

PG&E GAS R&D AND INNOVATION

WHITEPAPER

Renewable Natural Gas Demand

8/30/2018



Together, Building
a Better California



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Summary: RNG Demand

Definition: Once biomethane has been injected into PG&E’s gas pipeline system, there are a variety of ways it can be used, from traditional gas applications to specific use cases that take advantage of tax credits or incentive programs. Laying aside traditional gas applications, the two major uses for renewable natural gas are for maximizing GHG reduction for the grid, and/or as clean fuel in transportation.

The most immediate application for biomethane is as fuel for *clean transportation*, which offers substantial financial incentives from both the State of California and the US Federal Government - up to \$33/MMBTU¹ in 2018 (includes LCFS and RIN credits). Some near-future considerations may include using biomethane as a means of seasonal storage for renewable energy, reducing the GHG impact of PG&E’s gas peaking activity or gas residential consumption, and supporting PG&E’s goal of 40% GHG reduction by 2030. A third potential application in the more distant future is using biomethane as a chemical source for other outputs such as hydrogen.



Figure 1 Illustration of a CNG Station for Trucks (TruStar Energy CNG, 2018)

Sources of Demand for Biomethane:

1. *Decarbonized Traditional Natural Gas Demand*
2. **Now - Clean Transportation**
3. *Near Future - Power-to-Gas (P2G)*

¹ Sources: (California Air Resources Board, 2018), (California Air Resources Board, 2018) (Sheehy, 2017)



4. Long-Term - Source of Hydrogen or other Renewable Fuel

The growth of these markets may only be partially determined by the availability of biomethane. However, in order to reach the scale of demand needed for PG&E to reach its GHG goals, it is in the utility's best interest to actively foster the growth of these sources of demand. There are many procedural and operational changes associated with leveraging PG&E's natural gas system in service of seasonal storage for renewable energy or providing additional grid services to the electric business. However, there are no particular technical challenges that are specific to RNG – once in our system, the methane in **biomethane is chemically identical to the methane in fossil gas we are accustomed to transporting safely in our gas system**. The injection of hydrogen in our system may have impacts on the gas pipeline infrastructure and end-use appliances, but these will be discussed in the *Hydrogen Whitepaper Analysis from Gas R&D and Innovation* (PG&E R&D and Innovation, 2018).

RNG demand responds as-expected to market signals, meaning that the cost, and subsequent pricing for RNG, clean fuel credits, transaction costs, and adjacent infrastructure all play a critical role in the growth of demand for natural gas.

California Low Carbon Fuel Standard and Federal RIN Credits:

Clean transportation is the only way that biomethane is treated substantively differently from regular fossil gas at the point of demand. That is due to two major programs funded and regulated by the State of California and the US Environmental Protection Agency (EPA). Since, especially in California, transportation accounts for nearly 40% of all GHG emissions in the state - these programs described below are designed to incentivize the adoption of low carbon fuels in the transportation sector.

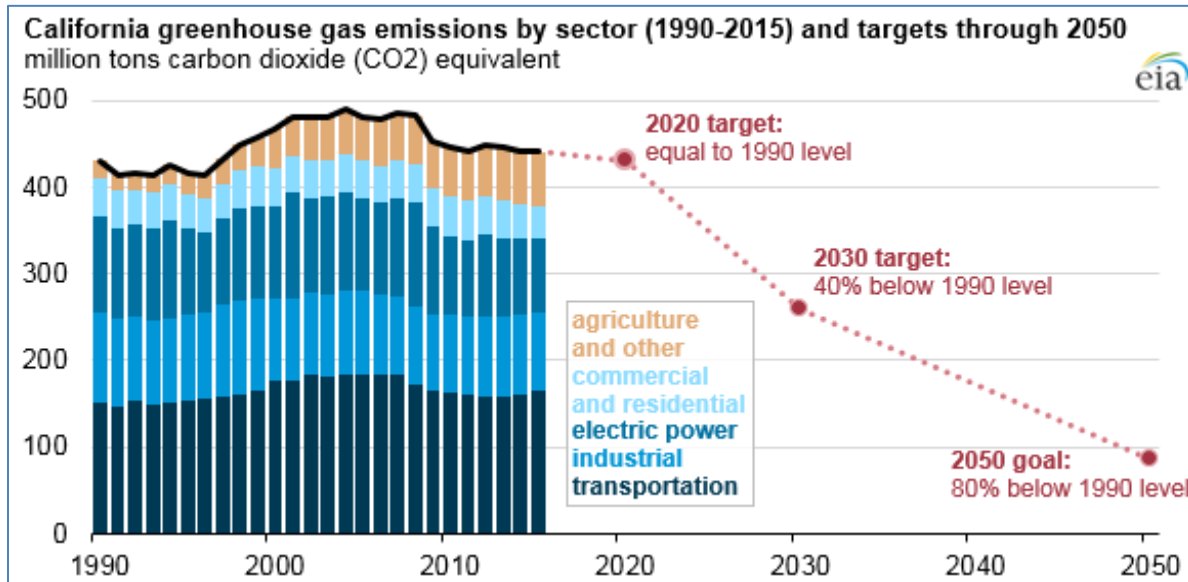


Figure 2 California Greenhouse Gas Emissions by Sector and Targets (Energy Information Administration, 2018)

LOW CARBON FUEL STANDARD (LCFS)

