INTRODUCTION TO
DE-CARBONIZATION AND
ENERGY EFFICIENCY TECHNOLOGY

SKP CLEANTECH CORP
309 Eversyde Circle SW
Calgary AB T2Y 5C7 Canada
Phone: +1 587 917 5798
Email: Contact@skpcleantech.com

FLARE GAS RECOVERY SYSTEM (FGRS)

Project Description:

Recovering of Methane gases (CH_4 +), LPG, VOCs from flare header using CHP (combined heat and power) technology to generate power and heat, which otherwise routed to the flare tip.

The recovery of flared gases can be performed either using CHP or VRU (vapor recovery unit). However, deploying CHP technology offers distinct major benefits over the VRU.

The flared gases comprised of purging, compressor seal venting, venting due to unit start-up, shutdown and releasing for maintenance, which is burned without extracting energy does not work out from plant economics and environmental perspectives.

Technology:

The CHP technology, comprised of *Microturbines*, generates power and heat, which the facility can benefit from by drawing reduced power from the grid and heat can be used for building heating, process heating, or producing steam from low-grade heat resources.

The Microturbines are available in a wide range of capacities and are highly reliable. The specifications are attached with this document for reference.

<u>Following are the benefits of deployment of this technology over Vapor Recovery Unit (VRU).</u>

- Reduced footprint
- Cost-effective / maintenance-free
- Classified / Remote area deployment
- No power consumption
- No cooling water requirements
- Reduced instrumentation and monitoring
- Self-sufficient and standalone unit
- Help to replace emergency DG set
- Serves the purpose of small scale boiler to recover low grade to medium grade heat water resources by converting to hot water
- Facilities having power constraints may benefit from deployment of such technologies
- Can accept partial sour gases without compromising efficiencies

Opportunity:

The proposed technology solves the problem by capturing and converting more potent GHG (methane) to a lower effect GHG (CO2) and at the same time liberating energy which counts toward offsetting the production of GHG. Overall proves a win-win situation solution both for the environment and for the facility economics.

The recycling of Flare Gases to the Fuel Gas System via VRU does help to convert methane to CO2; however, this practice remains highly inefficient and does not offer any flexibility or advantage. *Compared to these traditional practices, CHP offers tremendous benefits and flexibility.*

Quantitative Analysis[1]*:*

<u>ASSUMPTION:</u> assumed that the flare header is 24 inches in size and 0.1m/s of purging velocity. Natural gas purging @ 0.1 m/s velocity through 24" (ID=23.25") header will yield flowrate of 98.6 Am3/h ~130 Nm^3/h.

Assuming the net calorific value of 36 MJ/m^3 will yield 3550 MJ or 1096 kWh

<u>COST-BENEFIT ANALYSIS:</u>

- Assuming electricity cost of $0.4 per kWh, yields to $438 saving per hour
- Total estimated savings = 3,840,384 per year. (2,880,288 based on 75% efficiency)

<u>The total GHG reduction is estimated at 252 kg/h or 6048 kg/d upon deployment of the technology to its greatest potential.</u>

<u>GHG ESTIMATES:</u>
As estimated above, the GHG reduction per day is estimated at 6 t/d.
The cumulative GHG reduction per annum is anticipated at 2,190 tonnes.
The cumulative GHG reduction till 2030 is anticipated at 19,710 tonnes.
The cumulative GHG reduction till 2050 is anticipated at 61,510 tonnes.

Environmental/Operational Benefits:

Dramatic reduction in GHG emission as it offsets the other emission sources to achieve either carbon neutral or net negative carbon emission.

Continuous power generation, Continuous steam generation, Continuous building heating, Provides redundancy or replaces the emergency power generator, deployment at remote locations such as well head facilities to lit up surrounding or tying up to the grid and eliminate methane direct emission.

- Remote well-head platform deployment
- Helps prevent venting of Casing Head Gases
- Remote gathering system deployment
- Remote camp areas where grid connections are not available
- Designed for Class 1, Division 2 hazardous locations
- Operates on partial Sour Gas, LPG, VOCs as feedstock
- Emergency Diesel Generator can be replaced with CHP and battery back-up
- Payback period estimated at 3-5 years

[1] Ref: https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references

1) The real benefit of deploying this arrangement is that it sums up to net-zero emission of GHG.
2) The equipment is proven and operates almost maintenance-free and with high reliability and high availability.
3) Offers an opportunity to install pilot scale Carbon Capturing Process.

Areas of application:

- *OilSands (minable, Thermal)*
- *Upgrader*
- *Petrochemicals*
- *Refinery*
- *Fertilizers*
- *Gas Processing*
- *LNG*

i. Project Summary

Proposed Project: Recovery of Methane gas (CH_4 +) from flare header and utilizing to generate power and heat, which otherwise routed to the flare tip for atmospheric disposal.

Technology:

1. Micro Turbines operates on CH_4 to produce power and heat. Depending on inlet flow rate of methane + wide range of models are available in market can suffice the requirement.
2. Recovering the flare gas and utilize as a fuel gas in the process heaters

Opportunity: The flare gas which is vented to the environment without extracting energy does not work out from plant economics and environmental perspectives. When extracted the energy by deploying Micro Turbines, generates power and heat, which the facility can benefit by drawing reduced power from grid and natural gas used for building heating or other heating or producing steam from low temperature water resources.

