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Using The Rotapower® Engine

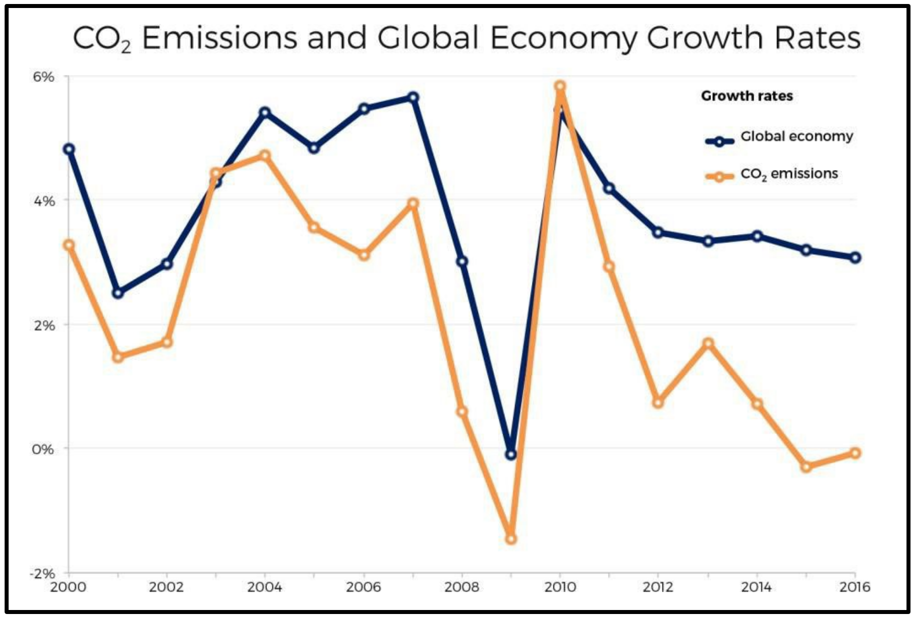
To Reduce Atmospheric Methane Content

Methane (CH_4) is the main component in natural gas and has been considered the second-most impactful global warming gas (GWG). That assumption is now being challenged by a growing number of scientists. Carbon dioxide (CO_2) has dominated most discussions of GWGs. However, the rate of increase in global CO_2 production has recently slowed to near zero while the rate of methane production has increased by a factor of 20. Since a molecule of methane traps 85 times more heat during its lifetime than one of CO_2, many Earth scientists believe that methane is a far more immediate threat due to its ability to create a "runaway greenhouse gas scenario".

Most of the methane increase is coming from biogas generated from man-made sources such as landfills and wastewater treatment plants. Ideally, this biogas would be used in an engine to produce electricity. However, if the methane content is too low or the hydrogen sulfide or silica content too high, the biogas may not be usable in a piston or microturbine engine and is flared or released to the atmosphere.

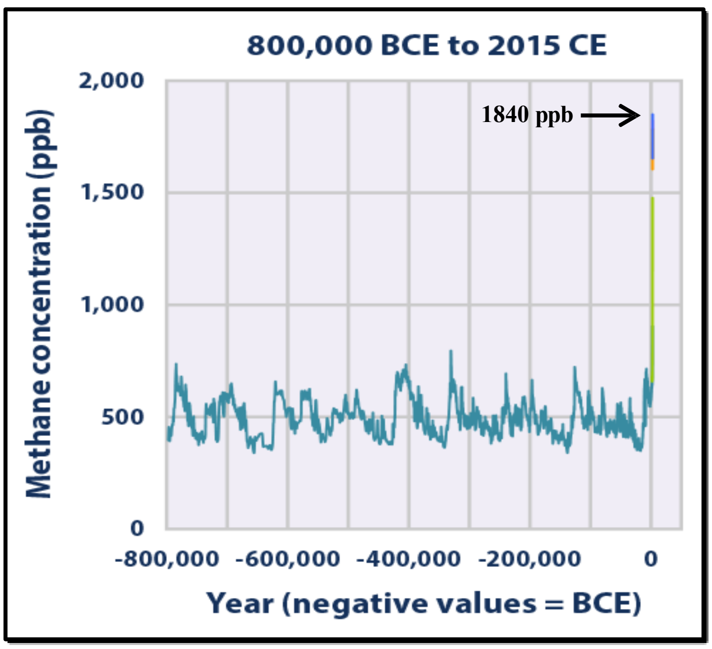
Freedom Motors' Rotapower® engine is resistant to hydrogen sulfide and silica, the primary contaminants in biogas. It can also operate on biogas with a lower methane content than its piston engine counterpart or at a fraction of the cost of a microturbine. It is uniquely able to generate electricity from methane emissions whether natural or man-made.