California Air Resources Board – LCFS Program (California Air Resources Board, 2018)

In 2007, California enacted the first low-carbon fuel standard mandate in the world, with specific eligibility criteria designed to reduce the greenhouse gas emissions from the transportation sector using credits and incentive programs (Low Carbon Fuel Standard, 2018). The program was designed and is run by the California Air Resources Board (CARB), which has managed the program since then, and has indicated (most recently at the 2018 Rethink Methane conference in Sacramento, CA) that they plan to continue operating the program for the foreseeable future. In the program, fuel providers are asked to measure the carbon intensity of their fuels through lifecycle analysis. CARB has set up a target carbon intensity curve in line with California’s cap and trade program, where fuels with higher carbon intensity (CI) generate deficits, and those that generate lower than the target generate credits, which can be sold into the cap and trade market. Natural Gas in and of itself is considered a desirable alternative fuel for transportation under this model, but landfill gas and other forms of biomethane generate significantly more credits even over traditional pipeline gas (CI of 67.7 for Pipeline CNG, and a CI of 11.26 for Landfill Gas CNG) (Low-Carbon Fuel Standard, n.d.). If the biogas can be generated with carbon capture, it can be the most GHG efficient of any form of transportation fuel, even above and beyond Hydrogen and Electricity, which also generate LCFS credits under this program.

LCFS credits are relatively volatile – in the month of July 2018, LCFS credits traded between \$140 and \$190 per metric ton, with an average price of \$176.97/MT. (Weekly LCFS Credit Transfer Activity Reports, 2018)

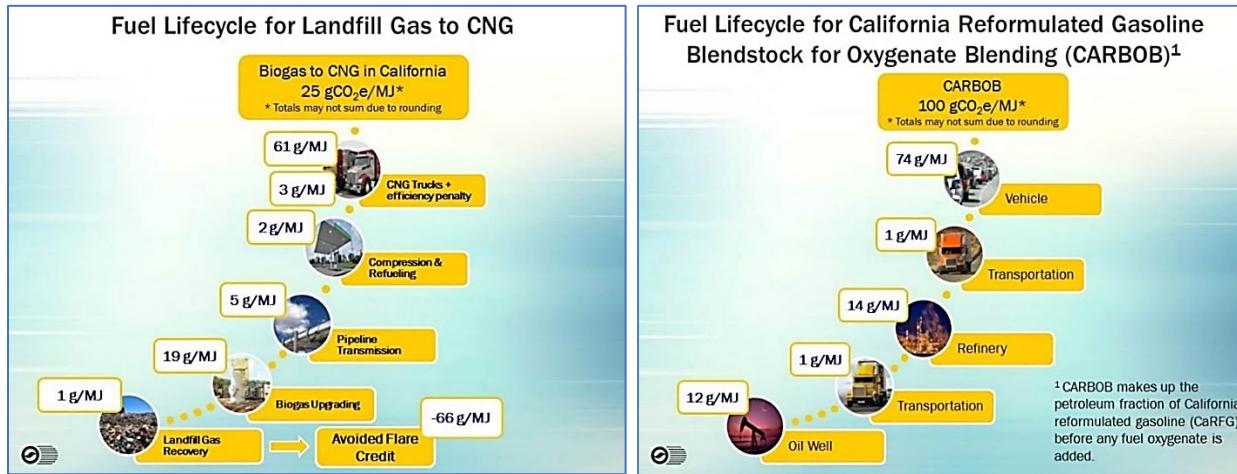


Figure 3 Fuel Lifecycles (California Air Resources Board, 2018)

RENEWABLE FUEL STANDARD PROGRAM (FEDERAL RIN CREDITS)

US Environmental Protection Agency – RIN Credits (Environmental Protection Agency, 2018)

In 2005, the US congress passed the Energy Policy Act of 2005, creating the first Renewable Fuel Standard program under the US EPA. In 2007, the program was updated to set quotas for the use of biofuels through 2022. In order to enforce the program, the EPA created the Renewable Identification Numbers (RIN) system which creates credits for compliance and trading and sets the rules for achieving the goals for renewable fuel use. The most well-known outcome of this program is ethanol blending in consumer gasoline. However, these credits can also be procured through the use of low-emission fuels or fully renewable CNG/LNG, biomethane, renewable diesel, and hydrogen.

RNG qualifies as an advanced biofuel under the Renewable Fuel Standard – defined as, “any fuel derived from cellulosic or advanced feedstocks.” Biomass-based diesel qualifies under this standard, as does cellulosic biofuel (RNG), which is defined as, “any fuel derived from cellulose, hemicellulose, or lignin—nonfood-based renewable feedstocks...[demonstrating] a life cycle GHG emissions reduction of at least 60%.” This definition encompasses nearly all forms of renewable natural gas discussed in this RNG Roadmap.

The cost of RIN credits differs according to the source of the renewable fuel type, and vary significantly over time. RIN Credits for advanced biofuels ranged in cost between \$1.20 per gallon to \$0.78 per gallon in 2017 with an average of around \$0.95 per gallon on average for that year. (Renewable Fuel Standard Program, n.d.)

