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National Renewable Energy Laboratory

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Nomenclature

Btu	British thermal unit
CH_4	methane
CHP	combined heat and power
EPA	U.S. Environmental Protection Agency
FCEV	fuel cell electric vehicle
gge	gasoline gallon equivalent
H_2	hydrogen
HSIP	U.S. Homeland Security Infrastructure Program
IIC	industrial, institutional, and commercial
kg	kilogram
lb	pound
LFG	landfill gas
LMOP	Landfill Methane Outreach Program
scf	standard cubic feet
SMR	steam methane reforming
tonne	metric ton
VS	volatile solids
WIP	waste in place
WWTP	wastewater treatment plant

Executive Summary

Biogas resources present an opportunity to address several key energy and environmental issues. Biogas contains significant amounts of methane, which can be used as a fuel for a variety of electricity and transportation applications [1]. It can help decrease greenhouse gas emissions and other environmental pollution to the air and water. Biogas is produced by anaerobic digestion, a process in which organic matter is broken down in an oxygen-free environment. The organic matter for anaerobic digestion can originate from a wide range of waste streams, such as municipal solid waste, discards from food processing, animal manure, sewage, stillage and glycerin from biofuels production, as well as energy crops and agricultural residues. The use of these waste streams for methane production by anaerobic digestion helps to reduce the amount of waste that must be disposed of using other methods that generally do not have environmental benefits. Anaerobic digestion can also produce other useful by-products in addition to the biogas, such as fertilizer, and can be a precursor for industrial chemicals and polymers.

This analysis updates and expands upon previous biogas studies to include total potential and net availability of methane in raw biogas with respect to competing demands and includes a resource assessment of four sources of biogas: (1) wastewater treatment plants (WWTPs), including domestic and a new assessment of industrial sources; (2) landfills; (3) animal manure; and (4) a new assessment of industrial, institutional, and commercial (IIC) sources [2, 3]. The net availability is calculated differently for each resource as follows: WWTPs are cross-referenced with a database of existing combined heat and power plants utilizing biogas captured from the WWTP [12], landfill net availability is calculated using the candidate sites that the U.S. Environmental Protection Agency (EPA) has identified for their strong energy project potential [18], and animal manure net availability is a reduction of the total from an estimate of existing digesters [24].

The results of the biogas resource assessment are used to estimate the potential production of renewable hydrogen from biogas as well as the fuel cell electric vehicles (FCEVs) that the produced hydrogen might support. The U.S. total methane potential in raw biogas from the sources examined here is estimated at about 16 million tonnes, but the net availability calculated is about 6.2 million tonnes (Table ES-1). For comparison, the U.S. natural gas consumption in 2013 was about 573 million tonnes [35]. The geographic distribution is also provided to help inform regional policies that might support increased utilization of biogas resources. The estimates do not include electricity, water, or other materials that may also be required in the biogas, biomethane, and hydrogen production processes. The geographic distribution of the analyzed biogas sources is shown in Figure ES-1.

Table ES-1. U.S. Methane and Hydrogen Potentials by Source

Source	Methane Potential (thousand tonnes/yr)		Hydrogen Potential (thousand tonnes/yr)	
	Total	Available	Total	Available
WWTPs[a]	2,339	1,927	618	509
Landfills[b]	10,586	2,455	2,795	648
Animal manure[c]	1,905	1,842	503	486
IIC organic waste	1,158	N/A	306	N/A
Total	*15,988*	*6,224*	*4,221*	*1,643*

[a] Total potential for WWTPs is higher, given that the analysis was done for only half of the WWTPs in the country (water flow data for the rest is missing).
[b] Total potential for landfills could be higher given that the estimate accounts for only the WIP recorded for a given year and does not take into account additional waste that may have come in since the record was taken (as it was done for the "available potential" estimate). It is an approximate value. Available potential for landfills is estimated using candidate landfills only. Available potential could be higher if we include "other" and "potential" landfills.
[c] Existing digesters (dairy, poultry, and swine) capture about 62,942 tonnes/yr [24].

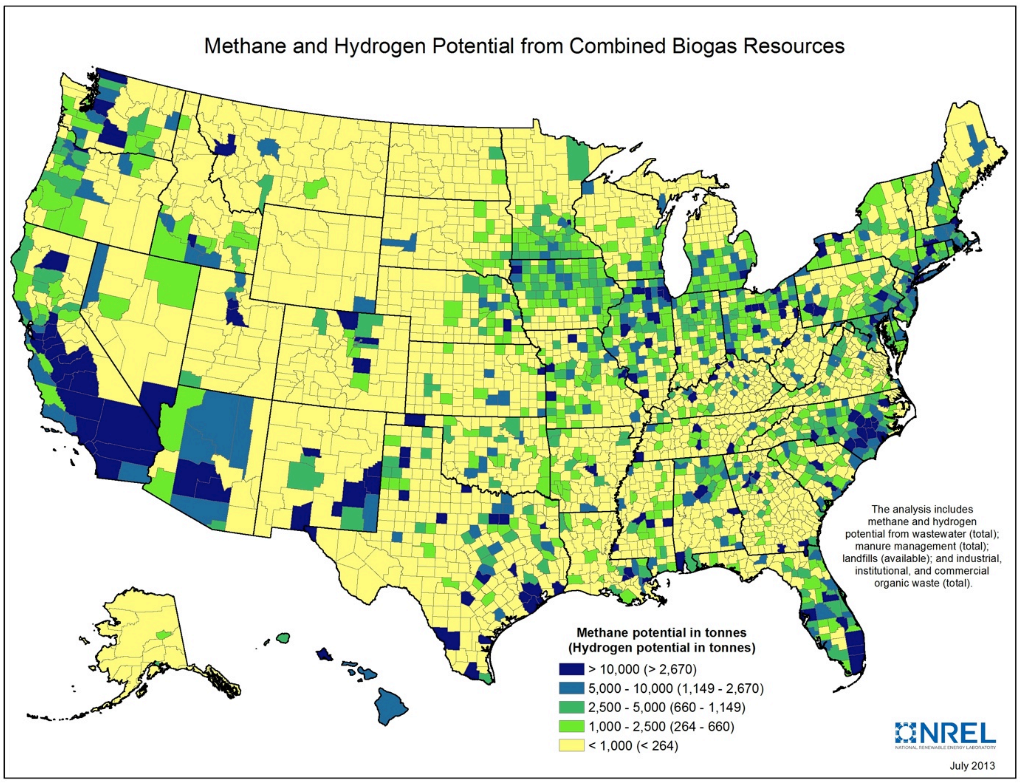


Figure ES-1. Methane and hydrogen potential from combined biogas sources in the United States by county

Landfills, in this study, represent the largest potential source of methane and hydrogen from both a total perspective as well as the current net availability. The total potential of methane in raw biogas is approximately 10.6 million tonnes of methane, or, if converted to hydrogen, about 2.8 million tonnes of hydrogen per year.[1] This total potential could be higher due to data recording gaps in landfill waste in place reporting (i.e., the quantity of waste at the site). The net potential

[1] The conversion to hydrogen assumes 87% of the methane content in the biogas can be purified to biomethane and a conversion factor of 3.3 kg CH_4/kg hydrogen for hydrogen production from biomethane.

of landfills is estimated at 2.5 million tonnes of methane or 648,000 tonnes of hydrogen[1] annually [18]. This net availability could be a conservative estimate because it does not include sites listed by the EPA as "potential" or "other," some of which might make feasible projects along with "candidate" sites. The top 20 counties in the United States for producing biogas from landfills account for more than 30% of the net availability but less than 10% of the number of landfill sites.

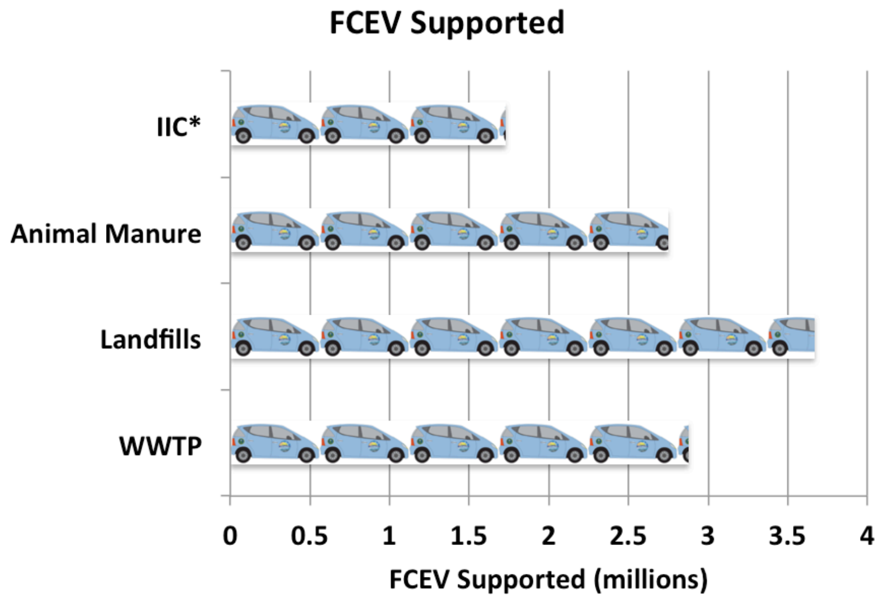
WWTPs can be a significant source of methane for hydrogen production. The total U.S. potential of methane in raw biogas for sites analyzed[2] is 2.3 million tonnes, which is approximately 618,000 tonnes of hydrogen per year.[1] Some sites have existing combined heat and power projects, which decrease the total amount of methane that might be available for hydrogen. We calculated the net availability of methane at WWTPs to be about 1.9 million tonnes of methane or, if converted to hydrogen, about 509,000 tonnes of hydrogen[1] [12]. The net availability is about 17% less than the total potential. Of the WWTPs analyzed, more than 90% have production capacities of less than 80 tonnes of hydrogen.

Animal manure is a more dispersed resource found in rural areas tending toward more, smaller sites than WWTPs and landfills. However, it can be a significant source of biogas if some of the economic issues of collection and aggregation can be overcome. The total methane potential in raw biogas from the three animal types studied (dairy cows, hogs, and broiler chickens) is estimated at about 1.9 million tonnes annually, which, if converted to hydrogen, would result in about 503,000 tonnes of hydrogen.[1] Existing digesters capture about 63,000 tonnes of methane, reducing the net availability to about 1.8 million tonnes of methane or 486,000 tonnes of hydrogen [24]. The top 20 counties in the United States for producing biogas from animal manure represent almost 32% of the U.S. total potential and could be a source of hydrogen for bridging transportation corridors between major metropolitan areas and bringing economic opportunities for rural areas.

The total potential from IIC sources is slightly less than from the other biogas sources examined, yet it still represents a significant source of methane and hydrogen. Only total potential is calculated in this new analysis. The total methane potential in raw biogas from IIC sources is estimated to be 1.2 million tonnes annually, or 306,000 tonnes of hydrogen.[1] The top 20 counties in the United States for producing biogas from IIC sources represent almost 20% of the total potential of IIC sources.

The number of FCEVs potentially supported by renewable hydrogen from biogas is estimated by assuming an average FCEV fuel economy of 56.5 miles per gasoline gallon equivalent and average annual miles traveled per vehicle of 10,000 miles per year. The total number of vehicles supported from all biogas sources—using net availability where available—if the methane is converted to hydrogen is about 11 million FCEVs annually, with landfills accounting for more than a third of that at 3.7 million FCEVs annually. The breakdown by biogas source is shown in Figure ES-2.

[2] The actual total potential and net availability could be higher, as only about half the sites analyzed included wastewater flow data needed to make the calculations.



* IIC is total potential.

Figure ES-2. The number of FCEVs supported by biogas source, utilizing the net availability of the biogas source (with the exception of IIC)

This study also presents results from two regional analyses performed on the Sacramento, California, and Boston, Massachusetts, areas using net availability of the biogas resources where available. The potential from all sources for the Sacramento region is about 93,300 tonnes of hydrogen annually, which could support almost 527,300 FCEVs. The Boston region has about 33,000 tonnes of hydrogen potential annually, which could support approximately 186,700 FCEVs.

