5. Potential Uses of Biogas and Biomethane

This chapter discusses the potential uses of biogas and biomethane. At present, dairy manure biogas is used on-farm for direct electricity generation and some of the waste heat is recovered for other uses. One of our goals was to explore alternative direct on-farm uses of raw and slightly cleaned biogas. Because of its highly corrosive nature (due to the presence of H_2S and water) and its low energy density (as obtained from the digester, biogas contains only about 80 Btu/gallon or 600 Btu/scf, the potential for off-farm use of biogas is extremely low. As a result, this chapter focuses on possible alternate on-farm uses of biogas.

This chapter also explores potential on- and off-farm uses of biomethane—dairy biogas that has been upgraded through the removal of CO_2, H_2S, and water. Biomethane contains a heat capacity of about 130 Btu/gallon, which is equivalent to about 1,000 Btu/scf. Because of this high energy content, biomethane could be sold for off-farm applications to industrial or commercial users, for injection into a natural gas pipeline, or as vehicular fuel.

Potential On-Farm Uses of Biogas

The most common and popular on-farm use of biogas is to fuel an engine-generator (generator-set or genset) to produce electricity for on-farm use, or, less commonly, for off-farm sale or under a net-metered arrangement with the utility. Heat recovered from combustion of the biogas (whether in boilers or internal combustion engines) can be used to maintain the operating temperature of the anaerobic digester or for other on-farm uses. Because of relatively low energy prices in the past, other on-farm uses of biogas have been minimal and the associated experience base is quite small. Recent increases in energy prices and the likelihood of continued high prices may increase the attractiveness of other on-farm uses. More development work and analysis is needed, however, particularly with regard to USA-specific issues (as opposed to somewhat more favorable i.e., subsidized situations in Europe).

Biogas could be used for the same applications off-farm; however, as discussed in Chapter 4, off-farm distribution of biogas is constrained by factors such as economics and corrosion of transporting equipment.

In the following sections, we discuss some of the general considerations related to the use of biogas as a direct on-farm fuel. Although many of these considerations pertain to combined heat and power (CHP) applications, they provide important background information for possible alternative uses of biogas.

We also consider specific alternative on-farm uses, including as fuel for irrigation pumps and refrigeration systems. Finally, we discuss practical (non-technical) factors that affect the viability of biogas as a fuel for alternate on-farm use such as how well production capacity is matched to on-farm demand.

Biogas as a Fuel for Combined Heat and Power Applications

Burners and boilers used to produce heat and steam can be fueled by biogas. The direct substitution of biogas for natural gas or LPG, however, will not work for most standard commercially available burners. At given fuel gas feed pressures, gas must flow into combustion in the right stoichiometric ratio with air. Because of its high CO_2 content, if biogas flows through the burner orifice at the pressure intended for feeding methane or propane, the fuel-to-air ratio is insufficient to ensure flame stability.

A relatively simple option is to provide the combustion equipment with a second “as is” biogas burner that operates in parallel with the first. In this case, regardless of the fuel used, air flow is kept constant. Burner orifices for the respective burners can be set such that each burner meters the proper amount of gas to meet combustion stoichiometry. This could require other control measures such as (for simplest control) complete switchovers from pure biogas fuel to the fossil alternative, and modest (a few hours’ worth) backup biogas storage, but is otherwise straightforward.

Some operations that use landfill gas have adapted standard equipment to allow easy switchover from different fuel sources, whether landfill biogas, natural gas, or oil. An example of such equipment is the Cleaver-Brooks boiler at the Ajinomoto Pharmaceutical plant in Raleigh North Carolina, which has operated successfully using landfill gas for more than 10 years (Augenstein and Pacey, 1992; US EPA, 2001).

Conversion of a boiler system to operate on biogas typically involves the enlargement of the fuel orifice and a restriction of the air intake. Important considerations include the capability of the combustor to handle the increased volumetric throughput of the lower-Btu biogas, flame stability, and the corrosive impact of raw biogas on the burner equipment.

To prevent corrosion from H_2S and water vapor, operating temperatures should be maintained above the dew point temperature (250° F) to prevent condensation. It may also be advisable to use propane or natural gas for start up and shut down of the system, since higher operating temperatures cannot be maintained at these times.

If the biogas has an energy content lower than 400 Btu/scf, the combustion system may be limited by the volumetric throughput of the fuel, which may result in de-rating of the equipment. In addition, the burner orifice should be enlarged to prevent a higher pressure drop across the burner orifice due to the decreased heating value and specific gravity of the biogas results. However, orifice enlargement will degrade the performance of the burner if it is ever operated on natural gas or propane. To resolve this problem, the propane or natural gas can be mixed with air to create an input fuel with an equivalent pressure drop and heat input as the biogas. It is also possible to achieve fuel flexibility by using a dual burner system, as mentioned above. This allows optimum performance of the burners since they maintain the pressure drop for each fuel independently.

Direct Use of Biogas for On-Farm Heating

The need for on-farm heating applications varies both seasonally and from farm to farm. All farms require hot water on a year-round basis, although for most, the amount needed is likely to be far less than what could be generated from the biogas production of an average farm. In California, the need to heat buildings is seasonal, with the exception of nursery and hog farrowing rooms, which may require some year-round heat. Depending on the type of anaerobic digester used, some heat may be needed to keep the digester system at the proper operating temperature. There are three common technologies that can be used to supply heat for these types of applications: hot water boilers, forced-air heat, and direct-fired heat.

Hot water boilers. A modified commercial cast-iron natural-gas boiler can be used to produce hot water for most on-farm applications. Modifications include adjustments to the air-fuel mixture and enlargement of the burner jets. All metal surfaces of the housing should be painted. Flame-tube boilers may be used if the exhaust temperature is maintained above 300° F to minimize condensation. The high concentration of H_2S in the gas may result in clogging of the flame tubes.

The typical capacities, efficiencies, controls, and operating schemes for on-farm hot water boilers are provided below:

- *Available capacities*: Cast-iron pot boilers are available in sizes from 45,000 Btu/hr and larger.
- *Thermal efficiencies*: Conversion efficiencies are 75% to 85%.
- *Control systems*: Typical commercial control systems supplied with boilers.
- *Operating schemes*: The boiler could be used to produce all the heat required for an anaerobic digester (if a heated digester is used) as well as the maximum on-farm demand for heat.

Forced-air furnaces. Hot-air furnaces can be fueled by surplus biogas from a covered lagoon; however, California farms generally do not have a year-round need for heat. Forced air furnaces are manufactured from thin metal and depend on metal-to-air heat exchange. Corrosion-resistant models are not available; therefore, the gas should be pretreated to remove H_2S and water.

The typical capacities, efficiencies, controls, and operating schemes for on-farm forced-air furnaces are provided below:

Available capacities: Forced air furnaces are made with capacities from 40,000 Btu/hr and up.

Thermal efficiencies: Conversion efficiencies are 75% to 85%.

Control systems: Typical commercial control systems supplied with furnaces are used for control.

Operating schemes: It is difficult to recover heat for digester heating from a hot air furnace, and because of the seasonal need for other types of heating, it would be unusual in California to find a use for forced hot air on a farm that could consume all of the available biogas production potential. On the positive side, this type of heat would produce few environmental impacts if a California-approved low-NO_x-emission furnace were used. Gas treatment to remove H_2S would also reduce potential SO_2 emissions.

Direct-fired room heaters. Direct-fired heating is commonly used in hog farrowing and nursery rooms. A farm will typically have multiple units and some heat is required virtually every day of the year. Commercial models of this equipment can be operated using treated biogas. Burner orifices should be enlarged for low Btu gas.

