Valorisation of biowaste in the United States:

Distributed biogas upgrading to Renewable Natural Gas (RNG) using biomethanation

IEA Bioenergy: Task 36

June 2022

Valorisation of biowaste in the United States:

Distributed biogas upgrading to Renewable Natural Gas (RNG) using biomethanation

Authors: Beau Hoffman, U.S. Department of Energy,

Edited by: Kevin Harrison, National Renewable Energy Laboratory,
Daniel Roberts, CSIRO
Mar Edo and Inge Johansson, RISE

IEA Bioenergy: Task 36

June 2022

ISBN, 978-1-910154-91-5.

Published by IEA Bioenergy

Index

Preface

This is the third of a case study compilation to explore lessons on material and energy valorisation of waste within the framework of IEA Bioenergy Task 36. The set of case studies will be published during 2021 covering social and public acceptance aspects, barriers in Waste-to-Energy (WtE) implementation, success stories for decentralized solutions, and integration of WtE within material and/or nutrient recovery. The purpose of these case studies is to showcase examples from which countries can get inspiration and support in implementing suitable policies and solutions in the waste/resource management and WtE sector that would facilitate their transition towards circularity.

IEA Bioenergy Task 36, working on the topic 'Material and Energy Valorisation of Waste in a Circular Economy', seeks to raise public awareness of sustainable energy generation from biomass residues and waste fractions including municipal solid waste (MSW) as well as to increase technical information dissemination. As outlined in the 3-year work programme, Task 36 seeks to understand what role energy from waste and material recycling can have in a circular economy and identify technical and non-technical barriers and opportunities needed to achieve this vision.

See http://task36.ieabioenergy.com/ for links to the work performed by IEA Bioenergy Task 36.

Summary

Renewable natural gas deployments in the United States have increased significantly in recent years. As of 3/31/2020, there are 119 operational projects with a further 88 under construction. Renewable natural gas upgrading is a mature technology that processes biogas into high purity methane. Historically, amine, membrane, water scrubbing, or pressure-swing adsorption technologies have been used to perform this gas upgrading through the separation of carbon dioxide and methane. The process of biomethanation instead converts the carbon dioxide into additional methane through the addition of hydrogen.

In addition to increased yields of methane compared to incumbent separations approaches, biomethanation offers potential as a grid-scale energy storage technology by utilizing otherwise curtailed low-carbon electricity to produce the hydrogen needed by the organisms. Being a biological process, the hydrogen and carbon dioxide conversion is quickly 'rampable'. There have been several pilot- and demonstration-scale installations of the technology and this case study explores some of the economic and environmental considerations.

Background

Decentralized solutions for resource and energy recovery from waste streams are a critical aspect of the circular economy. For key fractions of organic waste such as food waste, municipal sludge, fats, oils, and greases, amongst others, they are highly correlated with population. As such, they are a distributed resource and often can be available in varying quantities. Moreover, one of the key economic challenges with organic waste management are transportation costs. These feedstocks often contain high levels (>75%) of water, and thus it is inefficient to haul them significant distances for centralized processing. As a consequence, processes and technology solutions are needed that can scale to the available resource and also provide products of value to localized markets.

Anaerobic digestion is commonly practiced to recover energy from single and mixed streams of waste. It has been demonstrated for many decades as an industrially robust technology. However, existing anaerobic digestion technologies are capitally intensive and produce a relatively low energy value product in biogas. Renewable natural gas (sometimes referred to as biomethane), is the product of biogas upgrading: carbon dioxide (CO_2) and other impurities (hydrogen sulphide, water, siloxanes, etc.) are removed rendering it energetically equivalent to fossil-derived natural gas and compatible with existing natural gas engines and infrastructure.

Biogas upgrading technologies are commercially available, with the most common solutions being membrane separations, pressure swing adsorption and other configurations of amine adsorption. In particular, the carbon dioxide separation technologies are operationally intensive as they require significant inputs of energy to regenerate the adsorbent material. Thus, renewable natural gas is often a considerable price premium relative to fossil natural gas sources.

Waste sources and logistics

Biomethanation is a technology that could be co-located with any biogas or other CO_2 source. This represents one of the key value propositions of this technology in that the process does not require any changes to existing organic waste handling processes. The resulting product, high-purity methane, when properly conditioned, is also compatible with existing transmission, distribution, and geologic storage infrastructure.

