).

the environment. Greater certainty about the suitability of the fertilizer for agronomic uses could help WWTPs evaluate the benefits of investing in AD infrastructure, in both MA and the rest of the country (Barad, 2020).

There are financial barriers to RNG as well. Vanguard Renewables, a manure digester developer currently operating five digesters in MA, is interested in starting RNG projects as they are developing one on the Goodrich Farm in VT. However, they would need financial assistance from utility companies for the costs of the upgrader to purify the biogas, and for the pipeline that often needs to be built from the farm to the main pipeline (Ucciani, 2020).

Another barrier is public opposition to natural gas in the state and the associated infrastructure. Several MA cities (Brookline, Cambridge, Northampton, Somerville) are trying to ban new natural gas installations in commercial and residential buildings (McKenna, 2019). It is public knowledge that the Commonwealth has disproportionate level of gas leaks, due to aged infrastructure. MA has one of the oldest natural gas pipeline systems in the country with unprotected steel, cast-iron and wrought-iron pipes that are often corroded and leak prone, and environmental groups have been trying to get the utility companies to repair the leaks for years (Green, 2020; Kashinsky, 2020; O'Rourke, 2020). Activist groups in the state have been protesting a compressor station from being constructed at an industrial site in Weymouth for years in order to stop new fossil fuel infrastructure. In addition to opposing GHG emissions from fossil fuel use, these groups are worried about safety and environmental justice from the criteria air contaminants (NOx, CO) emitted from a compressor station (Wasser, 2019). Public opposition against natural gas combustion increased again in September 2018 when a series of explosions and fires occurred in around 40 homes in the Merrimack Valley, due to high-pressure natural gas lines owned by Columbia Gas of Massachusetts (Egg, 2020).

In spring 2020, the DOER is undertaking a study to look at starting RNG for pipeline injection in MA. The DOER allows renewable electricity from NY, Quebec, or New England to qualify under the RPS, which indicates that similar geographic constraints on RNG would be consistent with this boundary (Steltzer, 2020). Table 3 summarizes the barriers and opportunities for MA found in the interviews.

Table 3 – Barriers and opportunities specific to MA

Category	***Barriers***	***Opportunities***
RNG Feedstocks	Low RNG feedstock supply in comparison to NG usage	• MA utilities and institutions could purchase RNG attributes from New England region or elsewhere
	Dairy farms are small (less than 500 cows)	• Cluster an RNG plant around multiple dairy farms • Dairy farms will not be primary focus of RNG production in MA, but current digesters on dairy farms could upgrade to RNG
	WWTPs are small	• AD is a good approach to manage sewage sludge • Cluster sludge at regional facilities
	Landfills are closed	• Landfills can still produce methane for ~20 years after closing
	State organics ban needs compliance, low supply of food waste	• DEP considering reducing threshold of Organics Ban from places with 1 ton of organics/wk to 0.5 ton • DEP increasing outreach and enforcement
Spatial	NIMBY-ism when siting a digester	• Many WWTP and landfills could have space since they are already permitted as waste sites
Policy	Biogas to electricity pathway qualifies	• Create a separate Renewable Natural Gas Standard

	under RPS, no thermal carve-out	• MA already has numerous biogas facilities that could add RNG upgraders.
	Biogas qualifies in APS, but not to be injected into the pipeline	• Amend APS to allow RNG pipeline injection to qualify
Cost	RNG upgraders increase capital costs	• Use existing MA renewable energy grants for RNG upgraders, Leading By Example, and Mass CEC grants • Use RGGI funds
Public Opposition	Gas pipeline leaks are prevalent in MA	• Repair extreme leaks simultaneously with RNG development
Motivation	RNG projects have not yet been initiated in the state	• Eversource and National Grid are interested • Liberty Utilities will try for project approval soon • Proposed state legislation telling DPU to take climate change into account • DOER currently studying RNG

Chapter 5: Quantitative Results

RNG Potential as a Percentage of Natural Gas Consumption

The total technical potential of RNG production in MA from all feedstocks (WWTPs, landfill gas, organic waste, and animal manure) was calculated as 5,100 MMcf/year. Figure 13 shows which feedstocks have the largest potential for RNG production in the state (WWTPs) and the very least (animal manure) (National Renewable Energy Laboratory, n.d.).

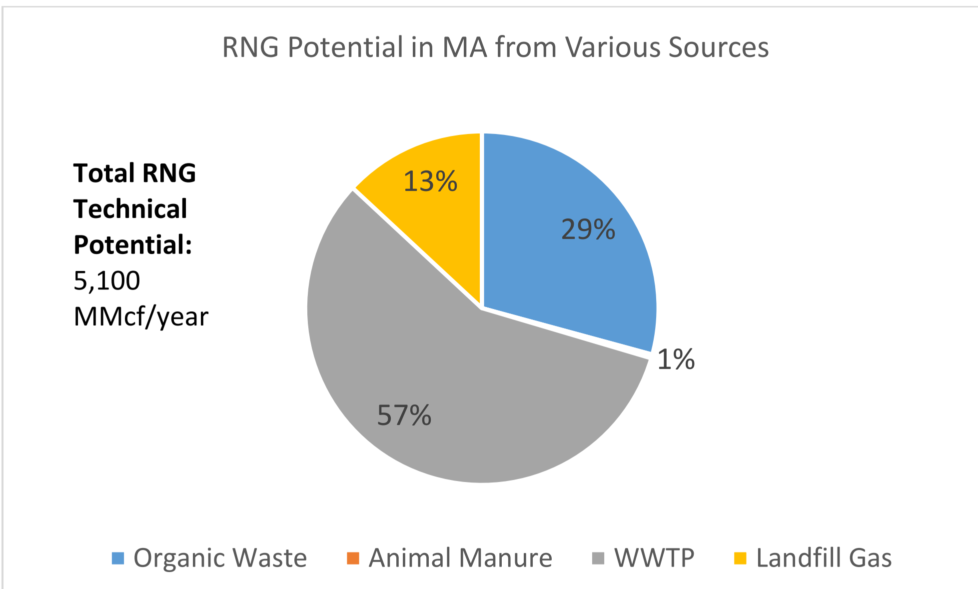

Figure 13 – Feedstock contribution to total RNG potential in MA (National Renewable Energy Laboratory, n.d.)

When comparing this technical potential to the total volume of natural gas consumed in MA in 2018 for the residential, commercial, and industrial sectors combined (296,599 MMcf), the RNG would displace 1.7% of that total. If just comparing the RNG technical potential to the industrial sector, it would be 10.7%, and would be 3.9% and 4.3% of the residential and commercial end uses, respectively. This data is shown in Figure 14. The natural gas consumption data from the EIA does not include natural gas used in the state for electricity or vehicle fuel (U.S. Energy Information Administration, 2020).

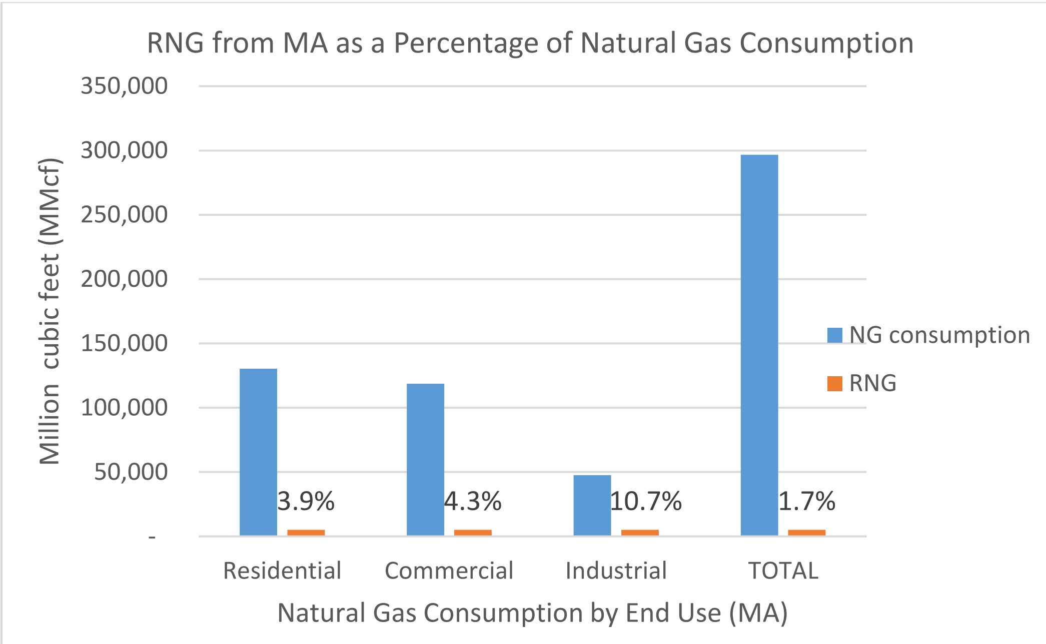

Figure 14 – RNG potential in MA in comparison to natural gas consumption (National Renewable Energy Laboratory, n.d.; U.S. Energy Information Administration, 2020)

GHG Mitigation Potential

Whereas the state's total lifecycle emissions from natural gas in the Reference Case are 25,407,080 $MTCO_2e$, they are 25,023,044 $MTCO_2e$ in the RNG Scenario. This means the potential for total emissions reduction is 384,036 $MTCO_2e$. This amount of GHG emissions reduction from RNG production in MA would be equivalent to taking 81,536 passenger vehicles off the roads each year (US EPA, 2019). See Figure 15 and Figure 16.