A direct-fired heater can be fueled by surplus biogas or by biogas from a covered lagoon. Biogas would be burned directly in the room for heat; therefore, the biogas would need to be treated to remove H_2S and water.

The typical capacities, efficiencies, controls, and operating schemes for on-farm direct-fired heat are provided below:

- *Available capacities*: Direct-fired room heaters are available in a wide range of sizes, ranging from 40,000 Btu/h and upward.
- *Thermal efficiencies*: Conversion efficiencies are generally 85% to 90%, as all gas is burned in the room.
- *Control systems*: Typical commercial control systems supplied with these units can be used.
- *Operating schemes*: It is difficult to recover heat for digester heating from a direct-fired room heater. The operating scheme would depend upon the balance of biogas supply and maximum demand of installed heaters. Biogas could be supplied to as many heaters as the winter gas production could support. However, seasonal daily heat demand would likely be less than the production potential and, therefore, a portion of the collected gas would likely be wasted. Most direct-fired room heaters are of too small a capacity to be covered by air pollution regulations, but treatment of the gas to eliminate H_2S would eliminate potential SO_2 emissions.

Biogas as an Engine Fuel

Electricity generation using biogas on dairy farms is a commercially available, proven technology. Typical installations use spark-ignited natural gas or propane engines that have been modified to operate on biogas. Biogas-fueled engines could also be used for other on-farm applications.

As discussed below, diesel or gasoline engines can be modified to use biogas. Potentially, the more efficient Stirling engines could also be operated on biogas. Although waste heat from engine operations is used frequently in CHP applications, it is probably not practical to recover the small amounts of heat generated by engines used directly for specific uses such as irrigation or refrigeration.

Internal combustion engines. Natural gas or propane engines (typically used for electricity generation) can be converted to burn treated biogas by (1) modifying carburetion to accommodate the lower volumetric heating value of the biogas (400-600 Btu/scf) compared to natural gas (1,000 Btu/scf) and (2) adjusting the timing on the spark to accommodate the slower flame velocity of biogas ignition systems. Gas treatment to prevent corrosion from H_2S is usually not necessary if care is taken with engine selection and proper maintenance procedures are followed. According to RCM Digesters, natural gas or propane engines operating on raw biogas should have an accelerated oil change schedule. Typically, oil changes are recommended every 600 hours for a natural gas engine. When operating on raw biogas, oil changes should be conducted every 300 hours.

Biogas can fuel engine-driven refrigeration compressor and irrigation pumps. Spark ignited gasoline engines may be converted to operate on biogas by changing the carburetor to one that operates on gaseous fuels. However, gas treatment may be necessary depending on the type of engine used. The inherent variable speed operation of a gasoline engine optimizes energy use by closely following the load profile of the compressor. Diesel engines can also be modified to operate on biogas in two ways: (1) by replacing the fuel injectors with spark plugs and replacing the fuel pump with a gas carburetor, and (2) by using diesel fuel for ignition and adding a carburetor for the biogas as well as advancing the ignition timing. The high compression ratio of a diesel engine (16:1) lends itself to operation on biogas. Spark-ignited gas engines tend to operate in the lower 7:1 to 11:1 range of compression ratios, whereas biogas engines ideally operate in the 11:1 to 16:1 range.

The metallurgy of the engine is a critical consideration if raw (digester) biogas is used. The presence of H_2S in the raw biogas may lead to the formation of sulfuric acids, which can result in bearing failures and damage to the piston heads and cylinder sleeves. Copper alloy wrist pins and bearings make engines particularly susceptible to corrosion damage. RCM Digesters has had positive experiences with both Waukesha and Caterpillar engines with regard to their metallurgical resistance to corrosion. To minimize condensation of acid fumes in the crank case, engine manufacturers recommend maintaining engine coolant temperatures above 190° F (Ross, et al., 1996).

Engine manufacturers also use positive crankcase ventilation filters to purge moisture and contaminant-laden gas from the crankcase.

Although biogas is not commonly used as a fuel for gasoline-fuel or diesel-fuel engines, this may change. Below is a synopsis of the typical capacities, controls, and maintenance schedules for on-farm natural gas or propane engines suitable for biogas use... More detail about gasoline and diesel engines for non-electrical generation is given in later sections of this chapter.

Available capacities: Natural gas engines suitable for on-farm biogas utilization range in capacity from 40 to 250 kW.

- *Thermal and electrical efficiencies*: A biogas-fueled engine-generator will normally convert 18% to 25% of the biogas thermal capacity (Btu) to electricity. Because of the lower energy content per unit volume of biogas as compared to diesel or natural gas, engines converted to biogas will be de-rated with respect to their rated power output for other fuels. This de-rating may be as much as 20% of the output rating when the engine is fueled by natural gas.
- *Control systems*: Commercial control systems for engine-generators are well-developed. In the harsh on-farm operating environment, excess automation often fails where simple manual and mechanical controls succeed.
- *Operation and maintenance*: The engine manufacturer should supply an operation and maintenance schedule. A biogas engine should be inspected daily for adequate coolant and lubricant. Oil should be changed regularly to protect the engine. RCM Digesters recommends an accelerated oil change schedule (once every 300 operating hours) for engines that operate using raw biogas. This enables capture and removal of the H_2S in the spent oil, and has resulted in successful operation of a Caterpillar 3306 engine at Langerwerf Dairy for 45,000 hours between major overhauls.

All engine mechanical safety devices should be checked monthly for proper function. Other engine components such as spark plugs require maintenance on a monthly to yearly basis. Normal engine wear requires valve jobs every 6 to 24 months and engine rebuilding or replacement every 2 to 4 years. Engine controls require periodic repair or replacement. Generator bearings may require lubrication annually. The industry-accepted standard for engine operation and maintenance is $0.015/kWh with a professional maintenance staff. As farms do most of their routine engine maintenance, their costs are a bit lower.

Stirling engines. The Stirling engine is a closed-cycle external-heat engine that uses the same working gas repeatedly without any valve. Modern Stirling engines produce high power and efficiency levels by using high pressure helium or hydrogen as the working gas. However, these engines have not achieved widespread use because of their heavy weight and high production costs.

A popular type of Stirling engine has two pistons that create a 90-degree phase angle and two different areas of the engine that are kept at different temperatures (Figure 5-1). The working gas is perfectly sealed within the engine. Gas expands when heated, and contracts when cooled. Stirling engines move the gas from the hot side of the engine, where it expands, through a regenerator, to the cold side, where it contracts.

The combustion of biogas can be used as an external source of heat for a Stirling engine. The advantage of this configuration is that the biogas does not enter the engine cylinder or come in contact with the working fluid, which results in fewer corrosion problems for the engine. In addition, better emissions controls can be achieved in an external combustion process that is geared toward heat exchange as opposed to power production.

The California Energy Commission conducted the Stirling Engine Generator Biogas Demonstration Project in November 1995. The project was conducted at Sharp Ranch in Tulare, California, by SAIC Corporation. The engine was a Stirling Power Systems V160 engine that used helium as the working fluid. However, the project was beset with a number of operational problems including difficulty operating in parallel with the existing Waukesha internal combustion engine (SAIC, 1995, p. 4-3). The poor performance of this particular demonstration engine is not indicative of the operation of Stirling engines in general, but demonstrates that support by the manufacturer is extremely important for the successful operation of such engines in an on-farm environment. There are currently two Stirling engine manufacturers in the USA: Stirling Thermal Motors of Ann Arbor, Michigan and Stirling Energy Systems of Phoenix, Arizona.