The biomethanation process uses a single-celled biocatalyst to convert CO_2 and hydrogen into methane, and in the case of biogas, the methane already present would pass through the biomethanation process unchanged. Opportunities for deployment of this technology are significant. In the United States, there are >2,000 anaerobic digesters that process a variety of organic waste streams including municipal wastewater residues, food waste, animal manure, and capturing biogas at landfills. As of the end of 2020, 312 upgrade the biogas into renewable natural gas (Energy Vision, 2020). Of those facilities that do not upgrade their biogas, many facilities are either flaring or combusting for on-site heat and power (Shen, 2015). In addition to biogas sources, CO_2 from other industries such as ethanol biorefineries are also potential sources of carbon for the technology.

The technology has a relatively small footprint (see figure 2 below): requiring the installation of a hydrogen-producing water electrolyzer system, the biomethanation reactor, and associated balance of plant equipment. This is a key consideration for space-constrained facilities in urban environments. The resulting product (renewable natural gas) must also have an offtake agreement such as on-site use by the wastewater treatment plant or development of an interconnect to an existing natural gas pipeline. The proximity to a natural gas pipeline is a key economic driver: in the United States, in urban areas this cost can be upwards of $1 million USD per mile and upwards of $250,000 per mile in rural areas (Lucas, 2015).

Organizations such as the Northeast Gas Association and other natural gas utilities have worked to establish shared specifications for renewable natural gas (Northeast Gas Association, 2019). This is a key step in ensuring compatibility across interstate pipelines and in lowering real and perceived risk of renewable natural gas injection into pipelines.

Technical Implementation

At the National Renewable Energy Laboratory (NREL), a 700 L biomethanation reactor and 125 kW polymer electrolyte membrane (PEM) electrolyzer were commissioned for this project and began operation in August 2019. The pilot project is a collaboration between Southern California Gas Company, Electrochaea GmbH, and NREL. The system processes 0.25 MMBtu/hr of methane, or approximately 250 scf/hr (7.07 m^3/hr). The process configuration is as follows:

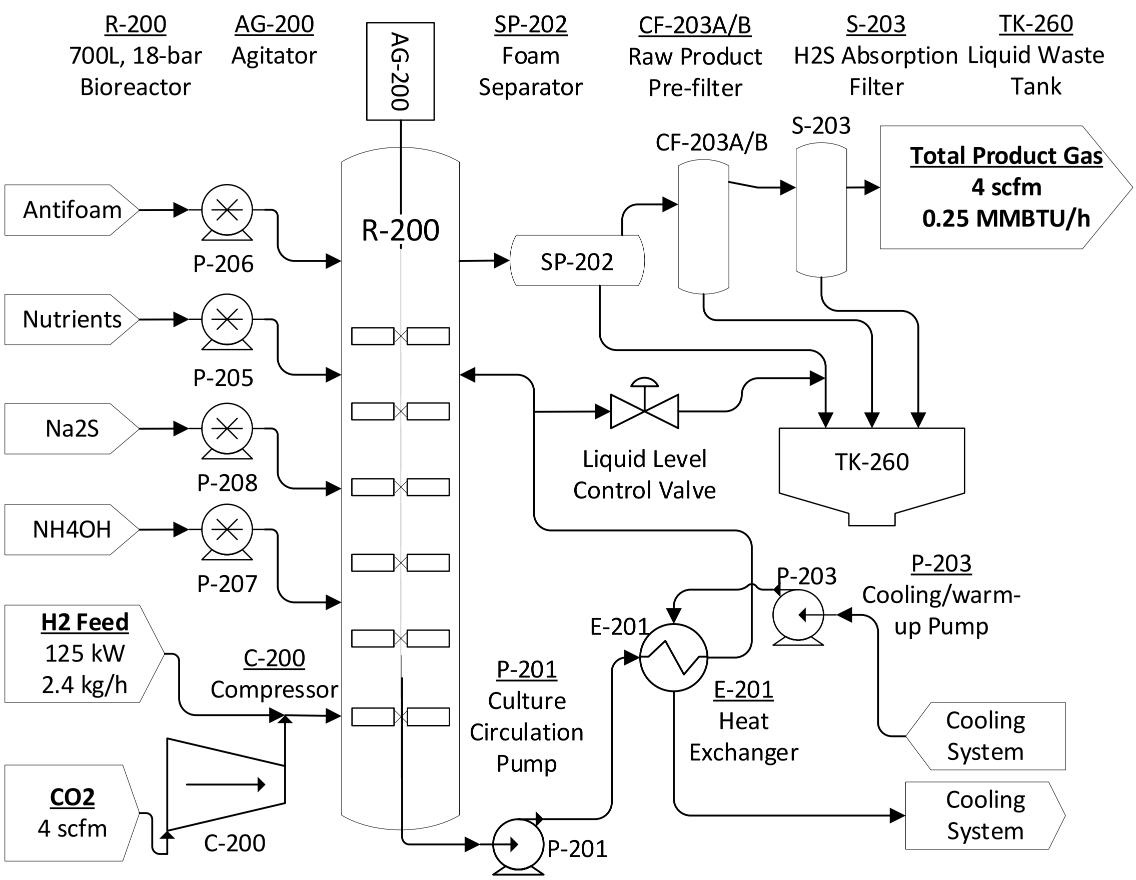

Figure 1. Biomethanation process flow diagram

In step 1, electricity is converted into hydrogen using a water electrolyzer. This step converts water and electrons into hydrogen, oxygen, and heat.

$$2\,H_2O + e^- \rightarrow 2H_2 + O_2 + Heat$$

A key aspect of the electrolyzer in this configuration is that the form of the hydrogen does not matter- whether it is dry or humid gas or even hydrogen dissolved in the electro-osmotically dragged water coming from the electrolyzer anode to the cathode. Oftentimes for hydrogen production, there are several drying steps necessary to remove excess water as liquid and vapor, especially when the hydrogen is to be used for fuelling of a fuel cell electric vehicle. Given that the downstream bioreactor operates in aqueous phase, this is not necessary and saves considerable capital and operating expense and increases hydrogen yield.

In step 2, the hydrogen is mixed with a CO_2 rich gas and fed to a bioreactor. The bioreactor contains a non-genetically modified microorganism (i.e., biocatalyst) that natively converts hydrogen and CO_2 into methane, water, and heat.

$$4\,H_2 + CO_2 \xrightarrow{Biocatalyst} CH_4 + 2H_2O\ + Heat$$

Due to its low solubility in water, hydrogen mass transfer is the limiting factor in the biomethanation process. The pilot-scale system at NREL operates at pressures up to 18 bar, which has been demonstrated to improve the requisite mass transfer rates of hydrogen to ensure CO_2 conversion. In addition, higher pressure reduces downstream gas drying and would reduce/eliminate downstream compression prior to gas injection. In addition to higher hydrogen mass transfer the NREL bioreactor operating pressure better matches the output pressure of the hydrogen coming from the electrolyzer. The temperature of the reactor is maintained at 60°C, which is the optimal temperature for the biocatalyst to produce methane. These factors enable lower capital and operating expenses compared to other industrial-scale processes. For example, thermochemical methanation using inorganic catalysis often operates at temperatures up to 300°C and 30 bar. Furthermore, large-scale industrial processes, like steam methane reforming operate at pressures up to 25 bar.

At the outlet of the bioreactor, sufficient CO_2 conversion has occurred such that the product gas stream contains less than 2% CO_2, giving it sufficiently high methane purity to be compatible with natural gas purity and energy content specifications.

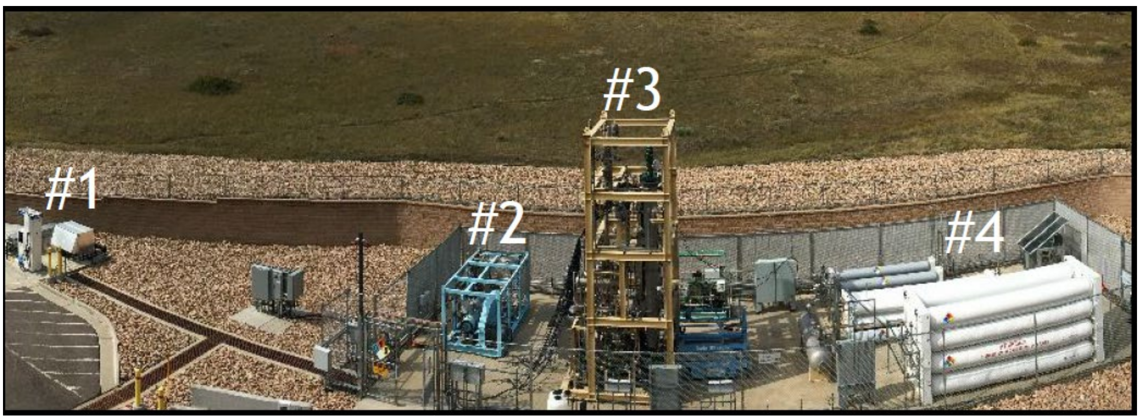

Figure 2. Biomethanation system installed at the National Renewable Energy Laboratory. 1: Hydrogen dispensing system; 2: Diaphragm and piston compressors; 3: Biomethanation bioreactor; 4: Pressurized