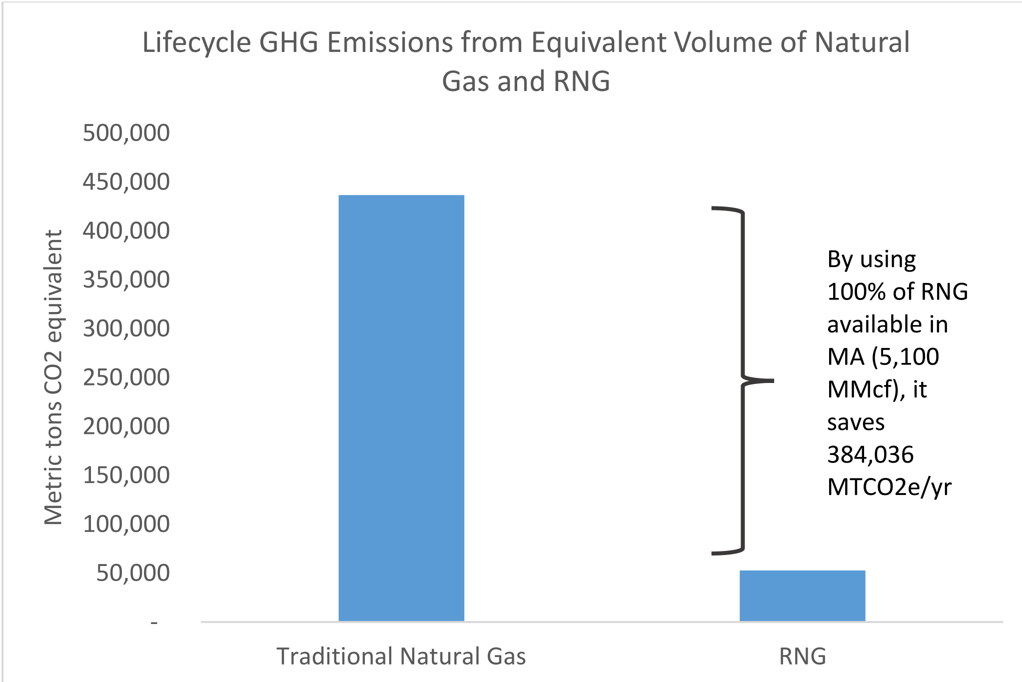

Figure 15 – Lifecycle GHG emissions from 5,100 MMcf of natural gas vs. RNG

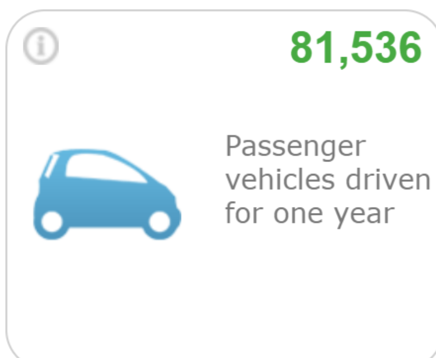

Figure 16 – GHG emissions reduction equivalent (US EPA, 2019)

The state's total GHG emissions from all sectors in 2017 was 73,300,000 $MTCO_2e$. These are not lifecycle emissions, but rather from fuel combustion as well as pipeline leaks (Massachusetts Department of Environmental Protection, 2020). For example, MA is just counting the emissions from natural gas transmission and distribution systems and does not count emissions from other stages in the lifecycle that occur out of state (e.g. production, venting and flaring) (Massachusetts Department of Environmental Protection, 2016). When comparing the absolute GHG emissions reduction from RNG production (RNG Scenario), there is a technical potential to decrease the state's gross GHG emissions by 0.5% at current levels of natural gas consumption (see Figure 17). Levels of natural gas consumption in future years could decrease due to improvements in energy efficiency, which would make this GHG emissions reduction a more significant percentage.

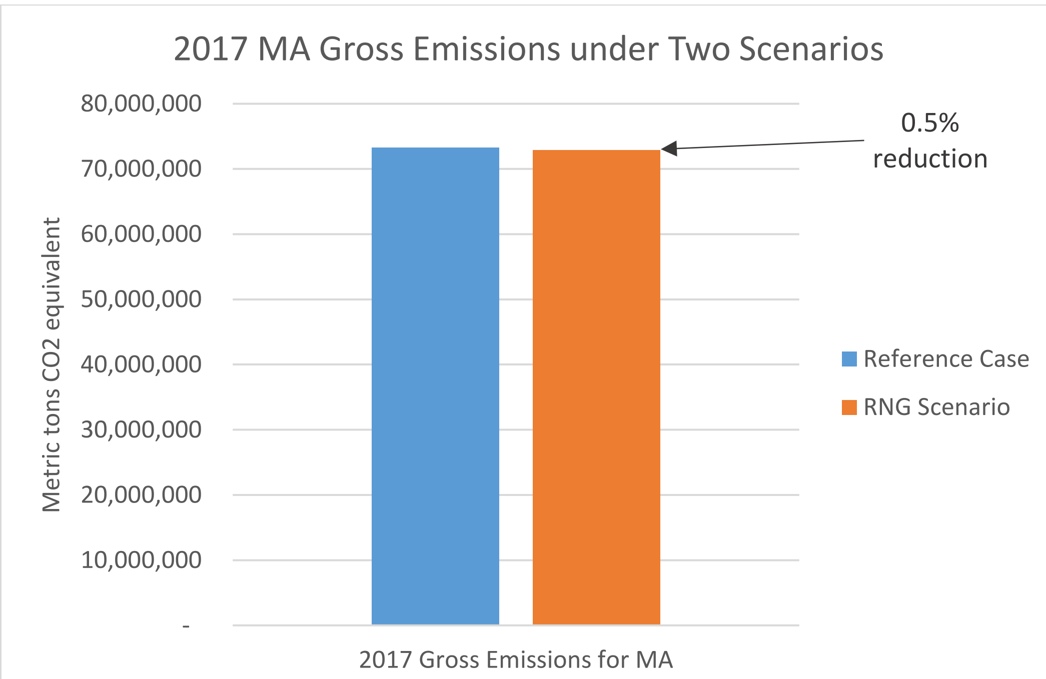

Figure 17 – 2017 MA gross emissions under two scenarios

Limitations

This analysis looked at the technical potential from RNG production in MA each year. Realized RNG production volumes in the state are likely to be lower due to inefficiencies in feedstock collection and economic constraints on RNG production. However, there is a possibility that the technical potential could increase if these feedstocks were co-digested, since co-digestion yields more biogas per unit-weight feedstock than single feedstock digestion.

The carbon intensities come from certified pathways under the CA LCFS, so the RNG carbon intensities are averages from production facilities are around the U.S. and the lifecycle emissions for traditional natural gas is from California. Also, the carbon intensities represent the emissions from combusting RNG in a vehicle. These carbon intensities were used to compare different fuels to each other (traditional natural gas to RNG) and see the difference in terms of absolute emissions. It would have been more accurate with certified carbon intensities for thermal use pathways, but this LCFS methodology was still reliable as it was an apples-to-apples comparison.

Chapter 6: Case Studies

Vermont Gas: A voluntary program and a dairy digester

Climate Goals

VT first developed GHG emissions reduction goals in 2005, calling for 50% reduction in emissions below 1990 levels by 2028 and 75% reduction by 2050. In 2015, they committed to reduce emissions 80-95% by 2050. The state updated their Comprehensive Energy Plan in 2015, focused on reducing energy consumption and increasing renewable energy to become 90% of the energy supply by 2050 (Vermont Official State Website, n.d.).

Voluntary Program and PUC approval

In 2015, Vermont Gas (VGS), the only gas utility in VT, saw RNG as an opportunity to de-carbonize their gas supply to work to mitigate their climate change impact. They originally filed a petition with the VT PUC in 2015, but re-vamped it in the following years, and by fall 2017, they received the final approval (Murray, 2020). Their voluntary program allows customers to choose how much of their gas supply will be replaced with RNG: 10%, 25%, 50%, or 100%. The customer is billed for the RNG price premium, which is calculated as the difference in price of conventional natural gas and RNG, adjusted quarterly. A customer can calculate their price premium on VGS's website. 880 Ccf was the average annual natural gas use for a VT residential customer in 2018, and 25% RNG would cost the average customer $23.71 a month (see Figure 18) (American Gas Association, 2019). VGS filed a formal tariff with the PUC with proposed rates for the RNG Adder in early 2018 (Kane & Murray, 2019). The customers who choose to participate in this voluntary program are mainly environmentally minded individuals and companies since they are choosing an extra payment (e.g. Seventh Generation and Vermont Coffee Company) (Murray, 2020).

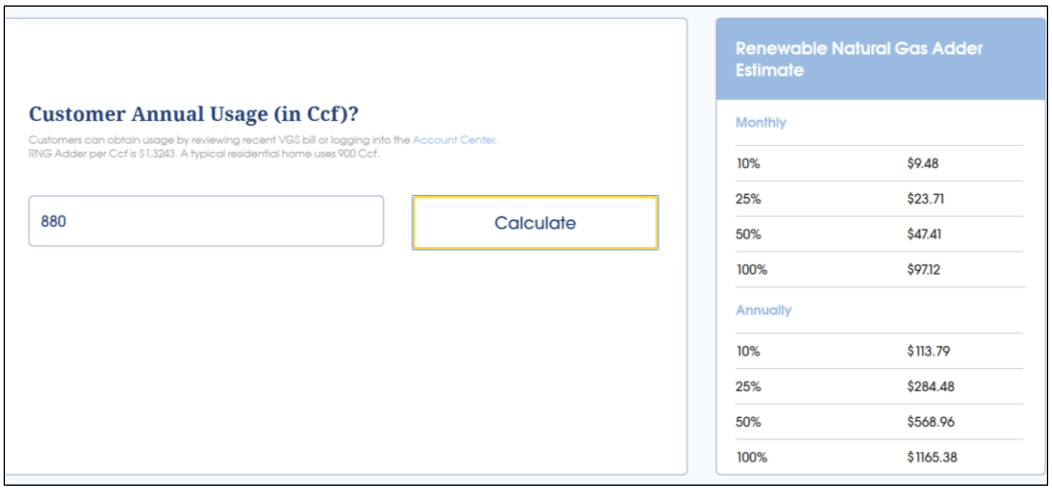

Figure 18 – RNG Adder Calculator on VGS's website (Vermont Gas, n.d.).

VGS accounts for the RNG attribute supply they are purchasing as well as what they are selling to customers. While they will be injecting RNG into their pipeline from one local RNG project, they cannot guarantee that the RNG molecules get to each customer who participates in the program. Customers are purchasing the environmental attributes, and with each purchase these attributes become "retired", to ensure no double counting of emissions reductions. The PUC order asked VGS to have a "*true-up* period of up to 12 months to balance the difference between RNG attributes sold to customers (demand) and RNG attributes purchased from VGS suppliers (supply)." In an oversupply scenario, VGS can try to sell the attributes to the RNG vehicle fuel market or receive permission from the PUC to add these RNG attributes to all customers' supplies, distributing the costs. In an undersupply scenario, VGS can purchase additional RNG attributes, or if there are none, may purchase carbon offsets instead. To verify these renewable attributes, VGS uses an independent third-party to confirm feedstocks, the production process, the fuel quality monitoring process, and the existence of a physical path (pipeline) for RNG transfer and distribution to customers (Kane & Murray, 2019).

Sourcing RNG Fuel and Attributes

The voluntary program started in 2018, and in the first year VGS purchased RNG from a facility in Ste. Genevieve, Quebec. In 2019, they purchased RNG environmental attributes from a WWTP in Dubuque, Iowa in a short-term contract. In 2020, VGS signed a 15-year contract for 120,000 MMBtu/yr. of RNG attributes from a digester in London, Ontario. They will also be purchasing 180,000 MMBtu/yr. of RNG from a VT dairy digester, which is slated for completion in late 2020. This project will allow VGS to inject the physical fuel into its pipeline and also purchase the environmental attributes, to distribute in the voluntary customer program (Kane & Murray, 2019).

Developing a Local Dairy and Food Waste Digester

A small developer had been working on building an anaerobic digester at the Goodrich dairy farm in Salisbury, VT for about seven years, but could not get the project off the ground and make it financially viable. The developer had already formed a partnership with VGS and their gas customer, Middlebury College, in which the two entities would buy the RNG to meet their decarbonization goals. They had already planned on building a 3-mile pipeline from the farm to get to the main gas pipeline to feed into the VGS system. Middlebury would buy a portion of the renewable attributes to de-carbonize about 50% of their heating and cooling demand (Mingle, 2019b). This is when Vanguard Renewables, a successful MA-based manure and food waste digester company, bought the project and took over as the developer, in early 2018. Vanguard had to get PUC approval to inject the RNG into the pipeline, which took many hearings with commissioners over two years. The RNG fuel will follow TransCanada specifications, since VGS is a subsidiary of that larger utility company.