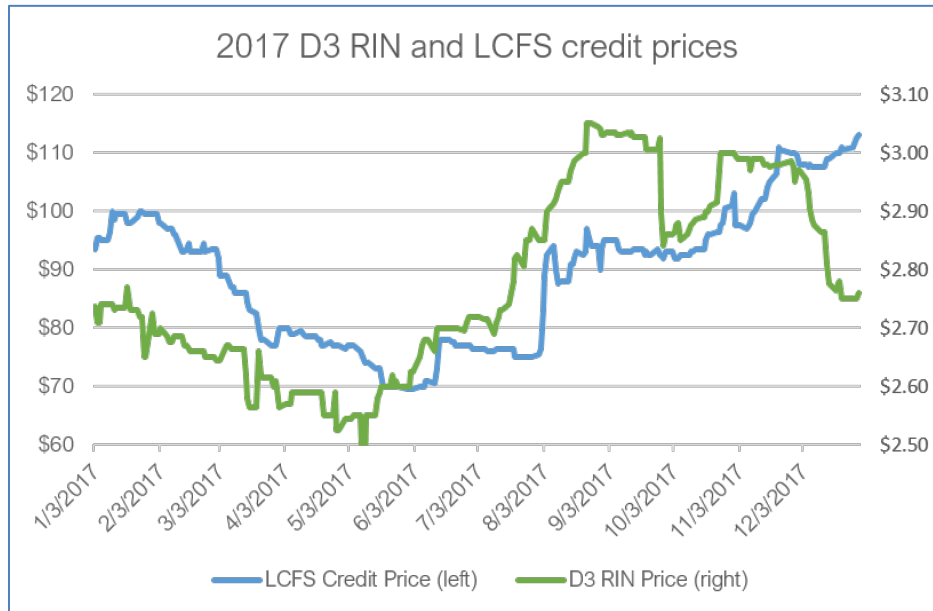


Figure 4 D3 RIN and LCFS Credit Prices (AMP Americas, 2018)

Combined together, often RIN and LCFS credits can provide enough subsidies to make biomethane, hydrogen or other low-carbon fuels economical to produce. The key challenge is to be able to find an off-taker for that fuel within the transportation industry, and to navigate the risk associated with the widely fluctuating prices of RIN and LCFS credits. No other source of biomethane demand has this sort of incentive linked to its use except for clean transportation, so the remaining focus of this paper will evaluate the development of technology in that market.

Current State of the Market: Existing Technology for RNG Demand

There is a variety of potential technologies that can use biomethane available on the market today. In fact, since biomethane is chemically identical to fossil methane, it can be used in all applications interchangeably with fossil natural gas. However, some sectors of demand are more likely to be considered as biomethane project off-takers.

What this analysis contains:

Below is an overview of the major categories of these technologies, starting with types of conversion (Fuel Cells, and Combustion), then an evaluation of the different forms of methane fueled transportation (vehicles, rail, shipping, and air), and finally an evaluation of substitute fuels for similar transportation applications.



Definition of CNG and LNG:

CNG or “Compressed Natural Gas” refers to methane gas that has been compressed using energy to become denser, often making the resulting stored gas’ energy density comparable with gasoline. LNG, or “Liquified Natural Gas” is not compressed, but instead *cooled* significantly to at least -260 degrees Fahrenheit, when the methane naturally liquifies, and subsequently becomes substantially denser. This offers by far the most energy density for any practical form of natural gas, but requires a high level of purity, and a great deal of energy to keep the gas at a low enough temperature to remain liquid. Due to its density, 5x more LNG can be stored in the same size container than compressed natural gas (CNG), saving valuable space and making refueling less frequent.

ELECTRICITY GENERATION: FUEL CELLS

If pipeline biomethane is used for the generation of electricity, it does all the things regular natural gas can do within PG&E’s system, with the added benefit of GHG reductions. Electricity can be generated through the combustion of biomethane to rotate a turbine in a traditional gas fired power plant, or by using methane as an input to fuel cells, which convert methane into electricity. It is easily stored, used for its peaking or reliability value for the electric grid, and can be moved easily through our existing pipeline system.

A *fuel cell* is a device that converts chemical potential energy from a fuel into electrical energy through an electrochemical reaction of methane with oxygen or another oxidizing agent. The inputs for a direct methane fuel cell are methane and oxygen, and the outputs are electricity, water, carbon dioxide, and heat (Phillips, 2014). One example of a methane fuel cell is the Bloom Box by Bloom Energy, which claims to have reduced CO₂ emissions compared to other fuel sources because of its overall better conversion rate. Note that the Solid Oxide Fuel Cell (SOFC) developed by Bloom Energy does not consume methane directly but includes a reformer that generates hydrogen as the fuel. The amount of CO₂ emissions when running on natural gas is 0.8 lbs/kWh, which is still favorable to the 2 lbs/kWh when electricity is produced from coal-fired plants, or 1.3 lbs/kWh from natural gas-powered plants (Jenkins, 2010). If the box is run on landfill gas or biogas, it produces net zero carbon emissions but fuel cells are very sensitive to impurities, especially H₂S and would require stricter gas quality standards. The most used technology use with bio-methane today is Molten Carbonate Fuel Cell (MCFC).

Fuel Cell Electric Vehicles (FCEVs) for example, are propelled using electricity to power the electric motor. Methane or hydrogen is fed into a fuel cell to create the electricity used to run the car, as compared to all-electric EVs, which are fed electricity from a battery. Since fuel cells offer significant efficiency and air quality advantages over combustion (fuel cells

often produce little to no NOx, SOx, volatile compounds, or CO₂), they are often the most efficient choice for energy conversion (PG&E R&D and Innovation, 2018).