storage. The biomethanation system is a collaboration between the National Renewable Energy Laboratory, SoCalGas Company, and Electrochaea.

The unit at the National Renewable Energy Laboratory has been demonstrated for more than 300 continuous hours. Other installations of this technology in Copenhagen, Denmark and Solothurn, Switzerland have achieved > 1,000 hours of operation.

Economical aspects

The NREL installation described above is purely intended for research and development purposes- it is not selling the renewable natural gas for revenue, nor is it collecting incentives. However, there has been interest by utilities and biogas producers across the United States, each with unique value propositions. For the purposes of this case study, those are described herein.

Curtailed electricity, especially renewable electricity, is a growing challenge in parts of the United States. In California, wind and solar electricity curtailments have been growing rapidly and in 2020 approached 1.6TWh

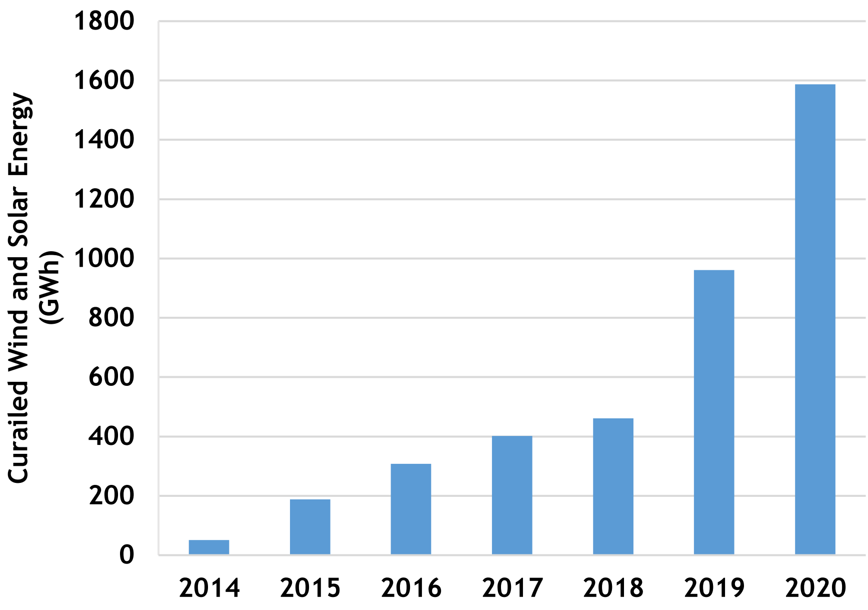

Figure 3. CAISO Wind and Solar Curtailments by year (GWh) (California ISO, 2021).

These curtailments are due to oversupply of renewable resources or localized transmission congestion could represent a barrier to further renewable energy penetration and therefore technologies that can serve in load-peaking or demand response roles are valued by system operators. In the case of biomethanation, the electrolyzer technology has demonstrated that it is capable of load following which could help to stabilize very high renewable electricity penetration on the grid. Furthermore, it has been shown that the biomethanation process is capable of load following the gas inputs to the process. Moreover, the product it produces, methane, is compatible with existing natural gas storage capacity and acts as a long-duration storage solution for the renewable electricity. In other portions of the United States, pipeline or grid congestion can cause challenges and this technology could also be used to alleviate concerns there. For example, states in the north-eastern United States are at the end of pipelines and generally pay more for natural gas. Localized production can also enable local resiliency both in times of energy shortages (e.g., natural disaster) or by enabling community ownership and supply. Individual system operators value these types of ancillary services differently, but they can be quite lucrative and could ultimately help to enable more renewable energy deployment.

