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Research paper

Renewable natural gas: A case study of Minnesota

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ABSTRACT

Renewable natural gas (RNG) often generates usable energy from waste products, reduces methane emissions, and creates new revenue streams. However, not all RNG projects are financially or technically feasible. We assessed the total RNG potential of currently available local waste feedstocks in the state of Minnesota and analyzed the financial and technical limitations for project development. We found that under ideal production conditions the RNG potential from municipal solid waste, dairy and hog farm manure, and municipal wastewater solids in the state could replace approximately 7.5% of current Minnesota natural gas use. We find that technical and financial factors such as project size, financing, and distance to an existing pipeline further reduce the number of feasible RNG project sites in Minnesota. Virtual pipelines – trucking RNG short distances to pipeline injection stations – improved the modeled profitability of 124 out of 175 projects (71%) by decreasing transmission costs. No projects are financially feasible without state or federal renewable fuel credit programs because direct sale of RNG alone does not cover project costs. Dairy manure projects have the lowest levelized cost of energy, the highest total revenue, and the shortest payback period compared to municipal solid waste landfill and wastewater treatment plant projects of similar size. This difference is because manure anaerobic digestion projects are eligible for larger credits under renewable fuel credit programs than municipal solid waste landfills and wastewater treatment plants, but this credit system limits end-use of the RNG to vehicle fuel. Our contribution helps provide an outline for the magnitude of current natural gas use in Minnesota replaceable via RNG projects.

1. Introduction

The world is now warming faster than at any point in recorded history and fossil fuels are the largest contributor to this global climate change [1]. Our current energy system is entwined with the production and use of fossil fuels, supported by physical, economic, and social constraints that make changes to the existing energy structure difficult [2]. Despite concerns about the climate and environmental impacts of natural gas leakage during production and transport, natural gas infrastructure continues to expand [3]. The rapid expansion of natural gas infrastructure has led to concerns that assets stranded by the transition to a low-carbon economy will result in major financial losses, and that these losses will hinder a renewable energy future [3,4].

Renewable natural gas (RNG) has the potential to serve as a “drop-in” replacement for fossil natural gas, thus preventing the financial loss of stranded natural gas infrastructure. When the RNG used to replace fossil natural gas is made by capturing methane (CH_4) released from decomposing waste materials, it reduces total greenhouse gas emissions compared to fossil gas and contributes to decarbonizing the energy system [5,6]. The substitution of RNG for fossil gas is straightforward because RNG is interchangeable with fossil natural gas in the pipeline network and can be mixed with fossil gas in distribution systems, which preserves the use of existing infrastructure associated with industrial use, electricity generation, and residential heating and cooking [1–3]. These factors make RNG an attractive renewable energy carrier.

There are several methods to produce RNG: from biomass through thermochemical means, by converting surplus renewable electricity to CH_4, or from purification of biogas. Biogas can be collected from landfill gas emissions or intentionally produced from anaerobic digestion facilities using wastes such as livestock manure, food scraps, agricultural residues, or wastewater solids [7–9]. The CH_4 and carbon

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dioxide (CO_2) content of biogas depends on the feedstock, and can range from 40%–80% CH_4 and 20%–60% CO_2 by volume, with trace amounts of contaminants [9–12]. To turn biogas into RNG, contaminants such as CO_2, water (H_2O), hydrogen sulfide (H_2S), and siloxanes must be removed, leaving mostly CH_4 [9,12,13]. The toxic or corrosive compounds H_2O, H_2S, and siloxanes are removed first through methods such as adsorption on activated charcoal, chemical absorption, and biological treatments to prevent damage to the biogas processing equipment [12,14,15]. The biogas is upgraded to a higher CH_4 content by removing excess CO_2 [12]. There are multiple methods for separating CO_2 from CH_4 in biogas including pressure swing adsorption, water washing, cryogenic processing, and membrane separation, and the choice of technique depends on multiple factors such as facility size and biogas flow rate [16–18]. The resulting RNG is chemically identical to fossil natural gas and can replace fossil natural gas in most applications [12].

Several previous studies have assessed RNG potential at national, state, and regional levels. These studies can be classified as either prospective analyses of the RNG production that would be possible with the advent of new technologies and feedstocks, such as sequential cropping of dedicated energy crops [19] or the conversion of surplus renewable electricity into RNG through electrolysis followed by methanation [20], or analyses of RNG potential using existing feedstocks and technologies [21–23]. Previous studies have carried out assessments for countries with diverse NG uses, economies, infrastructure, and waste streams such as Chile [21], Poland [22], Denmark, Germany and Italy [23], the United States [20], and Argentina, Italy, France, the United Kingdom, and the United States [19].

The European Union (EU) and United Kingdom (UK) dominate global RNG production. In 2022 they produced 45% of global biogas compared to 12% in the United States [24]. Multiple analyses have attributed the high level of production in Europe to the common European framework that provides a clear objective, as well as comprehensive and attractive regulations at the country level [23,25,26]. Cross-country comparisons show that long-term policies create a stable investment environment favorable to growth of biogas production [25,26]. The stability of biomethane support policies seems to be more important than the specific policy, with no one policy measure being critical to success [27]. Successful policies or instruments to stimulate biogas development depend on local or national context and may not be directly transferable from one country to another [25].

Each policy that incentivizes RNG production tends to favor specific technology, feedstock, or use. For example, the focus on renewables of Germany's Energiewende ('energy turnaround') policy led to the rapid early development of farm-based biogas plants with on-site electricity production from energy crops and livestock manure [23]. In Denmark, incentives introduced in 2014 and 2020 favored the injection of large volumes of RNG into the natural gas grid, achieving a 37.9% biomethane share in 2023 [23,24,26]. In Italy, biomethane policy has focused on injected biomethane for transportation, which in 2021 consumed over 5.7×10^{12} GJ of biogas [23,24,28].

Despite their success in promoting RNG development, policies directed at specific technologies, feedstocks, or uses can lead to lock-in effects that can be difficult or costly to reverse [26]. It can also be difficult to design policies and set subsidy levels that are economically efficient and sustainable [26]. For example, in the U.S., between 1982 and 2011 biomethane production was nearly all used for electricity production in response to state-level renewable portfolio standard (RPS) programs that require a certain percentage of the state's electricity generation portfolio come from a specific source [25]. However, as a result of the federal Renewable Fuel Standard (RFS) program and state programs like the California Low Carbon Fuel Standard (LCFS) about 87% of upgraded biogas is now used as natural gas vehicle fuel [25]. Unlike the EU, in the U.S. there is no comprehensive RNG development plan, but there are an increasing number of state incentive programs [25].