However, utility-scale electricity generation is not a preferred application for pipeline biomethane. Why not?

It is notable that biomethane as a fuel for electricity is one of the most expensive resources in our electricity generating mix – it provides little *added* value over fossil fuels, and can offer greater economic value in other applications (as renewable fuel). And finally, the reduction in GHG that biomethane can offer electric generation is an advantage that can be more cheaply met by other renewable energy sources like solar or wind.

Methane fuel cells *may* be used effectively in FCEVs or for very niche applications such as providing backup power to data centers. In these specific use-cases the high quality of electricity, consistency, and reliability of fuel cells over more intermittent sources of energy like solar or wind may offer enough targeted additional value to justify the significantly higher cost for some of PG&E’s customers in Northern California.

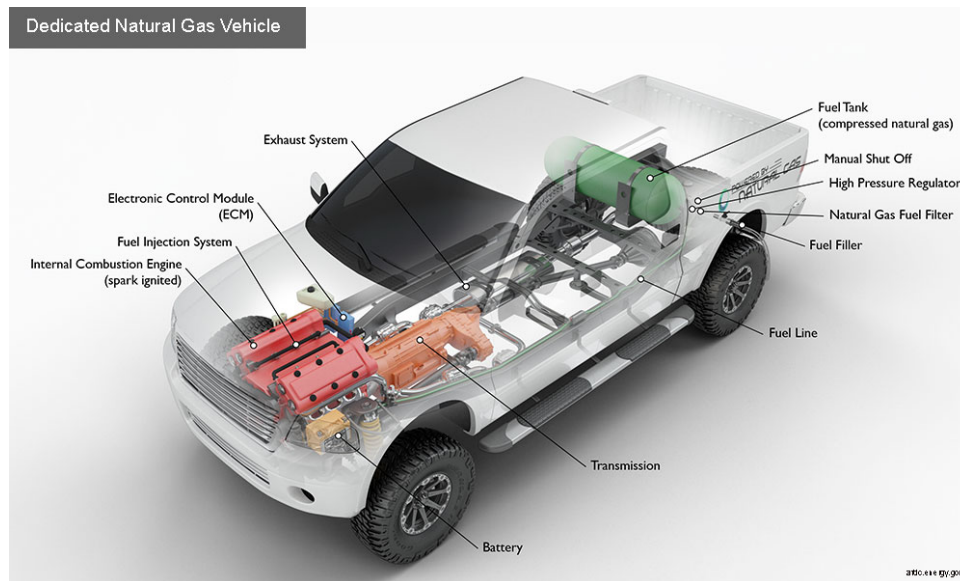


Figure 5 Example of a Dedicated Natural Gas Vehicle (U.S. Department of Energy, 2018)

CNG/LNG ENGINES: COMBUSTION

Renewable natural gas (RNG) can be used as a transportation fuel in the form of compressed natural gas (CNG) or liquified natural gas (LNG).



Unlike fuel cell vehicles, CNG vehicles function the same way gasoline-powered vehicles do, with a few specific modifications. These engines have a comparable MPG to gasoline-powered vehicles, but up to 40% less GHG emissions for the same work. The refueling process is also very similar, relying on highly compressed gas at refueling stations which (just like in a commercial gas station) travels through a pump to refuel a lower pressure storage cylinder on board the vehicle. Because the gas that is stored is significantly lighter in weight than a battery with an equivalent storage capacity, these types of engines are favored for more industrial uses and medium- and heavy-duty trucking, where the weight of the fuel is an important consideration to the bottom line. In the event that weight is a significant concern for transportation, or long trips are required carrying the maximum weight (heavy-duty trucks, shipping), LNG is the preferred method.

What does it cost to switch to a RNG-fueled CNG vehicle?

While operating costs for a CNG-fueled vehicle might be compelling, it is important to note that CNG vehicles are not generally commonplace, and so often any analysis of the economic benefits of buying a CNG/natural gas car or truck often involve the cost of switching. If a truck or car runs on natural gas, very few modifications must be made to accept RNG. However, if, like most trucks, the engine runs on renewable diesel, the switching costs are prohibitively high, and most fleet managers tend to make the switch only when they have to replace the entire truck. In addition, renewable diesel and CNG do not make use of the same fueling infrastructure (one is a liquid, and the other is a gas, requiring different equipment), so the refueling infrastructure must also be upgraded. That infrastructure benefits and also suffers from the opportunity/problem of network effect.

Typical modifications for CNG vehicles include hardened exhaust and valve seats. These changes do not impact the visual appearance of the engine, nor do they impact maintenance schedules. The expected after-market conversion cost to upgrade to a natural gas vehicle varies between \$20,000 and \$50,000 based on the amount of fuel storage installed.

CLEAN TRANSPORTATION TECHNOLOGIES

Critical to generating more biomethane, and successfully developing more biomethane projects is a stable off-taker in the transportation industry who can qualify for LCFS or RIN credits to make the project economical. At the moment however, there is a limited number of CNG or methane fuel cell vehicles, ships, trains, and other transportation systems that can generate the demand for these projects. Gas R&D can support the development of this industry by encouraging the

development of more CNG or methane fuel cell vehicles and a greater variety within each product line to accommodate different use cases for the vehicle. Many of these engines require significant testing and development which is a significant risk for the car manufacturer or OEM. *For more information about the potential development of these markets – please reach out to PG&E’s Clean Transportation Strategy Team.*

The CNG/LNG engines mentioned above provide some general guidance. Trucking and vehicle classifications are based on weight, with light-duty carrying the lowest weight amounts, and heavy-duty carrying the heaviest loads. Below are some of the forms of transportation for which methane is an alternative fuel option, as well as a brief discussion as to the viability of each market.