Although Vanguard has developed numerous manure and food waste digesters in MA and other states, this is their first RNG pipeline injection project. Whereas the Goodrich farm is currently milking 900 cows, farms in MA typically have fewer than 500 cows. It helps to have a larger supply of feedstock when making the investment for an RNG upgrader, which raises the capital costs from a typical biogas to electricity project. The Goodrich digester will also accept 165 tons of food waste per day, for co-digestion. Vanguard found VGS to be a helpful partner to bring the RNG to the pipeline, handle the regulatory hurdles, and assist with the marketplace for the RNG (Mingle, 2019a; Ucciani, 2020).

Future Plans

This is only the beginning of the RNG journey for this small utility company. In November 2019, VGS announced that they would reduce their GHG emissions 30% by 2030 and 100% by 2050, through increasing their investments in energy efficiency programs and increasing the percentage of RNG in their gas supply to 20% by 2030. As natural gas prices have decreased, VT ratepayers have seen average annual costs go down by $250 over the past 10 years. With this plan to add RNG attributes to the pipeline, ratepayers may end up paying $3 more on their monthly gas bills (Vermont Business Magazine, 2019).

With the current RNG projects that Tom Murray, Vice President of Customers and Communities, is working on, VGS will get to 5% RNG in their pipelines soon. He envisions getting to 10% from projects on other VT dairy farms and from landfills in Canada, by 2025. Since dairy manure RNG is carbon negative, Murray wants to keep investing in these projects to offset the emissions from fossil gas, as well. The next step is getting PUC approval to allow distribution of costs (rate recovery) to add RNG to all their customers' supplies. Murray feels fortunate to have a receptive regulatory environment in VT, giving them confidence that they will be able to inject more RNG into the pipeline and receive rate recovery. He is working with other progressive gas utilities across the country to build an online marketplace for RNG renewable attributes, and has been working with CRS to develop the protocol for *Green-e* certified RNG attributes. He also serves on the American Biogas Council board of directors to drive policy at the federal level, as well as serving on the American Gas Association's sustainability committee. VGS sees RNG as part of the renewable thermal solution for VT (Murray, 2020).

> *The idea that in colder climates you can magically electrify thermal is challenging. At some point you're fighting physics, when it gets below 10 degrees, you're trying to capture the ambient heat out of air that is cold; there is no ambient heat to*

use! Pipeline infrastructure is going to need to deliver thermal energy in these places (Murray, 2020).

Whether it is the cold climate, an RNG and climate-friendly regulatory environment, or the number of large dairy farms in this small, rural state, VT has ideal conditions for RNG pipeline injection.

VGS Pathway:

1. A local dairy farm partnered with a nearby college and the local utility company for a 3-way RNG contract.
2. The utility company (VGS) assisted with costs and permitting during digester development and committed to build a pipeline from the digester.
3. VGS created a voluntary opt-in RNG program. It took two years to get approved by the PUC.
4. VGS purchased RNG from out-of-state facilities in the first two years of the voluntary program and then signed two long-term contracts for RNG supply. VGS will use both in-state and out-of-state RNG attributes for the voluntary program.
5. VGS committed to 20% RNG by 2030 and works to get rate recovery approval from the PUC.

Liberty Utilities – New Hampshire: Utilizing thermal RECs

Climate Goals and Energy Policy

NH does not have state climate action goals, but as of spring 2020, has a proposed bill to develop a plan for 80% GHG emissions reduction below 1990 levels by 2050 (Allee, 2020). However, it is the only state in the country to create a carve-out in its Renewable Portfolio Standard for thermal technologies, ensuring that a certain amount of renewable thermal energy will be produced (Prevost, 2020). NH electric utilities have had to meet the Class I thermal RPS obligation since 2014. The qualifying thermal technologies include biomass (wood, biodiesel, RNG), solar thermal, and geothermal (Donalds, 2018). The NH Thermal RPS was originally created to establish a market for low grade wood and wood scrap for the logging industry. Liberty Utilities, a small utility company interested in "greening the molecules" of their natural gas supply saw the thermal RPS as an opportunity to generate revenue from an RNG project. They worked to get a bill passed to explicitly include RNG as one of the renewable technologies in this state policy (Clark & Montgomery, 2020). NH has just two regulated gas utilities, with Unitil serving 34,000 customers and Liberty serving 94,000 customers ("New Hampshire Public Utilities Commission," n.d.).

Sourcing RNG Fuel and Attributes

Liberty identified a landfill in Bethlehem, NH that was flaring off the gas, and saw an opportunity to create RNG in 2017, signing a long-term contract with a developer (RUDARPA) in summer 2018. Under the contract, RUDARPA owns the RNG processing facility and is financing its development, and Liberty will purchase the RNG for 17 years at a fixed per-therm cost with a consumer price index escalator with an annual cap of 2%. This long-term contract allows RUDARPA to secure financing via loans for the capital costs. Additionally, it is RUDARPA's responsibility to compress the RNG and transport it by trailer to the Liberty receipt points in other parts of the state. The contract allows for Liberty to choose to purchase the RNG facility in the future, which would result in cheaper RNG and savings for their customers (Direct Testimony of William J. Clark and Mark E. Saltsman, 2018; RUDARPA, n.d.).

Liberty and RUDARPA have negotiated minimum annual gas supply quantities. They expect at the very minimum, 490,000 dekatherms annually in the first 5 years of the plan, 375,000 in years 6-10, and 270,000 in years 11-17. The Bethlehem landfill may soon reach capacity and close, but these volumes of methane are still expected over the next 15-20 years (Ropeik, 2020). The expected RNG volumes over the first five years will represent approximately 6% of annual gas sales to their customers.

RUDARPA and Liberty are working to ensure that the RNG fuel quality will be tested as it is being compressed into trailers for transport, then tested again when the trailers arrive at the receipt points, before it is injected into the pipeline. Liberty's RNG specifications will be based on the *Interconnect Guide for RNG in New York State* that was written in 2019 (Direct Testimony of William J. Clark and Mark E. Saltsman, 2018; Northeast Gas Association, 2019).

Making the Case to the PUC

Liberty originally filed with the NH PUC in September 2018 in order to get approval of the RNG supply and transportation agreement between Liberty and RUDARPA. The docket has gone through a long process. There was testimony from Liberty, an RNG quality expert from the Gas Technology Institute, and the General Counsel from the Coalition for Renewable Natural Gas to show that RNG is a tried-and-true technology that has been injected into pipelines since 1982 (Direct Testimony of William J. Clark and Mark E. Saltsman, 2018). In November 2018, there was another hearing in front of the PUC where Liberty explained the provisions in their contract that will protect gas customers from risk. The NH Office of the Consumer Advocate (OCA) and the PUC questioned the many potential risks: operations and safety, the monetary value of the TRECs, the financial burden on customers, the remaining lifetime output of methane from the landfill (Patnaude, 2018). In December 2018, the OCA did an economic analysis to see if the RNG supply would meet the "least-cost acquisition" rule, meaning it would be cheaper than other gas supplies, and found that it did not meet this important condition (Chattopadhyay, 2019). After other hearings and technical sessions in 2019 and no agreement between Liberty and the PUC, the PUC closed the docket in February 2020. The PUC is requiring Liberty to show that the RNG will be the least-cost option for customers, otherwise they will not approve.

Liberty has several positive aspects of the project going into further negotiations with the PUC. They currently have letters of intent (LOI) from three large commercial customers to purchase approximately half of the RNG that will be produced from the landfill annually. Also, Liberty has a plan to put the remaining RNG fuel into the pipeline by selling the environmental attributes, the TRECs, to NH electric utilities that need to comply with the thermal RPS. Revenues from the sale of TRECs will be used to offset the cost of RNG production, with the ultimate goal of making RNG fuel less costly for ratepayers than conventional natural gas. They want to distribute the costs of the fuel across all their customers, however, ratepayers will not receive the RNG environmental attributes.

Another positive aspect is that the RNG will be a baseload supply during the winter and will "reduce purchases of propane, LNG, and spot gas commodities, which are more expensive than the RNG supply," (Clark & Montgomery, 2020; Direct Testimony of William J. Clark and Mark E. Saltsman, 2018).

Future Plans

William Clark, the Director of Business Development for Liberty, is confident that they will be able to make the economic case that this RNG project is in the best interest of NH consumers in their next filing during spring 2020 (Clark & Montgomery, 2020). Susan Fleck, president of Liberty Utilities New Hampshire operations, described Liberty's RNG commitment in 2018:

> *Renewable Natural Gas is a low-cost way to maximize local resources and reduce the carbon footprint of New Hampshire's heating sector. We intend for this project to be the first of many in New Hampshire, and Liberty Utilities plans to be at the center of this growing local clean energy industry. Our team is currently working with communities across New Hampshire on similar projects, and we hope to announce more New Hampshire RNG projects in the future (Liberty Utilities, 2018).*

Nevertheless, Liberty continues this project and works to transform their company from a gas utility to a thermal energy company. They see RNG as one step that they can take in the near-term to de-carbonize thermal energy. Liberty is a de-coupled utility in NH, meaning they do not earn money based on the volume of gas that they sell. This enables them to think beyond selling gas to turn a profit. They work on energy efficiency, geothermal, and district heating loop solutions, in addition to developing RNG projects in other states. In the future, they will look towards new technologies such as hydrogen blending, P2G, and thermal gasification.

Pathway for Liberty Utilities:

1. The utility company (Liberty) lobbied the NH state legislature to have RNG qualify as a fuel under the thermal RPS.
2. Liberty signed a long-term contract with an RNG developer to purchase gas from a landfill for 17 years.
3. Liberty secured two large commercial customers.
4. Liberty filed a docket with the NH PUC in fall 2018 showing the project proposal and financial analysis as low-risk and no cost increase for gas consumers. The PUC and OCA concluded that RNG does not adhere to least-cost principles.
5. The PUC closed the docket in February 2020, but Liberty has secured a third commercial customer and plans to improve the customer cost analysis in a new PUC filing in spring 2020.

Maine: A voluntary program and a separate dairy digester

Climate Goals and Energy Policy

In 2019, ME established a State Climate Council and GHG emission reduction goals to be 45% below 1990 levels by 2030 and at least 80% reduction by 2050. Climate change is one of the top priorities of their new governor, Janet Mills, elected in 2018 (State of Maine Governor's Office of Policy Innovation and the Future, n.d.).

Summit Natural Gas of Maine's Voluntary Program

Summit Natural Gas of Maine ("SNGME") came to Maine in 2013 and serves a small portion of the state, with a small customer base. SNGME proposed a voluntary opt-in RNG program for its customers to the ME PUC in May 2019. They decided that they could jumpstart the voluntary program by providing RNG attributes equal to 5% of their residential load for one year, at no cost to customers. SNGME is offering customers to choose a percentage of the average annual gas usage of their specific customer class. Therefore, their tariff will stay constant on the customer's monthly bill. For the residential monthly charge, see Figure 19.