State and regional assessments of RNG production potential have been reported for New Jersey [29], New York [30], California [31,32], Iowa [33] and Long Island in the state of New York [34]. When state and regional assessments compare feedstocks, they find landfills can produce the most RNG. However, RNG production potential is governed by feedstock availability and location, gas distribution infrastructure, technology, and policy particular to a location and time, which was not examined in all studies. For example, Myers, et al. (2023) found that a single, shared AD system and injection point for multiple swine farms in Iowa was more cost-effective than transporting natural gas from swine manure AD facilities at individual farms, but the financial feasibility depended on RNG credit systems [33]. Dyer, et al. (2021) found that more wastewater treatment plants in New Jersey are located near existing NG pipeline infrastructure compared to landfills, which makes wastewater treatment RNG projects more attractive from the perspective of transmission costs [29]. It is therefore important to consider factors that impact local economics, transportation feasibility, and feedstock availability.

This study is the first to examine RNG production potential in Minnesota (MN) using available local waste feedstock with consideration for economic and transportation factors. We focus on MN because in June of 2021, MN Governor Tim Walz signed the MN Natural Gas Innovation Act (NGIA) to encourage natural gas utilities in MN to develop innovative resources including RNG [35]. The NGIA permits natural gas utilities to file innovation plans with the MN Public Utilities Commission (PUC) outlining alternative natural gas resource development plans that cost-effectively reduce lifecycle carbon emissions. The first dairy anaerobic digester to produce RNG for pipeline injection in MN came online in 2021 [36], and the first MN landfill RNG project for pipeline injection came online in 2022 [37]. This highlights how RNG development is in the early stages in MN, and makes the state an interesting test case for analysis of RNG potential.

In this paper, we analyze the RNG production potential of available waste feedstock in the state of MN, with the goal of identifying the technical and economic limitations and advantages to RNG development. In Section 2, we examine the RNG feedstocks available in MN and the costs and revenue streams of production. In Section 3, we report the theoretical maximum possible RNG that could be produced from each feedstock and we consider the natural gas transmission capacity and geography, the finances of various RNG project types, along with relevant greenhouse gas emission reductions. In Section 4, we discuss the implications of our findings for the development of RNG in MN, with specific focus on the financial incentives that may be required for new projects to be feasible.

2. Materials and methods

2.1. Description of available feedstocks

To assess the RNG potential in MN, we first identified the volume of potential RNG feedstocks within the state. In this paper, we focus on municipal solid waste, animal manure, and wastewater treatment solids as feedstocks for RNG production. These feedstocks have existing methods in place for collection (e.g., trash trucks, manure flush systems, and city sewers) and storage (e.g., municipal solid waste (MSW) landfills, settling ponds or tanks on farms, and wastewater treatment plants (WWTPs)).

There are additional potential RNG feedstocks in MN, such as agricultural residues and food scraps, that are not considered in this analysis. We excluded food scraps because these are currently part of the municipal solid waste stream which is included in estimates of landfill gas production potential. Diverting food wastes from landfills to separate anaerobic digestion streams involves composting efforts on the part of municipalities that may be costly and reduces the RNG potential of landfills [38,39]. We did not consider food waste in our initial analysis because of these limitations. Agricultural residue was excluded because of uncertainty in available feedstock size and technical challenges associated with anaerobic digestion [40–43]. Agricultural residues are a challenging feedstock because the lignocellulosic composition of the woody and leafy fractions of these materials are difficult to digest anaerobically [38]. Large fractions of agricultural residues are also already used in secondary processes [40]. Finally, diverting and collecting agricultural residues for use in RNG production is also technically difficult due to their highly distributed nature and the lack of proven technology to collect and store these materials [42,43]. The theoretical RNG production potential of these materials are compared in Section 4.

Municipal Solid Waste Landfills

Landfill gas (LFG) is the gas produced within landfills from the breakdown of waste materials and contains 40%–60% CH_4 by volume. Peak gas production usually occurs five to seven years after wastes are placed in the landfill which results in a build-up of pressure if capped with an impermeable cover material [11]. To prevent excess pressure from building, pump wells are drilled through the deposited waste and LFG is collected. Landfills are federally required to be monitored and maintained for at least 25 years post closure, at which time LFG production is essentially zero [44]. The high concentration of CH_4 and the fact that LFG is produced by landfills consistently for many years post-closure makes LFG a viable RNG source [6].

Controlled Anaerobic Digestion of Manure and Wastewater

Controlled AD is the intentional microbial fermentation of organic material under controlled oxygen-free conditions. In this process, microbes digest decomposing organic solids and release biogas, composed of mainly CO_2 and CH_4. The type of organic material, the microbial community, and the digestion conditions all impact the quality of biogas produced [38]. AD systems are often used in wastewater treatment facilities to treat waste solids and can be used to contain and treat animal manure at livestock farms [5,7]. Animal manure used in anaerobic digestion is mostly made of animal feces and small amounts of water but may include other organic material, such as straw for bedding and other farm wastes [38]. We focus on dairy cattle and swine manure, and do not include poultry manure because there are approximately ten times fewer farmed poultry animals than either swine or cattle, and each bird produces far less manure volatile solids than swine or cattle [45,46].

2.2. Theoretical maximum RNG production

We calculated a theoretical maximum amount of RNG that could be produced from each feedstock based on the estimated mass or volume of feedstock material in MN and the maximal amount of CH_4 that could be produced from the feedstock per unit mass or volume. We assume no feedstock loss during collection or transport, that the CH_4 fraction of biogas produced through anaerobic digestion is 60% [47] and from MSW landfills is 50% [10], and that no CH_4 is lost during the gas cleaning processes (100% gas upgrading efficiency). The metrics and sources we used for calculating theoretical maximum RNG production potential are listed in Table 1.

We used publicly available data repositories, industry reports, and peer-reviewed journal articles to estimate both the amount of feedstock in MN and the potential for that feedstock to produce biogas. Information on the location and size of the potential RNG projects at dairy cattle farms, hog farms, and WWTPs in MN was collected from Minnesota Pollution Control Agency (MPCA) Geospatial Commons [48,49]. For animal manure, we estimated the total mass produced in a year from the number of animals reported by the MPCA [48,50]. For swine manure, we used pig animal units (AU) rather than the number of swine because the MPCA used these units to combine pigs of different sizes at each farm, and we assumed that 1 pig AU was approximately 0.4 pigs greater than 55 lbs [48,51]. We averaged CH_4 production per mass of swine manure from several studies that tested production from different types of digesters and swine farms. We included all head of dairy cattle reported by the MCPA, which includes dairy calves and non-milk producing dairy heifers. We included both domestic and industrial WWTP facilities. We focused on MSW landfills and did not consider other types of landfills such as industrial or hazardous waste. We used the MPCA SCORE reporting for MSW generation between 1999–2019 to estimate total tonnage of MWS that went to landfills [52].

Table 1
Metrics for theoretical maximum RNG production.