Methane's Contribution To Global Warming:



Earth scientist, Dr. Robert Jackson of Stanford University, is part of the renown Global Carbon Project and recently wrote, "Looking at the scenario for future emissions, methane is starting to approach the most greenhouse gas-intensive scenario." He further opined, "That's bad news. We are going in the wrong direction." As the CO_2 growth rate has approached zero, the methane growth has increased from 0.5 ppb to 10 ppb in the last few years [1].

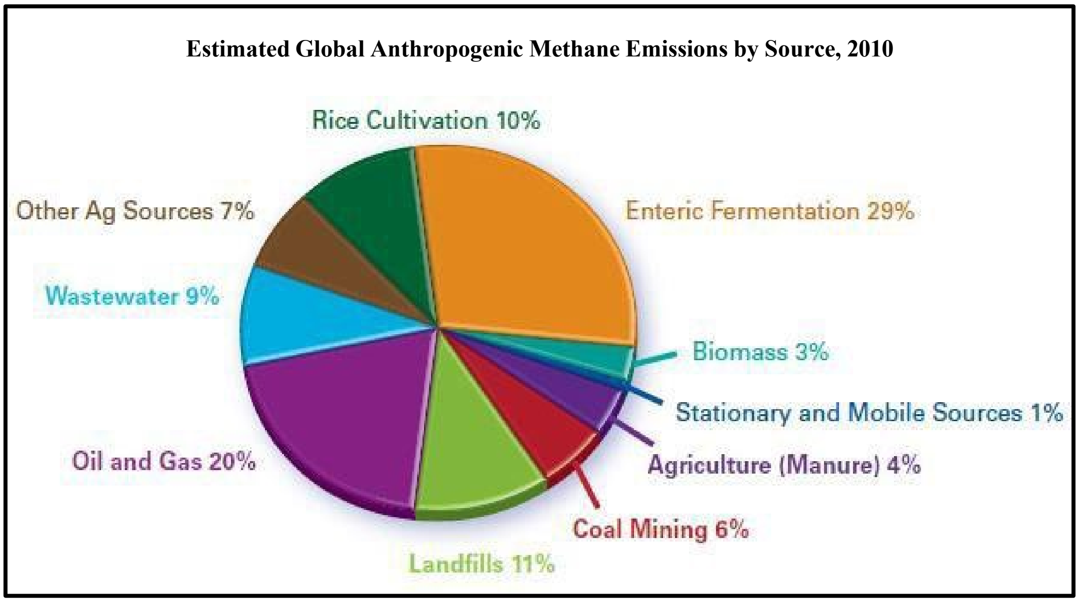
To distinguish the global warming effect of various gases, the Environmental Protection Agency (EPA) introduced the term Global Warming Potential (GWP) and assigned CO_2 the value of one. Methane has a GWP of 85 during its lifetime of approximately 10 years. This means a molecule of methane traps eighty-five times more heat than a molecule of CO_2.



According to Steve Hamburg, Chief Scientist at the Environmental Defense Fund (EDF), "By emitting just a little bit of methane, mankind is greatly accelerating the rate of climate change." [2] This concern was compounded by a study at Princeton University which showed that methane production is extremely sensitive to a temperature rise. This study concluded that methane production from agricultural sources increased fifty-seven times when atmospheric temperature rose 30 degrees Celsius [3]. Many peer-revised climatological articles use the phrase "runaway greenhouse effect" when describing the consequences of a positive feedback loop strong enough to cause a planetary body's water to boil off [4]. There is dispute as to whether CO_2 has a weak positive or a weak negative feedback loop. However, there is no debate whether methane has a strong positive feedback loop [5].

Sources Leading To The Increase In Methane:

The US is the leading source of anthropogenic (man-made) methane emissions, which make up 64% of the total methane produced world-wide annually [6]. The following figure shows world-wide sources of anthropogenic methane:



The methane sources that can be conveniently utilized to create energy are landfills, wastewater, animal manure, and associated petroleum gas (APG) which is a component in the oil and gas segment. In effect, approximately 30% of the total world-wide anthropogenic methane can be utilized to produce energy, and in the process, reduce the consequences of methane's very high global warming potential (GWP).

- **LANDFILL PRODUCED BIOGAS.** The Environmental and Energy Study Institute (EESI) notes that only 450 of the 2,300 landfills in the US have operational biogas projects, while 61% of landfills have no biogas collection systems. Despite this very small utilization of the potential energy available from landfills, the produced biogas provides 14.8 billion kWh annually along with 102 billion cubic feet of consumer quality natural gas [7]. This amount of methane removal is equivalent to the CO_2 emissions from approximately 240 million barrels of consumed oil.