NREL has conducted initial techno-economic analysis on the process as a whole. The table below outlines some of the base economic assumptions:

	Baseline Performance	Target Performance
System Scale – Electrolyzer (MW)	1	10
Bioreactor Power (kW)	45	220
System Scale – Total RNG (60/40) Output from digester and biomethanation process	125 Nm^3/h	1250 Nm^3/h
Electrolyzer Capital Cost (PEM)	$1,250,000	$4,000,000
Bioreactor/Biomethanation Capital Cost	$2,000,000	$6,000,000
Other Capital (Siting, Civil Works, Electrical, etc.)	$3,000,000 – 4,000,000	$10,000,000 - $15,000,000
Electricity Cost ($/MWh)	$40	$20
Excess Oxygen Credit ($/tonne)	$0	$40
Carbon Credit ($/tonne)	$0	$35
Bioreactor Conversion Rate (g CH4/L-hr)	13	20
Reactor Heat Recovery (%)	0%	80%
Electrolyzer Heat Recovery (%)	0%	80%
Footprint (m2)	150	450

Table 1. Economic parameters in techno-economic analysis. See figure 6 for sensitivity analysis on electricity cost and carbon dioxide credits.

In the table above, the Baseline column refers to performance that has been experimentally demonstrated to-date or the cost of existing systems. For example, the current PEM electrolyzer costs are estimated as $1,000,000 - $1,250,000/MW with an overall R&D target of achieving $400,000/MW. Likewise, the current bioreactor conversion rate is 13 g of CH_4/L-hr with a goal of achieving 20 g CH_4/L-hr with improved gas mixing at higher pressure. The ultimate goal is to achieve a renewable natural gas (RNG) selling price less than $14/MMbtu ($0.015/MJ) (Harrison 2021).

The current economics are very dependent on electricity costs for hydrogen production. A recent study by the American Gas Foundation (American Gas Foundation, 2019) estimates that the levelized cost of energy for renewable natural gas produced by this method would be around $40 - 50/MMBtu ($0.04-$0.05/MJ). By comparison in the United States, many sources of RNG utilizing pressure swing adsorption at large facilities are in the range of $7-$20/MMBtu ($0.007-$0.020/MJ).

Environmental Aspects

Avoided methane emissions are a key environmental aspect of this technology. As noted above, many wastewater treatment plants and other producers of biogas do not beneficially utilize this fuel. The result is the CO_2 and methane are vented into the atmosphere. Converting or upgrading this biogas into renewable natural gas results in a market-saleable product that when combusted only produces CO_2. Given the spread in greenhouse gas (GHG) potency between methane and CO_2, this results in considerable emissions savings. Recycling biogenic CO_2 and using renewable natural gas from waste streams avoids adding new carbon to the atmosphere from fossil sources.

Increasing revenues for anaerobic digesters could also increase their deployment and utilization, thereby increasing the amounts of organics that are diverted from landfills. Many of these organic waste streams (municipal sludge and food waste in particular), readily evolve into methane in a landfill and released to the atmosphere. This biodegradation into biogas often takes place before landfills are capped and capture technologies are implemented resulting in fugitive emissions. Regardless of outcome, it has been demonstrated, as shown in figure 4 below that any organics management strategies result in GHG reductions relative to business as usual (Lee, 2017).