Renewable hydrogen from biogas has the potential to aid early FCEV rollout. It is a local, sustainable resource, and based on this study, it can supply about 5% of the current U.S. light-duty vehicle fleet[3] if that portion were replaced by FCEVs. The biogas resources available locally to any given area will vary by region. The introduction of increased amounts of FCEVs into the vehicle fleet could have environmental benefits. The transportation sector is second only to the electric sector in greenhouse gas emissions, and renewable hydrogen used in FCEVs can offer environmental benefits.

Relying upon a renewable source of hydrogen would help highlight the clean car profile of FCEVs during early market introduction, and the state of California already has requirements for renewable hydrogen production. However, development of these biogas resources has challenges that may be unique for any given region, state, or urban area. State and local policies, rapport with local utilities, and the favor of local sources and stakeholders will all factor into successful project investment and resource development.

[3] The vehicle registrations in 2010 for cars and light-duty trucks (two axles, four tires) were approximated at 131 million and 99.5 million respectively [31].

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1 Introduction

Biogas is produced by anaerobic digestion, a process in which organic matter is broken down in an oxygen-free environment producing significant amounts of methane. The organic matter for anaerobic digestion can originate from a wide range of waste streams, such as municipal solid waste, discards from food processing, animal manure, sewage, stillage and glycerin from biofuels production, as well as energy crops and agricultural residues. The use of these waste streams for methane production by anaerobic digestion helps to reduce the amount of waste that must be disposed of using other methods that generally do not have environmental benefits. Biogas is made up primarily of 50%–70% methane and the rest carbon dioxide with trace amounts of other particulates and contaminants. Anaerobic digestion can also produce other useful by-products in addition to the biogas, such as fertilizer, and can be a precursor for industrial chemicals and polymers. Biogas resources present an opportunity to address several key energy and environmental issues because it can be used as a fuel for a variety of electricity and transportation applications [1]. Reducing waste through the use of anaerobic digestion can help decrease greenhouse gas emissions and other environmental pollution to the air and water.

The methane content of biogas is a renewable fuel that can support energy independence from imported petroleum when used in the transportation sector. One area of interest is as a source for renewable hydrogen, which can be used in stationary fuel cells and support the early market introduction of fuel cell electric vehicles (FCEVs). Hydrogen-powered FCEVs emit no tailpipe emissions other than water and are a clean transportation alternative to gasoline vehicles. In the United States, most hydrogen is produced by steam methane reforming (SMR) of natural gas. The same SMR technology can also use purified biogas, or biomethane, as a natural gas substitute to provide a lower carbon and renewable source of hydrogen. Producing hydrogen from biomethane provides a hedge against demand for fossil fuels and aids compliance with state policies on renewable fuels.

This analysis updates and expands upon previous biogas studies to include total potential and net availability of methane in raw biogas and includes a resource assessment of four sources of biogas: (1) wastewater treatment plants (WWTPs), including domestic and a new assessment of industrial sources; (2) landfills; (3) animal manure; and (4) a new assessment of industrial, institutional, and commercial (IIC) sources [2, 3]. The analysis addresses both the total resource available as well as a net availability with respect to currently competing demands for biogas. This resource assessment estimates the potential production of renewable hydrogen from biogas, as well as the FCEVs that it might support. The geographic distribution is also provided to help inform regional policies that might support increased utilization of biogas resources. The estimates do not include electricity, water, or other materials that may also be required in the biogas, biomethane, and hydrogen production processes.

Biogas production and subsequent purification to more readily useful products, such as biomethane, can incur significant costs, which is often due to the dispersed nature of biogas sources and economies of scale. This analysis begins to identify potential production system sizes and the geographic element of aggregating dispersed sources into larger, economically viable systems.

Biogas and renewable hydrogen from biogas will not meet all U.S. energy demands, but there is a growing interest and market for biogas and its use in fuel cells. However, it does have the potential of being a significant resource that can offset the growing dependence of the United States on fossil fuel use. These renewable energies can help foster energy independence, reduce air and water pollution, and decrease greenhouse gas emissions in the future.

2 Overview of Biogas Conversion to Hydrogen

There are three main calculations necessary for estimating the potential hydrogen from select biogas resources: (1) the resource assessment of the methane content in biogas, (2) biogas purification for natural-gas-quality biomethane, and (3) biomethane conversion to hydrogen. The methodology for estimating the resource potential is addressed in Section 3 for each biogas source. These calculations are specific to each resource category. All references to the methane potential show the methane content of biogas before any cleanup of carbon dioxide and other contaminants. The biogas purification and conversion to hydrogen are addressed in common for all resource categories.

The resource assessment in Section 3 provides the methane potential of raw biogas for each source by either assessing the methane content directly or by calculating the biogas potential and estimating the percent methane contained in it. The hydrogen potentials assume a conversion of the methane in biogas to biomethane, which is natural gas quality, and subsequent conversion by SMR to hydrogen. Potential pathways for biomethane include injection into natural gas pipelines, use as a feedstock in an SMR process for conversion to hydrogen, and other natural gas end uses such as stationary heat and power. Sections 4 and 5 address the FCEVs that could be supported, along with additional national and regional analyses and resource sensitivities, by the conversion of biogas into hydrogen. Some end-use applications may not require the same level of biogas purification as used in this report. These considerations are discussed in Section 6.

To calculate the biomethane potential, the process of purifying the methane content in biogas must be characterized. Various chemical and biological purification processes are available on the biogas market. Membrane purification, a purely physical process, has been gaining interest in recent years [4]. In this process, a thin membrane is used to separate the methane from the input biogas stream, which is composed mainly of methane, carbon dioxide, and saturated water. The methane stream is then approximately natural gas quality although some other processing may be required to remove specific contaminants. The other output stream, the tail gas, is mainly carbon dioxide with a small amount of methane. This tail gas is combusted in a thermal oxidizer to minimize the methane emissions. The process uses both electricity for compression to aid passing through the membrane and biogas as fuel for the thermal oxidizer. The efficiency of separating biomethane from biogas has been estimated to be 87%, which includes a membrane efficiency of 90% and a small share of input biogas being combusted in the thermal oxidizer to reduce emissions [4-6]. Therefore, the biomethane potential is 87% of the total methane available in the original biogas, as shown in Equation 1. This reduction factor is due to losses in upgrading and purifying the biogas to biomethane. The electricity usage is not considered in this report, but it would be included in total system life-cycle analyses.

Equation 1. Biogas to biomethane purification factor

$$biomethane\ potential = 87\% * methane\ content\ of\ biogas$$

Once the biogas has been upgraded to natural-gas-quality biomethane, it can be used as a substitute for natural gas in an SMR process to produce hydrogen. The conversion factor for converting biomethane to hydrogen is taken from the U.S. Department of Energy's H2A Production model case study for central production of hydrogen from natural gas [7]. The natural gas feedstock usage for the case study is 0.15625 million British thermal units (Btu) per kilogram (kg) hydrogen (H_2). The energy content in natural gas is mainly methane (CH_4), and this feedstock usage is converted to a conversion factor of 3.295 kg CH_4/kg hydrogen using the factors shown in Equation 2. The process electricity is not considered for the SMR in this analysis, but it would be included in total system life-cycle analyses.

Equation 2. Biomethane to hydrogen conversion

$$\frac{0.15625\ mmBtu}{kg\ H_2} * \frac{1055056\ kJ}{mmBtu} * \frac{mol\ CH_4}{802.5\ kJ} * \frac{16.04g}{mol\ CH_4} * \frac{1\ kg}{1000\ g} = 3.295\frac{kg\ CH_4}{kg\ H_2}$$

3 Resource Assessments

Resource assessments give an estimate of the quantity of resources available. They are useful in understanding the resource's potential and how it may compare to other resources of similar resulting by-products.

3.1 Wastewater Treatment Plants

WWTPs are facilities designed to remove biological, physical, and chemical contaminants from wastewater, therefore permitting the treated water to be used for other purposes. WWTPs can include domestic, agricultural, and industrial sources of wastewater.

3.1.1 Methodology

The data for WWTPs were obtained from the U.S. Environmental Protection Agency's (EPA's) 2008 Clean Watersheds Needs Survey [8]. The data are collected every four years by the EPA and states to comprehensively assess the water quality goals set in the Clean Water Act. The database includes information from four main categories of WWTPs:

- Publicly owned wastewater collection and treatment facilities
- Stormwater and combined sewer overflows control facilities
- Nonpoint-source pollution control projects
- Decentralized wastewater management.

The database includes approximately 35,000 records with location point sources, of which only about 18,000 included the wastewater flow in million gallons per day. This analysis only uses these 18,000 records.

The biogas potential from the wastewater is estimated to be about 1 cubic foot (ft^3) per 100 gallons of wastewater [9-11]. The biogas is assumed to be 65% methane by volume, and the methane content of the biogas was estimated using methodology from the "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2011" [10]. The annual methane potential is calculated as shown in Equation 3. In the results, the hydrogen potentials include a reduction of the methane from purification of the biogas and conversion by SMR as discussed in Section 2.

Equation 3. Annual methane potential equation for WWTPs [10]

$$annual\ methane\ potential = q * \frac{1\ ft^3\ biogas}{100\ gal\ wastewater} * \frac{0.0283\ m^3\ biogas}{ft^3\ biogas} * \frac{65\%\ m^3\ CH_4}{m^3\ biogas} * \frac{0.662\ kg\ CH_4}{m^3\ CH_4}$$

where q is the wastewater flow in gallons per year.

The net availability was calculated by cross-referencing the identified sites with a database of existing combined heat and power (CHP) plants utilizing biogas captured from a WWTP [12]. In other words, WWTPs with existing CHP projects were not considered in the net availability potential.

3.1.2 Potential

WWTPs can be a significant source of methane for hydrogen production. The total U.S. potential of methane in raw biogas from the sites analyzed is 2.3 million tonnes annually, which, converted to hydrogen, is approximately 618,000 tonnes of hydrogen. Some sites have an existing CHP project, which decreases the total amount of methane that might be available for hydrogen. The net availability of methane from raw biogas is 1.9 million tonnes annually, or about 509,000 tonnes of hydrogen. The net availability is about 17% less than the total potential. The actual total potential and net availability could be higher, as only about half the sites in the data analyzed included wastewater flow data needed to make the calculations.

The total U.S. potential and net availability in the top 20 counties can be seen in Table 1. These counties represent just over one quarter of the U.S. total potential, but less than 3% of the number of sites. Large sites dominate the top counties.

The size of the WWTP can vary greatly depending on the community it serves. The economic viability of the sites may depend on the wastewater throughput of a facility as well as how it processes the waste [13-15]. A distribution plot of the WWTPs considered in this analysis is shown in Figure 1. Fewer than 10% of the sites have capacities greater than 80 tonnes of hydrogen annually. The 146 sites with CHP projects, which were excluded from the WWTP net availability, have an average size of 750 tonnes of hydrogen annually. Therefore, the great majority of WWTPs are significantly smaller. The mean for all sites was 35.1 tonnes of hydrogen or 29.2 tonnes for net sites only. The median value was about 2.9 tonnes of hydrogen for both total and net sites. Understanding how to make smaller facilities economically viable for production of methane, biomethane, or hydrogen is a key to utilizing their potential.

The nature of WWTPs is such that they are clustered around population centers. Figure 2 shows the point locations of the WWTPs in the United States and their relative capacity of methane and hydrogen production.