  Landfill waste in the US totals 250 million tons annually [8]. One ton of municipal landfill can produce 120 cubic meters of methane [9]. Therefore, landfills in the US could provide 29.9 billion cubic meters of natural gas.

- **WASTEWATER FROM HUMANS AS A SOURCE OF BIOGAS.** One way to recover energy from wastewater is to use anaerobic digesters which create biogas through bacterial action in an oxygen-free environment. The biogas produced is a nearly equal mix of methane and CO_2. Two-thirds of the 3,200 large wastewater treatment plants (WWTPs) (> 1 million gallons per day) do not use anaerobic digestion to produce biogas. In addition, there are 12000 smaller facilities (< 1 million gallons per day) where only a few anaerobic digesters are used. One-third of those facilities that do produce biogas release it directly into the atmosphere [10]. The Water Environmental Research Foundation found WWTPs have the potential to generate 23.2 billion cubic meters of natural gas [11].

  Biogas created by anaerobic digesters using human waste can contain a high amount (up to 10,000 ppm) of hydrogen sulfide (H_2S). This complicates its use on-site to create energy and may account for why it is often flared or released directly into the atmosphere.

- **PETROLEUM EXTRACTION AND DISTILLATION AS A SOURCE OF METHANE.** Associated Petroleum Gas (APG) is a form of natural gas which is found with deposits of petroleum. It may be dissolved in the oil and removed during distillation or as a “gas cap” above the oil in the reservoir. Historically, this type of gas was released as a waste product from the petroleum extraction industry. It may be a stranded reserve due to the remote location of the oil field, either at sea or on land, and is simply burned off in a gas flare. When this occurs, the gas is referred to as ‘flare gas’. The World Bank estimates that 150 billion cubic meters of natural gas is flared annually with a value of 30.8 billion dollars [12]. The US flares 10.7 billion cubic meters of APG related natural gas annually [13].

- **MANURE FROM ANIMALS AS A SOURCE OF BIOGAS.** Animal waste has the potential, through the use of anaerobic digesters, to double the current biomass electric generation capacity in the US. Factory farms typically use manure filled lagoons to create anaerobic digestion. The resulting biogas is a nearly equal mix of methane and CO_2. Like biogas from human waste, it includes a relatively high amount of hydrogen sulfide (H_2S) gas which makes it difficult to use it in engines to generate electricity. Removing the H_2S adds a significant cost. Currently, there are 239 anaerobic digesters on dairy farms in the US. The potential exists to add digesters to an additional 51,242 dairy farms.

  Animal manure production in the US totals over one billion tons [14], and each pound of manure can create one cubic foot of biogas [15]. Assuming this biogas is 50% methane, manure could create 28.2 billion cubic meters of natural gas.

ELECTRICAL ENERGY PRODUCTION

The energy available from the methane content in the above four sources is equivalent to that in 92 billion cubic meters of natural gas. If converted to electrical energy through an engine driven genset, the output would be sufficient to provide the electrical needs of 30 million US homes.

PROBLEMS ASSOCIATED WITH USING BIOGAS TO FUEL AN ENGINE:

Four-stroke piston and typical rotary engines have many of the following limitations as a powerplant using biogas as fuel:

- The oil bath lubrication system used by these engines becomes acidified by hydrogen sulfide (H_2S). Biogas from human or animal waste contains 700 - 10,000 ppm of H_2S. Its presence in an engine is a major source of corrosion.

- Cannot tolerate small amounts of silica because of its abrasion affect and valve damage. Silica is becoming increasingly present in human waste due to its widespread use in many household items; particularly in cosmetics. Silica appears as a fine dust form of sand. During anaerobic digestion in landfills and WWTPs, it evolves into siloxane. This ceramic-like material is deposited on engine valves and wears surfaces with destructive consequences [16].

- Cannot maintain high enough combustion surface temperatures to efficiently combust biogas; particularly when the methane content is significantly below 50%.

- Genset cost per kilowatt of energy may limit the utilization of biogas conversion to electricity for anything but very large landfills, WWTPs or manure and APG sources.

- Has so many parts that any level of corrosive activity compounds the maintenance costs.

- H_2S above 250 ppm may void the engine manufacturer’s guarantee.

HOW THE ROTAPOWER ROTARY ENGINE OVERCOMES THESE LIMITATIONS:

The following features allow the Rotapower® rotary engine to efficiently utilize biogas to create energy:

- Uses a lubrication system where very small quantities of oil are metered to the roller bearings and seals. Any remaining oil then exits the engine before becoming acidic.