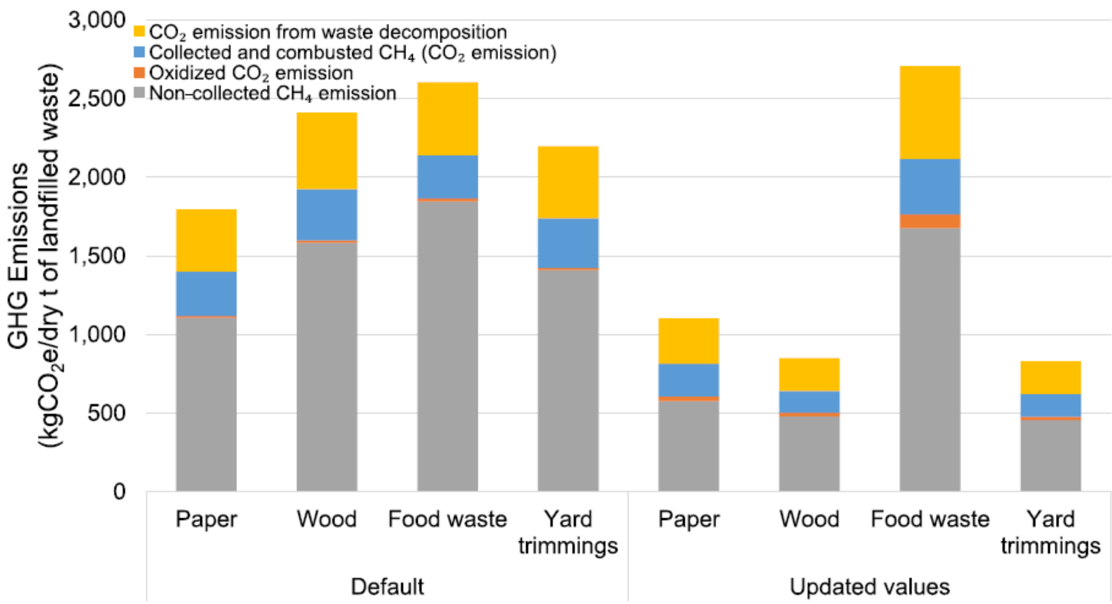

Figure 4. Emissions associated with various landfilled wastes. From Lee et al (2017). Updated values utilize individual degradable carbon actually decomposed values as opposed to a single value representing all MSW fractions.

Policy Aspects

Low Carbon Fuel Standard

In California, the low-carbon fuel standard (LCFS) is rapidly driving deployment of decarbonization strategies through renewable fuels. The LCFS was first adopted by the State of California to decarbonize the transportation sector. Since its implementation, several other states have implemented LCFS policies as has British Columbia, Canada. Other states are considering LCFS-like policies.

The credit value is based on a carbon intensity score that is assigned to the life cycle of the process including producing, distributing, and consuming the fuel (gCO_2e/MJ). Once the carbon intensity score is calculated, it is compared to the benchmark fuel. For liquid transportation fuels this would be the average gasoline or diesel carbon intensities (90.74 and 91.66 gCO_2e/MJ), respectively (California Air Resources Board, 2020). In the case of fossil natural gas, the carbon intensity benchmark is 74.1 gCO_2e/MJ.

Once the carbon intensity for the process is calculated and certified, credits can be obtained based on how far below the carbon intensity is compared to the benchmark fuel and credits are given based on the current carbon price. In this way, the policy incentivizes pathways and products that achieve greater carbon reductions. In early 2021, the carbon price has averaged around $200/metric tonne (California Air Resources Board, 2021). Figure 5 below shows the estimated LCFS credits available from a variety of biogas sources.

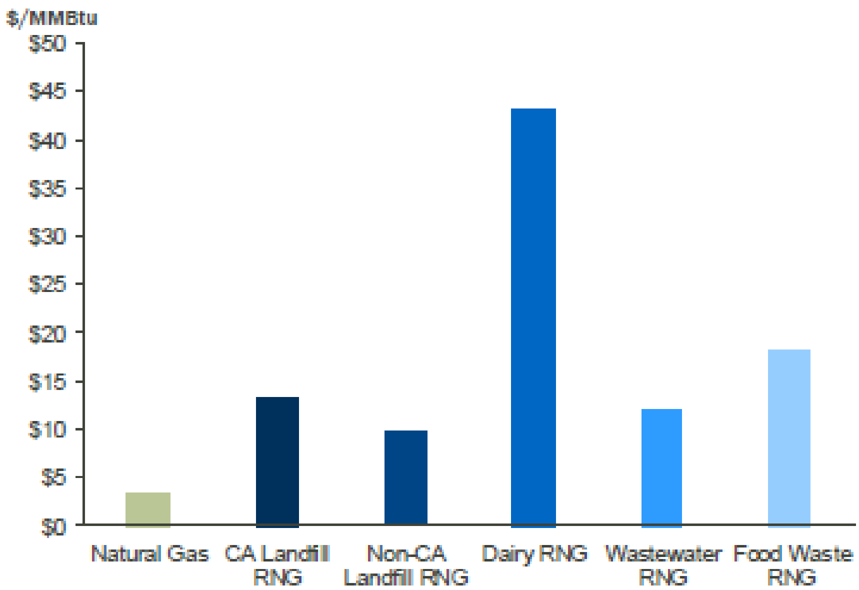

Figure 5. LCFS credit value by source of RNG. Source: California Air Resource Board assuming LCFS Credit price of $155/MT.