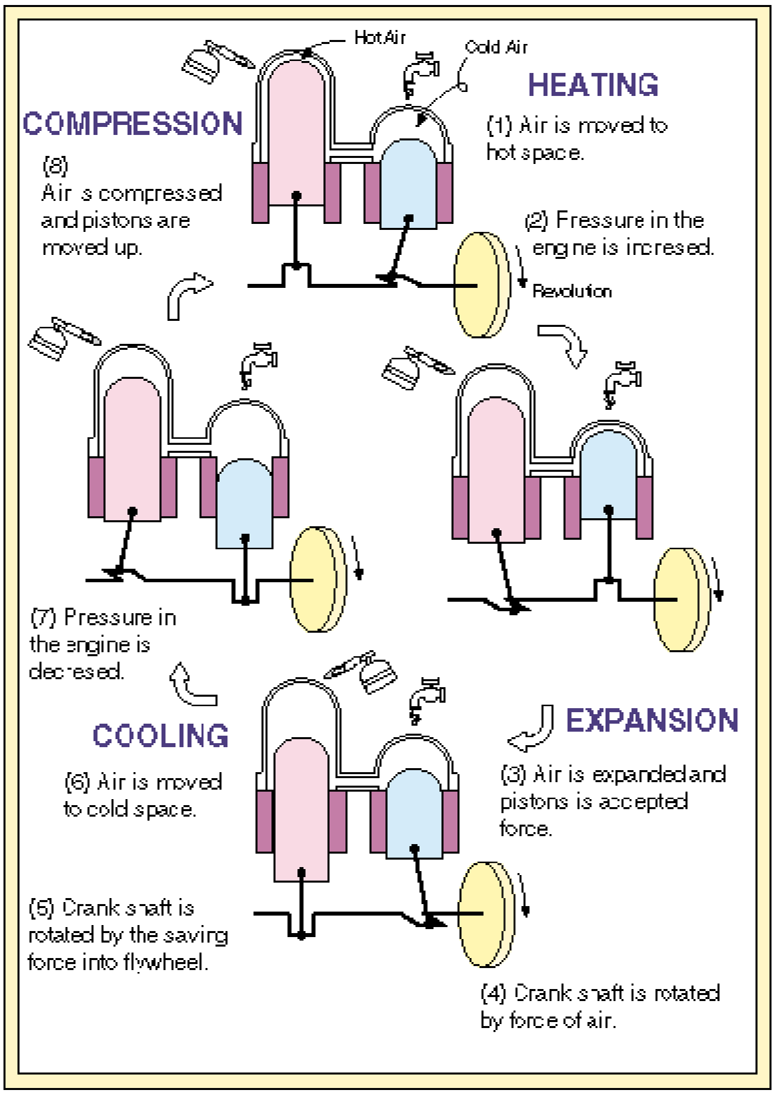

Figure 5-1 Principles of two-piston Stirling engine. (source: <http://www.bekkoame.ne.jp/~khirata/english/still_a.htm, accessed October 22, 2004>)

Recovering heat from biogas engines. For CHP applications, the key to energy savings is recovering heat generated by the engine jacket and exhaust gas. Nearly half of the engine fuel energy can be recovered through this waste heat by, for example, recovering hot water for process heat, preheating boiler feedwater, or space heating. One drawback of gas-driven systems is that the engines are said to require much more maintenance than an electric motor. It is also important to note that irrigation pumping is generally intermittent and refrigeration represents a relatively small component of the biogas use potential of a dairy.

Heat recovery from biogas engines is achieved by jacket-water and exhaust-gas heat-exchange devices. When biogas is produced by plug-flow or complete-mix digesters, the majority of the “waste” heat is used to maintain a digester temperature of around 100° F. When a heat recovery process is used, a balance must be struck between maximizing the amount of heat recovered and maintaining optimal engine operating temperatures. The engine operating temperatures must be high enough to minimize the condensation of carbonic and sulfuric acids in the oil, but low enough to avoid damage to engine components.

Heat recovery from the engine jacket is achieved through a liquid-to-liquid heat exchanger. The maximum temperature that can be supplied to the hot water load is 190° F. Heat recovery from exhaust is carried out through a gas-to-liquid heat exchanger. Exhaust temperatures can reach as high as 1,200° F coming from the engine. The heat recovery system should maintain temperatures no lower than 400° F to prevent acidic vapors from condensing and corroding the exhaust-heat recovery package.

In addition to meeting process heat loads, an engine must have a redundant means of shedding excess heat, whether it is used for CHP or other purposes. This is typically accomplished by an air-cooled radiator that is capable of meeting the engine’s maximum cooling requirements. The radiator, which is plumbed in parallel to the heat load, has a fan that is thermostatically controlled and powered by a variable frequency drive in order to modulate heat rejection.

Alternative Uses of Biogas

There are other potential uses of biogas on a farm besides combined heat and power, such as in agricultural pumps, refrigeration, and vehicles. The section below discusses these alternatives and concludes that these uses would be economically challenging and would use only a limited percentage of a dairy’s biogas production.

Biogas as a Fuel for Agricultural Pumps

The use of agricultural pumps varies widely from dairy to dairy depending on both on-site conditions and pumping needs. Where agricultural pumps are required (e.g., for irrigation or effluent pumping), dairy farmers have the option of using electric motors, diesel engines, or natural gas engines to drive them. Often the location of the pump and the price of electricity determine this choice. Recent estimates indicate that approximately 82% of the agricultural pumps in California are driven by electrical motors and 18% are driven by diesel engines (the number of agricultural pumps driven by natural gas engines is currently considered negligible) (CEC, 2003a).

Most stationary diesel engines on dairy farms are used for remotely located irrigation pumps (L. Schwankl, UC Davis Agricultural Extension, personal communication, 5 August 2004). Local conditions such as water source (well water vs. irrigation canals), well depth, waste management requirements, acres devoted to feed crops, etc., vary significantly and have a major impact on the pumping requirements. To meet differing requirements, irrigation pump power ratings vary considerably, ranging from about 10 horsepower (hp) to beyond 100 hp (J. Melo, Melo Pumps, personal communication, 30 August 2004).

Converting agricultural pumps to run on biogas. Diesel-driven irrigation pumps can potentially be converted to operate directly on raw biogas, although in practice, the biogas would probably need some amount of cleaning after it is collected from the digester to reduce particulates. The effects of H_2S can be mitigated by an accelerated oil change schedule. The diesel engine modifications required include replacing the fuel injectors with spark plugs, installing a natural gas ignition and carburetor system, installing different pistons to lower the compression ratio, and replacing some of the valve and valve seats. In addition, the diesel gas tank and fuel delivery system would be replaced by low-pressure biogas distribution pipes, valves, and regulators to supply biogas from the on-farm biogas storage tank to the remote irrigation pumps.

Hypothetical demand for biogas as a fuel for irrigation applications. Irrigation pump use is intermittent and highly seasonal and therefore would not consume biogas on a steady basis throughout the year. Also, it would probably be more cost-efficient to switch remote diesel-powered irrigation pumps to electrical power (which could be provided by a generator set using “raw” biogas as fuel) than to upgrade the biogas and transport it via pipeline to feed the remote irrigation pumps.