- Can tolerate siloxanes by using chrome carbide wear surfaces and silicon nitride seals (9 Mohs versus 6-7 Mohs for silica). The rotary engine does not need or use valves.

- Uses a stainless-steel rotor with a low thermal conductivity as opposed to aluminum used in piston engines. This results in a rotor surface temperature of up to 900°F versus a piston at 400°F. This contributes to combustion of biogas with lower methane content.

- The rotary engine, as distinct from a piston engine, has an intake chamber that is separate from the expansion chamber. This prevents the expansion chamber surfaces from being pre-cooled by the intake charge, which further aids in combustion.

- A two-rotor rotary engine has only three moving parts. By comparison, a two cylinder piston engine can have over fifteen moving parts with each subject to the corrosive effects of H_2S.

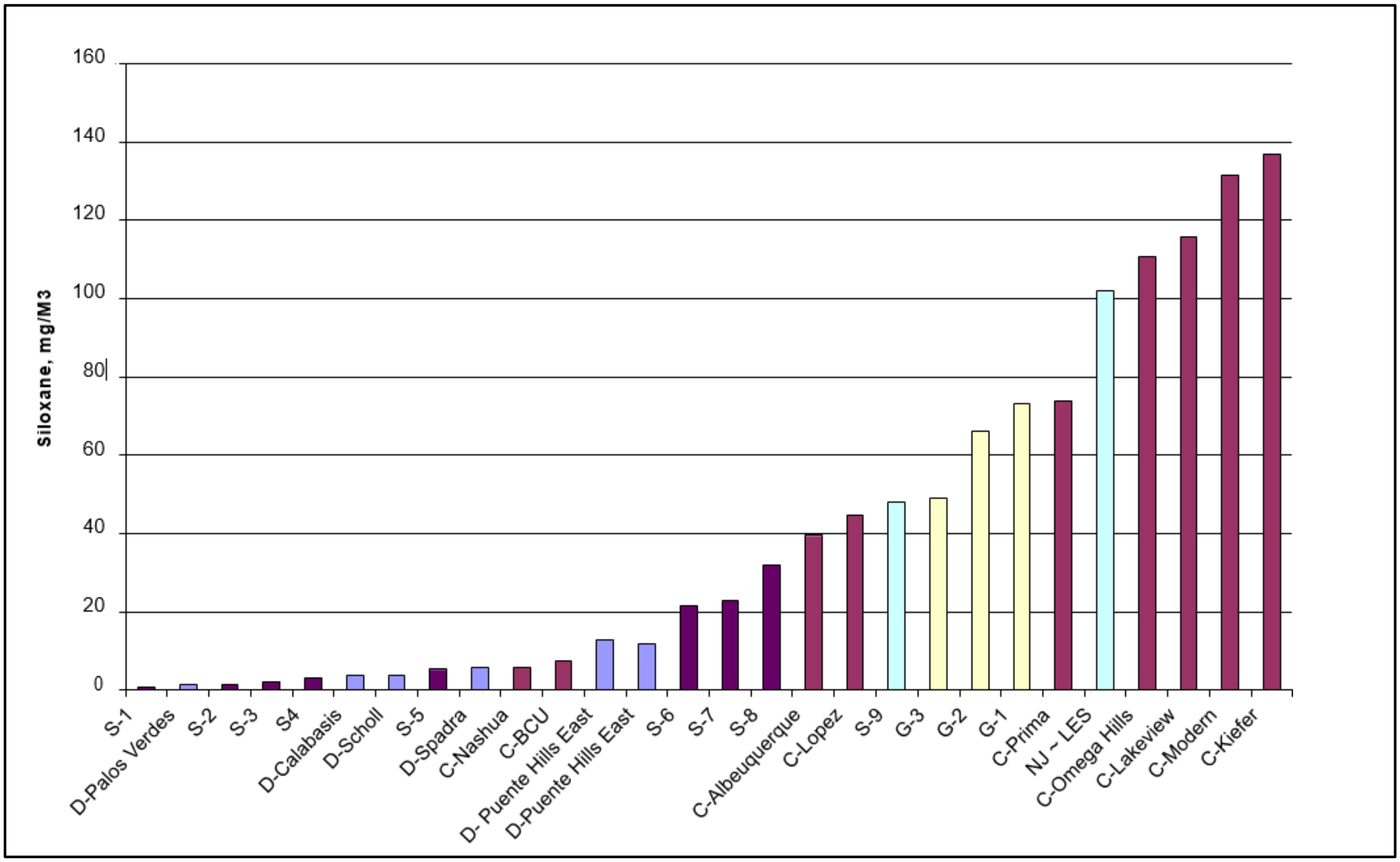
- The estimated capital cost for gensets powered by Rotapower® engines is substantially less than for those powered by either piston or microturbine engines.