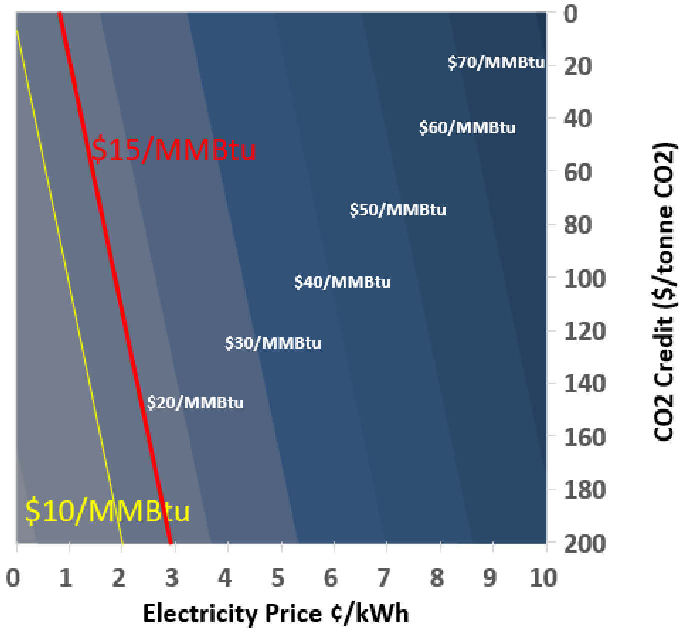

Figure 6. Surface plot showing sensitivity to RNG selling price relative to carbon dioxide credit price and electricity price to generate hydrogen. Individual contours so the price competitivity as a function of electricity price and carbon dioxide credit price. This analysis assumes a 10MW electrolyzer, bioreactor productivity of 20 g CH_4/L/hr, and electrolyzer capex of $400/kW. Source: National Renewable Energy Laboratory

Renewable Fuels Standard

The Renewable Fuel Standard (RFS) is another credit program for the production of renewable fuels. The RFS is available across the United States and is administered by the United States Environmental Protection Agency. The policy currently only covers transportation fuels, so any credits can only be given if the fuel is used in a transportation application. These credits are often traded and 'bought' by transportation users.

The RFS recognizes a handful of renewable fuels including starch-derived ethanol, renewable diesel, biodiesel, amongst others was created by the Energy Independence and Security Act of 2007. Under this program, fuels are categorized based on their greenhouse gas reductions and feedstock. For example, starch ethanol, considered a renewable fuel receives a "D6 Renewable Identification Number" or "D6 RIN". In the context of biomethanation, certain biogas sources such as manure or wastewater residuals are considered as cellulosic and are eligible for a more valuable "D3 RIN". Currently (as of March 1st, 2021) D3 RINs are trading for $2.07/RIN which equates to ~$27/MMBtu (~$0.028/MJ). Relative to the techno-economics described above, this credit is a significant incentive to RNG producers.

Renewable Energy Certificates

Renewable Energy Certificates (RECs) are a common incentive for a variety of renewable energy sources, including biogas or renewable natural gas. RECs are used in the United States to track the production and eventual use of renewable electricity. The price assigned to a REC varies by state and depends on several factors. Certain RECs have additional premiums due to specific renewable portfolio targets set forth by that state. These differ from feed-in-tariffs, as RECs prices can fluctuate based on market factors whereas feed-in-tariffs are fixed guarantees to that producer. REC prices have decreased over the years as many states have approached their renewables targets. Most RECs are under $50/MWh at present, down from hundreds of $/MWh around 10 years ago.

It is speculated that RECs associated with renewable natural gas could gain increased premiums if renewable gas standards are passed. At present the province of Quebec, Canada has set a target of 10% renewable natural gas by 2030.

45Q Tax Credit

The 45Q tax credit in the United States offers up to $35/tonne of CO_2 for technologies that capture and reuse carbon dioxide (Internal Revenue Service, 2020). In this case, only the CO_2 fraction of the biogas would be eligible for consideration. In the case of this technology, that credit value is estimated to be $2.24/MMBtu.

Landfill Organics Bans

As of the time of writing, six states have implemented organics bans to landfills with many other states and municipalities having established diversion targets. These organics bans are due in part to the desire to avoid fugitive methane emissions as well as due to decreasing landfill capacity. At present, there are limited technologies and capacity for managing the organic waste that can no longer be transported and disposed of in landfills. Anaerobic digestion is one mature technology that can serve to reduce the volumes of organics and thus may be poised for significant growth. Consequently, technologies for upgrading the biogas will be necessary as well. The financial implications of these policies are not certain; however, it is logical to expect that it will result in increased handling and tipping fees by processes that ultimately handle these wastes.