Despite these barriers to the direct use of biogas for agricultural pumps, we can estimate the hypothetical annual potential demand for irrigation pump fuel use on a 1,000-cow dairy based on the following requirements (J. Melo, Melo Pumps, personal communication, 30 August 2004) and using a conversion factor of 14.7 kWh/gallon of diesel (20 hp-hr/gallon of diesel) (SCAQMD, 2001):

- Number of pumps: 5
- Pump capacity: 40 hp
- Fuel usage per hour: 2 diesel gallon equivalents (DGE)

- Hours operated per year: 1,800 (this assumes an 8-month growing season with 3 months of partial irrigation and 5 months of full-time irrigation)[1]
- Fuel usage per year: 9,000 DGEs

Assuming that a 1,000-cow dairy will produce approximately 50,000 ft^3 of biogas (a cubic foot of biogas contains 600 Btu) there is 30 MM Btu of energy available daily. Since a diesel gallon contains about 140,000 Btu, the biogas from the dairy would be just over 215 DGE/day or about 78,000 DGE/year. Thus, the 9,000 DGEs required to power the average number of irrigation pumps that could be converted to direct use of upgraded biogas corresponds about 12% of the total upgraded biogas output for a 1,000-cow dairy.

Using Biogas to Run Refrigeration Equipment

In general, refrigeration accounts for about 15% to 30% of the energy used on dairy farms (U.S. EPA, 2004). Compressors used for milk chilling are the main sources of energy consumption in the refrigeration system. Since dairy cows are milked daily, a steady source of energy is required for refrigeration needs, unlike seasonal applications such as irrigation pumps.

Hypothetical demand for biogas as a direct fuel for refrigeration systems. Dairies cool milk every day of the year, and compressors for refrigeration run continuously during milking operations, often 20 hours or more each day. For a 1,000-cow dairy farm, the energy requirements for these compressors are typically in the range of 30 to 40 hp (22.5 – 30 kW). However, the implementation of the chilling process (and consequently energy usage) varies greatly according to the local conditions at each farm. In particular, milk prechilling (see below) can result in a significant reduction of the power required for refrigeration compressors.

Virtually all existing refrigeration compressors on dairy farms are driven by electrical motors. While natural-gas driven motors are commercially available for the low-hp ranges associated with dairy refrigeration equipment, they are significantly more expensive than electrical motors with similar output power ranges and therefore have not been traditionally considered as economically desirable choices for this application. Thus, the use of biogas as a direct fuel for refrigeration compressors is not likely.

[1] A typical irrigation cycle consists of 7 days on and 10 days off. Partial irrigation has an average duty cycle of 30% during the on portion and full irrigation has a 100% duty cycle during the on portion. This equates to approximately 100 hours/month on time during partial irrigation and 300 hours/month on time during full irrigation. Use of irrigation pumps outside the growing season is assumed to be negligible.

If we consider momentarily that such an application were feasible, we could use the following information to estimate the hypothetical annual potential demand for refrigeration compressor fuel use on a 1,000-cow dairy:

- Number of refrigeration compressors: Variable
- Compressor capacity: 40 hp
- Fuel usage per hour: 2 DGEs
- Hours operated per year: 7,300 (assuming an average duty cycle of 20 hours per day during milking cycles)
- Fuel usage per year: 14,600 DGEs

Using a conversion factor of 14.7 kWh/gallon of diesel (20 hp-hr/gallon of diesel) (Southern California Air Quality Management District, 2001), and assuming that a 1,000-cow dairy produces about 78,000 DGE/year, the potential annual fuel demand for on-farm refrigeration corresponds to less than 20% of the total annual biogas output of a 1,000-cow dairy.

Hypothetical demand for biogas as a fuel for prechilling milk. The temperature of dairy milk directly out of the cow is about 98º F; the milk is typically cooled to 38º F for on-farm storage. Although many dairies use well water for prechilling, chilled water or glycol can be produced from biogas-fired absorption or adsorption chillers and used in milk precoolers (these chillers could also be used for air conditioning, but the amount of use on dairy farms would be negligible). Milk cooling using absorption and adsorption chillers also presents a potential opportunity to use waste heat captured from a biogas-driven generator set. Use of this waste heat could significantly reduce the on-farm electrical refrigeration load.

Double-effect chillers, producing hot and cold water simultaneously, are available for applications over 30 tons and could be coupled with a heated digester (1 ton cooling = 12,000 Btu/h). Corrosion-resistant models are not available; therefore, biogas must be treated for water and H_2S removal before it can be used to fuel absorption or adsorption chillers. Absorption chillers can be used to prechill milk, but are typically not capable of providing chilling water below 44º F, which is not sufficient for most dairy needs. Adsorption chillers can generate chilled water temperatures of 37 º F and therefore are marginally capable of handling the entire cooling load without additional refrigeration equipment.

Below is a summary of the capacities, efficiencies, controls, and operating schemes for adsorption chillers that could run on upgraded biogas.

- *Available capacities*: Adsorption chillers are available at various capacities, from 1 ton of cooling per hour and up.
- *Thermal efficiencies*: Adsorption chillers deliver 50% of the biogas Btu as cooling.
- *Control systems*: Adsorption chillers come with commercial control systems.
- *Operating schemes*: Milk cooling requirements do not vary widely over the year. Neither absorption nor adsorption chillers have been widely used in dairy applications, due in part to their relatively higher costs compared to conventional cooling systems (C. Moeller, HIJC USA, personal communication, 3 September 2004).

Most chillers are smaller in capacity than the minimum output covered by air pollution regulations, although larger-scale applications would use California-approved low-NO_x units. Treatment of biogas to remove H_2S would eliminate potential SO_2 emissions.

Biogas as a Vehicular Fuel

There is neither an existing demand nor a projected future demand for raw biogas as a vehicle fuel in California.

The California Air Resources Board (CARB) alternative fuels regulations include specifications for natural gas used as a vehicle fuel (ref. California Code of Regulations, title 13, section 2292.5). While the text of the regulations specifically refers to CNG fuel specifications, it can be argued that biogas should meet the same specifications as CNG for use as a vehicle fuel. The purpose of having minimum CNG fuel specifications is to ensure the compatibility of engines designed to operate on natural gas.

Table 5-1 shows that the typical composition of raw (i.e., unprocessed) biogas does not meet the minimum CNG fuel specifications. In particular, the CO_2 and sulfur (as contained in H_2S) content in raw biogas is far too high for it to be used as vehicle fuel without additional processing. Therefore, according to current regulations, raw biogas is not an acceptable vehicle fuel in the state of California. In addition, no known vehicle engine manufacturers currently offer products rated to operate on raw biogas as a fuel.

Table 5-1 Compressed Natural Gas Fuel Specifications vs. Typical Raw Biogas Composition

Component	CNG Fuel Specification [a]	Raw Biogas Composition [a]
Methane (CH_4)	≥ 88	65
Ethane (C_2H_6)	≤ 6	≤ 0.1
C_{3+} (Propane, etc.)	≤ 3	≤ 0.1
C_{6+} (Hexane, etc.)	≤ 0.2	≤ 0.1
Hydrogen (H_2)	≤ 0.1	≤ 0.1
Carbon monoxide (CO)	≤ 0.1	≤ 0.1
Oxygen (O_2)	≤ 1.0	≤ 0.1
Inert gases (CO_2 + N_2)	1.5 – 4.5 (range)	35
Sulfur	16 ppm	50 – 2000 ppm
Dew point	≥ 10° F below 99% winter design temp [b]	Saturated (non-compliant)
Particulate matter	Non-damaging to engines, etc.	Variable
Odorant	Easily detectable	Detectable

[a] Expressed as % unless otherwise noted.
[b] ASHRAE, 1989 (Chapter 24, Table 1).