CNG LIGHT-DUTY VEHICLES:

While CNG light-duty vehicles exist, **it is extremely unlikely that a significant market for light-duty CNG vehicles will develop in the near- or long-term.** This market segment, currently dominated by gasoline powered ICE vehicles, is being rapidly transformed by battery electric vehicles (BEVs) such as Tesla models, and new product offerings from traditional car OEMs such as Chevy (Bolt), BMW (i3) and others.

To an extent that a secondary low-emission vehicle market will form, it seems likely that the slowly growing hydrogen fuel-cell electric vehicle (FCEV) market will claim that honor (such as the Toyota Mirai). Not only are these vehicles zero-emission (not low-emission like natural gas vehicles), but they are also enjoying greater acceptance within the consumer market, with significant existing infrastructure investment for EV charging, etc.



Tesla Model S (Autoblog, 2018)



Toyota Mirai (LeaseCar, 2018)



Chevy Bolt (Chevrolet, 2018)

CNG MEDIUM-DUTY VEHICLES

Medium-duty vehicles is a natural sweet spot for CNG vehicles. Generally, these vehicles can be used for route-based work (like trash collection, mail delivery, etc), where weight is not a critical issue or can be variable, and *not* for long-haul transportation. As working vehicles, the fast refueling of vehicles (compared to slower electric recharging) is a significant asset. These vehicles often also return to a central point (the post office, fleet garages or lots) where a single well-placed CNG/LNG refueling setup can serve multiple vehicles efficiently, and range is not a significant issue. CNG medium-duty trucks are already commonly used in vans and shuttles at airports, regional distribution/pickup or delivery trucks for food, beverage, or utility companies.

For Example:

United Parcel Service (UPS)

Investing \$1B in CNG/LNG Fleet and Refueling Infrastructure

UPS is well-regarded for its strong commitment to operational excellence and sustainability. In 2017, UPS announced a \$90M investment in 390 CNG tractors and trucks, 50 LNG vehicles, and 6 CNG stations, and in 2018 expanded that fleet by 700 new CNG vehicles, totaling nearly \$1B in alternative fuel and advanced technology vehicles in the 10 years from 2008-2018 (Smith J. , 2018). With this investment, UPS is the #1 largest consumer of CNG in the US transportation sector. UPS is not just doing this for the carbon savings, but also because historically, fuel is the biggest expense for transportation companies, and while diesel prices dipped in 2015-2016, the prices have been rising in lock-step with gasoline (UPS, 2018). Natural Gas has lower risk in the US with a strong, secure domestic supply at consistently low prices. Similarly, RNG is often subsidized to a comparable price while offering substantial carbon reductions as well. As more companies like UPS commit to company-wide GHG reduction initiatives, options like RNG-fueled trucks will become increasingly attractive by offering several different forms of value for competitive pricing.





Figure 6 UPS Natural Gas Vehicle (Gasper, 2018)

More Resources on UPS' CNG/LNG Fleet:

WSJ Profile on UPS CNG Investments: [UPS Is Adding 730 Alternative-Fuel Trucks to Its Fleet](#)

UPS 2017 CNG Fleet Expansion: [UPS Invests More Than \\$90 Million In Natural Gas Vehicles And Infrastructure](#)

UPS 2018 CNG/LNG Fleet Expansion: [UPS Adds More Than 700 Vehicles To Its Natural Gas Fleet](#)

CNG/LNG HEAVY-DUTY VEHICLES

Heavy-duty vehicles are another market in which RNG might feasibly be considered for significant adoption. Some examples of heavy-duty applications include intercity and transit buses, freight, and delivery of agricultural or building materials. Often heavy-duty vehicles require a significant amount of power and haul a great deal of weight. A significant majority of heavy-duty trucking applications require the trucks to travel long distances as well. Finally, due to their near constant use, and the use of dirty fuels, these are responsible for a proportionally greater amount of pollution and GHG emissions than other types of vehicles. The profitability of trucking is often determined by the cost of fuel (a major variable cost related directly to weight), the cargo they can transport (pay load) and the utilization time (trucks are only making money when they are on the road).