COMMENTS REGARDING THE USE OF BIOGAS THAT CONTAINS SIGNIFICANT AMOUNTS OF SILOXANES:

Siloxane content is of particular concern for biogas from landfills and wastewater plants (WWPS) and some manure sources.

The following chart and table show the siloxane content from various landfills in the US and the level of siloxanes that will void the manufacturers warrantee [17]. According to the table, microturbines will require void the essentially complete siloxane removal. Piston engines could be used in approximately one-half of the US landfills without siloxane removal and operate within the engine warrantee. However, even a small residue of siloxane present following the removal process reduces the time between top overhaul.

SILOXANE IN LANDFILL GAS



MANUFACTURER SILOXANE LIMITS	
Engine Manufacturer	**Siloxane, mg/m3 in Landfill Gas**
Caterpillar	28
Jenbacher	10
Waukesha	25
Deutz	5
Solar Turbines	0.1
IR Microturbines	0.06
Capstone Microturbines	0.03

The cost of removing 34 mg/m^3 of siloxane was shown by Waukesha engine company to be as high as 1.5 cents per Kwh [18]. For many smaller US landfills, siloxane removal would not be economically viable. The Rotapower® engine's use of wear surface and seals that are substantially harder than siloxane and its lack of valves eliminates this problem.

COMMENTS REGARDING THE USE OF BIOGAS CONTAINING SIGNIFICANT AMOUNTS OF HYDROGEN SULFIDE (H_2S):

Both animal and human waste create large amounts of H_2S during anaerobic digestion. In most cases the biogas contains sufficient H_2S to void the manufacturer's warrantee for piston engines. Microturbines can handle high H_2S content, but are far more expensive, less thermally efficient, and intolerant to essentially any siloxane content. The following table shows the cost and options available to remove H_2S [19].

Solid Scavenger System (SULFUR RITE ®)	Iron-Redox Regenerable System (LO-CAT ®)
System Cost $41,000 Operating Cost $3/lb Sulfur removed Media cost @ 1 MMSCFD 50 ppm. $3,800/year 100 ppm. $8,000/year 500 ppm. $40,000/year 1,000 ppm. $80,000/year	System Cost $1-2 million Operating Cost 10c./lb Sulfur removed Economic switching point (Scavenger to regenerable system) 1 MMSCFD 4,500 ppm. 2 MMSCFD 2,500 ppm. 5 MMSCFD 1,000 ppm.

The following table [20] shows a 500 Kw genset operating on biogas. Two thousand ppm of H_2S could result in a $203,000 increase in annual engine maintenance cost compared to that with little H_2S (<4ppm). H_2S can be as high as 10,000 ppm from solid waste digesters. Many piston engine manufacturers will not warrantee their engines to run on biogas with an H_2S content higher than 250 ppm.

H_2S Concentration	Annual Maintenance Cost
2000 ppm	$246,612
500 ppm	$80,180
< 4ppm	$43,171

The large landfills like Puente Hills (>5MMSCFD) can justify the cost to remove the H_2S and siloxane. Yolo County landfill (~IMMSCFD) does not remove either H_2S or siloxane, before using the biogas to fuel its four large Caterpillar engines. Apparently, it is willing to accept an annual top overhaul of $200,000 per engine.

HISTORIC RELIABILITY OF THE ROTARY ENGINES:

Three rotary engines that have entered production include:

- Ingersoll Rand- large rotary engines running at low RPM using natural gas accumulated an average of 34,000 hours without an overall before being taken out of service due to excessive oil consumption.
- Mazda RX7 rotary engine ran for over 20,000 hours on natural gas in endurance tests performed by the Gas Research Institute (GRI) in Chicago.
- Outboard Marine Corporation (OMC) produced 65,000 rotary engines for their production snowmobile. In this price competitive market, the life goal was 400 hours. Many engines exceeded 1,000 hours. Following the acquisition of the entire OMC rotary engine IP and production equipment, Freedom Motors undertook a program to double the power output, while lengthening its life to at least 20,000 hours.

The following steps were taken to achieve this reliability goal:
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- Replace the rotor roller bearing with a custom high load bearing by IKO.
- Use a patented way to cool both sides of the rotor equally. This eliminated the thermal gradient across the rotor that caused end loading of the roller bearing.
- Meter oil to critical points in the engine rather than mixing the lubricating oil with the gasoline or using an oil bath lubrication system.
- Use much harder apex seals which together with a proprietary grind on the wear surface allowed the seals to be seated resulting in a seal life of 22,000 hours.
- Liquid cooling the rotor housing and end plates. This allowed the horsepower to be doubled for the same displacement.
- Use chromium carbide wear surfaces (one Moh hardness below diamond), which have never failed. OMC used a similar wear surface on their rotor housing and never recorded a failure.