Beyond the regulatory impediments to using raw biogas as a vehicle fuel in California, the low methane content of raw biogas (typically 55% to 70%) combined with its inherent trace contaminants (especially H_2S) can have significant negative impacts on engine performance, durability, and emissions. While the degree of impact depends on both engine control and vehicle technology (e.g., open loop vs. closed loop, heavy duty vs. light duty), raw biogas is generally considered technically unsuitable as a vehicle fuel. For these reasons, there are no known vehicle engine manufacturers planning to offer products rated to operate on raw biogas as a fuel.

Summary of On-Farm Demand for Biogas

Table 5-2 summarizes the potential annual demand for raw and upgraded biogas on a typical 1,000-cow dairy. This table includes the most common current on-farm uses for biogas—heat, and electrical power generation as well as the potential alternate uses discussed above.

Table 5-2 Potential Annual Demand for Raw and Cleaned Biogas, Typical 1,000-Cow Dairy Farm

Source/*Use*	**Potential Annual Production**		**Potential Annual Consumption**			
	kWh [a]	**DGE** [b]	**kWh**	**Fuel (DGEs)**	**% of Total kWh**	**% of Total Fuel**
1,000-cow dairy farm	912,000	78,000	---	---		---
Electricity						
Older 1,000-cow dairy farm [c]	---	---	365,000	---	40	
Modern 1,000-cow dairy farm [c]	---	---	803,000	---	88	
Modern 1,000-cow dairy farm with fans [c]	---	---	1,095,000	---	120	
Irrigation pumps	---	---	---	9,000		12
Refrigeration [d]	---	---	---	14,600		19
Total	912,000	78,000	---	23,600		31

kWh = Kilowatt hour

DGE = Diesel gallon equivalent

--- = Not applicable

[a] Assumes that 1,000 cows each produce 50 ft^3 of biogas per day which is 60% methane, and that the biogas is combusted for electrical generation at 28% efficiency.

[b] Assumes that 140 ft^3 of biomethane is equivalent to 1 gallon of diesel, which yields a fuel production capacity of approximately 215 DGEs/day.

[c] Derived from information from energy audits conducted for the California Energy Commission by RCM Digester, which found that older dairies typically use less energy and operate in the 1 kWh per cow per day range, modern dairies operate at 2.2 kWh per cow per day, and modern dairies with fans for cow cooling operate at 3 kWh per cow per day.

[d] In actuality, the likelihood of converting refrigeration units to run on biogas is extremely small (see text discussion, above). However, biogas could be used for prechilling milk. The potential annual consumption for on-farm milk prechilling was not quantified for this study.

As shown in Table 5-2, a modern 1,000-cow dairy would have an annual energy usage ranging from around 800,000 to nearly 1,100,000 kWh per year. This matches well with the potential for electrical power generation of just over 900,000 kWh per year.

Based on the assumptions given, the total potential annual fuel demand for agricultural pumps and refrigeration equipment corresponds to less than a third of the total biogas output for a 1,000-cow dairy. As stated previously, however, irrigation pumps and refrigeration equipment are not necessarily cost-effective applications for biogas. For example, irrigation loads are seasonal. Refrigeration loads are both significant and consistent however electrically-driven refrigeration compressors are less expensive than refrigeration compressors driven by natural gas engines. There may be applications for waste heat to drive adsorption chillers for milk prechilling but the technology is not likely to be cost-effective at the scale of a typical dairy farm.

As shown in Table 5-2, the greatest demand for on-farm use of biogas is for electricity generation. This need matches well with the biogas production capacity and thus, at the present time, we conclude that the most practical use of raw/slightly upgraded biogas is its continued use for on-farm electrical generation.

Potential On-Farm and Off-Farm Uses of Biomethane

Biomethane is equivalent in chemical composition, and therefore in energy content, to natural gas. Equipment that can run on natural gas can run on biomethane; other equipment will have to be converted to accommodate biomethane fuel, as was explained earlier in the discussion about on-farm biogas use. Vehicles are the major category of equipment that can run on biomethane, but not on biogas.

Non-Vehicular Uses of Biomethane

Biomethane is higher quality (i.e., has a greater heating value) fuel than biogas and therefore could be substituted for biogas in all of the applications discussed above as potential or current uses of biogas.

Converting Agricultural Pumps to Run on Biomethane

Natural gas engines will run directly on biomethane. Diesel fueled agricultural pumps that could be converted to run on biogas (see above) would run more efficiently on biomethane using a similar conversion process. Biomethane could be moved around a farm more easily than biogas because it is a cleaner fuel; however, it will likely still be more cost-effective to use biogas to generate electricity to run pumps than to convert the pumps to run on biomethane.

A 1,000-cow dairy that produces 50,000 ft^3 of biogas per year will produce about 30,000 ft^3 of biomethane (assuming that the biogas contains approximately 60% methane), which is equivalent to about 78,000 DGE/year. Assuming the same conditions as described above under the biogas example, biomethane-fueled agricultural pumps would, on average, consume about 12% of a 1,000-cow dairy’s biomethane output.

Converting Refrigeration Equipment to Run on Biomethane

The motors in electrically driven refrigeration compressors could be replaced by natural gas engines and fueled by biomethane; however, this is highly unlikely for several reasons. For example, while natural gas engines can be coupled to refrigeration compressors, they are significantly more expensive than their electric counterparts and have much higher maintenance costs. Furthermore, electricity generated from “raw” biogas via a genset is a cheaper fuel than upgraded biogas. In addition, virtually all installed refrigeration compressors today are electrically driven.

Absorption and adsorption chillers driven by waste heat can potentially be used for milk prechilling and cooling on dairy farms but such applications do not appear to be well-suited at present due to higher costs compared to conventional equipment and technical issues relating to process stability. Also, it would be just as easy to operate these prechillers using waste heat from a biogas-fueled genset as it would be to upgrade the biogas and then use it as a fuel.

In summary, there are currently no obvious economic incentives for dairy farmers to either convert electrical refrigeration equipment to operate on biomethane or to replace electrical refrigeration equipment with absorption or adsorption chillers driven by waste heat. For new farms, there may be opportunities to use the waste heat from a biogas-driven genset to drive an absorption or adsorption chiller for milk prechilling, although the overall cost-effectiveness of such a system would be highly dependent on the particular conditions for each farm. Given the current state of technology, using biogas-generated electricity to drive refrigeration compressors may be the most realistic option for using biogas to supply refrigeration loads on dairy farms in the near-term.

Vehicular Uses of Biomethane

Both CNG and LNG vehicles will run on biomethane (i.e., on methane that has been compressed to CBM or liquefied to LBM as described in Chapter 3). Although it is technically feasible to use biomethane as a fuel for alternative-fueled vehicles, there are other important considerations in determining the viability of using biomethane as a vehicular fuel (or a source for other vehicular fuels such as methane). These include current and projected markets for these vehicles, the on-farm demand for vehicle fuel, the potential for on-farm use of alternate fuels, the requirements for converting on-farm vehicles to alternate fuels, and the infrastructure required to support alternative fuel vehicles (AFVs).

California’s Market for Compressed Natural Gas Vehicles

The current and projected CNG vehicle markets in California are summarized in Table 5-3. (See Appendix D for information about specific CNG vehicle models on the market as of late 2004.)