Customers can elect to participate based on the table below:

% of class average usage	Residential monthly charge	Small Commercial monthly charge
10%	$7.44	$31.79
25%	$18.60	$79.47
50%	$37.20	$158.95
100%	$74.40	$317.90

Figure 19 – RNG tariff for SNGME customers (Summit Natural Gas of Maine, n.d.)

As of early 2020, Summit has rolled out their voluntary RNG program to customers and is working on marketing the program and educating their customers on what RNG is and why it is a sustainable solution (Representative from Summit Utilities Inc., 2020).

PUC Approval

The voluntary program only took six months from the initial filing to final approval by the PUC. Through the process, the Maine Office of Public Advocate (OPA) and the PUC held hearings with SNGME to make sure the program was in the best interest of the customers, learning about RNG benefits, and felt satisfied that there would be no added burden on consumers with this purely voluntary program (King, 2019; Representative from Summit Utilities Inc., 2020).

Sourcing RNG Attributes

In order to start the voluntary program and the default 5%, they needed to obtain environmental attributes from an existing RNG facility, so they went through a third-party vendor. It was a challenge to find an RNG project with a small quantity of attributes to sell for their small customer base, but they settled on a landfill RNG project in Oklahoma, with very low overhead costs for the company. The attributes were verified through the same third-party vendor through in-person visits to the facility and a QA/QC process. SNGME is not making carbon reduction claims with the RNG, but just claiming that it is sourced from a renewable feedstock (Representative from Summit Utilities Inc., 2020).

Summit Utilities, Inc. – Developing a Dairy Digester in Maine

Summit Utilities, Inc, ("Summit") is the parent company for SNGME and is currently developing an anaerobic digester project in central ME. Summit looked for a local feedstock and found a dairy farm hub in the Kennebec Valley of ME, in their affiliates, SNGME, service territory. They partnered with area dairy farms, and plan to build the digester on Flood Brothers Farm in Clinton, ME. The amount of cow manure from these farms is expected to supply 125,000 MMBtu of RNG a year, enough to equal approximately 45% of the residential gas demand from SNGME's service territory (Valigra, 2019). Summit Utilities Inc. also provides gas in Colorado, Missouri, Arkansas, and Oklahoma and they wanted to be able to replicate developing an RNG plant in these states after learning from the project in ME. SNGME will build a mainline to interconnect to the RNG facility. As of spring 2020, this project is still in the development phases, with expected completion in 2021, pending regulatory approval and permitting (Valigra, 2019).

Summit will be selling the environmental attributes from the dairy digester they are building in Clinton to third-parties, and they will not incorporate those attributes into SNGME's voluntary program. The methane fuel (the physical attribute) will be sold to SNGME at natural gas market prices to use in their pipeline (Representative from Summit Utilities Inc., 2020).

Pathway for Summit Natural Gas of Maine and Summit Utilities, Inc.:

1. SNGME went through third-party vendor to acquire RNG attributes from out-of-state to begin a voluntary program, purchasing the initial 5% with internal funds.
2. SNGME brought the voluntary program to the PUC and received approval in six months.
3. SNGME begins advertising voluntary program to customers, jumpstarting with an initial 5% RNG for residential customers for one year for free.
4. Summit (the parent company) continues to develop dairy digester with a plan to sell attributes on the open market. They will need final approval from the PUC to inject the natural gas produced by the digester into their affiliate's, SNGME, pipeline.

Chapter 7: Cross-Case Analysis and Qualitative Data Summary

Cross-Case Analysis

These three utility companies in three New England states all took a different approach to adding RNG fuel into their pipeline and offering environmental attributes to their customers. Each case is influenced by the state's climate and energy policies and their unique Utilities Commissions (PUC). These key factors are shown in Table 4.

Table 4 – Comparison of RNG programs and projects across three New England states

	Vermont	***New Hampshire***	***Maine***
Driver for RNG	Small utility company and a committed institutional customer	Small utility company	Small utility company
Political climate	Created climate goals in 2005: 40% below 1990 GHG levels by 2030	No climate goals. Has thermal RPS policy.	Created climate goals in 2019: 45% below 1990 GHG levels by 2030
PUC process	2 years (started 2015)	1.5 years and ongoing, difficult (started 2018)	6 months, (started 2019)
Feedstock	Dairy manure and food waste	Landfill gas	SNGME: Landfill RNG sourced environmental attributes. Summit Utilities, Inc.: Dairy manure from multiple farms
Financial strategy for project	Long-term contracts with RNG attributes in-state and out-of-state for voluntary program	Long-term contract with RNG in-state, sell off TRECs and refund revenue to all customers evenly	SNGME: Out-of-state contract for RNG attributes for voluntary program. Summit Utilities, Inc.: Will sell dairy digester attributes on open market for added revenue.
Future plans	Get RNG rate recovery for all customers, beyond	Get RNG price to be the same as natural gas and distribute	SNGME: Grow voluntary program.

	voluntary program. Have PUC reject least-cost principles.	costs across all customers.	

VGS and SNGME are both offering voluntary RNG programs for customers, while Liberty is not. In Liberty's case, the customers will not get to claim any carbon reduction, even though the RNG fuel (identical to conventional natural gas) will be running through the NH pipeline. The thermal RPS in NH is unique and incentivizes a utility company to finance RNG development projects and sell the TRECs to electric utilities, but does not incentivize voluntary programs for residential customers to reduce their emissions. However, Liberty is hoping to provide RNG attributes to three commercial customers. Perhaps if there is an increased customer demand for a "green" option in NH in the future, Liberty will offer a voluntary program where customers purchase the attributes.

The SNGME voluntary program is somewhat like what VGS is doing in VT, but there are a few differences. Whereas VGS offers customers to purchase RNG as a percentage of each month's gas usage, which differs month-to-month, SNGME is offering customers to choose a percentage of the average annual gas usage, remaining the same tariff cost each month. VGS is incorporating the environmental attributes from their local digester project into their existing voluntary program, while SNGME is not using local attributes for their voluntary program. SNGME might eventually use in-state environmental attributes if there are changes to the RNG market and regulatory environment. Also, VGS is moving towards rate recovery when adding additional RNG to their pipeline, and

SNGME is not pursuing that. VT is likely a better regulatory environment for low-carbon energy given the fact that it has had GHG reduction goals for 15 years, whereas ME created these goals in 2019. Also, VT has many dairy farms, so there is confidence in producing several local dairy digesters. Lastly, in 2019 VT passed a new law that requires commercial waste haulers to offer food scrap collection services to non-residential customers and apartments with four units or more, whereas ME and NH do not have food waste bans (Vermont Agency of Natural Resources, 2019).

Liberty has had a difficult time getting its RNG pipeline injection approved by the PUC. The NH PUC seems the most concerned about least-cost acquisition, although all three Utilities Commissions took that into account. Perhaps the lack of climate policy in NH influences its PUC to closely scrutinize innovative renewable energy technologies, without seeing the benefits.

Both VGS and Liberty signed long-term contracts with RNG projects/developers before bringing their RNG proposals to the PUC. This was a strategy to present a low-risk project that will be sustainable for more than a decade into the future. It also enables the RNG developer to secure loans for capital costs, and have confidence in their ability to re-coup costs.

When ranking these utilities in terms of environmental achievement, VGS is most ambitious because they are financing a GHG reduction project in their own state and working towards making renewable thermal energy the norm in VT. However, the examples from Liberty and Summit show innovative ways to earn revenue and recoup capital costs by selling the environmental attributes from an RNG project.

Comparing the projected RNG volumes from these three facilities in VT, NH, and ME to the technical potential for RNG in MA shows that utility-developed RNG voluntary programs could have a future in the Commonwealth. See Table 5 below.

Table 5 – Estimated RNG production from projects under development in comparison to the technical potential for RNG in MA

	VGS manure project	***Liberty landfill gas project***	***Summit manure project***	***RNG technical potential for MA***
RNG production (MMcf)	174	473	121	5,100

Qualitative Data Summary

From the literature review, interviews, and case studies, many barriers and opportunities for RNG pipeline injection projects in the U.S. were found. They are listed in Table 6.

Table 6 – Barriers and opportunities for RNG pipeline injection in the U.S.

Category	***Barriers***	***Opportunities***
Cost	RNG upgrading equipment has high capital cost	• Utilities can do R&D to reduce costs from new thermal energy technologies • Utilities can provide project funding, assisting developers, and sign long-term contracts. • Creating an RNG attribute (like a REC) and a marketplace will increase the profit from the project. • State tax incentives for RNG developers or utilities

	Cost to gas customers	• Utilities can begin with a voluntary opt-in program • Utilities can sell environmental attributes and refund revenue to customers
	Natural gas is cheap, RNG cannot compete price-wise	• Cheap natural gas is reducing customers' gas bills, so there is more room to add a more expensive fuel, with little effect
	REC values can be unreliable	• Look to renewable electricity industry
Utilities Commission	PUC is risk-averse and does not know much about RNG	• Utilities can educate the PUC about RNG benefits • Utilities can explain to PUC how they will get RNG to spec and show examples of this tried-and-true technology in other states/Canada
	PUC strives for least-cost acquisition, therefore it's difficult to get rate recovery for a more expensive fuel	• Legislature has power to direct PUC with policies • Demonstrate long-term marginal cost savings with methane emission reduction • Put a price on carbon • Start with a voluntary opt-in program, not requiring rate recovery • Utilities can show PUC a long-term contract and letters of intent from customers
RNG Knowledge	Policy makers are not aware	• Utility companies are politically connected • Demonstrate the GHG reduction potential to policy makers
	Consumers are not aware	• Educate consumers on how they can reduce carbon footprint with RNG
Energy Innovation	Utilities are risk averse	• Utility company can shift from being a gas provider to a thermal energy company, utilizing all technologies and fuels, as we shift away from fossil fuels. • Small utility companies have less bureaucracy to pursue innovative technology
	Most people are advocating for electrification of heating and move towards renewable electricity	• Electrification has high capital costs and not 100% effective for cold weather climates • Renewable electricity has a low capacity factor[5] in comparison to RNG and there are still storage issues

[5] Capacity factor is the ratio between what a generation unit is capable of generating at maximum output versus the unit's actual generation output over a period of time. Renewable energy may have a low capacity factor, not always operating at full capacity if wind and sun are not available (NMPP Energy, n.d.).