Following these design changes, three different rotor displacements were produced. The largest rotor displacement (530cc) was also produced in a modular form, which allowed a family of higher horsepower engines to be created by adding modules using longer assembly bolts.

With metered oil and harder wear surfaces and seals, both the Mazda and Ingersoll Rand rotary engines would have been candidates to combust biogas.

Exhibit A compares the characteristics of Rotapower® engines with similar power piston engines. It also shows various products powered by this unique engine.

ROTAPOWER® GENERATING SYSTEM COST COMPARISONS:

The Rotapower® engine is a highly evolved version of a 530cc air-cooled rotary engine developed and put into volume production by Outboard Marine Corporation (OMC) for their snowmobile. OMC produced 65,000 rotary engines and was able to establish that, despite being a four-stroke engine, its production cost was within 10% of the two-stroke engine it replaced [21]. Four-stroke piston engines typically cost 25 to 35% more than two-stroke engines.

There are a few different technologies available for converting biogas into electricity. These include internal combustion engines, turbines, microturbines, fuel cells and burning the gas in Organic Rankine Cycle (ORC) systems. The cost for building power plants based on these technologies can be difficult to determine, however, similar systems were assessed by the California Public Utilities Commission (CPUC) in 2015 [26]. This report determined on average the total system installation cost for these various power plant technologies. Based on the methodologies used in the report, and the cost of the Rotapower® engine generator system, we can compare these various power plant technologies. The following table shows cost comparisons for the plant installation cost, not including any waste heat handling or biogas cleanup equipment.

Average Estimated Costs for Power Generation systems	
Description	**Total Installed Cost**
Rotapower® Engine Generation System	$1,501 per Kw
Gas Turbines	$2,932 per Kw
Microturbines	$3,204 per Kw
Capstone Microturbines (without grants) [27]	$2,472 per Kw
Internal Combustion Engines	$2,386 per Kw
Organic Rankine Cycle (ORC) System	$3,600 per Kw
Fuel Cell	$7,500 per Kw
Wind Energy System	$6,452 per Kw

BUSINESS OPPORTUNITY:

It is unrealistic to expect to compete with the 1,000+ Kw piston powered gen-sets at landfills and wastewater treatment plants (WWTPs) that are large enough to justify the capital and operating costs to remove either or both H_2S and siloxane. However, now that the impact of methane emissions on global warming is being recognized, the large number of smaller anthropogenic methane sources will begin to be emphasized. For example, there are 51,481 dairy farms in the US. The average farm has 180 cows and can produce enough methane from its manure to power a 55 Kw. genset running year-round. However, the dairy will probably not be able to justify the $41,000 capital cost and $8,640 annual maintenance cost to remove 5,000 ppm of H_2S. The dairy would have the following choices:

- Flare the biogas, which may be restricted in the future.
- Use what might be called a throwaway piston engine powered genset at $125 per Kw, with a life of less than 1,000 hours.
- Use a Capstone microturbine, at an engine cost of $1,133 per Kw and a total installed cost of $1,733 per Kw after or $2,472 per Kw before grants, that may need a siloxane removal system.
- Use a long-life Caterpillar G3400 piston engine genset at $904 per Kw and total installed cost of $2,386 per Kw, that will need a H_2S

removal system and may need a siloxane removal system.

- Use a Rotapower® engine generation system at $501 per Kw engine cost and a total installed cost of $1,501 per Kw and it does not need a H_2S removal system and may not need a siloxane removal system.

There are over three times as many beef cattle than dairy cows in the US. For much of the less developed world, anaerobic digestion of manure needs nothing more than a covered slurry lagoon and a hydrogen sulfide tolerate engine. Commercial digesters are available in all sizes and likely to be required in the developed world.

Wastewater treatment plants (WWTPs) are another source of recoverable energy from biogas. The average town in the US has a population of 20,000. Each human generates approximately one pound of feces per day, which through anaerobic digestion can produce 5.65 $ft.^3$ of biogas [23]. By using this biogas in a gen-set, each town could provide a quarter of a megawatt of electrical power. Freedom Motors is located in the town of Dixon, CA with a population of nearly 20,000. The town has just installed a state-of-the-art WWTP, however, it still releases its biogas into the atmosphere. The growing regulatory pressure to reduce methane emissions will change that.