Resource	Number in MN	Gas from waste
Municipal solid waste	40.6 million tons MWS [52] at active landfills between 1999–2019	1.85 m^3/yr LFG/million tons MSW [53]
Dairy cattle manure	1.2 million dairy cows and 19,856 kg manure/cow/yr [48,50]	0.023 m^3 CH_4/kg wet manure [5]
Swine manure	2.75 million pig AU and 4565.6 kg manure/pig AU/yr [48,54]	0.038 m^3 CH_4/kg manure [33,55–57]
Wastewater treatment solids	1419 domestic and industrial plants, 1.08 billion m^3 wastewater/yr [49]	0.12 m^3 biogas/m^3 wastewater [58]

2.3. Techno-economic feasibility

After calculating the theoretical maximum RNG production, we estimated the total RNG that could be produced considering technical and financial feasibility. Economies of scale dictate that there is a minimum viable project size for each biogas production technology. Facility size is an important factor in determining the capital cost of gas processing technology, the operating expenses, and biomethane potential of a project. The supply of feedstock must be large enough to produce sufficient biogas to cover capital and operational expenses and be sufficiently uniform to allow high-capacity utilization without incurring large feedstock storage costs.

Table 2 outlines the minimum viable project sizes we identified as cut-off values for feasible biogas projects in MN. The size cut-off for WWTP comes from a review of existing facilities which showed that WWTP must have a flow rate of at least 3785 m^3/day to be technically and financially feasible for RNG development [7]. The EPA recommends at least 500 head of cattle for dairy manure AD systems, though an analysis of existing projects in the EPA digester database shows that most projects have at least double this number [59,60]. We chose 2000 cows as a conservative cut-off for our financial feasibility analysis based on interviews with individuals involved with dairy cattle anaerobic digester projects and we included only milk-producing cows in feedlots. For swine manure, we focused on facilities that had more than 2000 pig AU, or approximately 5000 swine [51]. The EPA AgSTAR program recommends 2000 swine for AD systems, but notes that 5000 swine is more reasonable for farms that use deep pit manure management systems, which represents 50% of the farms in MN [61]. We focused on cattle and swine located in concentrated animal feeding operations (CAFOs) because the manure from these types of facilities can feasibly be collected as compared to animals on pasture.

The EPA has recommendations for how to select MSW landfills suitable for RNG development, which were used by Dyer, et al. to assess RNG potential from landfills in New Jersey [29,62]. These recommendations include volume of waste, depth of the landfill, average annual rainfall, landfill age, and minimum LFG flow rate. We focused on active landfills in MN in 2019, as all closed landfills monitored by the MPCA were older than 20 years and would produce insufficient LFG for RNG production [8,63]. We did not limit inclusion of landfills in our calculations beyond their age. In 2019, there were 20 active landfills

Table 2
Facility requirements for feasibility assessment.

Feedstock	Technical feasibility requirements
Dairy manure	>2000 cattle, located in CAFO
Swine manure	>2000 pig AU, located in CAFO
Landfill gas	Active Landfills inventoried by [53,65,66]
Wastewater treatment solids	>3785 m^3/day [7]

accepting waste and one landfill in the process of closing [52,64]. To calculate the total amount of waste at each landfill, called the waste-in-place, we used the EPA's Landfill Methane Outreach Program (LMOP) database for data on 11 landfills, and annual reports for data on two additional landfills [53,65,66], meaning that nine further landfills were unaccounted for. To account for the age of landfills, we annualized the waste-in-place numbers for each landfill and considered the viable waste to be 20 years of annualized waste. This is because areas of landfills that have not received waste for several decades (closed faces) have very low biogas production capacity [44], but the total waste in those areas is included in the EPA LMOP database. Several of the active landfills in MN have been open for over 50 years and have sections that have been closed for decades [53]. By annualizing the waste volume and using 20 years of annualized waste, we reduce the overestimate in our analysis.

We next compared the cost to connect each facility to the existing natural gas pipeline infrastructure by either physical or virtual pipelines. Connection by physical pipeline involves laying new pipe from the facility to the existing infrastructure. Connection by virtual pipelines means trucking RNG from production facilities to injection stations along existing physical pipelines. The choice of transportation method is a function of potential production volume because virtual pipeline transportation is only cost-effective at small production volumes while physical pipelines represent a large upfront cost. We assumed that new pipeline would cost $612,000 per kilometer for a 10 cm diameter pipe ($1 million per mile for a 4 in diameter pipe) [67]. The transportation costs of compressed natural gas (CNG) for small volumes at short distances is estimated at $1.90 per GJ ($2 per mmBTU) [68]. We compared the costs of connecting to a physical pipeline with using a virtual pipeline to identify the most cost-effective method for transporting the RNG for each potential RNG facility. For both methods, installation of an injection station is necessary, which has associated costs for permitting, interconnection fees, and equipment, but with virtual pipelines the injection station cost may be shared among multiple facilities using the same station.

In analyzing economic feasibility, we considered typical costs as a function of facility size and potential revenue streams. Costs associated with an RNG project are separated into upfront capital costs (CAPEX) and annual operation and maintenance costs (OPEX). The CAPEX includes procurement, purchase, and installation of process equipment involved in a project, We estimated CAPEX to scale linearly with project size for WWTPs and dairy manure digesters [9,69]. For MSW facilities and swine manure digesters we used empirical correlations determined from literature [32,33,70]. OPEX encompasses the annual costs required to run and maintain a system, including annualized costs for major repairs and employee salaries. We included electricity and natural gas costs to run the RNG production equipment in our OPEX calculations, both of which scaled linearly with RNG production capacity based on literature scaling factors [20,71]. We estimated annual OPEX costs as 10% to 15% of the CAPEX depending on the feedstock [20,69].

Three revenue streams are included in this analysis: the sale of natural gas, payments from the federal carbon credit system under the RFS program, and payments from the LCFS program. The RNG projects derive revenue from the sale of the produced gas. Utilities paid $3.62 per GJ ($3.82 per mmBTU) to natural gas providers (the Citygate price) in 2019 [72]. If a facility chooses to upgrade their biogas to the standard for use in vehicles, the RNG is eligible for the RFS federal carbon credit program [73]. All RNG within the scope of this report is considered cellulosic biofuel and earns $3/D3 RIN, which equals $36.96/GJ produced [73]. The LCFS program, administered by the California Air Resources Board, is an example of a state program that aims to reduce the carbon intensity of the transportation fuel mix in California [32]. The eligibility of MN RNG projects for the LCFS credit program is discussed in Section 4. In the LCFS program, each RNG feedstock has a lifecycle GHG impact which determines LCFS credit value. We assumed $115/MT CO_2eq LCFS price. Table 4 lists the LCFS credit values for each feedstock. Both RIN and LCFS credits are subject to fluctuation and vary depending on market conditions [32,73].

Table 3
General parameters for economic feasibility modeling.