		• Manufacturers still require combustion for process heat
Motivation	RNG for pipeline injection is not yet prevalent in the U.S. and would need an entity to drive innovation	• Utilities can drive RNG industry growth by committing to a % of RNG in their gas supply by certain date and supporting R&D • Academic institutions, companies, and governments can be drivers with their carbon neutrality goals, working on decarbonizing thermal energy in the near-term future
Standards	No national standard for RNG spec guidance	• Northeast Gas put out a standard in 2019 that New England utilities are starting to use
	Difficult to find an RNG project to purchase attributes when starting a voluntary program	• Create an online RNG environmental attribute marketplace • Use a third-party vendor
	No national REC for RNG	• RNG REC guidance is being created by CRS
Location	Rural areas don't have gas service	• RNG is not a solution for places not on gas grid, but entities can still purchase the environmental attributes
	Typically, states don't want RNG from outside their region	• There are pipelines that transmit gas between states • Local projects tell a good story
Competing Markets	LCFS and RFS are the most profitable market to sell RNG as vehicle fuel, with RINs	• This is a back-up market for developers and utilities to know they have a place to sell the attributes if they do not receive rate recovery or customer sign-ons to a voluntary program
Environmental Effects	PFAS are detectable in sewage sludge, making fertilizer byproduct from WWTP digester questionable	• Do more research on the byproduct to see if PFAS are at levels where they hurt the environment or human health when used as fertilizer

Chapter 8: Discussion

There is not enough feedstock in MA to make a large volume of RNG from AD, however there are feedstocks and existing biogas facilities to create numerous RNG projects in the state. The feedstock that exists would be a very small percentage of overall natural gas consumption in MA as of 2017 data. A few things to note about the feedstock potential is that this is the “technical potential”. Full exploitation of the technical potential is unlikely. Second, the quantitative results assume the feedstocks would all be in an anaerobic digester separately, meaning no co-digestion of feedstocks. Research shows there is higher methane production when co-digesting various feedstocks (e.g. food waste and sewage sludge), so this should be a consideration as well. As MA continues to improve energy efficiency, natural gas consumption is likely to decrease over time, which will make RNG represent a larger percentage of the whole. Nonetheless, RNG production in MA will not have a significant impact on the state’s GHG reduction goals, but it can be a small part of the many solutions that will need to be employed.

In order to have RNG for pipeline injection projects start in the state, the examples from ME, NH, and VT provide a valuable template. Utilities need to drive the projects, using their financial capital and partnering with developers. It would be helpful to have a mechanism, such as thermal RECs or an opt-in voluntary customer program that would make these projects financially viable. Also, an RNG incentive program funded by the state would jump-start project financing and perhaps there are funds from RGGI, or from the RPS’s alternative compliance payments, that could be used for this. Some of the existing anaerobic digesters in MA could use these funds to upgrade the gas to RNG, partnering with utilities who can make the case to the DPU. Utilities will need to finance building pipelines out to digesters. They can rely on the guidelines set-out by the Northeast Gas Association when determining the gas specifications to meet with their RNG upgrading and testing equipment.

It is understandable that MA would have a small amount of dairy manure feedstock in comparison to its natural gas use, seeing as how it and other Southern New England states are much more densely populated than Northern New England states (VT, NH, and ME). Also, being densely populated, there is a higher likelihood of NIMBY-ism[6] when building RNG plants. The opportunities to building more digesters at WWTPs in the state include determining which remaining plants without digesters have a high enough flow rate to support a digester or developing regional digesters to collect sludge from many small WWTPs. Sewage sludge at WWTPs should be co-digested with food waste for maximum gas production. Additionally, more research needs to be done on the application of fertilizer produced from WWTP digestion to see if the PFAS put human health at risk, or if this byproduct should instead be landfilled or incinerated. Improving the outreach and enforcement of the Commercial Food

[6] NIMBY means “Not in My Backyard” and is a phenomenon where people oppose project development close to their residence.

Material Disposal Ban in the state will also ensure that digesters can capture more food waste.

Despite having a low level of feedstocks for RNG production in-state, there is potential for MA utilities and institutions, such as businesses and universities, to purchase RNG attributes from neighboring states such as New York, VT, NH, and ME, or perhaps even from other states in the U.S. This market is rapidly developing as *Green-e* works on a standardized REC for RNG and other groups work on an online marketplace for these RNG attributes. It is comparable to how RECs are treated in the electric sector, where institutions purchase them from out-of-state if needed, and the RPS allows purchases of RECs from the New England region.

The greatest takeaway from the New England case studies is that the state's Utilities Commission is the most important factor to get approval for: 1) RNG for pipeline injection within state boundaries or, 2) RNG attribute programs for gas utilities operating in the state. There are several factors to look at within this takeaway. The people who are on the Utilities Commission may be naturally more inclined to newer technologies or rather, more than likely, they will be very risk averse to new technologies and fuels. The DPU's main goals are supplying a fuel to consumers that will have the lowest price and protecting consumers in other ways (e.g. safety). In order to get RNG approved, utilities either need to educate the DPU on the benefits and well-known safety of the RNG industry while making the cost to the customer equal to the cost of natural gas, or the state needs to take legislative action to direct the DPU.

As shown in the case studies, a utility can make RNG financially more attractive by 1) allowing ratepayers to opt-in to a voluntary program where they choose to pay the increased price for RNG or 2) selling environmental attributes from RNG out-of-state to recoup project costs. However, option #1 can be inequitable, especially if the voluntary tariff is expensive, and option #2 removes the GHG emissions reduction claim from the state. If there were a way for the voluntary program to be more equitable, perhaps a sliding scale cost based on income, or an extremely small increase to the monthly gas bill, this may be a good option. At present, the voluntary programs in VT and ME would cost a residential customer ~$23 or $18 extra per month to displace 25% of their natural gas usage with RNG. However, a voluntary program allows customers with financial means to start funding RNG, which could eventually lead the DPU to trust RNG and approve rate recovery. Additionally, utilities might be able to make the case that the long-term marginal cost savings from reduced methane emissions by using RNG is in the best interest of consumers. Otherwise, legislative action to direct the DPU is the best option.

There are numerous different policy options to choose from to direct the DPU. A Renewable Natural Gas Standard can mandate a certain percentage of RNG in the state's gas supply and allow for utility rate recovery, in which case, the DPU would have to approve these projects. Another solution is adding a thermal carve-out to the RPS that attaches monetary value to the TRECs generated from RNG projects (perhaps even out-of-state projects) and an obligation for electric utilities to purchase a set percentage of TRECs each year.

MA already qualifies thermal energy as part of its RPS, with the APS, so this solution may be a good fit if the APS were amended to include RNG injected into the pipeline. Broader policies that focus on carbon pricing or directing the DPU to consider GHG emissions reduction as part of their mission statement will also allow the DPU to approve rate recovery from RNG projects, despite being more expensive than natural gas. Policy models are available from several states (see Table 2).

Small utilities can make an impact in these RNG projects since they may move faster than large companies, but large utilities will be helpful in shaping policies with policy makers. These RNG projects will not be high-risk because of mature existing markets with vehicle RNG revenues to fall back on. Gas utilities and the state's DPU can also support research and development with RNG pilot projects as well as piloting other emerging thermal technologies like hydrogen blending, geothermal, and P2G. Energy efficiency should also continue to be prioritized.

Ultimately, RNG is one of the first steps for gas utilities to shift from being gas providers to thermal energy companies, where they provide heating to customers through multiple methods, still using the pipeline system that is currently being patched up. If these pipelines were abandoned soon, they would be a stranded asset. VGS described their transition to decarbonize the pipelines in a presentation to the VT state legislature in 2019, showing that after pursuing RNG they will do pilots for hydrogen injection and eventually use syn-gas and carbon capture technologies (see Figure 20).

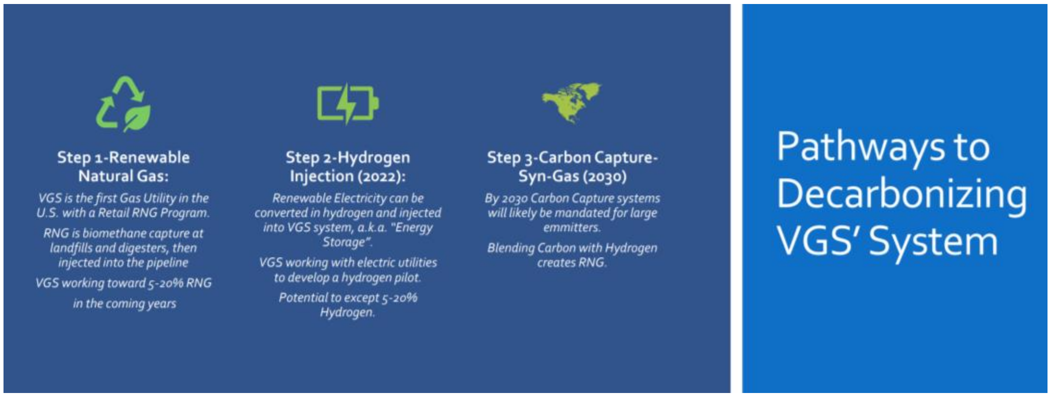

Figure 20 – VGS's plan to decarbonize thermal energy (Vermont Gas, 2019).

Supporting RNG and future thermal technologies is not an argument against electrifying thermal energy. Instead, these technologies can work together with electrifying heating where that makes sense.

Future Research

There should be more research on the lifecycle GHG emissions from RNG injected into the pipeline and used for thermal applications. As of spring 2020, there are no published lifecycle emissions factors (carbon intensities) of RNG produced from wet AD and injected into pipelines for thermal end uses in the U.S.

In order to upgrade biogas plants to RNG or locate new RNG facilities, there needs to be research on areas with high feedstock volume in the state and their distance from the natural gas pipeline, to optimize project financial viability.

Chapter 9: Conclusion & Recommendations

There are many barriers to introducing RNG for pipeline injection or an out-of-state RNG attribute purchase in MA, but there are also many opportunities and solutions. Therefore, it seems RNG has a promising future in the state.

RNG projects in the state should be pursued as much as possible, while remaining cognizant that these projects alone will have a minor effect on overall GHG emissions. MA utilities, their customers, and institutions can support RNG projects in neighboring states by purchasing the environmental attributes. This market is on the cusp of going mainstream.

Policy initiatives are needed to create legislation and regulations that account for the effects on climate change, allowing utilities to pursue rate recovery as they transition to RNG and other decarbonizing strategies.

As of spring 2020, there is proposed legislation in MA that would allow RNG rate recovery, and utility companies have started to make the case to the DPU. The MA Senate recently passed a bill to introduce carbon pricing and to give DPU the task to prioritize GHG emissions reductions when making regulatory decisions. Eversource is disclosing future plans for RNG and geothermal. The DOER is studying the potential for RNG in the state. It is only a matter of time before the barriers are overcome and RNG programs become a reality for gas customers in the Commonwealth.

Near-term recommended steps for MA include:

1) Start RNG voluntary opt-in programs through utilities with out-of-state attributes, moving toward rate recovery.
2) Pass legislation requiring the DPU to prioritize GHG emissions reductions in their decisions, allowing RNG rate recovery by utilities.
3) Utilities should partner with WWTPs and other anaerobic digester developers to do research on regional hubs and finance in-state projects.
4) Amend the APS to include RNG injected in the pipeline or develop and implement a Renewable Natural Gas Standard.