Table 1. Hydrogen Potential from WWTPs for the United States and the Top 20 Counties

County	Population (2010 Census) [16]	Total Hydrogen Potential (tonnes)	Number of Sites (total)	Net Hydrogen Availability (tonnes)	Number of Sites (net)
U.S. (all counties)	*308,747,508*	*617,700*	*17,573*	*508,900*	*17,427*
Cook IL	5,194,675	23,900	9	9,800	8
Los Angeles CA	9,818,605	15,500	28	10,000	23
Wayne MI	1,820,584	12,800	6	12,800	6
Harris TX	4,092,459	9,900	253	9,900	253
Clark NV	1,951,269	8,800	16	8,800	16
Essex NJ	783,969	8,400	5	200	4
Kings NY	2,504,700	8,100	6	4,400	3
Maricopa AZ	3,817,117	7,900	58	7,900	58
King WA	1,931,249	7,500	15	900	13
Dallas TX	2,368,139	6,900	8	5,200	7
Suffolk MA	722,023	6,700	1	0	0
Philadelphia PA	1,526,006	6,100	3	3,700	2
Orange CA	3,010,232	5,900	13	3,500	11
Cuyahoga OH	1,280,122	5,400	21	5,400	21
Miami-Dade FL	2,496,435	5,200	5	2,000	3
San Diego CA	3,095,313	5,200	34	3,800	29
New York NY	1,585,873	5,200	2	5,200	2
St. Louis MO	998,954	4,900	7	4,900	7
Queens NY	2,230,722	4,400	5	4,400	5
District of Columbia DC	601,723	4,300	1	4,300	1

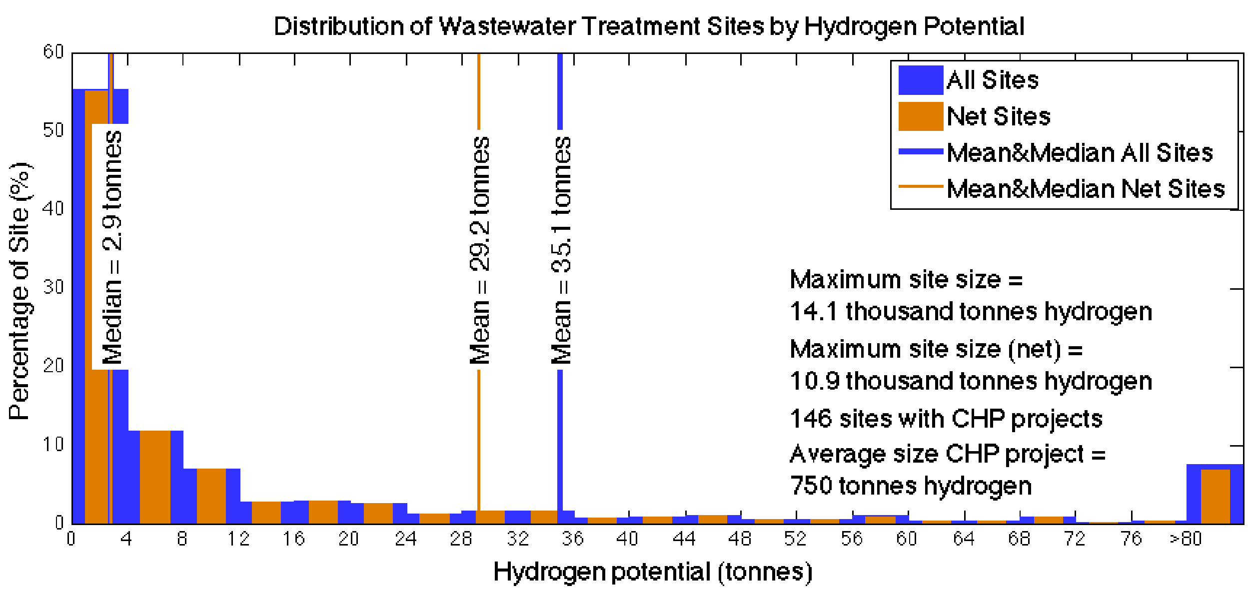


Figure 1. Distribution of WWTPs by hydrogen potential

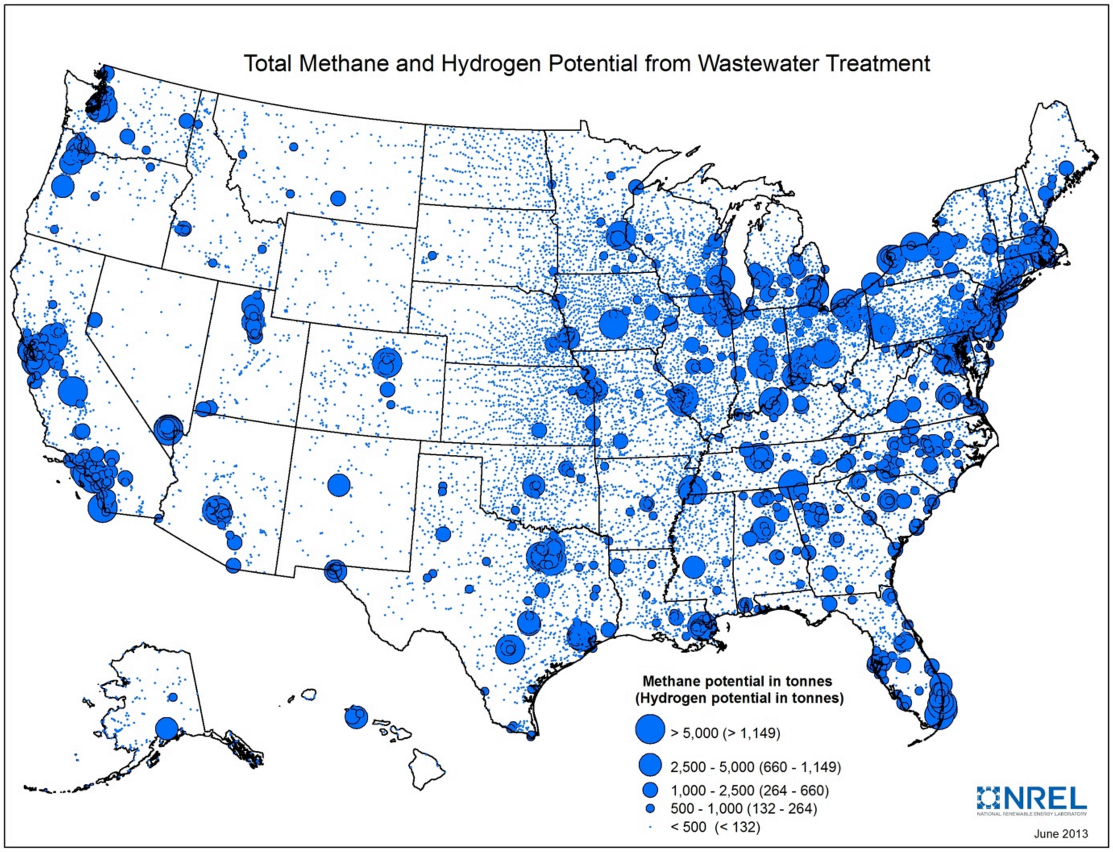


Figure 2. Methane and hydrogen potential from WWTPs by point source location

3.2 Landfills

Landfills are designated locations for disposal of waste, such as product packaging, food scraps, bottles, furniture, appliances, and yard clippings. The waste can come from residential, industrial, or commercial entities. The quantity of trash that ends up in landfills can vary based on reuse, composting, and recycling patterns. In 2011, the United States generated approximately 250 million tons of garbage and recycled or composted approximately 87 million tons [17]. The biogas from landfills is generally called landfill gas (LFG) due to the digestion process taking place in the ground rather than in an anaerobic digester.

3.2.1 Methodology

The potential of a landfill to generate methane is mainly dependent on the amount of waste in place (WIP), the length of time the waste has been *in situ*, and the climate of the location (arid versus non-arid). The data used in this analysis were provided by the EPA's Landfill Methane Outreach Program (LMOP), which is designed to minimize emissions from landfills and encourage best practices for dealing with the waste [18]. The LMOP's database as of October 2012 contains approximately 2,400 records of landfills in the United States and its major territories. About 600 of these locations have existing LFG-to-energy projects. The remaining sites are designated as candidates for LFG-to-energy projects, potential locations for such projects, or shut-down sites. The total potential for methane from LFG is estimated at a county level only due to data gaps, and it is based on the total amount of WIP in a recorded year and using the LMOP's Interactive Conversion Tool.[4] The methodology for estimating the net availability is described below using only candidate sites from the database.

The net methane potential is based upon candidate sites that the EPA has identified for their strong energy project potential [19]. The criteria for these candidate landfills include not having an existing or planned energy project, having at least 1 million tons of WIP, and actively accepting waste or having been closed for less than 5 years. The LMOP identifies these criteria as strong indicators for an economically successful landfill energy project. This analysis used 495 candidate landfills for the net methane potential, of which only 321 had all the requisite data for the calculations. In the results, the hydrogen potentials include a reduction of the methane from purification of the biogas and conversion by SMR as discussed in Section 2.

The LFG generated is not a steady quantity over time; it will ramp up over years to a peak then slowly decline. It is also affected by whether the site is closed or new waste is being accepted. A first-order decay equation is sometimes used to approximate output in a given year. However, this analysis estimates the annual potential of methane from a simplified calculation of 300 standard cubic feet (scf) per minute of LFG per 1 million tons of WIP, and it assumes that the LFG is composed of 50% methane by volume [20]. For open candidate landfills, the WIP data are normalized to the year 2012 by taking the WIP in the recorded year, different for each record, and adding additional years of waste based upon the annual waste acceptance rate of the site up to the year 2012. For closed candidate landfills, the WIP was calculated similarly to the open landfills, but additional years of waste are only added up to the year the site closed. Only candidate landfills closed within the last five years were included in this analysis. The annual methane potential is then calculated as shown in Equation 4.

Equation 4. Annual methane potential for landfills

$$annual\ methane\ potential = WIP * \frac{300\ scfm\ LFG}{1\ MM\ tons\ WIP} * \frac{50\%\ CH_4}{LFG} * \frac{0.0423\ {lb}/{min}}{1\ scfm} * \frac{525{,}600\ min}{yr} * \frac{1\ ton}{2204.62\ lb}$$

where WIP is million tons of waste in 2012 for open landfills and for the year closed for closed landfills.

3.2.2 Potential

Landfills, in this study, represent the largest potential source of methane and hydrogen from both a total perspective as well as the current net availability. The total potential is approximately 10.6 million tonnes of methane in raw biogas annually, or, if converted to hydrogen, about 2.8 million tonnes of hydrogen. The net potential of landfills, based upon candidate sites that meet the criteria listed above, is 2.5 million tonnes of methane annually or 648,000 tonnes of hydrogen if converted. This net availability could be a conservative estimate because it does not include sites listed by the EPA as "potential" or "other," some of which might make feasible projects. As shown in Table 2, the top 20 counties in the United States account for more than 30% of the net availability but less than 10% of the number of sites.

[4] http://www.epa.gov/lmop/projects-candidates/interactive.html

Table 2. Hydrogen Potential from Landfills in Top 20 U.S. Counties

County	Population (2010 Census) [16]	Net Hydrogen Availability (tonnes)	Number of Sites (net)
U.S. (all counties)	*308,747,508*	*648,200*	*321*[a]
Los Angeles CA	9,818,605	27,400	3
Orange CA	3,010,232	19,000	1
Livingston IL	38,950	16,500	1
Stanislaus CA	514,453	13,700	1
Alameda CA	1,510,271	13,000	2
Maricopa AZ	3,817,117	12,900	2
Okeechobee FL	39,996	11,700	1
Stark OH	375,586	9,500	1
Ogle IL	53,497	9,200	1
Pinellas FL	916,542	8,000	1
Kings CA	152,982	7,600	1
Nueces TX	340,223	7,500	1
Jefferson AL	658,466	7,400	2
Brazoria TX	313,166	6,900	1
Wayne MI	1,820,584	6,800	1
Ascension LA	107,215	6,300	1
Butts GA	23,655	6,100	1
Gregg TX	121,730	5,700	1
Miami-Dade FL	2,496,435	5,400	1
Jefferson TX	252,273	5,200	3

[a] Out of 495 candidate sites, only 321 included all requisite data needed for calculation.

The size distribution of candidate sites tends to be less than 6,300 tonnes of hydrogen annually with only 5% of the sites analyzed larger than that, as shown in Figure 3. However, there are some large available candidate sites, the largest of which has a potential of 21,800 tonnes of hydrogen annually. The mean site capacity was much smaller, at only 2,000 tonnes of hydrogen, and the median site capacity was 1,300 tonnes of hydrogen annually. Just fewer than 48% of sites fall into the range of 315 to 1,260 tonnes of hydrogen annually, making those smaller sites an important category to tap into.

The geographic distribution of the candidate landfills, which represents the net availability of methane, is shown in Figure 4. Landfills tend to be clustered around populated areas, making them more economically viable sources of renewable hydrogen (compared to wind, for example) due to the relatively short distances required for hydrogen delivery.