Parameter	Assumed value
Installation and contingency costs	25% of CAPEX [20]
Interconnect cost	$2,000,000 [32]
Capacity factor	95% [20]
Physical pipeline cost	$61,200/km-cm
Pipe diameter	10 cm
Virtual pipeline cost	$1.90/GJ
Discount rate	0.07
Project lifetime	20 yr
Tax rate	21%
Depreciation	Straight-line over lifetime
Price of natural gas	$3.62/GJ [72]
Carbon intensity of fossil-fuel based natural gas	67.70 gCO_2eq/MJ [73]

Using these cost and revenue streams, we estimated the economic feasibility of potential RNG projects in MN. Modeling was performed in Microsoft Excel. Each potential RNG production facility used either virtual transmission to a centralized injection point (no interconnect fee) or natural gas piped to a bespoke injection point (interconnect fee charged) depending on which was less expensive. General modeling parameters are listed in Table 3, while feedstock-specific parameters are listed in Table 4.

2.4. Avoided greenhouse gases

To calculate the total GHG avoided, we accounted for both the replaced fossil gas and the avoided CH_4 emissions. Fossil gas on average results in approximately 50 gCO_2/MJ when fully combusted, not accounting for leaks and other inefficiencies [75]. We assume this same offset on a per volume basis for all RNG feedstocks. The second category of GHG reductions is found in the CH_4 releases that RNG production avoids. We used the carbon intensity of each representative feedstock according to the California LCFS program to calculate the avoided CH_4 emissions [74]. We then calculated a levelized cost of avoided GHG emissions and compared these costs to the MN social cost of carbon. The social cost of carbon is an estimate of the cost of the damage due to one ton of carbon emissions, or how much money can be saved by preventing the damage from one ton of carbon emissions. The MN Public Utilities Commission calculated social cost of carbon for 2019 ranges from $10.51 to $49.34 per metric ton of CO_2 equivalent (MT CO_2-eq), depending on the discount factor used [76].

2.5. Example cases

To demonstrate the method of financial analysis and cost-sensitivity, we examined three example RNG projects more closely. The three facilities are the West River Dairy, the Spruce Ridge Landfill, and the Seneca Wastewater Treatment Plant. Each facility could produce approximately 750 m^3/h of biogas, although none of these facilities currently produce biogas for RNG production. We assumed the same OPEX, CAPEX, and revenue streams as was used in the techno-economic feasibility modeling. Reported payback periods are calculated with the simple payback period formula (neglecting the time value of money)

Table 4
Feedstock-specific parameters for economic feasibility modeling.

Parameter	MSW landfill	Dairy farm AD	WWTP	Swine farm AD
CAPEX	$6 \times 10^6 \times e^{0.0003 \times BG}$ [32]	$1500/cow [50,69]	4.77×10^{13}/m^3 wastewater [7]	$9900 \times V^{.59} + 2.3 \times 10^6 \times BG^{0.552}$ [33]
OPEX (% CAPEX)	15% [20]	10% [5,20]	10% [20]	10% [5,20]
California LCFS credit ($/GJ) [73]	2.61	33.66	5.19	19.23
Baseline carbon intensity of RNG (gCO_2eq/MJ)	45 [74]	−225 [74]	22.5 [74]	−100 [33]

Table 5
Theoretical RNG production from biogas sources.

Biogas source	Theoretical production (GJ/yr)	Replacement of existing NG (% NG use)
Municipal solid waste	1.45×10^6 GJ	0.25%
Dairy cattle manure	20.4×10^6 GJ	3.6%
Swine manure	17.8×10^6 GJ	3.1%
Wastewater treatment solids	2.95×10^6 GJ	0.52%

whereas all net present value and levelized cost of energy calculations account for the time value of money. The example cases normalized by gas production are used to demonstrate the significant differences in cost structure and revenue streams between these representative RNG project, as well as the of sensitivity of the project valuation results to key assumptions.

3. Results

3.1. Theoretical RNG production of available feedstocks

Table 5 lists the theoretical maximum renewable natural gas production for each unique feedstock and the percentage of 2019 MN natural gas use, 5.70×10^8 GJ, that this RNG could replace [77]. The theoretical maximum RNG production represents an upper limit for each feedstock in terms of its potential to produce RNG each year. In total, the fraction of total MN natural gas use in 2019 that could be produced from each feedstock is 7.5% of the current fossil gas use. Manure from swine and dairy cattle has the largest RNG production potential, then wastewater treatment solids, and finally MSW.

The calculation of theoretical RNG production includes facilities that may not be viable for RNG development from an economic or technical perspective. We limited the number of landfills, dairy manure farms, and wastewater treatment plants considered for further analysis as discussed in Section 2.3. These limitations reduced RNG production potential from dairy manure by 86.3%, from swine manure by 94.4%, from wastewater treatment solids by 20.0%, and from MSW by 28.6% (Fig. 1).

3.2. Technical feasibility of transportation

After RNG is produced from local feedstocks, cleaned, and upgraded, it must be transported to the location of end use. The RNG can use the same infrastructure as fossil natural gas for transportation, but the proximity of feasible RNG projects to transmission pipelines is a major economic limitation. This section examines the proximity of RNG project locations to the transmission pipeline network and the potential for either physical or virtual connections to the existing gas pipeline system.

Fig. 2 shows the locations of potential RNG facilities considered for feasibility relative to the existing fossil NG interstate transmission pipeline infrastructure. Much of the southern part of the state is near an existing pipeline. In the north there is little pipeline coverage, but the few potential RNG facilities are WWTPs near transmission pipelines. Large dairy CAFOs and swine CAFOs tend to be in the southern and western region of the state within a few kilometers of a pipeline. Open landfills tend to be distributed throughout the state, some of which are near a pipeline in the south.