Appendix A: Interview Questions

Interview Questions for RNG Industry experts

1. Why is RNG mainly being used for vehicle fuel in the U.S. rather than for pipeline injection? Do you think this will change?
2. Why is RNG being introduced in other New England states, but not yet in Massachusetts?
3. Massachusetts has X number of biogas facilities, but none upgrading to RNG. It's estimated that the state can produce X MMBTU of RNG each year, which is X% of the non-electricity natural gas supply. Should the state continue using biogas for CHP or should some or all of it be upgraded to RNG?
4. Do you think there are potential RNG projects, or existing biogas projects, in MA where there is enough energy to make it worth the capital costs associated with RNG upgrading? Where are they?
5. What would need to happen to start producing RNG in MA and injecting it into the pipeline? State and local policies? Partnerships? Feedstock collection?
6. What other factors would be helpful in starting an RNG pipeline injection project in the state?
7. Do you think this is likely to happen? What are the barriers and solutions?
8. What would need to happen in the state for a utility company to be able to offer RNG environmental attributes to gas customers? Policy changes?
9. Do you think this is likely to happen? What are the barriers and solutions?
10. Would one of these two things have to happen first? Or, could you have one of these happen without the other?
11. What has been discussed about this topic in MA so far? Is there anything on the horizon for RNG in MA?
12. How does the state's commercial organic waste ban play a role in this?
13. How do the state's environmental goals play a role?
14. Are there other existing state policies and initiatives that support this? Are more policies needed?
15. Who should champion RNG in the state? The waste industry, energy industry, policy makers, utility companies?
16. Who would benefit?
17. Would this have a negative effect on anyone or any entity in the state?
18. What are your recommendations for MA moving forward with regards to RNG?

19. **If interviewing a utility company, also ask:** What are your utility company's next steps with regards to RNG in MA?
20. Is there anyone you recommend I interview for this project and could you connect me?

<u>Interview Questions for Case Studies in New England</u>

1. What was the impetus for this RNG project? (For the purposes of the interview, "project" will refer both to the RNG production facility and to the utility company offering of RNG environmental attributes to their customers)
2. Which RNG projects/locations did you look to for inspiration?
3. What was the first thing that needed to happen to start off the project?
4. What partnerships were needed to start the project and how were those relationships formed?
5. What problems did you run into at the beginning of the project and how were they solved?
6. What policies needed to be changed at the state and local level and how was this done?
7. Were these policy changes driven by state goals and initiatives?
8. Who or what was the driver?
9. What were the barriers to policy implementation and project implementation?
10. Were there any other key steps to project implementation?
11. How are you able to cover the capital costs and operating costs?
12. Is there a regulation for the gas quality to be injected into the pipeline? How do you ensure high quality RNG?
13. How does the RNG get to the pipeline?
14. How are the environmental attributes being verified for the project?
15. Will this project grow over time?
16. Are there any ongoing challenges with the project?
17. Do you plan on there being more RNG projects in the state? When?
18. How have the utility customers responded?
19. What is the pricing structure?
20. Is there anyone you recommend I interview for this project and could you connect me?

Appendix B: Interviews

Name	Organization	Date	Method	Area of Expertise
Amy Barad	Massachusetts Clean Energy Center	3/2/20	In-Person	MA context
William Clark and Huck Montgomery	Liberty Utilities – New Hampshire	3/5/20	In-Person	NH RNG case study, MA context
Michael Green	Climate Xchange	3/4/20	Phone	MA context
Brian Jones	M.J. Bradley & Associates	3/3/20	Phone	RNG industry and policies
Barbara Kates-Garnick	The Fletcher School of Law and Diplomacy	3/10/20	Phone	MA context
Thomas Murray	Vermont Gas	3/19/20	Phone	VT RNG case study
Thomas O'Rourke	Eversource Energy	3/5/20	Phone	Thermal energy and MA context
Representative	Summit Utilities, Inc.	3/10/20	Phone	Maine RNG case study
Eric Steltzer	MA Department of Energy Resources (DOER)	3/5/20	Phone	MA context
Sol Ucciani	Vanguard Renewables	2/21/20	Phone	RNG industry, MA context, and VT RNG case study

Bibliography

Adelt, M., Wolf, D., & Vogel, A. (2011). LCA of biomethane. *Journal of Natural Gas Science and Engineering*, *3*, 646–650.

Allee, D. (2020, January 21). Bill For A N.H. State Climate Action Plan Gets First Hearing. *New Hampshire Public Radio*. Retrieved from https://www.nhpr.org/post/bill-nh-state-climate-action-plan-gets-first-hearing#stream/0

American Biogas Council. (2015). *Biogas State Profile: Massachusetts*. Retrieved from https://americanbiogascouncil.org/wp-content/uploads/2019/02/ABCBiogasStateProfile_MA.pdf

American Gas Association. (2019). Average Annual Residential Consumption per Customer by State 2005-2018. Retrieved March 24, 2020, from https://www.aga.org/contentassets/6894914d95e6467fae106015cbcb2abc/table6-14.pdf

Banks, C. J., Salter, A. M., Heaven, S., & Riley, K. (2011). Energetic and environmental benefits of co-digestion of food waste and cattle slurry: A preliminary assessment. *Resources, Conservation and Recycling*, *56*, 71–79. https://doi.org/10.1016/j.resconrec.2011.09.006

Barad, A. (2020, March 2). Interview with author.

Beaton, M. (2015). *Massachusetts Clean Energy and Climate Plan for 2020 - 2015 Update*. Retrieved from https://www.mass.gov/files/documents/2017/12/06/Clean Energy and Climate Plan for 2020.pdf

California Air Resources Board. (2020). LCFS Pathway Certified Carbon Intensities. Retrieved February 17, 2020, from https://ww2.arb.ca.gov/resources/documents/lcfs-pathway-certified-carbon-intensities

Cancela, Y. SB-154 An act relating to natural gas (2019). Nevada State Legislature. Retrieved from https://legiscan.com/NV/text/SB154/id/2012438/Nevada-2019-SB154-Enrolled.pdf

Center for Resource Solutions. (2019). *Terms of Reference Green-e Renewable Fuels Standard for Canada and the United States*. San Francisco. Retrieved from https://www.green-e.org/docs/rf/Green-e Renewable Fuels TOR.pdf

Chattopadhyay, P. (2019, February). *In the matter of Liberty Utilities (EnergyNorth Natural Gas) Corp. Docket No. DG 18-140 Petition for Approval of a Renewable Natural Gas Supply and Transportation Contract Direct Testimony*. Retrieved from https://www.puc.nh.gov/Regulatory/Docketbk/2018/18-

140/TESTIMONY/18-140_2019-02-22_OCA_DTESTIMONY_CHATTOPADHYAY.PDF

Clark, W., & Montgomery, H. (2020, March 5). Interview with author.

Coggan, T. L., Moodie, D., Kolobaric, A., Szabo, D., Shimeta, J., Crosbie, N. D., … Clarke, B. O. (2019). An investigation into per- and polyfluoroalkyl substances (PFAS) in nineteen Australian wastewater treatment plants (WWTPs). *Heliyon*, *5*(8). https://doi.org/10.1016/j.heliyon.2019.e02316

Consolidated Edison, I. (2019). *June 2019 Company Update*. Retrieved from https://investor.conedison.com/static-files/41f32524-8a25-44c4-a36f-793a3a23d091

Cook, J. (2020). *Sites Accepting Diverted Food Material in Massachusetts*. Retrieved from https://www.mass.gov/doc/map-list-of-massachusetts-sites-accepting-diverted-food-material-february-2020/download

Crane, K. (2019). *Direct Testimony of William J. Akley and Douglas P. Horton*. Retrieved from https://www.eversource.com/content/docs/default-source/investors/ema-gas-review-2019-case-overview.pdf?sfvrsn=5b9fd762_0

Cronin, T. (2020a, January 23). Mass. Senate’s Climate Bills: Overview, Summary, & Context. Retrieved March 23, 2020, from https://climate-xchange.org/2020/01/23/mass-senates-climate-bills-overview-summary-context/

Cronin, T. (2020b, January 31). Massachusetts Senate passes economy-wide carbon pricing, net zero emissions target. Retrieved March 23, 2020, from https://climate-xchange.org/2020/01/31/massachusetts-senate-passes-economy-wide-carbon-pricing-net-zero-emissions-target/

Daniel-Gromke, J., Rensberg, N., Denysenko, V., Stinner, W., Schmalfuß, T., Scheftelowitz, M., … Liebetrau, J. (2018). Current Developments in Production and Utilization of Biogas and Biomethane in Germany. *Chemie Ingenieur Technik*, *90*(1–2), 17–35. https://doi.org/10.1002/cite.201700077

Direct Testimony of William J. Clark and Mark E. Saltsman. (2018). *Docket No. DG 18-XXX Liberty Utilities (EnergyNorth Natural Gas) Corp. d/b/a Liberty Utilities Approval of Renewable Natural Gas Supply and Transportation Contract*. Retrieved from https://www.puc.nh.gov/Regulatory/Docketbk/2018/18-140/INITIAL FILING - PETITION/18-140_2018-09-07_ENGI_DTESTIMONY_CLARK_SALTSMAN.PDF

Donalds, S. (2018). *Renewable Thermal in State Renewable Portfolio Standards*. Retrieved from https://www.cesa.org/assets/Uploads/Renewable-Thermal-in-State-RPS-April-2015.pdf

Donnelly, A., & Haddadin, J. (2020, February 20). How Massachusetts Farms

Turn Food Waste Into Renewable Energy. NBC Boston. Retrieved from https://www.nbcboston.com/investigations/massachusetts-farms-food-waste-renewable-energy/2078887/

Ebner, J. H., Labatut, R. A., Rankin, M. J., Pronto, J. L., Gooch, C. A., Williamson, A. A., & Trabold, T. A. (2015). Lifecycle Greenhouse Gas Analysis of an Anaerobic Codigestion Facility Processing Dairy Manure and Industrial Food Waste. *Environmental Science & Technology*, *49*, 11199–11208. https://doi.org/10.1021/acs.est.5b01331

Egg, J. (2020, February 3). The $9 Billion Question: Stranded Assets or GeoMicroDistricts? *PHCP Pros*. Retrieved from https://www.phcppros.com/articles/10829-the-9-billion-question-stranded-assets-or-geomicrodistricts

Ehrlich, L. A., Minicucci, C. A., Barber, C. P., Chandler, H. L., Eldridge, J. B., Gordon, K. I., … Stanley, T. M. HOUSE No. 2849 -An Act for utility transition to using renewable energy (FUTURE) (2019). Retrieved from https://malegislature.gov/Bills/191/HD3719

Energy and Technology Committee. HB-5350: An Act Concerning Natural Gas Infrastructure. Connecticut General Assembly. Retrieved from https://www.cga.ct.gov/asp/cgabillstatus/cgabillstatus.asp?selBillType=Bill&bill_num=HB-5350

Evoqua Water Technologies LLC. (2019). AnMBR Reduces Ken's Foods' Operation and Maintenance Costs by 50%. Retrieved March 22, 2020, from https://www.evoqua.com/en/brands/adi-systems/Pages/anmbr-reduces-kens-foods-costs.aspx

Fischer, J. (2019). *MassDEP Organics Subcommittee Meeting Summary*. Boston. Retrieved from https://www.mass.gov/doc/meeting-notes-22/download

Fischer, J. (2020). *MassDEP Organics Subcommittee Meeting presentation*. Retrieved from https://www.mass.gov/doc/presentation-238/download

Gasper, R., & Searchinger, T. (2018). *The Production and Use of Renewable Natural Gas as a Climate Strategy in the United States*. Retrieved from https://www.wri.org/publication/renewable-natural-gas

General Law - Part I, Title XXII, Chapter 164, Section 144. (n.d.). Retrieved January 5, 2020, from https://malegislature.gov/Laws/GeneralLaws/PartI/TitleXXII/Chapter164/Section144

Grayson, T. AB-3187 Biomethane: gas corporations: rate: interconnection (2018). State Assembly. Retrieved from http://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201720180AB3187

Green-e. (n.d.). Frequently Asked Questions. Retrieved January 4, 2020, from https://www.green-e.org/programs/renewable-fuels/faq

Green, M. (2020, March 4). Interview with author.