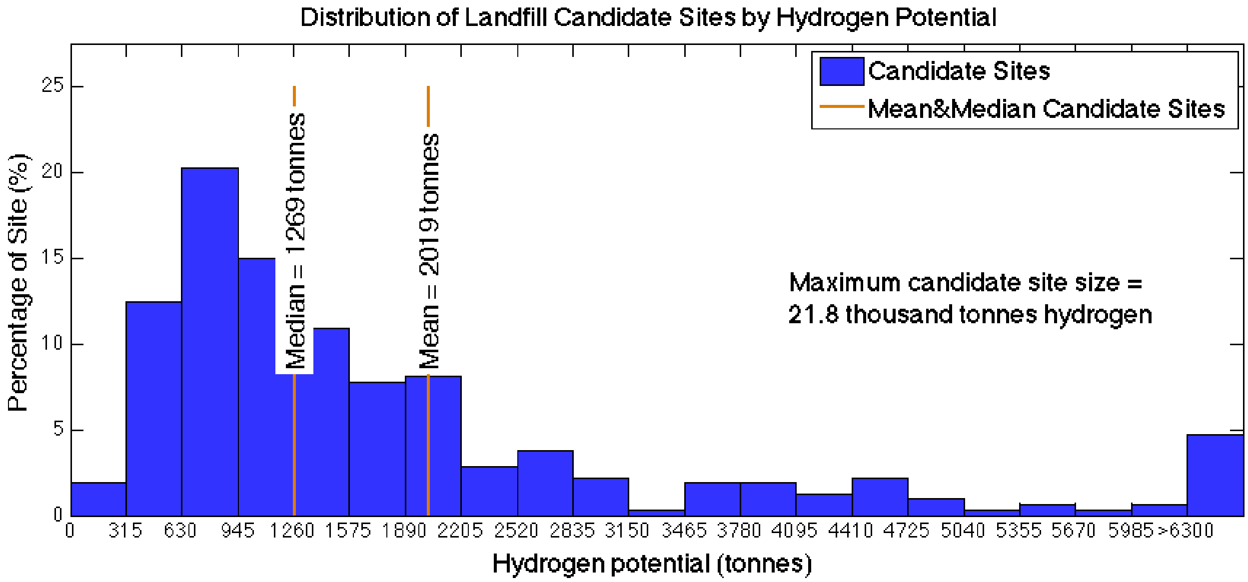


Figure 3. Distribution of landfill sites by hydrogen potential

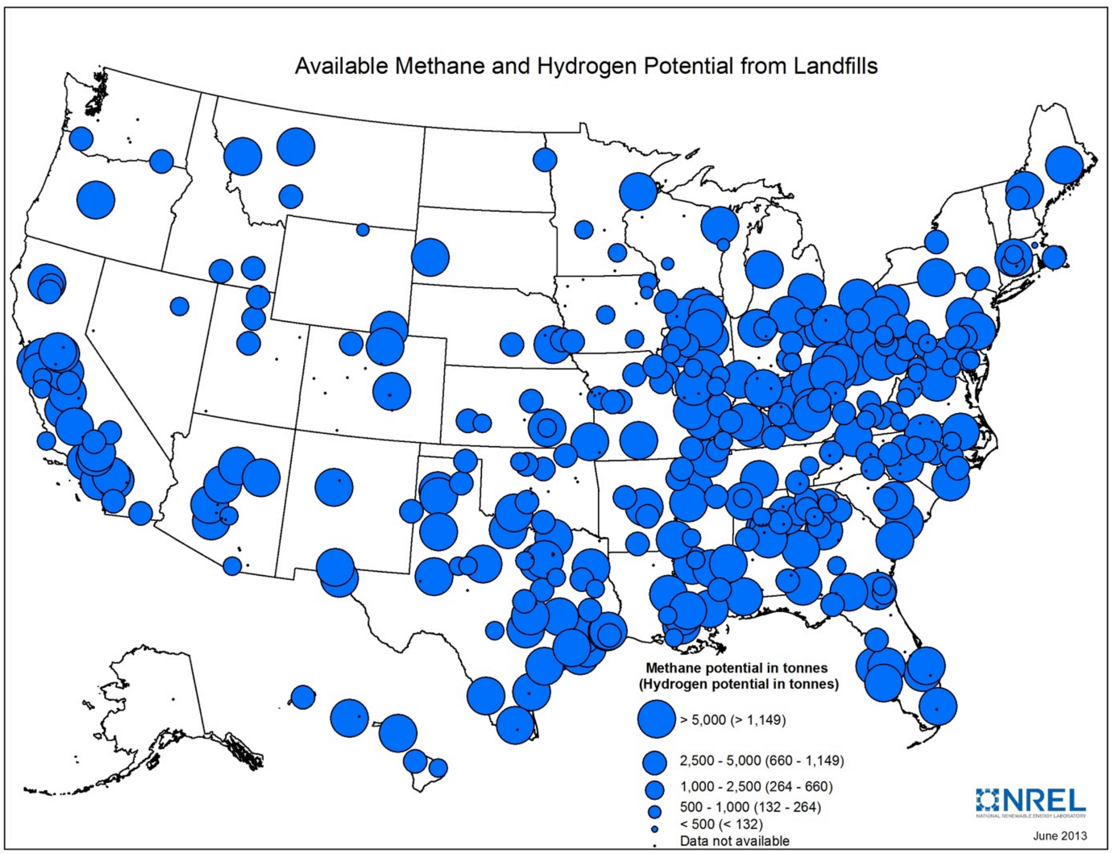


Figure 4. Available methane and hydrogen potential from landfills by point source location

3.3 Animal Manure

Animal manure can be a good source of organic matter for use in anaerobic digestion. However, the most practical manure management systems for anaerobic digestion are those in which the manure is stored in liquid or slurry forms with little non-digestible bedding mixed in [21]. Other management systems may work, but will not be as successful. In this analysis, we consider three animal types that have been identified as generally having manure management systems well suited to anaerobic digestion: milk cows, hogs, and broiler chickens.

3.3.1 Methodology

The U.S. Department of Agriculture's most recent (2007) Census of Agriculture includes data on the number of animals by county [22]. Because the data are provided at the county level, the assessment results are also limited to the county level, unlike the point source results above for WWTPs and landfills.

The following steps were used to calculate methane emissions from manure management systems, based on a 1995 EPA state workbook on the subject [23].

Step 1: Annual production of volatile solids by each animal type

The following equation was used to calculate pounds of volatile solids produced by each animal type using numbers for the typical animal mass and annual volatile solids shown in Equation 5. Tables for the typical animal mass can be found in the EPA workbook [23].

Equation 5. Volatile solids produced by animal type

$$VS_i = Animal\ Population_i(head) * TAM_i * vs_i$$

where:

VS_i = total volatile solids produced [lb/yr] for animal type i
TAM_i = typical animal mass for animal type i [lb/head]
vs_i = average annual volatile solids production per unit of animal mass of animal type i [lb VS/lb animal mass/yr]

Step 2: Methane emissions for each manure management system and animal type

The methane emissions were calculated using the solution to Equation 5 for total volatile solids along with additional data found from Equation 6.

Equation 6. Methane emissions for each animal type and manure management system

$$CH_4\ emissions\ for\ each\ animal\ i\ in\ system\ j\ \left[\frac{ft^3}{yr}\right] = VS_i * B_{o,i} * MCF_j * WS\%_{i,j}$$

where:

VS_i = total volatile solids produced per year by animal type i (Equation 5) [lb/yr]
$B_{o,i}$ = maximum methane producing capacity per lb VS for animal i [ft^3/lb VS]

MCF_j = methane conversion factor for each manure management system j [%]
$WS\%_{i,j}$ = percent of animal i's manure managed in manure management system j [%]

Tables for MCF and WS% are found in the EPA workbook [23].

Step 3: Summation across animal types and manure management systems and conversion to tonnes of methane

The methane emissions are summed across the different animal types and manure management systems and then converted to tonnes using Equation 7.

Equation 7. Summation of methane across animal types and manure management systems

$$Total\ CH_4\ [tonnes] = \sum CH_{4\,i,j} * \rho * \frac{tonne}{2205\ lb}$$

where:

$CH_{4\ i,j}$ = methane emissions for each animal type i in manure management system j [ft^3/yr]
ρ = density of methane [0.0413 lb/ft^3]

The results of Step 3 provide the total methane potential for animal manure. The large majority of the methane that can be captured comes from liquid and liquid slurry manure management systems.

Step 4: Hydrogen potential

In the results, the hydrogen potentials include a reduction of the methane from purification of the biogas and conversion by SMR as discussed in Section 2.

3.3.2 Potential

Animal manure is a more dispersed resource found in rural areas tending toward more, smaller sites than WWTPs and landfills. However, it can be a significant source of biogas if some of the economic issues around collection and aggregation can be overcome. The total methane potential in raw biogas from the three types of animal studied (dairy cows, hogs, and broiler chickens) is estimated at 1.9 million tonnes annually, which, if converted to hydrogen, would be about 503,000 tonnes of hydrogen. Existing digesters capture about 63,000 tonnes of methane, reducing the net availability to about 1.8 million tonnes of methane or 486,000 tonnes of hydrogen [24]. The total potential of the top counties in the United States is shown in Table 3. The top 20 counties represent almost 32% of the U.S. total potential and could be a source of hydrogen for bridging transportation corridors between major metropolitan areas and bringing economic opportunities for rural areas.

Table 3. Hydrogen Potential from Animal Manure for the United States and in the Top 20 U.S. Counties

County	Population (2010 Census) [16]	Total Hydrogen Potential (tonnes)
U.S. (all counties)	*308,747,508*	*503,100*
Tulare CA	442,179	21,700
Duplin NC	58,505	18,000
Sampson NC	63,431	16,900
Merced CA	255,793	12,500
Stanislaus CA	514,453	9,300
Texas OK	20,640	8,000
Kings CA	152,982	7,500
Chaves NM	65,645	6,400
Bladen NC	35,190	6,400
Kern CA	839,631	5,700
Fresno CA	930,450	5,600
Maricopa AZ	3,817,117	5,300
San Bernardino CA	2,035,210	5,000
San Joaquin CA	685,306	5,000
Curry NM	48,376	4,800
Roosevelt NM	19,846	4,600
Wayne NC	122,623	4,200
Dona Ana NM	209,233	4,000
Pinal AZ	375,770	3,700
Yakima WA	243,231	3,700

Due to a lack of data, the distribution of individual farms cannot be illustrated as in the WWTP and landfills analyses. The results are shown by county (Figure 5). Farm sizes can vary by region, but as an example, data taken in the Central Valley of California found that most dairy farms have 199 to 699 cows [25]. In this example, the economic feasibility of anaerobic digestion at dairy farms with fewer than 1,000 cows might hinge on air and water regulations as well as other technical factors.