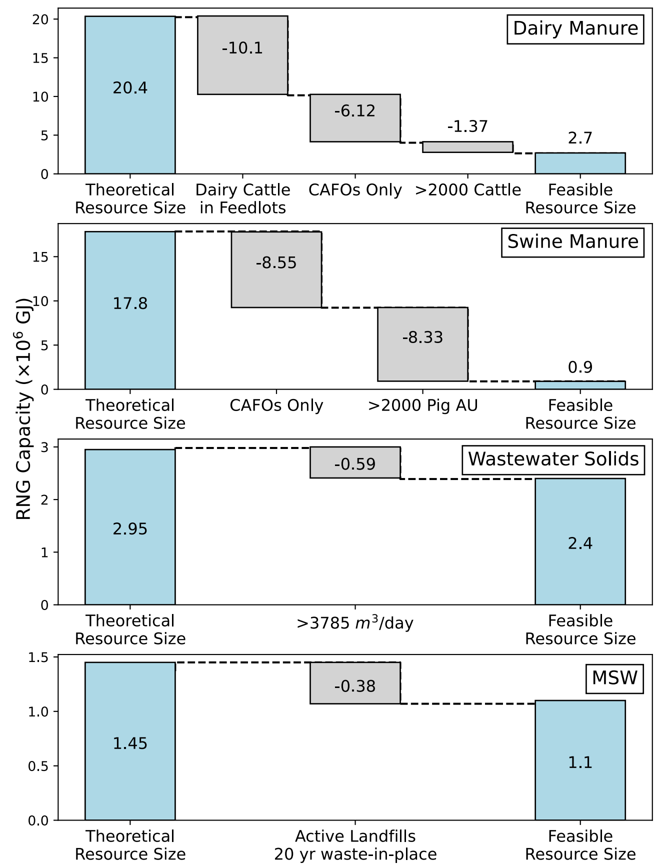

Fig. 1. Change in RNG capacity between the theoretical maximum RNG production and feasible resource size when accounting for facility limitations. Changes between theoretical and feasible resource size are represented by gray boxes. Dairy manure (top) has the largest decrease from theoretical to feasible. Wastewater solids (middle) and MSW (bottom) show only a modest decrease in RNG capacity. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 6
Total resource potential connected by physical and virtual pipelines (GJ) and the percent of all such facilities per connection type.

Feedstock	Physical pipeline	Virtual pipeline	Total
Dairy manure	1.4×10^6 (37.5%)	1.3×10^6 (62.5%)	2.7×10^6
Swine manure	0.0 (0%)	0.9×10^6 (100%)	0.9×10^6
MSW	0.79×10^6 (31%)	0.23×10^6 (69%)	1.1×10^6
WWT solids	1.3×10^6 (5%)	1.1×10^6 (95%)	2.4×10^6

The decision to use a physical versus virtual pipeline connection is a function of the distance from an RNG project to a pipeline and the volume of RNG produced. A project must generate sufficient RNG to cover the capital costs of building an interconnection and a pipeline from the project to transmission pipeline for the physical connection to be built. Table 6 lists the breakdown of virtual and physical pipelines for each feedstock based on the minimum cost option for each feasible facility. Most RNG volume from MSW and wastewater treatment solids comes from a few large projects that are connected by a physical pipeline: 31%

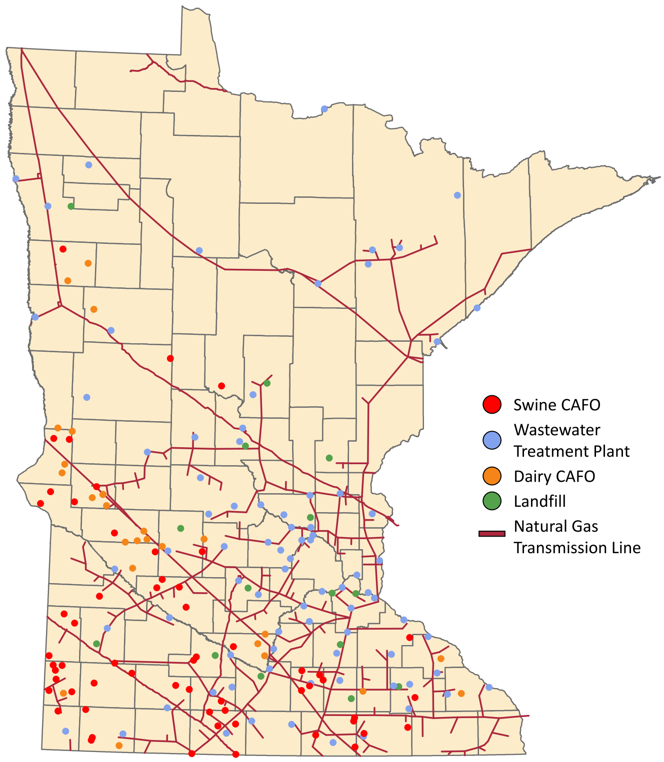

Fig. 2. Locations of viable RNG sources relative to existing natural gas transmission pipelines in MN. Dairies with more than 2000 head of cattle are marked in orange, swine farms with more than 2000 pig AU are marked in red, open MSW landfills are marked in green, and WWTP with flow rates greater than 3785 m^3/day are marked in blue. The existing pipeline infrastructure is shown as dark red lines. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

of MSW landfill projects are connected by a physical pipeline but this represents 77.9% of the potential RNG produced by landfills, and 5% of WWTP projects could use a physical pipeline but this represents 54.8% of potential WWTP RNG. Dairy manure AD projects are more evenly distributed with 37.5% of projects connected by physical pipelines producing 51% of potential dairy RNG. No swine manure AD projects produce enough RNG or are close enough to transmission pipelines to justify a physical pipeline connection, so all swine manure projects use virtual connections.

It is important to note that Fig. 2 does not show utility-owned distribution pipeline infrastructure, only interstate transmission pipelines. We do not include distribution pipelines in our model when deciding between virtual or physical pipeline connections because distribution pipelines are smaller than interstate transmission lines and may not be able to accept the volume of RNG produced by a project.

To verify that this decision is reasonable, we examine the transport decision for each potential project based on the volume of RNG production and the distance to a pipeline, seen in Fig. 3. Even at a distance of 0.0 km from a pipeline, any project smaller than ≈79, 100 GJ/yr would not be selected for a pipeline connection because of the cost of the interconnection infrastructure. There are six projects we identified as using virtual connections that could produce sufficient RNG to justify the cost of connecting to a distribution pipeline if one was close enough.

Because maps of the utility-owned distribution pipeline network is not readily available, we assume that a municipality with less than 500 residents would not have a distribution network sufficient to handle RNG injection. Of the six projects that produced enough RNG to financially justify a physical pipeline connection if one was nearby, the closest municipality with over 500 residents is further away than a transmission pipeline for five projects, so it would be more cost-effective to connect to the interstate transmission line in these cases. The remaining potential project with enough RNG production to consider physical pipeline connection is a WWTP in the western suburbs of Minneapolis. Because only one project out of the 175 total projects in this study would be potentially impacted by including distribution pipeline connections, we believe that excluding distribution pipelines from our transmission model of pipeline connections is adequate for a state-level analysis.

Although we assign either a virtual or physical connection to each facility based on cost per volume of RNG produced, an individual facility may choose a different transportation method based on other factors. For example, a facility we identify as being close enough for physical pipeline connection may choose instead to use a virtual pipeline because they decide to use some RNG on site and therefore only need to transport a small fraction of the total RNG produced.