Social aspects

Organic waste handling and conversion practices require significant amounts of stakeholder engagement and community support to be successful. In the United States, there have been numerous biogas projects that have resulted in odor, lower air quality, and other protests from local community members. Organic waste handling infrastructure is also disproportionately sited in disadvantaged and already pollution-burdened communities. There are many known and hazardous impacts resulting from these facilities including odor, noise, infectious disease vectors, litter, and particulate emissions (Krystosik, 2020). There are also documented impacts associated with these air and water quality impacts including sleep interruption, mental health deterioration, increased anxiety, and overall decreased quality of life (Donham, 2017). It can sometimes be difficult to decouple the anaerobic digestion or upgrading processes from other waste handling practices and often, concerns from the community members get directed at the whole system.

As a relatively new technology, it will be important for utilities that implement biomethanation to proactively engage in stakeholder engagement and education about the benefits and risks of the technology. Considerations include but are not limited to:

- Use of extremophilic microorganisms and handling practices
- Aggregation of wastes to a centralized location (odor, water quality impacts, volatile organic compounds)
- Use of pressurized hydrogen (noise, combustion hazards)
- Physical footprint concerns
- Physical appearance and aesthetics of equipment in the community
- Natural gas pipeline interconnections and right-of-ways
- Workforce requirements/opportunities
- Perceptions of natural gas
- Impacts on utility rates

References

American Gas Foundation (2019). Renewable Sources of Natural Gas: Supply and Emissions Reductions Assessment.

California Air Resources Board (2020). *Low Carbon Fuel Standard.* https://ww2.arb.ca.gov/sites/default/files/2020-09/basics-notes.pdf

California Air Resources Board (2021). *Weekly LCFS Credit Transfer Reports.* https://ww3.arb.ca.gov/fuels/lcfs/credit/lrtweeklycreditreports.htm

California ISO (2021). *Managing Oversupply.* http://www.caiso.com/informed/Pages/ManagingOversupply.aspx

Donham, K. J. et al. (2017) Community Health and Socioeconomic Issues Surrounding Concentrated Animal Feeding Operations. *Environmental Health Perspectives.* 115(2) 317-320. doi: 10.1289/ehp.8836

Energy Vision. (2020) Study Shows Rapid Expansion of US RNG Industry. *Biomass Magazine.* http://biomassmagazine.com/articles/17605/study-shows-rapid-expansion-of-us-rng-industry

Harrison (2021). BETO 2021 Peer Review : Biomethanation to upgrade biogas to pipeline natural gas. https://www.energy.gov/sites/default/files/2021-04/beto-14-peer-review-2021-organic-harrison.pdf

Internal Revenue Service (2020). Section 45Q Credit for Carbon Dioxide Sequestration. US Department of the Treasury.

Krystosik A, Njoroge G, Odhiambo L, Forsyth JE, Mutuku F and LaBeaud AD (2020) Solid Wastes Provide Breeding Sites, Burrows, and Food for Biological Disease Vectors, and Urban Zoonotic Reservoirs: A Call to Action for Solutions-Based Research. *Front. Public Health* 7:405. doi: 10.3389/fpubh.2019.00405

Lee et al 2017. Evaluation of landfill gas emissions from municipal solid waste landfills for the life-cycle analysis of waste-to-energy pathways. *Journal of Cleaner Production.* 166 (2017) 335-342. https://doi.org/10.1016/j.jclepro.2017.08.016

Lucas, Jim (2015). Utility Case Study: Build, Own, Operate. 4th Annual Anaerobic Digestion and Biogas Summit. San Diego, CA.

Northeast Gas Association (2019). Interconnect Guide for Renewable Natural Gas (RNG) in New York State.

Shen, Y. et al (2015). An overview of biogas production and utilization at full-scale wastewater treatment plants (WWTPs) in the United States: Challenges and opportunities towards energy-neutral WWTPs. *Renewable and Sustainable Energy Reviews.* 50 346-362. https://doi.org/10.1016/j.rser.2015.04.129

IEA Bioenergy

Technology Collaboration Programme