Hamberg, K., Furseth, D., Wegrzyn, J., LaRusso, A., Chahbazpour, D., Richardson, G., … Chase, B. (2012). *Renewable Natural Gas for Transportation: An Overview of the Feedstock Capacity, Economics, and GHG Emission Reduction Benefits of RNG as a Low-Carbon Fuel*. Retrieved from https://www.npc.org/FTF_Topic_papers/22-RNG.pdf

Hansen, L., Spencer, R., & Barbagallo, T. (2019, February). Deep Dive Into Danish Biogas. Retrieved April 12, 2020, from https://www.biocycle.net/2019/02/01/deep-dive-danish-biogas/

Horschig, T., Adams, P. W. R., Gawel, E., & Thrän, D. (2018). How to decarbonize the natural gas sector: A dynamic simulation approach for the market development estimation of renewable gas in Germany. *Applied Energy*, *213*, 555–572. https://doi.org/10.1016/j.apenergy.2017.11.016

House Appropriations. HB-1257 Concerning energy efficiency (2019). Washington State Legislature. Retrieved from http://lawfilesext.leg.wa.gov/biennium/2019-20/Pdf/Bills/Session Laws/House/1257-S3.SL.pdf#page=1

Hueso, B. SB-1440 Energy: biomethane: biomethane procurement (2018). California State Senate. Retrieved from https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201720180SB1440

ICF. (2019). *Renewable Sources of Natural Gas: Supply and Emissions Reduction Assessment*. Retrieved from https://www.gasfoundation.org/2019/12/18/renewable-sources-of-natural-gas/

ITM Power. (2020, January 2). HyDeploy: UK Gas Grid Injection of Hydrogen in Full Operation. Retrieved April 5, 2020, from https://www.itm-power.com/news/hydeploy-uk-gas-grid-injection-of-hydrogen-in-full-operation

Jones, B. (2020, March 3). Interview with author.

Jones, T. (2016). *How Renewable Energy Certificates Make a Difference*. Retrieved from www.resource-solutions.org

Kane, S., & Murray, T. (2019). *VGS Renewable Natural Gas Program Manual*. Retrieved from https://www.vermontgas.com/renewablenaturalgas/

Kashinsky, L. (2020, January 1). Thousands of gas leaks plagued Massachusetts in 2018, new DPU report says. Retrieved March 23, 2020, from https://www.bostonherald.com/2020/01/01/thousands-of-gas-leaks-plagued-massachusetts-in-2018-dpu-report-says/

King, A. (2019). *Direct Testimony of Angus King III Chief Development Officer of behalf of Summit Natural Gas of Maine, Inc. Docket No. 2019-00116*. Retrieved from https://mpuc-cms.maine.gov/CQM.Public.WebUI/Common/CaseMaster.aspx?CaseNumber=2019-00116

Kougias, P. G., & Angelidaki, I. (2018). Biogas and its opportunities-A review. *Frontiers of Environmental Science & Engineering*, *12*(3), 14. https://doi.org/10.1007/s11783-018-1037-8

Lauer, M., Hansen, J. K., Lamers, P., & Thrän, D. (2018). Making money from waste: The economic viability of producing biogas and biomethane in the Idaho dairy industry. *Applied Energy*, *222*, 621–636. https://doi.org/10.1016/j.apenergy.2018.04.026

Liberty Utilities. (2018, September 27). Liberty Utilities Announces Renewable Natural Gas Project. Retrieved March 21, 2020, from https://new-hampshire.libertyutilities.com/manchester/residential/news/post/liberty-utilities-announces-renewable-natural-gas-project-.html

M.J. Bradley & Associates. (2019a). *Natural Gas Utility Business Models for Facilitating Renewable Natural Gas Development and Use*. Retrieved from https://www.northerngasnetworks.co.uk/event/h21-launches-national/

M.J. Bradley & Associates. (2019b). *Policy Options to Facilitate Renewable Natural Gas Use and Development*.

MA Gas Division. (n.d.). Natural gas companies. Retrieved March 22, 2020, from https://www.mass.gov/service-details/natural-gas-companies

Macias-Corral, M., Samani, Z., Hanson, A., Smith, G., Funk, P., Yu, H., & Longworth, J. (2008). Anaerobic digestion of municipal solid waste and agricultural waste and the effect of co-digestion with dairy cow manure. *Bioresource Technology*, *99*, 8288–8293. https://doi.org/10.1016/j.biortech.2008.03.057

Massachusetts Department of Energy Resources. (n.d.). Anaerobic Digestion & Organics Diversion. Retrieved January 5, 2020, from https://www.mass.gov/lists/anaerobic-digestion-organics-diversion

Massachusetts Department of Energy Resources. (2018). *Massachusetts Comprehensive Energy Plan Commonwealth and Regional Demand Analysis*. Retrieved from https://www.mass.gov/files/documents/2019/01/10/CEP Report- Final 01102019.pdf

Massachusetts Department of Environmental Protection. (n.d.-a). Commercial Food Material Disposal Ban. Retrieved April 4, 2020, from https://www.mass.gov/guides/commercial-food-material-disposal-ban#-regulations-&-guidance-

Massachusetts Department of Environmental Protection. (n.d.-b). Financial & Technical Assistance for Anaerobic Digestion Projects. Retrieved January 5, 2020, from https://www.mass.gov/info-details/financial-technical-assistance-for-anaerobic-digestion-projects

Massachusetts Department of Environmental Protection. (2016). *Statewide Greenhouse Gas Emissions Level: 1990 Baseline and 2020 Business As Usual Projection Update*. *July* (Vol. 1). Boston. Retrieved from http://www.mass.gov/eea/agencies/massdep/climate-

Massachusetts Department of Environmental Protection. (2018). *MassDEP Fact Sheet - Biogas Production*.

Massachusetts Department of Environmental Protection. (2019). *Draft for Public Comment, Massachusetts 2030 Solid Waste Master Plan*. Retrieved from https://www.mass.gov/doc/draft-2030-solid-waste-master-plan/download

Massachusetts Department of Environmental Protection. (2020). *Appendix C: Massachusetts Annual Greenhouse Gas Emissions Inventory 1990-2017, with Partial 2018 Data*. Retrieved from https://www.mass.gov/lists/massdep-emissions-inventories

Massachusetts Department of Public Utilities. (2018). *Department of Public Utilities 2018 Annual Report*. Retrieved from https://www.mass.gov/files/documents/2019/02/14/DPU 2018 ANNUAL REPORT - WEB.pdf

McKenna, P. (2019, December 12). These Cities Want to Ban Natural Gas. But Would It Be Legal? Retrieved March 23, 2020, from https://insideclimatenews.org/news/12122019/natural-gas-ban-cities-legal-cambridge-brookline-massachusetts-state-law-berkeley-california

Milbrandt, A. (2005). *A Geographic Perspective on the Current Biomass Resource Availability in the United States*.

Mingle, J. (2019a). Could Renewable Natural Gas Be the Next Big Thing in Green Energy? - Yale E360. Retrieved September 20, 2019, from https://e360.yale.edu/features/could-renewable-natural-gas-be-the-next-big-thing-in-green-energy

Mingle, J. (2019b, November). Vermont Gas sees growing demand and potential for renewable natural gas. *Energy News Nerwork*. Retrieved from https://energynews.us/2019/11/19/northeast/vermont-gas-sees-growing-demand-and-potential-for-renewable-natural-gas/

Mohareb, E. A., Maclean, H. L., & Kennedy, C. A. (2011). Greenhouse Gas Emissions from Waste Management-Assessment of Quantification Methods. *Journal of the Air & Waste Management Association*, *61*(5), 480–493. https://doi.org/10.3155/1047-3289.61.5.480

Morero, B., Groppelli, E., & Campanella, E. (2015). Life cycle assessment of biomethane use in Argentina. *Bioresource Technology, 182*, 208–216.

Murray, T. (2020, March 19). Interview with author.

Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., … Zhang, H. (2013). Anthropogenic and Natural Radiative Forcing. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 73–73.

National Grid. (2010). *Renewable Gas-Vision for a Sustainable Gas Network A paper by National Grid*. Retrieved from https://www9.nationalgridus.com/non_html/ng_renewable_wp.pdf

National Grid. (2019, April 30). National Grid Files Rate Review Proposals for Downstate New York. Retrieved March 22, 2020, from https://www.nationalgridus.com/News/2019/04/National-Grid-Files-Rate-Review-Proposals-for-Downstate-New-York/

National Institute of Standards and Technology. (2018). Isothermal Properties for Methane. Retrieved from https://webbook.nist.gov/cgi/fluid.cgi?T=60&PLow=.8&PHigh=1&PInc=.1&Applet=on&Digits=5&ID=C74828&Action=Load&Type=IsoTherm&TUnit=F&PUnit=atm&DUnit=kg%2Fm3&HUnit=kJ%2Fmol&WUnit=m%2Fs&VisUnit=uPa*s&STUnit=N%2Fm&RefState=DEF

National Renewable Energy Laboratory. (n.d.). Biopower Atlas. Retrieved February 3, 2020, from https://maps.nrel.gov/biopower-atlas/

National Renewable Energy Laboratory. (2014). U.S. Biomass Resource Maps. Retrieved from https://www.nrel.gov/gis/biomass.html

Natividad Pérez-Camacho, M., Curry, R., & Cromie, T. (2019). Life cycle environmental impacts of biogas production and utilisation substituting for grid electricity, natural gas grid and transport fuels. https://doi.org/10.1016/j.wasman.2019.05.045

New Hampshire Public Utilities Commission. (n.d.). Retrieved March 21, 2020, from https://www.puc.nh.gov/Gas-Steam/gas-steam.htm

NMPP Energy. (n.d.). Understanding Capacity and Capacity Factor. Retrieved April 22, 2020, from http://www.nmppenergy.org/feature/capacity_factor

North East Biosolids and Residuals Association (NEBRA). (2019). *The Mass Sludge Survey 2018 v.1.1 Wastewater Solids Generation and Management in Massachusetts*. Retrieved from https://files-cdn.masscec.com/NEBRA-MassCEC-MassSludgeSurvey2018-v.1.1-FINAL-30Dec2019.pdf

Northeast Gas Association. (2019). *Interconnect Guide for Renewable Natural Gas (RNG) in New York State*. Retrieved from https://www.northeastgas.org/pdf/nga_gti_interconnect_0919.pdf

O'Rourke, T. (2020, March 5). Interview with author.