Table 5-3 California Market for Compressed-Natural-Gas-Fueled Vehicles

Vehicle Type	Estimated/Projected Number of CNG Vehicles [a]		
	2004	2007	2010
Light duty [b]	15,500	17,400	19,600
Medium and heavy duty [c]	4,850	7,400 – 8,400	11,200 – 14,500
Total	20,350	24,800 – 25,800	30,800 – 34,100

[a] While exact figures are not available, estimates of the current CNG vehicle market size are based on information provided by the California Natural Gas Vehicle Coalition (CNGVC). These figures have been corroborated with similar estimates in the U.S. Department of Energy Energy Information Administration (DOE EIA) database and supplemented by conversations and reports from various industry sources.

[b] Shuttles, taxis, and municipal fleet vehicles.

[c] Transit buses, school buses, and refuse trucks.

According to the US Department of Energy Energy Information Administration (DOE EIA), the average annual growth rate of the CNG vehicle market in the U.S. has been 12.4% during the last decade and 9.7% during the last three years, with a relatively consistent volume of 8,000 to 12,000 new vehicles per year. (In the western region of the USA, the annual growth rate for the CNG vehicle market was 8.9% in 2002 and 10.8% in 2003.) A breakdown of the statistics for 2001 to 2003 by weight category reveals that the light-duty CNG vehicle market experienced only minor growth (3.9% in 2002 and 4.4% in 2003); however there was significant growth in the combined medium- and heavy-duty markets (20.6% in 2002 and 24.6% in 2003).

Projections for the light-duty CNG vehicle market have been based on recent historical growth rates of approximately 4%. The growth in this market is expected to be fueled primarily by increased demand for CNG shuttles and taxis, which have been successfully demonstrated as ideal applications for this technology, as well as by AFV requirements for government fleets, which are primarily light-duty. Furthermore, many California airports now have regulations and/or incentive programs (for example, SCAQMD Rule 1194, Commercial Airport Ground Access Vehicles) that either require shuttles and taxis serving the airport to use low-emissions AFVs or make it economically attractive for them to do so.

Projections for the medium- and heavy-duty CNG vehicle market are more difficult to make. This is largely because the market tends to be more dependent on the current regulatory environment, which in turn is subject to variability in the political climate (see Chapter 6 for more about the regulatory environment). New, more stringent US EPA heavy-duty truck and bus emissions standards, scheduled to be phased in between 2007 and 2010, may increase demand for medium- and heavy-duty CNG vehicles, as they are expected to result in a price increase for compliant heavy-duty diesel engines and exhaust after-treatment systems. Conversely, the emerging hybrid heavy-duty truck and bus market may have a negative impact on the corresponding segments of the CNG vehicle market.

In general, the growth in this market is expected to be fueled by continued strong demand for CNG transit buses and to a lesser extent, school buses and refuse trucks. There are several regulatory incentives for growth of these market segments:

- CARB Fleet Rule for Transit Agencies
- CARB Clean School Bus Program
- SCAQMD rules for clean transit buses, school buses, refuse trucks, and other public heavy-duty fleet vehicles.

Given the potential variability in the medium- and heavy-duty market, a range of projections has been given based on a conservative annual growth rate of 15% to 20%.

California's Market for Liquefied Natural Gas Vehicles

The current and projected LNG vehicle markets in California are summarized in Table 5-4 below. See Appendix D for information about specific LNG vehicle models on the market as of late 2004.

Table 5-4 California Market for Liquefied-Natural-Gas-Fueled Vehicles

Vehicle Type	Estimated/Projected Number of CNG Vehicles [a]		
	2004	2007	2010
Light duty	Negligible	Negligible	Negligible
Medium duty	0	0	0
Heavy duty [b]	1,200	1,400 – 1,600	1,600 – 2,100
Total	1,200	1,400 – 1,600	1,600 – 2,100

[a] Estimates of the current LNG vehicle market size are based on information obtained from the California Natural Gas Vehicle Coalition, the South Coast Air Quality Management District, INFORM, the DOE EIA database and various additional industry sources.

[b] Transit buses, refuse trucks, Class 8 urban delivery.

According to the DOE EIA, the average annual growth rate of the LNG vehicle market in the U.S. has been 20.1% during the last decade and 8.4% during the last three years; however, volumes have generally been low (typically 100 to 500 vehicles per year) and there has been little consistency from year to year. (In the western region of the USA, the annual growth rate for the LNG vehicle market was 4.1% in 2002 and 12.7% in 2003.) The heavy-duty market accounts for the vast majority of the LNG vehicles in California.

Projections for the heavy-duty LNG vehicle market are subject to the same regulatory and competitive factors as the medium- and heavy-duty CNG vehicle market (see Chapters 6 and 7). In general, the growth in this market is expected to be fueled by continued niche demand for LNG transit buses, refuse trucks, and Class 8 urban delivery trucks (regional heavy delivery). One of the key factors limiting wider acceptance of LNG vehicles is the much lower availability of LNG refueling infrastructure compared to diesel and even to CNG refueling infrastructure. In addition, all of the LNG sold in California is currently imported from LNG production facilities located in other states. Given the current limited emphasis on expanding LNG refueling infrastructure, a range of projections for the heavy-duty market has been given based on a conservative annual growth rate of 5% to 10% assuming that there continues to be a sufficient supply of LNG available in California.

Current and Projected Market for Methanol Vehicles

Methanol (CH_3OH), which is typically manufactured from natural gas feedstock, has been used as an alternative vehicle fuel. The manufacture of methanol from landfill biogas has been demonstrated and manufacturing of methanol from dairy biogas feedstock is theoretically possible (see Chapter 3).

Estimates based on DOE EIA figures show that there are still approximately 3,700 methanol-fueled vehicles in California today, more than 99% of which are light-duty vehicles. In reality, however, virtually all of these vehicles are flexible-fuel vehicles that can operate on either M85 fuel (85% methanol, 15% gasoline) or gasoline. Since there are no longer any M85 refueling facilities operating in California, it is assumed that all methanol-fueled vehicles in the state now use gasoline as their only source of vehicle fuel.

There have been no M85 fuel vehicles offered for sale by vehicle manufacturers since 1998. Naturally this has been a key contributor to the rapid decline in the availability of M85 refueling infrastructure. In addition, other alternative fuel technology such as E85 (85% ethanol, 15% gasoline) has become increasingly well established in this market. As a result, there are no M85 vehicles being planned for future production.

In summary, while there may still be an opportunity to provide methanol to a small number of vehicles in California, there is currently no methanol refueling infrastructure available. The few methanol vehicles on the road are being retired without being replaced. As a result the small potential for methanol as a vehicle fuel in California will disappear.

Summary of Alternative Fuel Vehicles in California

As discussed above, CNG- and LNG-fueled vehicles are the only types of vehicles which are either currently operating or projected to be operating on methane-based vehicle fuels by 2010. This section reviews the present and forecasted markets for CNG- and LNG-fueled vehicles in California, by vehicle type, and provides estimates of the annual fuel consumption represented by these markets.

Current and projected markets. The current and projected natural gas vehicle markets in California are summarized in Table 5-5.

Table 5-5 Summary of California Market for Natural-Gas-Fueled Vehicles

Vehicle Fuel	2004	2007	2010
Raw Biogas [a]	0	0	0
CNG [b]	20,350	24,800 – 25,800	30,800 – 34,100
LNG [c]	1,200	1,400 – 1,600	1,600 – 2,100
Methanol [d]	0	0	0
Total	21,550	26,200 – 27,400	32,400 – 36,200

[a] Biogas does not meet California's vehicle fuel specifications (see Table 5-1).
[b] See Table 5-3.
[c] See Table 5-4.
[d] No M85 refueling infrastructure.