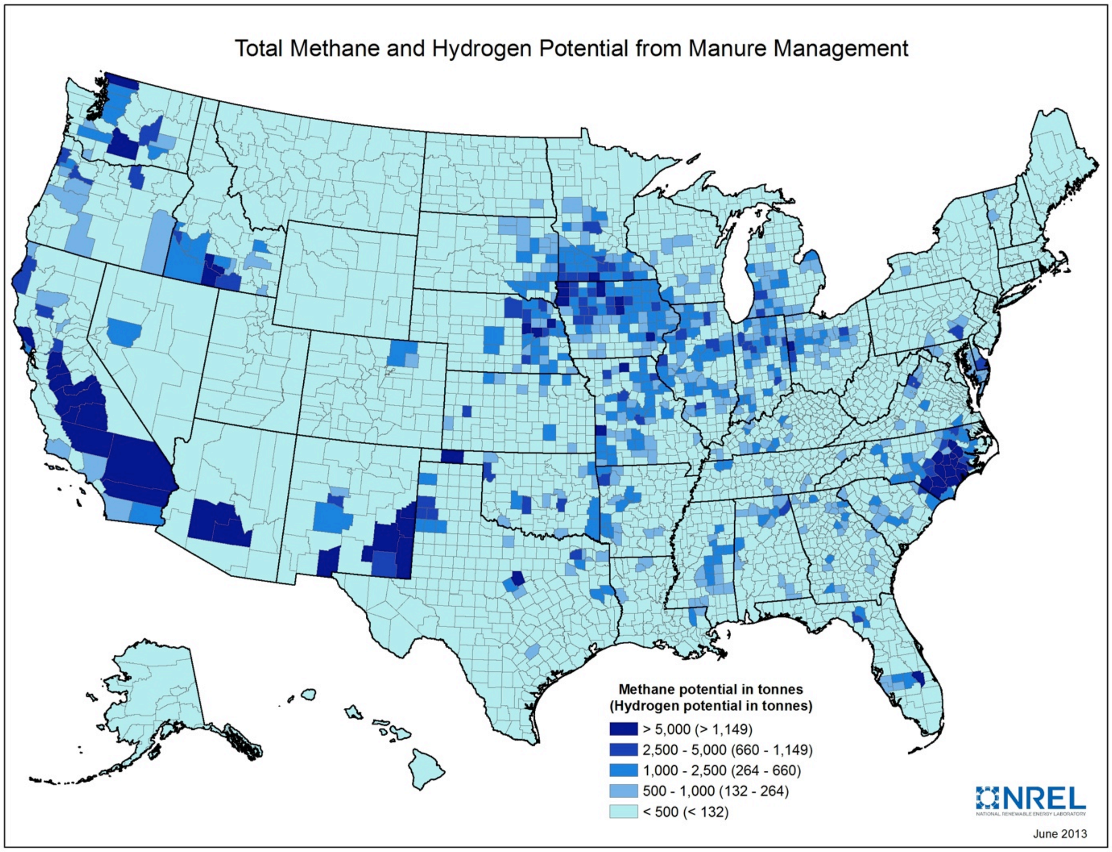


Figure 5. Total methane and hydrogen potential from animal manure in the United States by county

3.4 Industrial, Institutional, and Commercial

The resource potential of IIC sources of organic waste represents a new analysis not based upon previous work. This analysis uses data from the U.S. Census Bureau's County Business Patterns [26] and the Homeland Security Infrastructure Program (HSIP) [27]. Data from the U.S. Census Bureau includes food manufacturing and wholesalers such as fruit and vegetable canneries; dairy creameries (milk, cheese, yogurt, ice cream, butter); vineyards; meat packing and processors; slaughterhouses; coffee and tea production; breweries and distilleries; bakeries; and soft drink bottling plants, as well as organic waste facilities such as supermarkets, restaurants, and hotels. Data from the HSIP include primarily institutional facilities, namely hospitals, nursing homes, education facilities (universities, colleges, schools), and correctional facilities.

3.4.1 Methodology

Data on the number of businesses and employees in each county were obtained from the County Business Patterns; data on the number of beds, students, and inmates at each location were gathered from the HSIP and further aggregated to the county level for consistency. Then, a ratio of food disposed per employee, bed, student, or inmate was applied to estimate the amount of organic waste by county (Table 4). Assuming that biogas yield is 5,000 standard cubic feet per ton of organic waste and that the composition of biogas from organic waste is 60% methane and

40% carbon dioxide, we estimate the methane potential by anaerobic digestion of organic waste [28]. The hydrogen potentials include a reduction of the methane from purification of the biogas and conversion by SMR as discussed in Section 2.

Table 4. Methodology for Estimating Organic Waste from IIC Sources [29]

Business	NAICS code	SIC code	Food Disposed (tons/year)
Food and beverage manufacturing	311/// and 3121//	20	0.41 per employee
Food wholesalers/ distributors	4244//, 4245//, and 4248//	51	0.4 per employee
Supermarkets, food stores	445///	54	1.25 per employee
Restaurants	722///	58	1.1 per employee
Hotels/motels	7211//	70	0.18 per employee
Hospitals	N/A (HSIP)	N/A (HSIP)	0.62 per bed
Nursing homes	N/A (HSIP)	N/A (HSIP)	0.33 per bed
Colleges, universities, schools, and day cares	N/A (HSIP)	N/A (HSIP)	0.05 per student
Correctional facilities (prisons)	N/A (HSIP)	N/A (HSIP)	0.18 per inmate

N/A = not available
NAICS = North American Industry Classification System
SIC = Standard Industrial Classification

3.4.2 Potential

The total potential from IIC sources is slightly less than from the other biogas sources examined, yet it still represents a significant source of methane and hydrogen. In this new analysis, only total potential is calculated. Estimating the net availability fell beyond the scope of this study but could make a valuable follow-up study. The total methane potential in raw biogas from IIC sources is estimated at 1.2 million tonnes annually, or 306,000 tonnes of hydrogen.

The top 20 counties are shown in Table 5. These counties represent almost 20% of the total potential. The geographic distribution within the United States by county is shown in Figure 6. The geographic distribution tends to be close to population centers, making it another good resource for hydrogen vehicle introduction.

Table 5. Hydrogen Potential from IIC Sources in the Top 20 U.S. Counties

County	Population (2010 Census) [16]	Total Hydrogen Potential (tonnes)
U.S. (all counties)	*308,747,508*	*305,700*
Los Angeles CA	9,818,605	9,800
Cook IL	5,194,675	5,400
Harris TX	4,092,459	4,400
Maricopa AZ	3,817,117	4,300
New York NY	1,585,873	3,500
Orange CA	3,010,232	3,400
San Diego CA	3,095,313	3,300
Dallas TX	2,368,139	2,700
Clark NV	1,951,269	2,500
Miami-Dade FL	2,496,435	2,500
King WA	1,931,249	2,300
Tarrant TX	1,809,034	2,000
Santa Clara CA	1,781,642	1,800
Broward FL	1,748,066	1,800
Bexar TX	1,714,773	1,800
Riverside CA	2,189,641	1,800
Middlesex MA	1,503,085	1,700
San Bernardino CA	2,035,210	1,700
Allegheny PA	1,223,348	1,600
Philadelphia PA	1,526,006	1,600

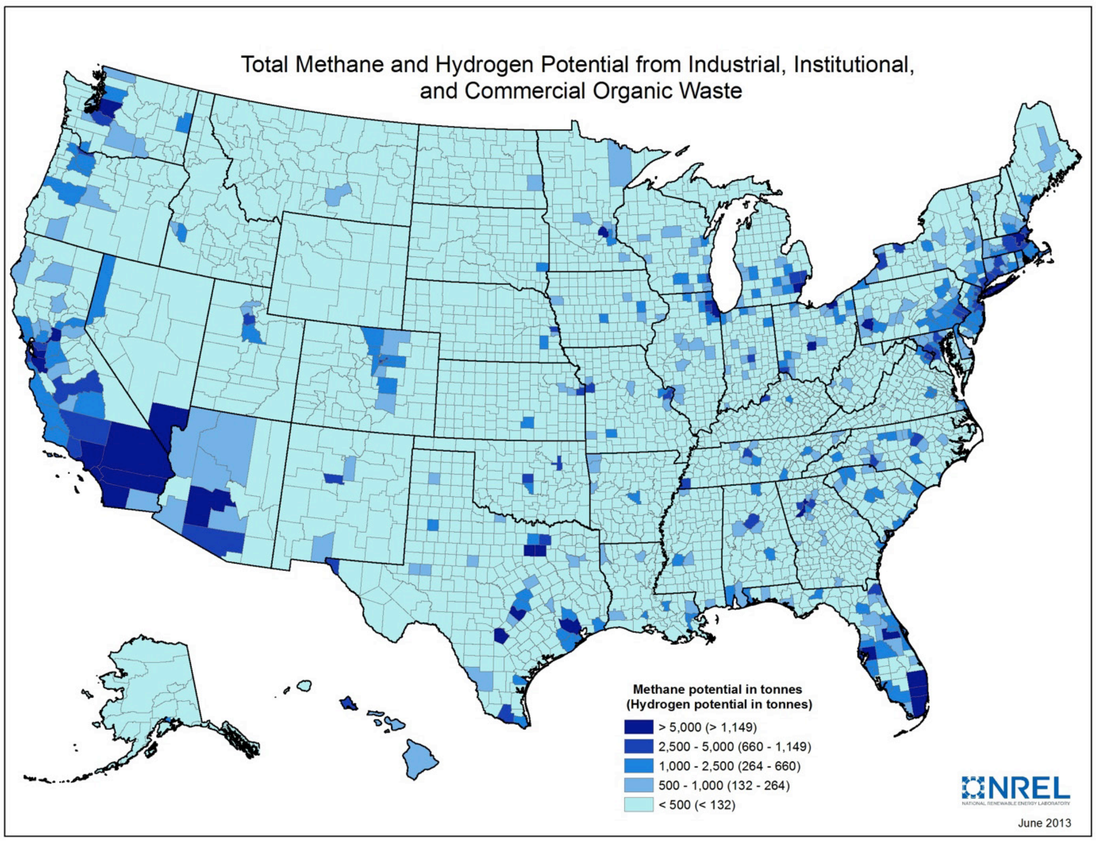
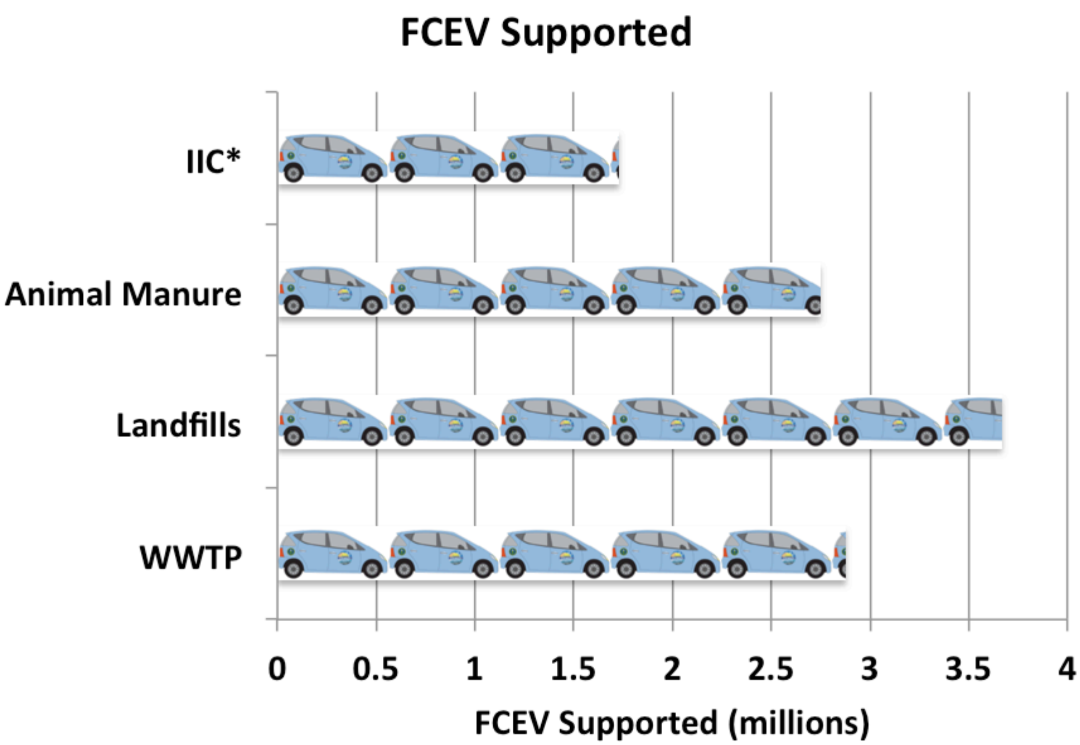


Figure 6. Methane and hydrogen potential from IIC sources in the United States by county

4 Vehicles Supported by Renewable Hydrogen

One area in which there is interest in renewable hydrogen from biogas is as a fuel for FCEVs. The transportation sector is the largest consumer of petroleum products and second only to the electric power sector in greenhouse gas emissions [30]. Therefore, from energy security and environmental perspectives, it is of interest to displace some of that petroleum demand with domestic renewable fuels such as hydrogen from biogas.