3.3. Economic feasibility

We developed a levelized cost-curve for RNG to assess what fraction of the technically and economically feasible RNG is cost-competitive with current natural gas prices. We assessed each project individually, which neglects operations where multiple resources below the minimum viable size thresholds could work together. Fig. 4 shows the estimated levelized cost curves for active landfills, WWTP with greater than 3785 m^3/day flow rate, CAFO swine farms with more than 2000

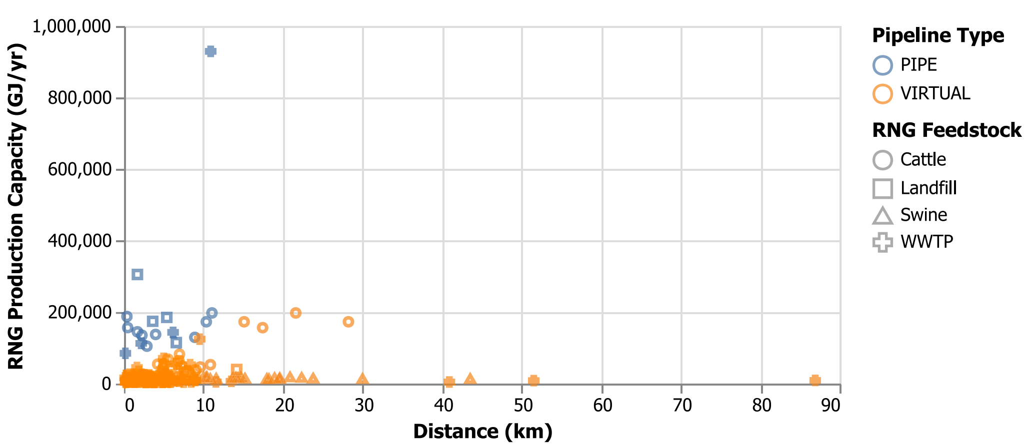

Fig. 3. Project decision for virtual (orange) or physical (blue) pipeline connection. Few projects are sufficiently large enough to afford a physical pipeline connection, and many are with 10 km of a transmission pipeline. Many potential RNG projects are insufficiently large to be able to build a pipeline interconnection and will use a virtual pipeline connection. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

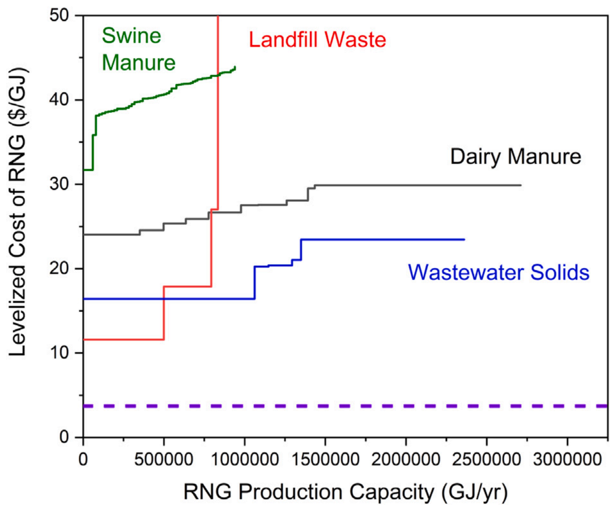

Fig. 4. Levelized cost curves for RNG production facilities in MN across three studied technologies. Wastewater solids are in blue, MSW landfills in red, dairy manure AD in black, and swine manure AD in green. Purple dashed line represents 2019 natural gas price in MN [72]. Projects included were all technically feasible RNG production facilities. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

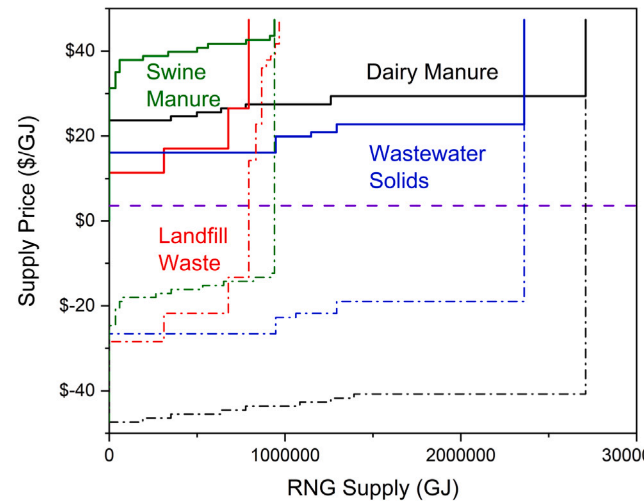

Fig. 5. Cumulative supply curve for analyzed RNG sources. A project was considered feasible at a sale price if its combined revenue streams per GJ CH_4 sold exceeded its levelized cost of energy. Solid curves represent revenues from RNG sales only. Dot dashed supply curves include RFS and LCFS subsidies. Wastewater solids are in blue, MSW landfills in red, dairy manure AD in black, and swine manure AD in green. Purple dashed line represents 2019 Citygate natural gas price in MN [72]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

pig animal units, and CAFO dairy farms with more than 2000 cows. Across technologies, RNG production is feasible at a cost of $11.59-31.71/GJ in MN, which at the low end still does not approach the 2019 Citygate price of natural gas ($3.62/GJ) [72]. Landfill gas and wastewater treatment plant production capabilities are dominated by a few large facilities that provide significant RNG potential. By contrast, anaerobic digestion of animal manure occurs in smaller facilities and therefore has a smoother cost-curve. However, very large projects for all technologies that have the lowest levelized cost also have high CAPEX (often $20 million or above) that may be cost-prohibitive.

Given that the bulk of technically feasible RNG supply is not cost competitive with fossil natural gas on sales revenue alone, we sought to explore the effect of available government subsidies that could impact the supply of RNG. Fig. 5 is the supply curve for RNG with (dot-dashed lines) and without (solid lines) inclusion of the LCFS and RIN credit programs that make RNG for vehicle fuel more valuable. Without subsidies there is little available supply that is cost-competitive with historical natural gas supply prices. The inclusion of subsidies dramatically shifts the supply curves, causing nearly all projects to be feasible at historical natural gas sale prices.

3.4. Avoided greenhouse gas emissions

A key benefit of RNG is the reduction in GHG emissions achieved when it replaces fossil gas. Fig. 6 shows the levelized cost per GHG avoided for the four feedstocks we analyzed. Only anaerobic digestion of dairy manure reduces GHGs at a cost that is near the MN social-cost of-carbon $10.51 to $49.34 per metric ton of CO_2 equivalent (MT CO_2-eq), and none of the analyzed technologies reduce GHG emissions at a price within or below this range. Far more GHG emissions can be avoided through implementation of dairy digesters relative to other studied technologies because dairy facilities have large GHG emissions. In comparison, landfill gas is federally required to be flared, so there are few avoided CH_4 emissions when the biogas is converted to RNG [44].