In landfills, the existence of H_2S is less of a problem than is siloxane. The Calabasas landfill provides an example of the use of microturbines to produce electricity [24]. Ten 30 Kw Capstone microturbines were used at a purchase price of $34,000 per engine. Because microturbines are particularly sensitive to siloxane, a double siloxane removal system was used that included both activated carbon and silica gel. These 10 gensets had a total net electrical output of 300 Kw or $1,133 per Kw. The full system installation cost, including the biogas conditioning, was $1,733 per Kw after or $2,472 per Kw before grants [27]. Operating and maintenance cost was 2.5 cents per Kwh which with sales to the grid at 6.5 cents per Kwh would have a pay back of approximately 10 years (includes grant). A Rotapower® engine system at a cost of $1,501 per Kw without the need for a siloxane removal system would have a payback of less than 10 years.

California is a global leader with regard to addressing the methane/manure challenge. Senate Bill SB1383 **requires** a 75% reduction in methane generated by manure by the year 2030. Manure creates 25% of California's total methane emissions. Landfills generate a comparable 20% of methane emissions and SB 1383 **requires** that they be reduced by 40% by 2030 as well. Thus far, only 1% of California's dairy farms utilize anaerobic digesters and implementation of SB 1383 is to begin January 1, 2018 [25]

As California goes, so goes the nation.

ROTAPOWER ENGINE TESTS USING SOURGAS EQUIVALENT AS A FUEL:

As seen below, Freedom Motors constructed a portable dynamometer ("dyno") for purposes of testing our 530cc engine using a mixture of compressed natural gas and carbon dioxide. Testing the engine's capabilities in a controlled environment such as our facility in Dixon, CA, enabled us to constantly vary the percentage of methane versus CO_2 within the fuel.

The dyno's portability will allow us to easily demonstrate our engine's capabilities on site at a landfill. For various reasons (e.g. odors, permitting, etc.) the testing of our engine on the dyno may not be allowed within city limits. The testing at a landfill is beneficial because the sour gas generated from the landfill will introduce the corrosive effects of hydrogen sulfide.

It should be noted that during our recent testing, the engine was normally aspirated and consequently the power output was much lower than would be expected compared to when a turbocharger is added. Remarkably, the engine was able to run on a methane content of 40%, which may not have been possible with a normally aspirated piston engine. Toxic emissions were recorded at a typical 50/50 mixture of methane and CO_2. Some tests included a small amount of water as an effective way to reduce NO_x emissions. Further tests will determine the precise relationship between water quantity, NO_x emissions, and power following the addition of a turbocharger, supercharger or through compounding the engine.

The table below shows the toxic emission results:

Tests with 50% Natural Gas (Methane) and 50% CO_2				
Emissions (ppm)	Test Results (No Water)	Test Results (Water)	NSPS Standard* (Natural Gas)	NSPS Standard (Biogas)
NO_x	< 100	< 55	82	250
CO	< 120	< 120	270	610
HC	< 1	< 1	60	80
(*) New Source Performance Standards				

ADDITIONAL CONSIDERATIONS:

Reducing atmospheric methane emissions qualifies for carbon credits and is in the national interest. It should therefore qualify for grants to mitigate methane's much higher GWP.

Methane generated by anthropogenic sources are far more amenable to nearly immediate reduction. This could provide the additional time needed to address the more difficult goal of reducing CO_2 emissions.

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EXHIBITS

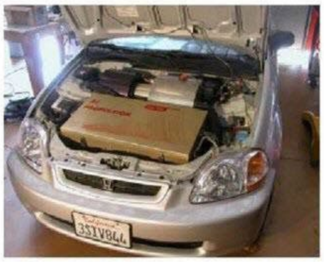
COMPARISON OF ROTAPOWER® VERSUS COMMON ENGINES

		Displacement	HP	Weight	Volume		Critical Parts
Briggs & Stratton Piston Engine		100cc	2.8	28 lbs.	$1.5ft^3$		8
Rotapower Engine		27cc or 54cc equiv.	2.8	4 lbs	$.2ft^3$		2

		Displacement	HP	Weight	Volume		Critical Parts
Vangard Piston Engine		570cc	18	90 lbs.	$3ft^3$		15
Rotapower Engine		150cc or 300cc equiv.	18.5	18 lbs	$.35ft^3$		2

		Displacement	HP	Weight	Volume		Critical Parts
Kohler CH-1000 Piston Engine		1 liter	40	132 lbs.	$4.5 ft^3$		15
Rotapower Engine		530cc or 1060cc equiv.	40	48 bs.	$1.1 ft^3$		2

Applications Using Rotapower®



Hybrid fuel-electric vehicle (530 cc)