The number of FCEVs potentially supported by renewable hydrogen from biogas was estimated by assuming an average FCEV fuel economy and average annual miles travelled per vehicle. We have used the 2020 medium case from a U.S. Department of Energy report on future light-duty vehicles to make these estimates [31]. The medium case is a mid-optimistic scenario with respect to vehicle fuel economy. Based upon this source, an FCEV with fuel economy of 56.5 miles per gasoline gallon equivalent (gge) and annual travel of 10,000 miles per year is used to calculate the annual number of FCEVs supported. The results shown in Figure 7 and Table 6 are based on the assumption that 1 gge is equal to 1 kg of hydrogen. The total vehicles supported from all biogas sources are about 11 million FCEVs annually with landfills accounting for more than a third of that at 3.7 million FCEVs annually.



* IIC is total potential.

Figure 7. The number of FCEVs supported by biogas source, utilizing the net availability of the biogas source (with the exception of IIC)

Table 6. FCEVs Supported and Percentage of U.S. Fleet by Biogas Source, Utilizing the Net Availability of the Biogas Source (with the Exception of IIC)

Biogas Source	FCEVs Supported (millions)	Percentage of 2010 U.S. Light-Duty Fleet
WWTPs	2.9	1%
Landfills	3.7	2%
Animal Manure	2.7	1%
IIC [a]	1.7	1%
Total	*11.0*	*5%*

[a] IIC is total potential.

To put these numbers of vehicles in perspective, these values were also compared to the light-duty vehicle fleet as of 2010 to demonstrate the impact this would have on the total vehicle fleet. The vehicle registrations in 2010 for cars and light-duty trucks (two axles, four tires) were approximated at 131 million and 99.5 million respectively, or about 230 million light-duty vehicles in the 2010 U.S. fleet [32]. The comparison to the 2010 U.S. light-duty fleet is shown in Table 6. Hydrogen from biogas could support about 5% of the 2010 light-duty vehicle fleet if those vehicles were replaced with FCEVs. This estimate accounts for only the net availability of methane in the biogas sources, except for IIC sources, in which only the total potential was estimated. The real potential from other sources (WWTP, landfills, and animal manure) could be higher as discussed in the respective resource assessments and the overview analysis below.

5 Discussion

This section discusses the sensitivities of sources and examines the combined resource potential of the United States as well as select regions of interest. These analyses further aggregate the information and provide more detail, thus helping to inform strategies for development of the diverse biogas sources.

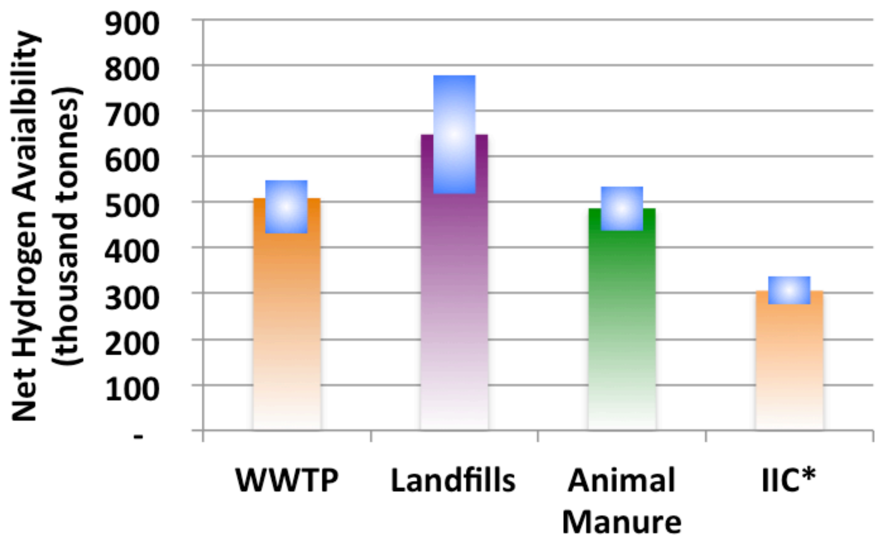
5.1 Resource Sensitivities

Biogas is a variable resource and the resource estimate is only approximate. To highlight this, approximate ranges for the different sources were used to indicate some of the uncertainty in calculating an annual estimate.

Ranges were used to calculate high and low amounts from the base default methane potential. Estimates of the methane content in the biogas produced were used for WWTPs and landfills of 65% and 50% by volume, respectively. However, the methane content of the biogas can and does vary from site to site, based on the content of the waste, as well as within a site annually, due to climate-related factors. Table 7 shows the default values as well as high and low methane content of the biogas produced by volume. For animal manure and IIC sources of biogas, a sensitivity range was more difficult to identify, so an uncertainty range for methane of ±10% was used. Figure 8 shows the relative capacity of the different renewable hydrogen sources along with the uncertainty ranges described in Table 7.

Table 7. Range of Methane Content in Biogas

Source	Default Methane Content of Biogas by Volume	High	Low	Reference
WWTPs	65%	70% (CH_4 by volume)	55% (CH_4 by volume)	[33]
Landfills	50%	60% (CH_4 by volume)	40% (CH_4 by volume)	[34]
Animal Manure	Calculates methane, not biogas	+10%	-10%	
IIC	60%	+10%	-10%	



* IIC uses total potential, no net availability identified.

Figure 8. Relative intensity and range of hydrogen potential from biogas sources

5.2 U.S. National Methane and Hydrogen Potential

The U.S. total methane potential in raw biogas from the sources examined is almost 16 million tonnes, but the net availability calculated is about 6.2 million tonnes. The net availability excludes IIC sources for which net availability was not calculated. For comparison, the 2013 U.S. natural gas consumption was almost 573 million tonnes [35]. If the methane is converted to hydrogen, it represents a total potential of 4.2 million tonnes and a net potential of 1.6 million tonnes. These are only rough estimates due to a variety of reasons. The data used for WWTPs are missing significant amounts of information that would be needed for a full assessment: only about half the sites included the necessary fields. The landfill data also have discrepancies that make higher totals possible. The LMOP database may have additional sites capable of supporting feasible energy projects that are not included in candidate sites. Although some of the estimates are uncertain and based upon limited data, it appears that there is significant biogas resource potential. Table 8 shows the U.S. total potential and net availability rounded to the nearest thousand tonne for methane and hydrogen if converted from that methane. Landfills, in this study, represent by far the largest total resource, and even when the net availability from candidate sites only is taken into account, the landfill potential is larger than that of the other resource types. WWTPs, landfills, and IIC sources all tend to be clustered around population centers. If production logistics and diseconomies of scale due to dispersed locations can be overcome, the delivery of hydrogen to demand centers may have lower costs than that for other renewable sources, such as wind or solar. Animal manure is more prevalent in rural areas but could bring economic opportunities for export to more populated areas or supply hydrogen stations located along interstates.

A map of the combined resources in the United States is shown in Figure 9. This overview resource map is useful in helping to understand the distribution and possible challenges that may be found in developing biogas resources. The geographic distribution and the resource quantities are important in helping to inform strategy and policies that may support future development.

Table 8. U.S. Methane and Hydrogen Potentials by Source

Source	**Methane Potential (thousand tonnes/yr)**		**Hydrogen Potential (thousand tonnes/yr)**	
	Total	Available	Total	Available
WWTPs[a]	2,339	1,927	618	509
Landfills[b]	10,586	2,455	2,795	648
Animal manure[c]	1,905	1,842	503	486
IIC organic waste	1,158	N/A	306	N/A
Total	*15,988*	*6,224*	*4,221*	*1,643*

[a] Total potential for WWTPs is higher, given that the analysis was done for only half of the WWTPs in the country (water flow data for the rest is missing).
[b] Total potential for landfills could be higher given that the estimate accounts for only the WIP recorded for a given year and does not take into account additional waste that may have come in since the record was taken (as it was done for the "available potential" estimate). It is an approximate value. Available potential for landfills is estimated using candidate landfills only. Available potential could be higher if we include "other" and "potential" landfills.
[c] Existing digesters (dairy, poultry, and swine) capture about 62,942 tonnes/yr [24].

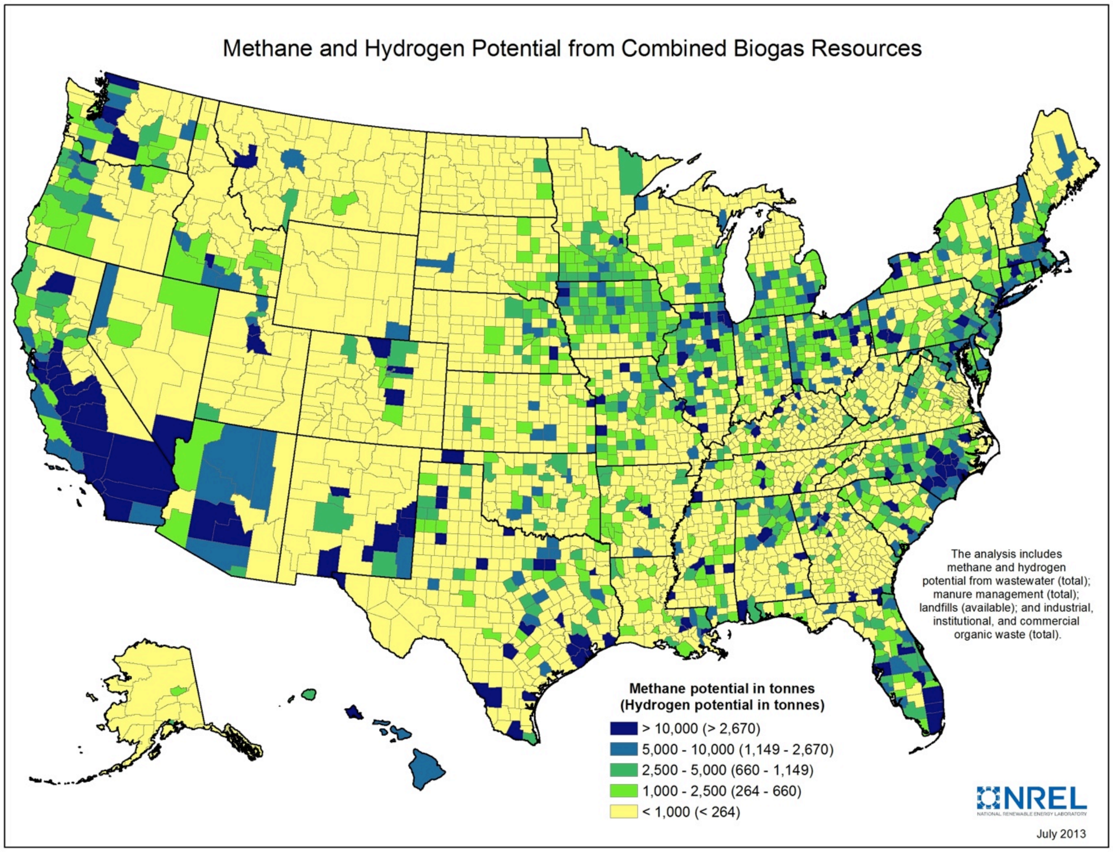


Figure 9. Methane and hydrogen potential from combined biogas sources in the United States by county

5.3 Comparison to Previous Study

The current analysis updates and expands the biogas resource assessment and hydrogen potential estimates in a 2006 study by Milbrandt and Mann [3]. New data availability and calculation methods have been used to create better estimates of both the methane potential and the hydrogen conversion. The refinements to the assessment process make a direct comparison of the results difficult, but the differences are highlighted below to examine the changes and updates.

The methodology for calculating the methane potential of each resource was refined in various ways. In the previous study, methane from WWTPs was not calculated at specific sites as it is here; it used census data and the biochemical oxygen demand (BOD) per capita in its estimate. This analysis uses EPA's 2008 Clean Watersheds Needs Survey database of actual WWTPs and their waste flow for a better estimate of the methane potential [8]. Landfill estimates were updated with new data from the EPA's LMOP database and the methane potential calculation was refined with guidance from the EPA. The animal manure assessment was updated from 2002 data to 2007 data from the U.S. Department of Agriculture Census of Agriculture. The manure estimates were also refined to only include milk cows, hogs, and broiler chickens; the previous assessment also included beef cows, sheep, layer chickens, and turkeys. This change was made due to subsequent research that deemed the other animal manure types somewhat less suitable for anaerobic digestion due to either lower resource availability, less-suitable material, or generally practiced manure management systems that aren't amenable to anaerobic digestion. This, of course, does not mean that farms raising these animals could not be successful at anaerobic digestion applications. It only means that their contribution to the methane and hydrogen potential at a national level is relatively small, but they could still play a major role at local levels. Changes were also made regarding the methane conversion to hydrogen. In the previous study a conversion factor of 2.34 kg CH_4/kg H_2 was used, 85% of the stoichiometric maximum efficiency for SMR. This analysis assumes there is a 13% loss of methane during the purification process (see Section 2). Additionally the hydrogen conversion factor of 3.295 kg CH_4/kg H_2 is used based upon an updated SMR case study from DOE's H2A Production model [7]. These changes have lowered the expected hydrogen output from the different methane resources.