3.5. Example cases

To highlight the financial differences between feedstocks, we compared three facilities in MN that would each produce approximately 750 m^3/h of biogas. Fig. 7 shows the estimated revenue streams for

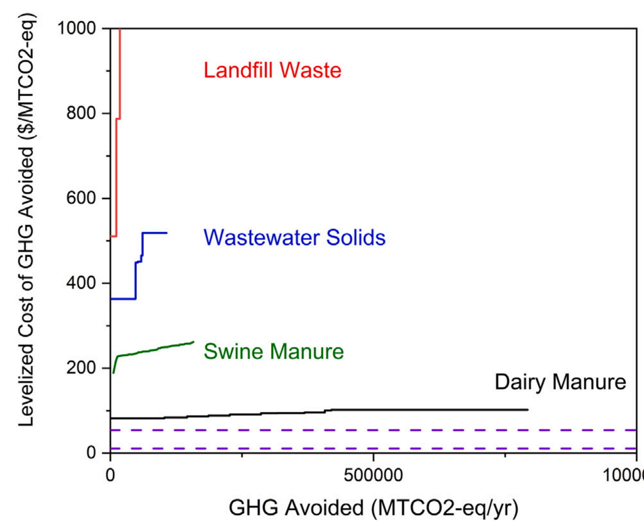

Fig. 6. Levelized cost of GHGs avoided for dairy manure, municipal solid waste, and wastewater solids RNG production facilities.Wastewater solids are in blue, MSW landfills in red, dairy manure AD in black, and swine manure AD in green. Purple dashed lines are the minimum and maximum MN 2019 social cost of carbon. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

each potential project. The three projects generate similar revenue from natural gas sales, but none of these projects are financially feasible if the only revenue stream is from natural gas sales. All three projects make most of their revenue from carbon credits. All technologies can claim RFS credits, but dairy digesters can also generate significant revenue from LCFS credits due to the large GHG reduction relative to their baseline carbon intensity.

The economic viability of each of the three example projects was assessed using the standard metrics of levelized cost of energy (LCOE), net present value (NPV), and payback period (Table 7). Although the dairy digester project has higher initial costs, it would generate more revenue over time because it qualifies for significant LCFS and RFS

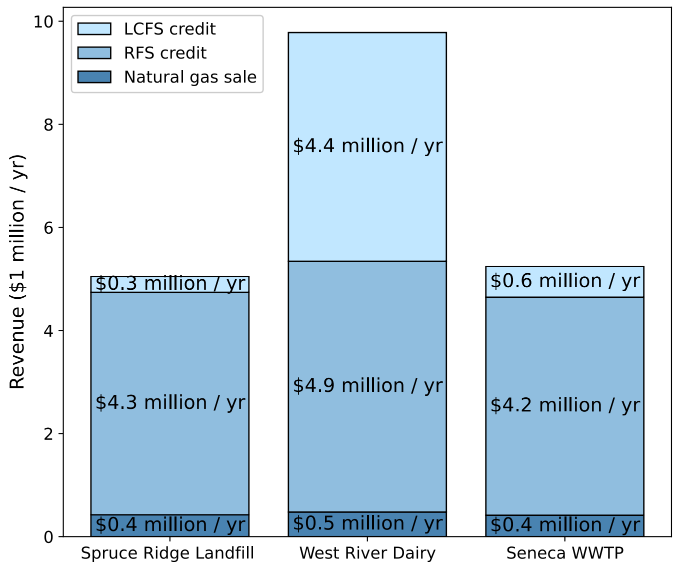

Fig. 7. Annual revenue streams of example MN RNG production projects. Each project would produce 710–780 m^3/h of biogas and utilize pipeline transmission.

Table 7
Economic accounting of three representative RNG production facilities.

	Spruce Ridge Landfill	West River Dairy	Seneca WWTP
Biogas production (m^3/h)	727	778	712
Total CAPEX ($)	13.6 million	21.0 million	11.9 million
OPEX ($/yr)	1.9 million	1.9 million	1.2 million
LCOE ($/GJ)	27.04	29.51	20.27
Net present value including RFS and LCFS credits ($)	14.1 million	46.8 million	23.0 million
Payback period (yr)	5.2	3.2	3.6

payments when the RNG produced is sold as a vehicle fuel. This results in the dairy project having more than double the NPV of the other two projects. Dairy digesters have a high levelized cost of natural gas due to the high CAPEX. Because market based RFS and LCFS revenues are subject to volatility, the shorter payback period of dairy digesters should be attractive to investors. By contrast, landfills are already legally required to collect gas and WWTPs already collect waste in tanks. As a result, they have lower CAPEX costs, which makes the total cost of a project lower. This may make these projects more attractive compared to the dairy digester, which shows higher upfront costs.

To further understand the business case for these example projects, we performed a cost-sensitivity analysis (Fig. 8). In this analysis, parameters were displaced from the value used in modeling, and the impact on the final LCOE was assessed. The largest impact comes from the discount rate, which, when varied between typical benchmarks of 3% and 10%, shows an impact of 10–15% on the LCOE of RNG. Empirical parameters- biogas per unit waste and CAPEX per unit waste- impacted the LCOE of RNG by more than 5%, implying that these parameters also play a significant role and should be revisited during a feasibility study for any specific RNG project.

4. Discussion

Our analysis of theoretical maximum RNG production showed that RNG cannot replace all fossil gas use in the state of MN if MSW, WWT solids, and swine and dairy cattle manure are used as feedstocks. Even assuming maximum RNG production from these feedstocks, total RNG can replace less than 10% of the state's 2019 fossil natural gas use. While we use this as an upper limit, there are additional feedstocks that we did not consider such as agricultural residues and food wastes that may increase this maximum RNG production.

Agricultural residues are a large potential source of RNG. By using the crop residue footprint per area of harvested crop for corn and sugar beets, we can estimate the theoretical maximum RNG production from these two crops, assuming CH_4 yields of 210 m^3 CH_4/ton corn stover and 150 m^3 CH_4/ton sugar beet pulp [78–80]. The theoretical maximum from these two agricultural residues is 1.53×10^8 GJ/yr. This is approximately 26% of 2019 fossil NG use. However, there are numerous barriers to efficient use of agricultural residue in RNG generation such as competing uses, financial barriers to collection, and insufficient technology for pre-processing of the wastes. For example, most oilseed meals and more than half of crop processing byproducts such as sugar beet and cereal bran are currently used as animal feed, so there are economic considerations to diverting these residues for RNG production [39]. The use of crop residues such as corn stover is also limited by the need to leave sufficient but uncertain amounts in the field to prevent soil, moisture, and nutrient losses [40,41].