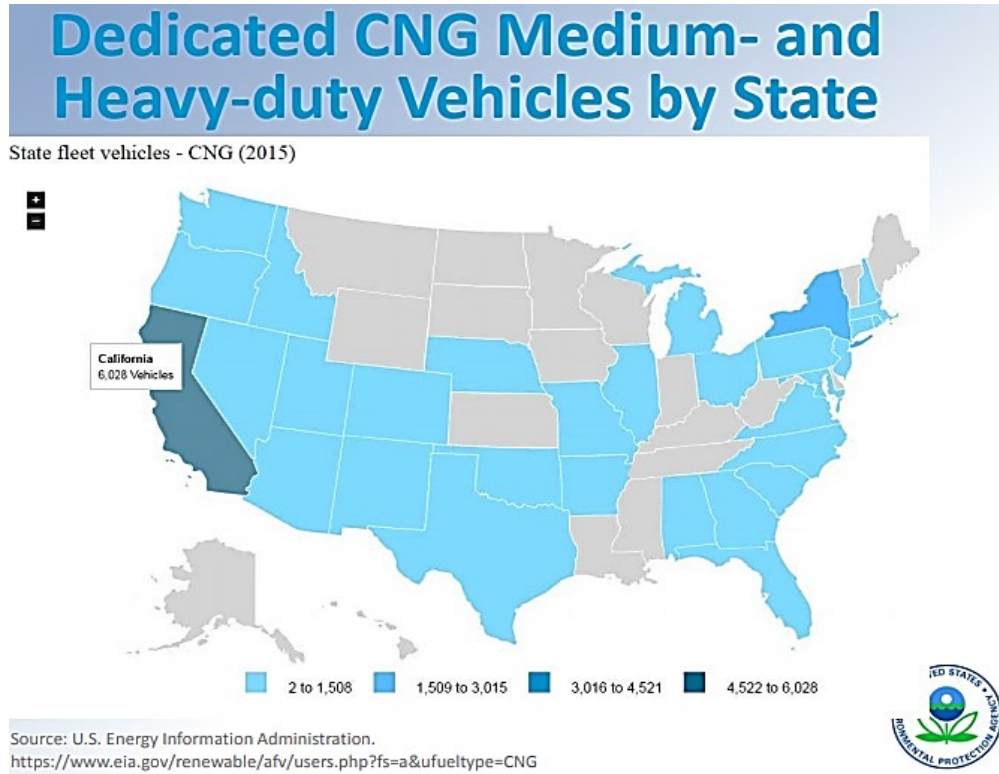


Figure 7 Dedicated CNG Vehicles by State (Energy Information Administration: Fleet & Fuel Data, 2018)

While it is possible that electric trucks might someday gain market share in this space, the long-recharge time of a battery-powered EV, and the significant weight of batteries (often taking up 25-30% the total carrying capacity of the truck) limit the adoption of electric heavy-duty trucks. Even so, RNG fueled CNG/LNG trucks will compete for market share with renewable diesel, ethanol, methanol and hydrogen fuel cells. *For a discussion on some of the remaining challenges associated with adopting renewable CNG for heavy-duty transportation, please see below under “[Macro-Challenges](#)”.*

CNG/LNG IN SHIPPING, RAIL, AND OTHER APPLICATIONS

The same economics that makes CNG viable for heavy-duty vehicles also make biomethane an attractive fuel source for other forms of transportation, namely shipping, rail, and potentially air transportation. Some of these forms of transportation use the very dirtiest forms of fuel in the world, so the opportunities to see truly dramatic improvements in GHG emissions reduction are possible by converting to natural gas.

Shipping:

According to the International Chamber of Shipping, about 90% of all world trade will travel on ships at some point in the supply chain, and the vast majority of cargo ships still use “bunker fuel”, which is the remnants of the fossil fuel refining process (Loveland, n.d.). It is by far the cheapest form of fuel, and also the dirtiest (Gallucci, 2017). This is especially important to the State of California, which is home to some of the largest ports (and some of the dirtiest air quality cities) in the United States (1. Los Angeles, CA 2. Long Beach, CA, and 6. Oakland, CA). (Inbound Logistics, 2015)

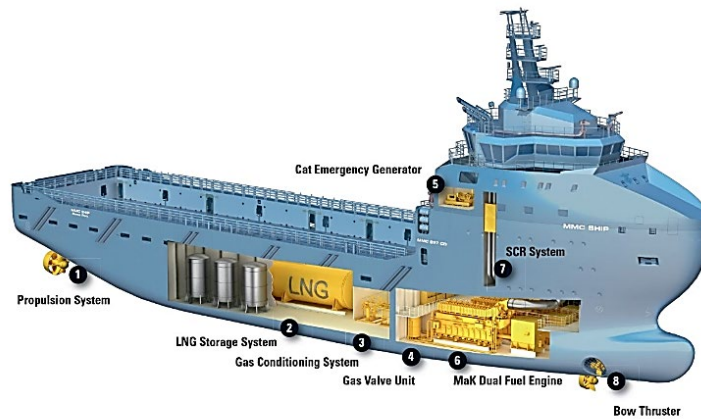


Figure 8 Illustration of a LNG Ship (Caterpillar, 2018)

Moving from bunker fuel to LNG for fueling ships offers some dramatic advantages (Brynolf, 2011):

- 25% reduction in GHG emissions (using Biomethane, GHG reduction would be even greater)
- ~100% reduction of SOx emissions
- 85% reduction of NOx emission
- 70% cheaper cost for natural gas over bunker fuel before LNG compression costs

Several companies have begun to build LNG ships. The *Isla Bella* and her sister ship *Perla del Caribe*, built in San Diego, CA, were commissioned in October 2015 and were the world’s first ever LNG-powered container ships, built by TOTE Maritime. However, it is hard to understate the enormous cost of making this transition – both the *Isla Bella* and her sister cost \$324M each to build, and a dedicated LNG filling station is being built to resupply them. However, other ships – such as ferries that operate set routes and carry less weight – can be built cheaper and more quickly. Several such ferries are operational in Northern Europe (such as the first LNG-powered ferry, *Glutra*, which has been in service in Norway since 2001) (Thomson, 2015). Ferries also tend to fall under local jurisdictions, which makes incentivizing the switch to natural gas

possible. Most container ships are not regulated by any one country, but by the supra-national International Maritime Organization (IMO) (International Chamber of Shipping, 2018).