All these modifications were made to reflect the current understanding of the systems being assessed and to use better quality data where possible, but they result in assessments that are not directly comparable. Table 9 reviews the estimates made in the two studies.

Table 9. Review of Previous Study

Source[a]	Milbrandt and Mann (2006) Methane Potential Total (thousand tonnes/yr)	Milbrandt and Mann (2006) Hydrogen Potential Total (thousand tonnes/yr)	Saur and Milbrandt (2013) Methane Potential Total (thousand tonnes/yr)	Saur and Milbrandt (2013) Hydrogen Potential Total (thousand tonnes/yr)
WWTP	500	200	2,339	618
Landfills	12,400	5,300	10,586	2,795
Animal manure	2,200	900	1,905	503

[a] Only total potential is shown since the previous study did not include net availability.

5.4 Select U.S. Local Regions

The methane and hydrogen capacities on a national level are useful, but understanding the distribution of resources on a local level can help characterize challenges and opportunities for different communities. To this end, examples of local maps have been developed for two areas: Northern California and Boston, Massachusetts. Relying upon a renewable source of hydrogen would help highlight the clean car profile of FCEVs during early market introduction, and the state of California already has requirements for renewable hydrogen production. However, development of these biogas resources has challenges that may be unique for any given region, state, or urban area. State and local policies, rapport with local utilities, and the favor of local sources and stakeholders will all factor into successful project investment and resource development. Understanding a local region's resources is one step toward a better understanding of policies or initiatives that may spur development of renewable hydrogen biogas projects.

5.4.1 Northern California

California has been a leader in the United States in developing hydrogen infrastructure in preparation for the 2015–2017 commercial rollout of FCEVs. There are state and local policies, such as the Zero Emissions Vehicle mandate and energy and environmental standards for hydrogen production (SB 1505), which regulate vehicle sales and emissions, as well as hydrogen production, including renewable hydrogen. California has done a lot of work developing clean energy policies that will foster its clean air and environmental goals [36, 37]. A map of Northern California (Figure 10) shows good hydrogen potential from all the biogas sources examined in this report.

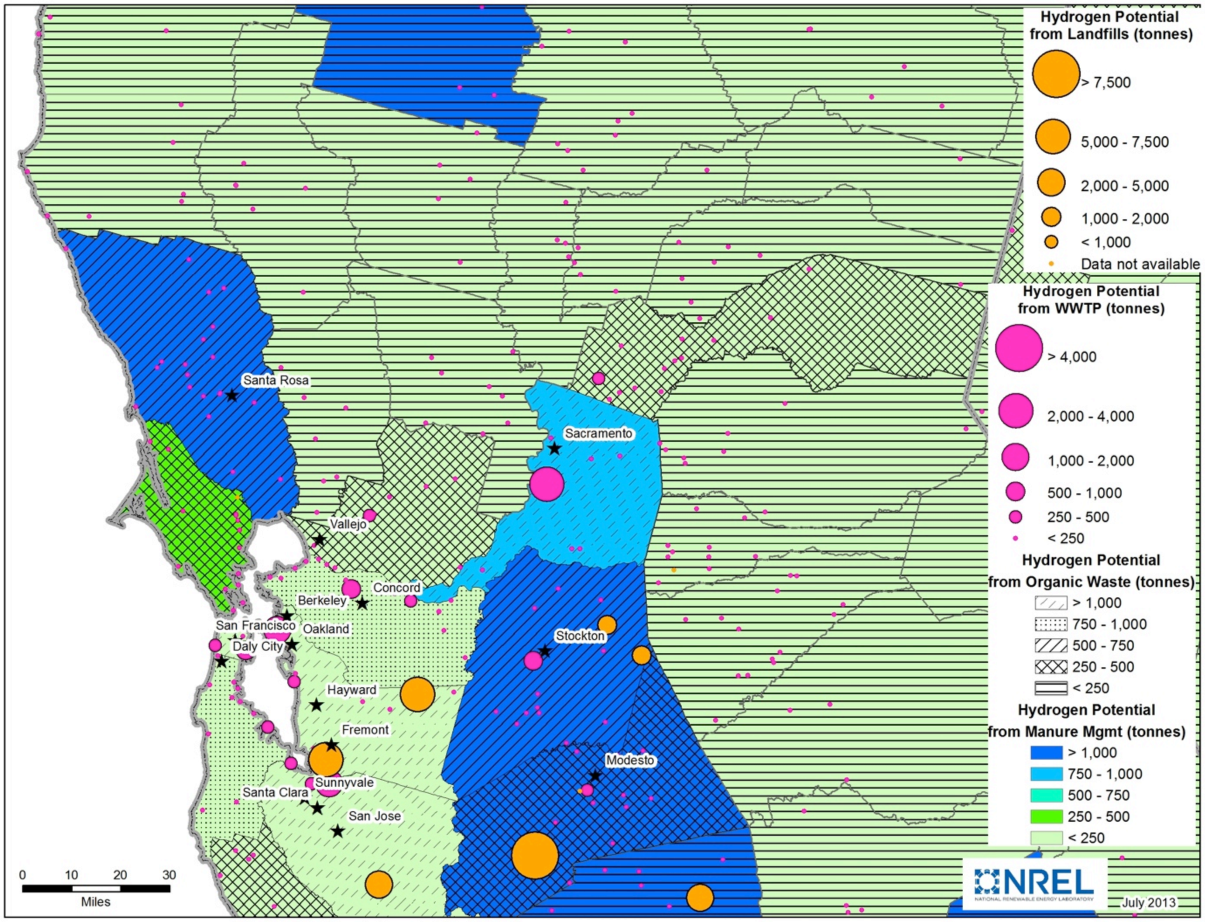


Figure 10. Net (as available) hydrogen potential from biogas in Northern California

The Northern California area shown in Figure 10 has 41 counties with biogas resource potential. The total potential for this region is about 93,300 tonnes of hydrogen annually, which could support almost 527,300 FCEVs. The totals and breakdown by biogas source are shown in Table 10. A breakdown of the hydrogen potential from all biogas sources for the top 20 counties in Northern California is shown in Table 11. Almost three quarters of this comes from animal manure and landfill sources in the region, 34,500 and 34,700 tonnes of hydrogen annually, respectively.

Table 10. Net (As Available) Hydrogen Potential By Biogas Source in Northern California

Source	Hydrogen Potential (tonnes)	FCEVs Supported (thousands)	Counties	Sites
WWTPs	11,800	66.8	39	251
Landfills	34,700	196.2	5	7
Animal Manure	34,500	194.9	29	[a]
IIC [b]	12,300	69.4	34	[a]
Total	*93,300*	*527.3*	*41*	

[a] Individual sites not counted, data at county level.
[b] Total IIC potential.

Table 11. Net (As Available) Hydrogen Potential of Top 20 Counties in Northern California

County	Population (2010 Census) [16]	Hydrogen Potential (tonnes)	FCEVs Supported (thousands)
Total Region	*14,536,321*	*93,300*	*527.3*
Stanislaus CA	514,453	24,200	136.9
Alameda CA	1,510,271	15,600	88.3
Merced CA	255,793	15,000	84.9
San Joaquin CA	685,306	9,400	53.0
Sacramento CA	1,418,788	4,900	27.8
Santa Clara CA	1,781,642	4,900	27.5
Madera CA	150,865	3,600	20.6
Contra Costa CA	1,049,025	2,600	14.7
Sonoma CA	483,878	2,100	12.1
San Mateo CA	718,451	1,700	9.5
San Francisco CA	805,235	1,300	7.4
Glenn CA	28,122	1,100	6.1
Marin CA	252,409	1,100	5.9
Placer CA	348,432	1,000	5.6
Solano CA	413,344	1,000	5.8
Yolo CA	200,849	600	3.3
Butte CA	220,000	500	2.6
Napa CA	136,484	500	2.7
El Dorado CA	181,058	300	2.0
Mendocino CA	87,841	300	1.5

5.4.2 Boston, Massachusetts

The Boston urban area is a promising candidate for FCEV market expansion on the East Coast due to the relatively high historical demand for novel vehicle technologies, such as hybrid electric vehicles, and the manageable logistics of planning for hydrogen infrastructure development (compared to the New York region, for example, which is a larger overall market but more challenging logistically).

A map of the Boston area is shown in Figure 11. Landfills show a lower prevalence than expected due to several in the area having existing energy projects that make them unavailable for renewable hydrogen production from LFG. However, the population centers have availability in WWTPs, and the immediate Boston area has good amounts of IIC source availability. Biogas from animal manure may not be the first resource developed due to the relatively low and dispersed sources. Overall, Boston shows a little less potential from biogas than the Sacramento area, but there are still significant sources that could be targeted with the right types of policies and incentives.

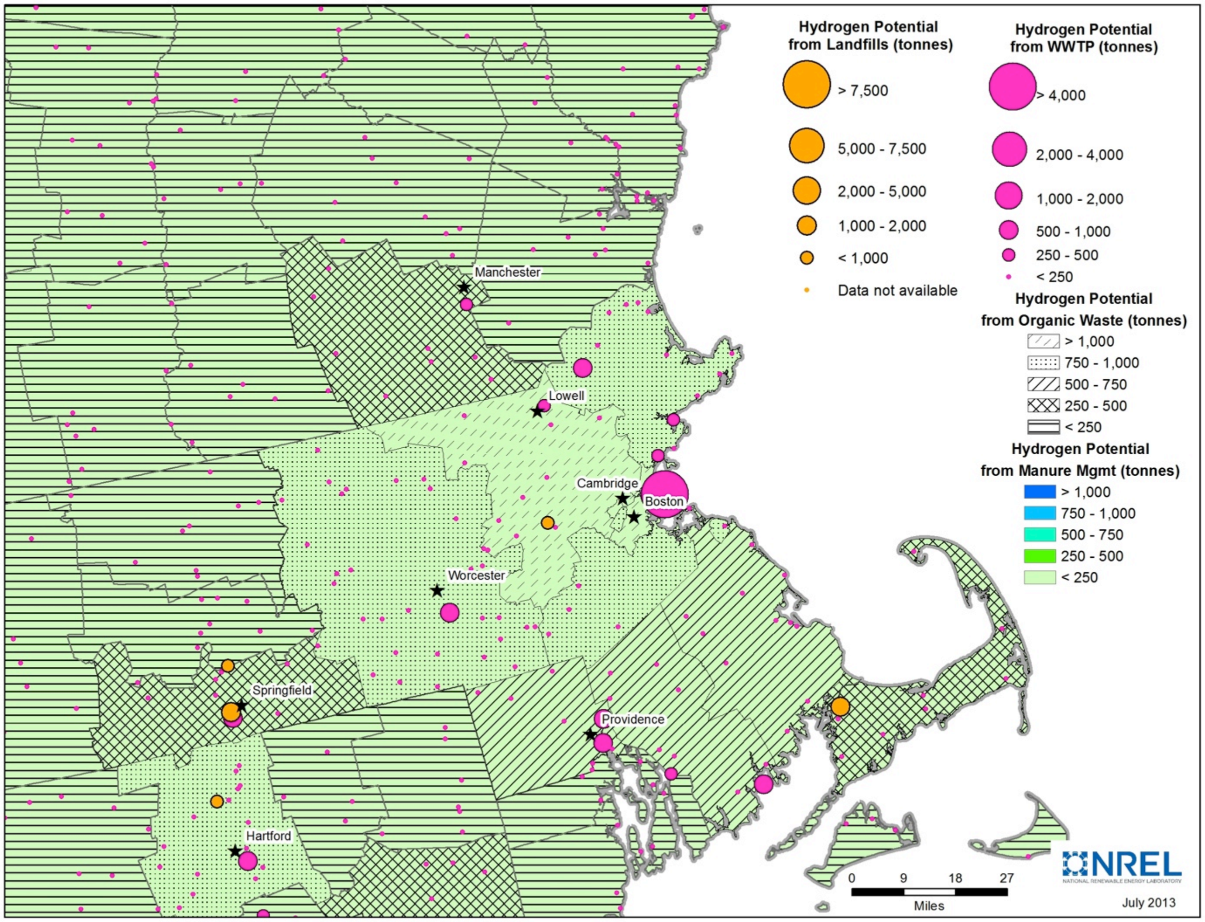


Figure 11. Net (as available) hydrogen potential from biogas in Boston, Massachusetts

The Boston region has about 33,000 tonnes of net (as available from the analysis) hydrogen potential annually, which could support approximately 186,700 FCEVs. Table 12 shows the breakdown by biogas source for the Boston region, and Table 13 shows the total potential of the top 20 counties in the area. More than 85% of the potential comes from WWTP and IIC biogas sources, both situated close to urban areas. Animal manure is not a big source for the area and is relatively spread out, making it less useful for vehicle infrastructure. The methane from manure could be better used in niche applications, such as on-site generation, if it is developed.