A second category of RNG feedstock that we did not include in our theoretical maximum calculation is food wastes. Food waste can include food and scraps that are generated during production, processing, transportation, sale, and consumption [38]. The content of food waste from each source varies, which will impact the biogas composition and yield: waste from consumption (i.e., table scraps) tend to be more biodegradable and have fewer impurities than food waste from processing, transportation, and sale [81]. Although removing food waste from the municipal solid waste stream will reduce the CH_4 content of landfill gas, the food wastes can be used immediately to generate biogas and will have a higher short-term impact on RNG production [82]. Assuming that MSW is 17.8% food waste, with a 70% water content and CH_4 production potential of 300 m^3 CH_4/dry Mg food, food wastes could produce 1.16×10^6 GJ/yr, based on 2019 MSW landfilling rates [52,82,83]. This is 0.2% of 2019 fossil NG use in MN. The small RNG potential of food scraps does not justify the costs and technical difficulties associated with diverting this waste stream from the existing MSW infrastructure.

For the three RNG feedstocks that we included for further technological and economic feasibility analysis, we found that virtual pipelines increase the number of technically feasible projects. Having an injection station where RNG from local facilities can be injected into the transmission pipeline reduces total costs for projects and makes projects with smaller RNG production economically feasible. An injection station may be built at a central point that is designated and shared by a group of small RNG facilities or at a larger facility that already invested in the transmission pipeline costs. It is important to note that we did not include the cost of purchasing or renting a vehicle to transport the RNG in our economic analysis. Depending on how a facility would choose to handle transportation, this could result in either a large CAPEX of purchasing a vehicle with lower OPEX for maintenance, or high OPEX for regular renting of a vehicle. One shared vehicle for multiple small facilities may also help to reduce this cost burden.

Once the RNG is produced and transported to a pipeline, it must be sold to a consumer. We found that sales revenue from natural gas at the Citygate price was not enough for RNG projects to be financially feasible. Additional revenue from renewable fuel credit programs is required to make all RNG projects financially feasible in our analysis. Previous analyses of RNG production in the US have found similar results and that financial incentives vary on a state-by-state basis [29,31,33]. Our renewable fuel credit program analysis is optimistic, as the California LCFS credits will likely be changing how they account for carbon intensity of fuels [32]. Lee and Sumner (2018) and Myers et al. (2023) showed that RNG selling price fluctuates with RFS and LCFS credit values, which are subject to market volatility [33,84]. In addition, we assumed that all RNG projects could collect LCFS credits, which may not be true for actual facilities. RNG from anaerobic digestion of dairy and swine manure has the highest credit value, so more money can be

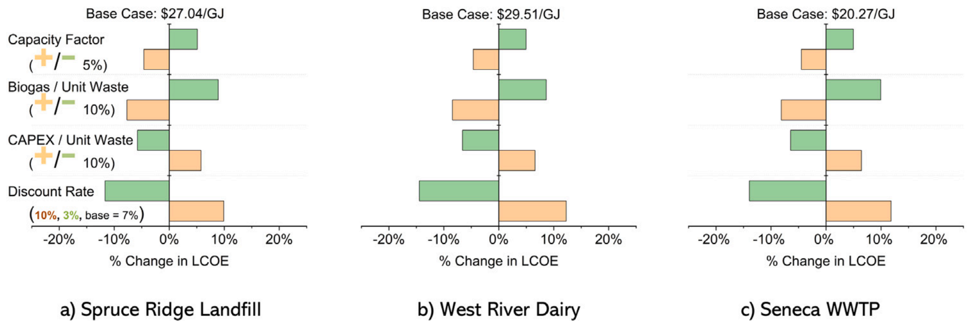

Fig. 8. Cost sensitivity analyses for three representative projects that would produce approximately 750 m^3/h of biogas each. Panel A shows Spruce Ridge Landfill, panel B shows West River Dairy, and panel C shows Seneca WWTP.

made selling RNG from manure than from landfills or WWTPs [85]. The low value of LCFS credits from landfill or WWTP RNG projects makes them less attractive in carbon markets.

The LCFS program and the federal RFS program also require that RNG be used as a vehicle fuel, which limits end-use options. To transition from fossil natural gas regardless of end use, alternative credit systems are needed. For example, rather than focusing on the carbon intensity comparison of a single end use (e.g., vehicle fuel), a credit system that had no end use requirement would encourage additional RNG production. Such a credit system would need individual accounting, which would increase program oversight and management requirements, but would likely encourage more innovative approaches to RNG use and development. The NGIA in MN is a first step towards such a program, as the intent of the bill is to encourage innovative approaches to energy generation in the state.

5. Conclusions

It is unlikely that RNG development is a stand-alone solution for decarbonization in MN. Our theoretical maximum RNG production from the four identified feedstocks was approximately 7.5% of total MN fossil gas use. Our analysis suggests that RNG production is feasible at a cost of $11.59-31.71/GJ from the sale of natural gas alone, or at the Citygate price when revenues from state and national carbon credit systems are included. Carbon credit systems are subject to market volatility and the amount of revenue from these credits depends on the type of feedstock. In addition, revenues from the RFS, LCFS, and similar credit programs are limited to projects making RNG for vehicle fuel. Rather than focus on end-use of RNG for credits, a system based on carbon intensity reductions with no end-use requirements would increase project feasibility.

The cost of greenhouse gas emissions reduction from the feedstocks considered in this report exceeds the MN PUC social cost of carbon estimates of $10.51 to $49.34 per MT CO_2-eq. Dairy manure anaerobic digesters represent the most-cost effective methods for reducing GHG emissions, achieving a minimum cost of around $59/MT CO_2-eq at some potential facilities. This is because biogas from animal manure is currently not required to be captured, unlike biogas from landfills and WWTPs.

This analysis shows that no RNG projects in the state of MN are economically feasible using the sale of gas as the sole revenue stream. Some form of state or federal credit system based on the greenhouse gas offsets necessary to make RNG projects financially viable. However, the largest projects that have the lowest levelized cost of energy may have cost-prohibitive capital expenditures.

CRediT authorship contribution statement

Alicia Hoffman: Writing – original draft, Visualization, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Unni Kurumbail:** Writing – review & editing, Visualization, Software, Methodology, Formal analysis, Conceptualization. **Noah Rhodes:** Writing – review & editing, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Jamey Anderson:** Methodology, Conceptualization. **Robert Anex:** Writing – review & editing, Supervision, Conceptualization.

Data availability

Location and size information for dairy cattle farms, hog farms, and wastewater treatment plants can be found at the Minnesota Pollution Control Agency Geospatial Commons at https://gisdata.mn.gov/dataset. Annual MSW landfilled in MN can be found in the Minnesota Pollution Control Agency SCORE report visualization at https://public.tableau.com/app/profile/mpca.data.services/viz/SCOREOverview/1991-2021SCORE. Landfill data in the EPA LMOP database can be found on the EPA LMOP website at https://www.epa.gov/lmop/lmop-landfill-and-project-database. The technoeconomic model developed in this study is available in a University of Wisconsin MINDS@UW repository: https://minds.wisconsin.edu/handle/1793/84665.

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