Unfortunately, however, while converting shipping to natural gas fuel would have a significant impact on the throughput demand for PG&E’s natural gas resources (especially for biomethane), it is unlikely that PG&E (through R&D efforts or otherwise) can provide assistance in developing this market. The technology is known, the business is regulated independently from the US/California, and the development process for building new ships is even more capital intensive than the utility business. Instead, PG&E can keep an eye on the development of this market and prepare by interconnecting enough biomethane projects to meet the potential demand from LNG ships.



Figure 9 Illustration of an LNG Ship (Wilhelm, 2016)

Rail:

Like shipping, rail has largely been spared of efforts to improve GHG emissions but has slowly been exploring natural gas as an alternative fuel. Most rail cars are fueled primarily with non-renewable diesel, but some efforts have been made to fuel trains with LNG fuel.

Here’s how it works: An LNG tender car follows the engine car. The tender car is built with double walled stainless steel to keep the LNG cold for as long as 14 days (Energy Conversions Inc., n.d.). A heat exchanger converts the LNG back into natural gas, which then flows into the locomotive through a flexible hose connection to fuel the engine. Because of a few safety accidents during the period when regulators were considering this technology, the resulting regulation is extremely rigorous. While industry players joke that an LNG tender car is so safe that it would still be standing after a nuclear attack,

that rigor also makes LNG tender cars prohibitively expensive, which is a major (policy) barrier to the adoption of LNG/CNG in rail.

However, like shipping, certain rail applications that have less requirements for distance travel, weight limits, or that operate in a limited geographic region may be viable for CNG, and be viable at lower costs.

For Example:

The Napa Valley Wine Train

Napa Valley, California

The Napa Valley Wine Train is a privately-operated excursion train that runs on a limited route between Napa and St. Helena, California. While originally designed to run on diesel, train #73 was retrofitted from to run on CNG, and other trains have been built to support a mix of CNG and diesel (Napa Valley Wine Train, 2018).



Figure 10 Napa Valley Wine Train (Napa Valley Wine Train, 2018)

Air Travel:

LNG-fueled air travel is still the stuff of laboratory experiments in 2018. Companies like MIT-based startup Savion is targeting some niche applications for LNG aircraft (EnergyWire, 2013). However, even the most ambitious projects max out with LNG comprising less than 5% of the total aircraft fueling market by 2030 at the earliest. The real-world application of natural gas in aviation is likely to be more on the 20-30-year adoption timeline, if at all.

Macro Challenges (High Level):

There are few barriers to adopting CNG or natural gas fuel cell vehicles for medium-duty applications, and in fact, there are many industries in which CNG vehicles are commonly used today for such purposes. However, there are significant hurdles

to the widespread adoption of RNG fueled vehicles in the heavy-duty segment, however, and several of these challenges also apply to the opportunities for CNG/LNG in shipping, rail, and aerospace detailed above.

- **Product Development in Transportation is Expensive, Policy-Driven, and Specialized –**

Transportation operates at nearly as large a scale as energy does, and the development of new engine, or a new type of ship, can easily run into the hundreds of millions of dollars for a single project. PG&E's R&D dollars will have little impact on such projects. And since much of that development is in partnership with different regulatory bodies, customer segments, and often requires a specialization that PG&E doesn't have, it's unclear how PG&E can support these projects except by being a willing partner for demonstrations or specific pilot projects.

- **CNG/LNG Fueling Infrastructure –** heavy-duty trucking often requires long-haul trucking over long

distances, or long usage over the course of a day. To avoid losing money, there needs to be significant infrastructure for refueling when and where each truck needs to refuel, which implies a need for significant infrastructure investment not just within urban centers or even in California, but also across state lines where these forms of transportation often are required to go. That infrastructure is growing, but lacks the ubiquity of diesel and gasoline refueling infrastructure in the US. (Smith & Gonzales, 2014)

- **Heat of Compression –** The speed of refueling is important, since a truck is only profitable when it is on the

road. However, when refueling CNG vehicles at a very fast rate, the compressed gas dispensed into a fuel tank becomes extremely hot. This is a limitation.

- **CNG Takes up Space –** In heavy-duty vehicles (including rail, shipping, etc), and to an extent in medium-duty

vehicles, often weight and space is a critical factor in the profitability of a vehicle. The more space or weight that is taken up by the CNG engine or storage tank, the less space or weight there is for other, more profitable cargo. Unfortunately, CNG takes up more space per GGE (gasoline gallon equivalent). For some cases, this can be solved by using LNG, an ultra-compressed and liquid form of natural gas that solves both space and weight limitations of CNG (Richmond, 2015). However, LNG can be expensive and may offer different challenges (see below).

- **Technical and Operational Challenges of Adopting LNG –** LNG is a cryogenic liquid, so it requires more

training as well as protective equipment. LNG makes the most economic sense and least safety risk if used in a dedicated fueling fleet with fueling personnel. In addition, if left unattended for some time, LNG experiences a phenomenon called 'boil off'. Since LNG is stored at -260 degrees F, when it heats up, it boils in the tank and will eventually vent off. This risk is minimized because LNG is most likely to be adopted for heavy-duty applications, and these same trucks are unlikely to be idle for any significant period of time as idleness reduces profitability.