Table 12. Net (As Available) Hydrogen Potential By Biogas Source in the Boston Region

	Hydrogen Potential (tonnes)	FCEVs Supported (thousands)	Counties	Sites
WWTPs	15,400	86,700	38	283
Landfills	4,400	24,700	5	5
Animal Manure	500	2,800	37	[a]
IIC [b]	12,800	72,500	41	[a]
Total	33,000	186,700	41	

[a] Individual sites not counted, data at county level.
[b] Total IIC potential.

Table 13. Net (As Available) Hydrogen Potential of Top 20 Counties in the Boston Region

County	Population (2010 Census) [16]	Hydrogen Potential (tonnes)	FCEVs Supported (thousands)
Boston Region	*11,966,888*	*33,000*	*186.7*
Hartford CT	894,014	3,800	21.3
Hampden MA	463,490	3,500	19.7
Essex MA	743,159	2,700	15.1
Providence RI	626,667	2,500	14.2
Middlesex MA	1,503,077	2,400	13.4
Worcester MA	798,552	2,400	13.4
Bristol MA	548,285	2,100	11.9
Barnstable MA	215,888	1,500	8.4
Hampshire MA	158,080	1,100	6.2
Suffolk MA	722,023	1,100	6.4
Norfolk MA	670,850	900	4.9
Hillsborough NH	400,721	800	4.6
Plymouth MA	494,919	800	4.4
New Haven CT	862,477	800	4.6
Middlesex CT	165,676	500	2.9
Rockingham NH	295,223	500	2.9
York ME	197,131	500	3.0
Berkshire MA	131,219	400	2.4
Kent RI	166,158	400	2.5
Merrimack NH	146,445	400	2.1

6 Biogas Purification Challenges

In this analysis of hydrogen production potentials from biogas resources, we have estimated upgraded biogas, or biomethane, available after treating biogas through a process sometimes referred to as purification or sweetening, resulting in a natural-gas-quality product [9, 38]. The energy content of untreated biogas is approximately 600–800 Btu/ft^3, which is significantly lower than that of natural gas, which ranges from approximately 950–1,050 Btu/ft^3. Biomethane can be used relatively interchangeably with natural gas and as an alternative feedstock for the SMR process to make hydrogen, as well as other applications.

The contaminants in untreated biogas pose several challenges for its use. There are applications in which the lower-energy-content biogas can be used, usually on site, such as in an internal combustion engine, gas boiler, or even certain fuel cells such as molten carbonate fuel cells or solid oxide fuel cells [25, 39-41]. These applications may be able to use minimally treated biogas where some of the worst contaminants are removed but the gas has not been purified to natural gas quality. This could be more economically viable at smaller sites or where the heat and electricity can be used on site. These applications will compete with other uses of the biogas that require natural-gas-quality biomethane, such as other kinds of electricity generation technologies and use in compressed natural gas vehicles or in FCEVs when converted to hydrogen.

For this analysis, we considered upgraded biomethane as a renewable substitute for natural gas, making it more easily integrated with some of the current infrastructure of natural gas pipelines and natural gas vehicle refueling stations [42, 43]. The resource and infrastructure could be developed as one component within a larger alternative fuel infrastructure supporting FCEVs as well as compressed natural gas vehicles for a larger mass market of sustainable transportation fuels. An important factor in developing biogas for a larger mass market, rather than in niche areas, is that it can be upgraded to biomethane and easily incorporated into existing infrastructure.

Contaminants in biogas are a challenge for its integration into the natural gas infrastructure and account for some of the resistance by gas utilities to injection of biomethane into pipelines. Raw biogas is composed mainly of methane (CH_4) and carbon dioxide (CO_2) and is saturated with water (H_2O). However, it also contains a corrosive contaminant, hydrogen sulfide (H_2S), as well as oxygen (O_2), nitrogen (N_2), mercaptan sulfur, and sulfur (S) that are of interest to natural gas suppliers. Some biogas sources have other contaminant issues, such as siloxanes, in addition to those listed above [9, 39, 43, 44]. Siloxanes are organosilicons, and they are present in many consumer products, which then get into biogas from WWTPs and landfills. When combusted, siloxanes can be converted into silicon dioxide (SiO_2), similar to sand, which can damage engines, turbines, and fuel cells [45-47]. Table 14 shows some of the requirements for biomethane injection into natural gas pipelines for two California utilities; many gas utilities disallow biomethane completely [25, 39, 48-51].

Table 14. Biomethane Quality Requirements for Injection into Natural Gas Pipelines [25, 39, 48-51]

Gas Quality	PG&E	SoCalGas
CO_2	≤1%	≤3%
O_2	≤0.1%	≤0.2%
H_2S	≤0.25 grains/100 scf (4 ppm)	≤0.25 grains/100 scf
Mercaptan sulfur	≤0.5 grains/100 scf (8 ppm)	≤0.3 grains/100 scf
Total sulfur	≤1 grain/100 scf (17 ppm)	≤0.75 grains/100 scf
H_2O	≤7 lb/million scf	≤7 lb/million scf
Total inerts	No requirement	≤4%
Heating value	Specific to receipt point	970–1,150 Btu/scf
Landfill gas	Not allowed	No requirement
Temperature	60°–100°F	50°–105°F
Gas interchangeability	Per AGA Bulletin 36 [52]	Per AGA Bulletin 36
Wobbe number	Specific to receipt point	Specific to receipt point
Lifting index	Specific to receipt point	Specific to receipt point
Flashback index	Specific to receipt point	Specific to receipt point

AGA = American Gas Association
ppm = parts per million

Beyond the specific quality criteria for natural gas, the biogas must also be free of pathogens, bacteria, and other substances hazardous to people and the environment [25, 36, 37, 39, 49]. In general, the anaerobic process kills or reduces the pathogens and bacteria inherent in the organic matter if done correctly, but there are other elements that may pose health risks and should be accounted for and monitored [36, 37, 53]. A list of other biogas and biomethane constituents of concern developed for California regulation AB 1900 is shown in Table 15.

Table 15. Biogas and Biomethane Constituents of Concern Developed for California AB 1900 [37]

Constituent	Landfill	WWTP	Dairy
Antimony	X		
Arsenic [a]	X		
Copper	X		
p-Dichlorobenzene [a]	X	X	
Ethylbenzene [a]	X	X	X
Hydrogen sulfide	X	X	X
Lead	X		
Methacrolein	X		
n-Nitroso-di-n-propylamine [a]	X		X
Mercaptans (alkyl thiols)	X	X	X
Toluene	X	X	X
Vinyl chloride [a]	X	X	

[a] Denotes the chemical is a carcinogen; constituents not indicated by “a” included due to chronic hazard quotient.

Another potential hurdle for the introduction of biomethane into the natural gas infrastructure is restriction of injection only to the transmission system, not the smaller distribution system pipelines [25]. The production of biogas can fluctuate due to humidity, temperature, and season, which can create a pressure problem for distribution pipelines that are not designed to handle the extraction pressure differentials. Injection into the transmission system is possible, if more expensive, and requires larger purification plants and higher compression. This requirement could limit the economic viability of smaller biogas-producing sites unless they can aggregate their gas production or supplement their organic matter waste sources with co-digestion of other organic matter, both of which have their own technical and regulatory issues [25, 39].

7 Conclusions

Biogas is a relatively dispersed resource. In this report we have examined the total potential and net availability from four classifications of organic waste: WWTPs, landfills, animal manure, and IIC sources. They each have unique challenges in their potential development. The smaller sizes of many plants, farms, and facilities may challenge the economic feasibility of a biogas facility. The right policies, incentives, and collaboration with key players are necessary for success. Nevertheless, biogas and hydrogen from biogas can have a place in sustainable energy futures, but other clean energy technologies will also need to be developed. This analysis combines data from multiple databases and agencies (EPA, U.S. Department of Agriculture, and U.S. Census Bureau) to show results in a standardized format and analyzed with a consistent approach.

Landfills represent by far the greatest total potential (10.6 million tonnes methane from raw biogas or 2.8 million tonnes of hydrogen) and net availability (2.5 million tonnes of methane from raw biogas or 648,000 tonnes of hydrogen) even when factored conservatively using only LMOP candidate sites. The potential from all sources probably falls somewhere between the total potential (16 million tonnes of methane from raw biogas or 4.2 million tonnes of hydrogen) and the net availability (6.2 million tonnes of methane from raw biogas or 1.6 million tonnes of hydrogen) due to some conservative estimates in the net availability. Net availability excludes IIC sources. Many of these sources, such as WWTPs, landfills, and IIC sources, are close to population centers, making the delivery costs lower than for rural sources. However, rural sources can provide economic opportunities for export or bridging infrastructure along interstates.

Reaching the point of economic feasibility for developing these resources has several hurdles. The size of many of the sources may make aggregating resources a better option either through co-digestion or more centralized cleanup plants that make biomethane (methane of natural-gas-quality purity). Contaminants are also a challenge and somewhat unique to each source. While comprising a very small portion of the biogas, contaminants must be removed on some level to protect equipment using biogas as a fuel or for health and environmental risk factors. For injection into the natural gas pipeline network, the biogas must be purified to natural-gas-quality biomethane, at which point it can be used relatively interchangeably with natural gas. However, there may be resistance by gas utilities to its injection, in general, or the location of injection, in particular; the cost of biogas cleanup can also be significant. In addition, there are competing applications for the biogas that may affect how it is used.

Understanding the geographic distribution and size elements of different biogas sources can help decision makers to tailor policies and incentives on the federal, state, and local level. Strategies for aggregating sources or designing economically viable systems for different capacities will help the overall development of the biogas resources. Sacramento and Boston are highlighted to show the regional differences. Understanding the geographic elements can help early development and pilot projects take advantage of these resources.

Biogas and hydrogen from biogas can aid early FCEV rollout. They are produced from local, sustainable resources that can supply upwards of 5% of the current U.S. vehicle fleet if that portion were replaced by FCEVs. The transportation sector is second only to the electric sector in greenhouse gas emissions, and renewable hydrogen used in FCEVs can offer environmental benefits.

8 Future Work

There are several areas not addressed in this analysis that can be expanded in the future. Other sources of organic waste exist that could be used to produce biogas, for example lipids (fats, oils, and grease). Additionally, lignocellulosic biomass (e.g., crop and forest residues or dedicated energy crops) could be used to produce biogas via anaerobic digestion (dry fermentation, co-digestion) or through thermo-chemical means (e.g., gasification). An analysis that compares the various conversion processes and uses of biogas (power, fuel, etc.) could determine the most efficient use of biogas sources. Understanding the full resource potential and its geographic distribution would help in designing better systems. This analysis does not address the economic viability of producing biogas nor the costs for purification. The cost and quality will greatly affect the economic feasibility and what applications will compete for its use. These issues will be affected by regional policies and incentives that are not accounted for here. A pathway assessment of the spatial qualities of the resources to aid either co-digestion or better economies of scale in purification technologies was beyond the scope of this initial report.

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