All Terrain Vehicle - ATV (530 cc)

Mini-Jet Boat (1060 cc)

Trimmer (27 cc)

Snowmobile (1590 cc)

Jetski (1590 cc)

Portable Gen-Set
(150 cc)

Aviation - Related Applications

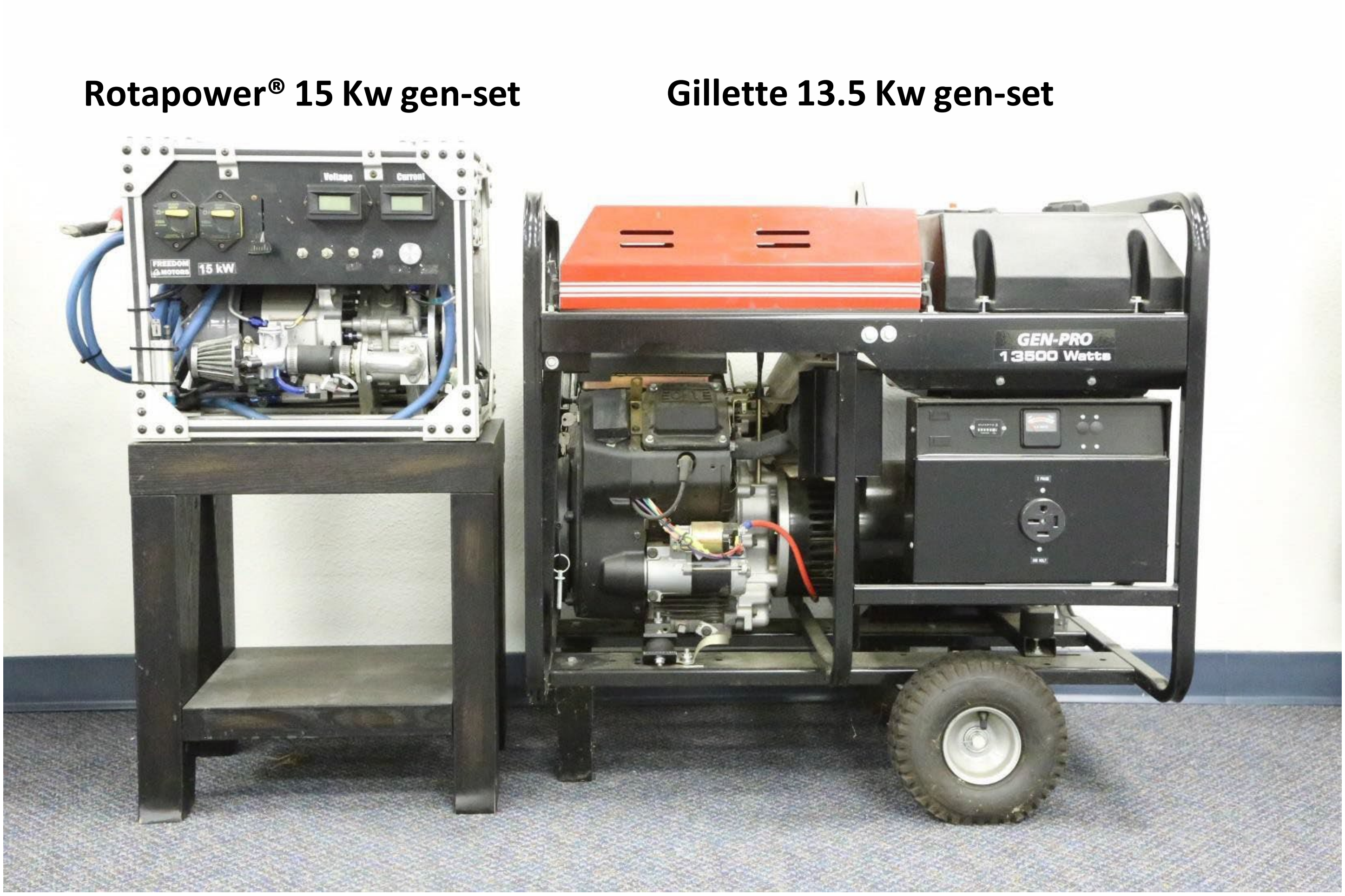
Aerobot

Neuera

Skycar

Most recent application

Motor Scooter (150cc)



Rotapower® 15 Kw gen-set	Gillette 13.5 Kw gen-set
Total Volume: 1.3 cu.ft	Total Volume 12 cu.ft.
Weight: 75 lbs	Weight: 395 lbs
Frequency: variable	Frequency: fixed
Voltage: variable	Voltage: fixed