- **LNG Safety Hazards –** However, the most significant safety concern is the high energy density of LNG. Despite

that being the greatest advantage of LNG, it also means operators must guard against gas leaks and potential



explosion hazards. Since LNG is a relatively new fuel, standards for safe handling are less established than other potential fuel sources.

Potential R&D Projects for RNG Demand

These are the categories of technologies that are priorities in addressing some of the key challenges facing the adoption and usage of biomethane as a transportation fuel in California. Since demand is closely linked to supply, much of the development of markets that will demand RNG are outside the control of PG&E. However, that demand is critical to increasing throughput through PG&E's gas business (as opposed to burning biogas for electricity or consuming biogas on site), so it will be critical for PG&E to support the development of these technologies. However, there are frankly few technical hurdles – much of the work removing these barriers will be in the policy or operational realm.

Since PG&E also has a clean transportation team, the Gas R&D team can expect partnership and support from that team in funding and developing these projects. This list does not include potential opportunities for hydrogen-fueled transportation.

1. BIOMETHANE TRUCKING

An intriguing mix of both transporting biomethane to the point of demand and using RNG directly as fuel, some have proposed the idea of using RNG-fueled CNG trucks to transport RNG to interconnection points or to fuel gas microgrids. This may be a cheaper alternative in some cases (especially smaller developer projects) to building gathering pipeline to the point of interconnection. It may also provide additional benefits of reducing pollution and GHG emissions in some air quality management districts like the Central Valley.

2. GAS MICROGRIDS

There is some support for building gas microgrids similar to those that exist for the electric business, converting isolated communities to move from non-natural gas fuels (eg. propane) to natural gas. This would likely involve biomethane trucking, and building small gas grids in locations otherwise uneconomical due to the high cost of building transmission. Some of these communities are isolated in part because of their proximity to sources of biomethane such as farms or in wooded regions.

3. HEAVY-DUTY CNG TRUCK ENGINES

There are very few commercially available heavy-duty truck engines designed specifically for CNG. The Cummins-Westport Near-Zero engine is an exception, and its “near zero” moniker refers to its ability to nearly eliminate NOx emissions (O'Dell, 2016). This might have especially beneficial applications in the Central Valley in California, meeting stringent air quality standards, and operating in a region with significant potential for RNG production. Fleet managers and Trucking industry veterans, however, suggest that having a diverse product line with many sizes of engine can



encourage adoption. PG&E could be a potential partner as Cummins-Westport navigates the complex regulatory environment to develop a greater diversity of products.

4. CHEAPER OR MORE EFFICIENT COMPRESSION AND COOLING

Compression is the single biggest cost associated with creating and using CNG (as cooling is to LNG). If there may be more efficient motors to run compression systems, or methods for cooling that are more energy efficient, it might help bring down the fueling costs.

Key technologies to investigate and Timeline?

For the market to grow, demand must be balanced in growth with supply. However, when it comes to prioritizing PG&E’s involvement in developing biomethane demand – the team must incorporate the complex and wide-ranging nature of clean transportation. The significant impact that transportation could have on PG&E core business in the future, and the dynamic nature of the current state of these markets cannot be overstated. Long-term planning must be done in conjunction with PG&E’s electric business, fleet, and with a keen eye on tangential markets like battery electric vehicles, EV charging, hydrogen transportation, and other transportation sectors like shipping and rail. Therefore, prioritizing and developing this market must be done in tight coordination with several interdisciplinary teams across PG&E.

Unfortunately, after many interviews with academics, industry leaders, and PG&E SME’s, it is clear that most of the significant barriers to adopting biomethane as a fuel for clean transportation lie primarily in the realm of policy and regulatory issues. PG&E R&D should prioritize supporting pilot projects and other demonstrations necessary to make a positive case to regulators and policymakers that natural gas as a fuel is clean, safe, and cost effective.

1. Biomethane Trucking
2. Heavy-Duty CNG Truck Engines
3. Gas Microgrids

Who are Experts in this field?

Experts specific to individual types of CNG Demand technologies:

Table 1 Individual and Technology Specific Experts

Industry Experts	Expert	Alternative
California	PG&E Clean Transportation Team: Gracie Brown, Principal	PG&E Fleet



United States	UC Davis Institute of Transportation Studies: Amy Myers Jaffe Nathan Parker Rosa Dominguez-Faus	
International	European Commission (Energy and Transportation) Nicolae Scarlat	European Biogas Association (Biomethane in Transport): Susanna Pfluger
Technologies		
CNG Heavy Duty Vehicles	Cummins Westport	
CNG Light/Med Duty Vehicles	UPS	
Methane Fuel Cells	Bloom Energy	
CNG/LNG Stations	PG&E Internal SME's: Steve Sheridan	Mitchell Pratt, COO, Clean Energy
Trucked Biomethane	PG&E Internal SME's: Karen de Gannes Steve Moorlegghen David Lewis Ken Brennan	
CNG Shipping	General Dynamics	
CNG Rail + Other	GE Transportation: Nextfuel Locomotives	
LCFS Credits	PG&E Internal SME's: Mukul Shakur	
Federal Rin Credits	Environmental Protection Agency (Congressional Budget Office) Terry Dinan, Ron Gecan, David Austin	

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