Annual fuel consumption. Certain types of vehicles are normally associated with high annual fuel consumption. Key factors affecting annual fuel consumption include vehicle weight, fuel efficiency, duty cycle, annual hours of operation, and annual mileage. High-fuel-usage vehicles (HFUVs) have an average annual fuel consumption of 5,000 gasoline gallon equivalents (GGEs) or more. By comparison, the remaining vehicles, referred to here as low-fuel-usage vehicles (LFUVs), typically have an average annual fuel consumption of approximately 600 GGEs. School buses, with an average annual fuel consumption of 1,000 to 2,000 GGEs, fall between these two classifications.

The combined annual market for CNG and LNG vehicle fuel in California is approximately 80 million GGEs. Table 5-6 provides estimates of the key contributors to annual CNG and LNG vehicle fuel consumption in California by vehicle type.

Table 5-6 Estimated Annual CNG and LNG Vehicle Consumption in California, 2004

Vehicle Type [a]	**Category**	**No. of Vehicles** [b]	**Fuel Consumption (GGEs)**	
			Vehicle [c]	**Total**
Compressed Natural Gas Vehicles				
Taxis	Light duty	2,000	6,500	13,000,000
Shuttles	Light & medium duty	2,000	6,500	13,000,000
Transit Buses	Heavy duty	3,600	10,800	39,000,000
School Buses		900	1,500	1,000,000
Refuse Trucks		350	8,600	3,000,000
CNG Subtotal	NA	8,850	NA	69,000,000
Liquefied Natural Gas Vehicles				
Refuse Trucks	Heavy duty	700	8,600	6,000,000
Transit Buses		400	10,800	4,000,000
Class 8 Urban Delivery		100	11,500	1,000,000
LNG Subtotal	NA	1,200	NA	11,000,000
			Total	80,000,000

GGEs = Gasoline gallon equivalents (1 GGE contains 120,000 Btu and uses 120 ft^3 of methane gas)
CNG= Compressed natural gas
LNG = Liquefied natural gas
[a] Vehicle types include school buses and heavy fuel use vehicles with significant representation in the California CNG vehicle market.
[b] Estimated number of vehicles in California.
[c] Typical values

Demand for On-Farm Alternate-Fuel Agricultural Vehicles

Agricultural vehicles include both non-road and on-road vehicles used primarily for farming operations. Examples of non-road agricultural vehicles include tractors, combines, threshers, etc. Examples of on-road agricultural vehicles include pickup trucks and medium- and heavy-duty trucks.

There are currently no commercially available CNG- or LNG-fueled non-road agricultural vehicles. There are, however, commercially available versions of some on-road agricultural vehicles such as pickup trucks. In practice, however, CNG and LNG vehicles are rarely used in on-farm applications due to the lack of convenient refueling infrastructure.

At least one demonstration project has converted several agricultural tractors to CNG fuel and measured the performance of these tractors using CNG versus traditional fuels. The results of this study indicate that CNG tractor conversions are technically feasible and that CNG tractors can meet the expected functional and performance requirements (Davies and Sulatisky, 1989). The economics of farm-tractor conversions to CNG, however, were shown to be very poor due to fuel rebates to farmers, expensive CNG conversion equipment, and the low-annual, high-peak fuel use pattern common for farm tractors (Sulatisky and Gebhardt, 1989). On-farm pickup truck conversions to CNG, performed as part of the same demonstration project, were shown to have much more reasonable payback periods when slow-fill home compressors were used (Sulatisky and Gebhardt, 1989). Another disadvantage noted with respect to CNG-fueled tractors is that tractors are often required to operate for extended periods of time (e.g., 12 hours) during peak seasons such as harvest time; at such times, the need to stop during the workday and return to a central refueling station could be economically undesirable (M.T. Kaminski, Saskatchewan Research Council, personal communication with Brad Rutledge, 5 August 2004).

Liquefied petroleum gas is currently the most widely used type of alternative fuel for agricultural vehicles. Some of the disadvantages of CNG relative to LPG include a lack of CNG refueling infrastructure, higher CNG conversion costs and larger, heavier CNG fuel tanks (National Propane Gas Association website <http://www.npga.org>). As a result, there is little incentive for farmers to choose CNG over LPG.

Table 5-7 shows an estimate of the potential annual fuel demand for a typical 1,000-cow dairy broken down by vehicle type (Nathan DeBoom, Milk Producers Council, personal communication with Brad Rutledge, 30 August 2004). Based on the assumptions provided in the table, total fuel production of a 1,000-cow dairy is about 78,000 DGEs/year. For this case, the potential annual fuel demand corresponds to less than 46% of the total upgraded biogas output for a 1,000 cow dairy. However the lack of factory produced CNG or LNG farm vehicles, the cost of vehicle conversion (discussed below), the cost of storing and pumping the fuel, and the uneven pattern of usage create substantial barriers to the use of CNG (and consequently, CBG) for on-farm vehicles.

Table 5-7 Potential Annual Vehicle Fuel Demand for Typical 1,000-Cow Dairy [a]

Vehicle Type	No. of Vehicles	Hours Operation/Day	Fuel Usage (DGEs)	
			Per Hour	Per Year
Large Tractor	1	4	6	8,760
Med. Tractor	1	5	4	7,300
Small Tractor	1	4	2	2,920
Feeder Truck	1	6	7	15,330
Pickup Trucks [b]	2	2	1	1,460
			Total	35,770

DGE = Diesel gallon equivalent

[a] A 1,000-cow dairy is assumed to produce 30,000 cubic feet (ft^3) of biomethane or 215 DGEs per day (1 DGE = 140 ft^3 methane).

[b] Difference between gasoline gallon equivalents (GGEs) and DGEs ignored for pickup trucks.

As a check on the above estimates, in 2003 the average monthly cost for vehicle fuel and oil expenses on California dairy farms was about $3.00 per cow (CDFA, 2003b). Based on an average non-road price of approximately $1.00/gallon in 2003 (California Farm Bureau Federation, 2004), this implies a fuel usage of around 3 gallons/cow/month. For a 1,000-cow dairy, this translates to an annual vehicle fuel consumption of approximately 36,000 gallons.

Requirements for Converting Agricultural Vehicles to Run on Biomethane

The basic technologies and equipment necessary to convert agricultural vehicles to use upgraded biogas are the same technologies and types of equipment used to convert vehicles to use compressed natural gas (CNG). The main vehicle components and subsystems requiring modification are the engine, fuel storage tanks and fuel delivery system. Conversion of vehicles to use liquefied natural gas (LNG) involves similar modifications to the same vehicle components and subsystems. Note that while retuning natural gas vehicle engines to operate on partially cleaned low-methane biogas may be theoretically possible, such engines are not commercially available and therefore the topic of converting vehicles to use low-methane biogas as fuel has not been investigated further.

Engine modifications are dependent on whether the original engine is diesel- or gasoline-driven. With respect to the types of vehicles normally found on dairy farms, tractors and trucks typically have diesel engines while pickup trucks may have diesel or gasoline engines. Diesel engines employ compression ignition to ignite fuel injected into the cylinders whereas gasoline engines employ spark-ignition. Single-fuel natural gas engines which operate purely on natural gas (the most common type) employ a spark-ignition system. In addition, there is a combination type system called a dual-fuel system where a small amount of diesel fuel is injected into the cylinder with the natural gas and acts as a pilot to ignite the natural gas via compression ignition.