Patnaude, S. (2018, November). *RE: DG 18-140 LIBERTY UTILITIES (ENERGYNORTH NATURAL GAS) CORP. d/b/a LIBERTY UTILITIES: Petition for Approval of a Renewable Natural Gas Supply and Transportation Contract. (Prehearing conference)*. Concord: State of New Hampshire Public Utilities Commission. Retrieved from https://www.puc.nh.gov/Regulatory/Docketbk/2018/18-140/TRANSCRIPTS-OFFICIAL EXHIBITS-CLERKS REPORT/18-140_2018-12-13_TRANSCRIPT_11-28-18.PDF

Patrizio, P., & Chinese, C. (2016). The impact of regional factors and new bio-methane incentive schemes on the structure, profitability and CO2 balance of biogas plants in Italy. *Renewable Energy*, *99*, 573–583.

Pennington, M. (2019). *Anaerobic Digestion Facilities Processing Food Waste in the United States in 2016*. Retrieved from https://www.epa.gov/sites/production/files/2019-09/documents/ad_data_report_v10_-_508_comp_v1.pdf

Phillips, N. (2020). Power Dialog Webinar Climate Solutions for Massachusetts 4/7/2020. Retrieved from https://docs.google.com/document/d/1zqosznXgVWGCJYKZ6JPXbl7-MNowb8_zA90c8gD8qJc/edit

Pike, B. (2014). *Municipal Development of Anaerobic Digestion/ Combined Heat and Power in Massachusetts*. Tufts University.

Poeschl, M., Ward, S., & Owende, P. (2010). Evaluation of energy efficiency of various biogas production and utilization pathways. *Applied Energy*, (87), 3305–3320.

Poeschl, M., Ward, S., & Owende, P. (2012). Environmental impacts of biogas deployment - Part II: Life Cycle Assessment of multiple production and utilization pathways. *Journal of Cleaner Production*, *24*, 184–201. https://doi.org/10.1016/j.jclepro.2011.10.030

Prevost, L. (2020, January). New Hampshire a regional outlier on climate, clean energy under Gov. Sununu. *Energy News Network*. Retrieved from https://energynews.us/2020/01/08/northeast/new-hampshire-a-regional-outlier-on-climate-clean-energy-under-gov-sununu/

Renewable Energy World. (2012). Italy Abandons RPS, Adopts System of Feed-in Tariffs. Retrieved February 23, 2020, from https://www.renewableenergyworld.com/2012/12/06/italy-abandons-rps-adopts-system-of-feed-in-tariffs/#gref

Representative from Summit Utilities Inc. (2020, March 10). Interview with author.

Roberts, D. (2020). California's natural gas fight shows the false promise of “renewable natural gas. Retrieved February 17, 2020, from https://www.vox.com/energy-and-environment/2020/2/14/21131109/california-natural-gas-renewable-socalgas

Rodgers, R. (2019). *Optimizing Biogas Treatment Systems: Improved O&M and RNG production*. Urban Elephant Media. Retrieved from https://urbanelephantmedia.com/

Ropeik, A. (2020, February 27). Proposals to Halt Private Landfill Construction in N.H. Get Heated Hearings. *New Hampshire Public Radio*. Retrieved from https://www.nhpr.org/post/proposals-halt-private-landfill-construction-nh-get-heated-hearings#stream/0

RUDARPA. (n.d.). About Us. Retrieved March 21, 2020, from https://www.rudarpa.com/about-us

Russell, P., Lowell, D., & Jones, B. (2017). *Renewable Natural Gas: The RNG Opportunity for Natural Gas Utilities*.

Senate Interim Committee on Environment and Natural Resources. SB-98: An Act relating to renewable natural gas; and prescribing an effective date (2019). Oregon Legislative Assembly. Retrieved from https://olis.leg.state.or.us/liz/2019R1/Downloads/MeasureDocument/SB98/Enrolled

Skahill, P. (2017, April 21). From Waste To Watts: How This Grocery Chain Turns Old Food Into New Energy. Retrieved March 22, 2020, from https://www.wbur.org/bostonomix/2017/04/21/anaerobic-digester-food-waste-energy

Søndergaard, M. M., Fotidis, I. A., Kovalovszki, A., & Angelidaki, I. (2015). Anaerobic Co-digestion of Agricultural Byproducts with Manure for Enhanced Biogas Production. *Energy & Fuels*, *29*, 8088–8094. https://doi.org/10.1021/acs.energyfuels.5b02373

Southern California Gas Company. (2019). SoCalGas Announces Vision to Be Cleanest Natural Gas Utility in North America. Retrieved February 23, 2020, from https://www.prnewswire.com/news-releases/socalgas-announces-vision-to-be-cleanest-natural-gas-utility-in-north-america-300807922.html

Stark, M. (2018). Greening the gas in the grid. Retrieved February 23, 2020, from https://www.accenture.com/us-en/blogs/blogs-greening-gas-grid

State of Maine Governor’s Office of Policy Innovation and the Future. (n.d.). Climate Change. Retrieved March 22, 2020, from https://www.maine.gov/future/initiatives/climate

Steltzer, E. (2020, March 5). Interview with author.

Summit Natural Gas of Maine. (n.d.). Renewable Natural Gas. Retrieved April 12, 2020, from https://summitnaturalgasmaine.com/RenewableNaturalGas

The Coalition For Renewable Natural Gas. (2020). RNG Production Facilities in North America. Retrieved April 5, 2020, from http://www.rngcoalition.com/rng-production-facilities

U.S. Energy Information Administration. (2020). Massachusetts Natural Gas Consumption by End Use. Retrieved March 1, 2020, from https://www.eia.gov/dnav/ng/NG_CONS_SUM_DCU_SMA_A.htm

Ucciani, S. (2020, February 21). Interview with author.

Union of Concerned Scientists. (2014, June 19). Environmental Impacts of Natural Gas. Retrieved April 4, 2020, from https://ucsusa.org/resources/environmental-impacts-natural-gas

Union of Concerned Scientists. (2017). The Promises and Limits of Biomethane as a Transportation Fuel. *The Union of Concerned Scientists*, (Babson). Retrieved from https://www.ucsusa.org/sites/default/files/attach/2017/05/Promises-and-limits-of-Biomethane-factsheet.pdf

University of New Hampshire Sustainability Institute. (n.d.). Cogeneration & EcoLine (Landfill Gas). Retrieved March 23, 2020, from https://sustainableunh.unh.edu/ecoline

US EPA. (n.d.-a). Basic Information on PFAS. Retrieved April 11, 2020, from https://www.epa.gov/pfas/basic-information-pfas

US EPA. (n.d.-b). History of Voluntary Markets. Retrieved April 5, 2020, from https://www.epa.gov/greenpower/history-voluntary-markets

US EPA. (n.d.-c). Landfill Gas Energy Project Data | Landfill Methane Outreach Program (LMOP). Retrieved January 2, 2020, from https://www.epa.gov/lmop/landfill-gas-energy-project-data

US EPA. (n.d.-d). Livestock Anaerobic Digester Database. Retrieved March 22, 2020, from https://www.epa.gov/agstar/livestock-anaerobic-digester-database

US EPA. (2018). *Market Opportunities for Biogas Recovery Systems at U.S. Livestock Facilities*. Retrieved from https://www.epa.gov/sites/production/files/2018-06/documents/epa430r18006agstarmarketreport2018.pdf

US EPA. (2019). Greenhouse Gas Equivalencies Calculator. Retrieved January 3, 2020, from https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator

US EPA. (2020, March). Project and Landfill Data by State. Retrieved March 22, 2020, from https://www.epa.gov/lmop/project-and-landfill-data-state

USDA, US EPA, & US Department of Energy. (2014). *Biogas Opportunities*

Roadmap Voluntary Actions to Reduce Methane Emissions and Increase Energy Independence. Retrieved from https://www.epa.gov/sites/production/files/2015-12/documents/biogas-roadmap.pdf

Valigra, L. (2019, May 24). Maine natural gas company has big plans to turn cow manure into renewable energy. Retrieved March 21, 2020, from https://wgme.com/news/local/maine-natural-gas-company-has-big-plans-to-turn-cow-manure-into-renewable-energy

Vermont Agency of Natural Resources. (2019, June). 2019 Summary of Legislative Changes to Vermont Solid Waste Laws. Retrieved April 12, 2020, from https://dec.vermont.gov/sites/dec/files/wmp/SolidWaste/Documents/2019-Summary-Changes-Solid-Waste-Law.pdf

Vermont Business Magazine. (2019, November). VGS plans to eliminate greenhouse gas emissions by 2050. *Vermont Business Magazine*. Retrieved from https://vermontbiz.com/news/2019/november/14/vgs-plans-eliminate-greenhouse-gas-emissions-2050

Vermont Gas. (n.d.). Renewable Natural Gas Adder Calculator. Retrieved March 24, 2020, from https://www.vermontgas.com/renewablenaturalgas/adder-calculator/

Vermont Gas. (2019). *Vermont Gas Today & Tomorrow*. Retrieved from https://legislature.vermont.gov/Documents/2020/WorkGroups/House Energy and Technology/Energy/Fossil Fuels/W~Tom Murray~Vermont Gas Today and Tomorrow PowerPoint Presentation~4-11-2019.pdf

Vermont Official State Website. (n.d.). Emissions & Goals. Retrieved March 22, 2020, from https://climatechange.vermont.gov/climate-pollution-goals

Von Wald, G. A., Stanion, A. J., Rajagopal, D., & Brandt, A. R. (2019). Biomethane addition to California transmission pipelines: Regional simulation of the impact of regulations. https://doi.org/10.1016/j.apenergy.2019.05.031

Wasser, M. (2019, June 19). Confused About The Weymouth Compressor? Here’s What You Need To Know. Retrieved March 23, 2020, from https://www.wbur.org/earthwhile/2019/06/19/proposed-weymouth-gas-compressor-explained

Weiland, P. (2010). Biogas production: current state and perspectives. *Applied Microbiology and Biotechnology*, *85*, 849–860. https://doi.org/10.1007/s00253-009-2246-7

Wong, S. C. (2011). *Tapping the Energy Potential of Municipal Wastewater Treatment: Anaerobic Digestion and Combined Heat and Power in Massachusetts Massachusetts Department of Environmental Protection*

"Research Advisor" Allexe Law-Flood. Retrieved from https://www.mass.gov/files/documents/2016/10/wa/chp-11.pdf

Yoshida, H., Gable, J., & Park, J. (2012). Evaluation of organic waste diversion alternatives for greenhouse gas reduction. *Resources, Conservation and Recycling*, *60*, 1–9.

Young, C. (2020, February 27). Baker Cites "Real Benefits" In Eversource-Columbia Gas Deal. Retrieved March 22, 2020, from https://www.wgbh.org/news/local-news/2020/02/27/baker-cites-real-benefits-in-eversource-columbia-gas-deal

Zaks, D. P. M., Winchester, N., Kucharik, C. J., Barford, C. C., Paltsev, S., & Reilly, J. M. (2011). Contribution of Anaerobic Digesters to Emissions Mitigation and Electricity Generation Under U.S. Climate Policy. *Environ. Sci. Technol*, *45*, 6735–6742. https://doi.org/10.1021/es104227y