Conversion of diesel engines to run on 100% natural gas (i.e., single-fuel systems) normally requires replacing the fuel injectors with spark plugs, installing a natural gas ignition and carburetor system, installing different pistons to lower the compression ratio, and replacing some of the valve and valve seats. Dual-fuel conversion systems are currently marketed by Clean Air Power in conjunction with Caterpillar diesel engines. This system requires the addition of an electronic control unit to control the relative amount and timing of natural gas vs. diesel fuel injected into a standard, Caterpillar diesel engine. The system also requires a natural gas carburetor and dual-fuel injectors. Dual-fuel conversion systems are normally associated with medium and heavy duty vehicles where performance requirements are more severe. Conversion of gasoline engines to operate on CNG is somewhat simpler since gasoline engines already employ a spark-ignition system. A natural gas mixer to control the ratio of low-pressure natural gas vs. air is the main element of the engine modification.

For single-fuel systems, the diesel tank(s) is replaced by several high pressure CNG storage cylinders. These cylinders hold biogas in compressed form at 3,000 or 3,600 psi in order to provide sufficient fuel to attain a reasonable vehicle range without refueling. The primary drawbacks associated with CNG storage cylinders are their weight, volume and cost. Dual-fuel systems require both a diesel tank and CNG storage cylinders; however, a given vehicle range can be attained with a much smaller diesel tank and somewhat reduced CNG storage requirements compared to a single-fuel system.

LNG has 3.5 times the energy density of CNG and is stored at relatively low pressure (50 to 150 psi). It therefore takes considerably less LNG storage on a vehicle to achieve the same range, resulting in lower weight, volume and cost for LNG storage systems compared to CNG. The primary drawbacks associated with LNG storage cylinders are that the LNG must be stored at very low temperatures (e.g., -260º F) and will evaporate over time due to thermal losses.

For single-fuel systems, the diesel fuel delivery system is replaced by a high pressure gas delivery system including high pressure hoses, a high pressure regulator, a low pressure regulator and miscellaneous monitoring and control devices. In dual-fuel systems, the high pressure gas delivery system is in addition to the existing diesel fuel delivery system. LNG fuel delivery systems are similar to single-fuel gas delivery systems except that the hoses and devices must be insulated for very low temperatures and, in comparison to CNG, will have to handle only relatively low pressures.

Infrastructure for Converting Agricultural Vehicles

Agricultural vehicles on dairy farms usually consist of three basic types of vehicles: tractors, feeder trucks, and pickup trucks. There are currently no companies performing CNG or LNG tractor conversions in the USA. (There is, however, an existing infrastructure to perform LPG tractor conversions, which could provide a framework for the development of a CNG infrastructure.) There are also currently no (original equipment manufacturers) offering new CNG or LNG tractors for sale in the USA.

A feeder truck is usually a class 8 straight truck (a class 8 truck has a gross vehicle weight rating of between 33,000 and 150,000 lbs and a straight truck has a combined body and trailer—i.e., it is not a tractor-trailer combination) upfitted with a feeder box and a mixer. There is no existing infrastructure to convert feeder trucks to CNG or LNG; however, some of the feeder truck chassis manufacturers (e.g., Mack and Peterbilt) offer alternative fuel engine options for their class 8 truck chassis. In addition, there are similar class 8 vehicles (e.g., yard hostlers) that are available from the manufacturer fitted with LNG engines. Thus, it is theoretically possible to procure a CNG or LNG feeder truck through the feeder truck upfitter, although no dairy farmers are known to have ordered such equipment to date.

As of 2005, General Motors (GM) is the only original equipment manufacturer offering CNG-fueled pickup trucks (e.g., the Chevrolet Silverado and the GMC Sierra) in the USA. Ford previously offered CNG- and bi-fueled versions of the F-150 pickup truck, but discontinued production of all CNG vehicles at the end of 2004.

The past decade has shown a marked decrease in the demand for light-duty CNG vehicle conversions and a general trend among CNG component suppliers to align themselves with vehicle original equipment manufacturers. As shown in Table 5-8, a small number of companies in the western USA still convert vehicles to CNG; these companies could help satisfy any demand for CNG conversions of pickup trucks for dairy farms.

Table 5-8 Companies Performing Vehicle Conversions to Compressed Natural Gas Fuel, Western USA

Company	Location	Comments
Baytech Corporation	Los Altos, CA	GM vehicles only
Clean-Tech LLC	Los Angeles, CA	Primarily GM vehicles
DRV Energy, Inc.	Oklahoma City, OK	CNG & dual-fuel conversion kits

LNG pickup trucks are not available from either vehicle original equipment manufacturers or vehicle converters.

Summary of On-Farm Demand for Biomethane

Though the costs of converting all the listed farm equipment to run on biomethane would be very high, Table 5-9 summarizes the potential annual demand for biomethane on a typical 1,000-cow dairy. This table includes heat and electrical power generation as well as uses such as vehicles, agricultural pumps, and refrigeration equipment. As with biogas, however, irrigation pumps and refrigeration equipment are not likely to be cost-effective applications for biomethane. Vehicles cannot run on biogas but they can run on biomethane. However the lack of factory produced CNG or LNG farm vehicles, the cost of vehicle conversion (discussed below), the cost of storing and pumping the fuel, and the uneven pattern of usage create substantial barriers to the use of CNG (and consequently, CBG) for on-farm vehicles.

While the table shows that a typical dairy could theoretically use 76% of the biomethane it produced, the substantial barriers involved make it much more likely that the dairy would seek an external user of the fuel.

Table 5-9 Potential Annual Demand for Biomethane, Typical 1,000-Cow Dairy Farm

Source/*Use*	**Potential Annual Production**		**Potential Annual Consumption**			
	kWh [a]	**DGE** [b]	**kWh**	**Fuel (DGEs)**	**% of Total kWh**	**% of Total Fuel**
1,000-cow dairy farm	912,000	78,000	---	---		---
Electricity						
Older 1,000-cow dairy farm [c]	---	---	365,000	---	44	
Modern 1,000-cow dairy farm c	---	---	803,000	---	88	
Modern 1,000-cow dairy farm with fans [c]	---	---	1,095,000	---	120	
Vehicles [d]				35,770		46
Irrigation pumps	---	---	---	9,000		12
Refrigeration [e]	---	---	---	14,600		19
Total	912,000	78,000	---	59,370		76

kWh = Kilowatt hour
DGE = Diesel gallon equivalent
--- = Not applicable

[a] Assumes that 1,000 cows each produce 50 ft^3 of biogas per day which is 60% methane, and that the biogas is combusted for electrical generation at 28% efficiency.

[b] Assumes that 140 ft^3 of biomethane is equivalent to 1 gallon of diesel, which yields a fuel production capacity of approximately 215 DGEs/day.

[c] Derived from information from energy audits conducted for the California Energy Commission by RCM Digester, which found that older dairies typically use less energy and operate in the 1 kWh per cow per day range, modern dairies operate at 2.2 kWh per cow per day, and modern dairies with fans for cow cooling operate at 3 kWh per cow per day.

[d] The lack of factory produced CNG or LNG farm vehicles, the cost of vehicle conversion, the cost of storing and pumping the fuel, and the uneven pattern of usage create substantial barriers to the use of CBG for on-farm vehicles.

[e] In actuality, the likelihood of converting refrigeration units to run on biogas is extremely small (see text discussion, above). However, biogas could be used for prechilling milk. The potential annual consumption for on-farm milk prechilling was not quantified for this study.