Benefits: Continuous power generation, Continuous steam generation, Continuous building heating, Provides redundancy or replaces the emergency power generator, deployment at remote locations such as well head facilities to lit up surrounding or tying up to grid and eliminate methane direct emission, may work with sour gas

Environmental Benefits: Reduction in emission of GHG, Improved plant economics

ii. Technology Opportunity

Describe the problem that the technology is solving.

Problem Statement:

- Methane is a powerful greenhouses gas with a 100-year global warming potential 25 times that of CO2. As per United States emission estimates, Oil and Gas sector is accountable for approximately 31% of contribution that of all other sources. The increase in methane concentration has accelerated the global warming and climatic disruptions.
- Repsol is deeply concerned and have decided to lead by example by making its facilities methane emission free and in turn GHG emission free by capturing carbon and sequestering.
- Therefore, Repsol have thrown open challenge to the innovators and called out for coming up with potential cost effective and efficient solutions to demonstrate strong stewardship to environment.

Solutions:

- The proposed technology solves the problem by capturing and converting more potent GHG (methane) to a lower effect GHG (CO_2) and at the same time liberating energy which counts toward offsetting the production of GHG. Overall provides win win situation solution both for the environment and for the facility economics.
- We identified that the purge gas and other vent gases from the facilities are disposed of into the flare header, are making their way through flare knock out drum and ended up to flare tip to be combusted to produce CO2 and other gases, which itself are a Green House Gases. Depending of the combustion efficiency some of the methane gas escapes into the atmosphere unburned.
- The flare gas can be recovered and used to produce energy in terms of electricity and heat. We found out that the micro turbine could be a good fit for such services. Micro turbines are available in wide range of capacities and would be able to operate on flare gas as a feedstock.
- Some of the micro turbines are capable of handling sour gas as a feedstock as well without any additional process.

Description of Technology[2]:

- Depending on the flare gas flow the micro turbine size selection can be performed.
- The micro turbine vendors shall be consulted to find out inlet feed arrangement, utilities requirements, power integration and exhaust management to perform engineering design
- Micro turbines comprise a compressor, combustor, turbine and electric generator on a single shaft or two. They can have a recuperator capturing waste heat to improve the compressor efficiency, an intercooler and reheat. They rotate at over 40,000 RPM and a common single shaft micro turbine rotate usually at 90,000 to 120,000 RPM.[1] They often have a single stage radial compressor and a single stage radial turbine. Recuperators are difficult to design and manufacture because they operate under high pressure and temperature differentials.
- Micro turbines can be designed for Class 1, Division 2 hazardous locations
- The environmentally-focused companies continue to rely on micro turbines because they meet strict emissions requirements, uphold high reliability in dangerous environments.
- The micro turbines, which operate on sour gas and wellhead gas
- The micro turbines, which range from providing 10kW and 65kW of power, run safely in hazardous locations, take up minimal space, and require very limited maintenance.
- Capable of powering DCS, SCADA (Supervisory Control and Data Acquisition), fire and gas, emergency shutdown, communication, lighting, and auxiliary systems
- The expected payback period is from two to five years

[2] Ref: https://en.wikipedia.org/wiki/Microturbine

- The integrated heat exchangers installed on micro turbine that capture waste heat energy naturally produced when the micro turbines run

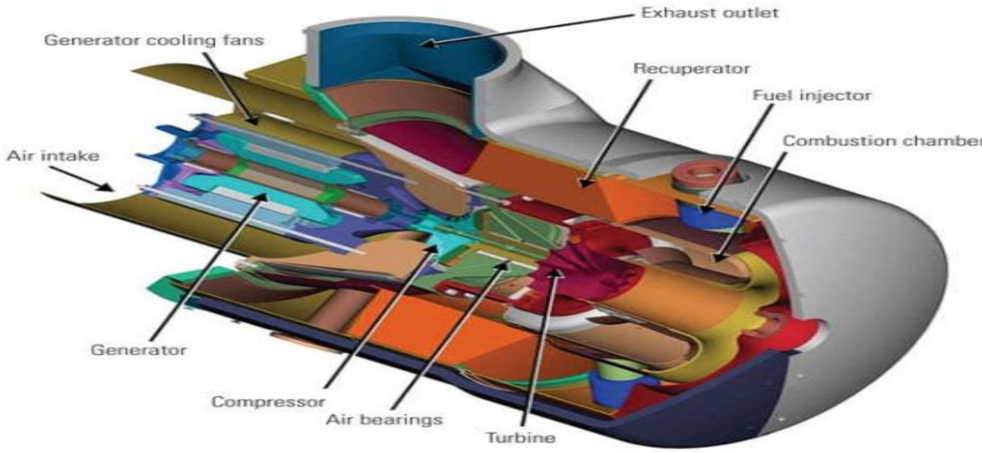


Figure 1: Recuperated MicroTurbine[3]

- The micro turbine system works flawlessly, safely, and efficiently
- Used to achieve ultra-low emissions and reliable electrical/thermal generation from natural gas

[3] Ref: https://www.powermag.com/microturbine-technology-matures/

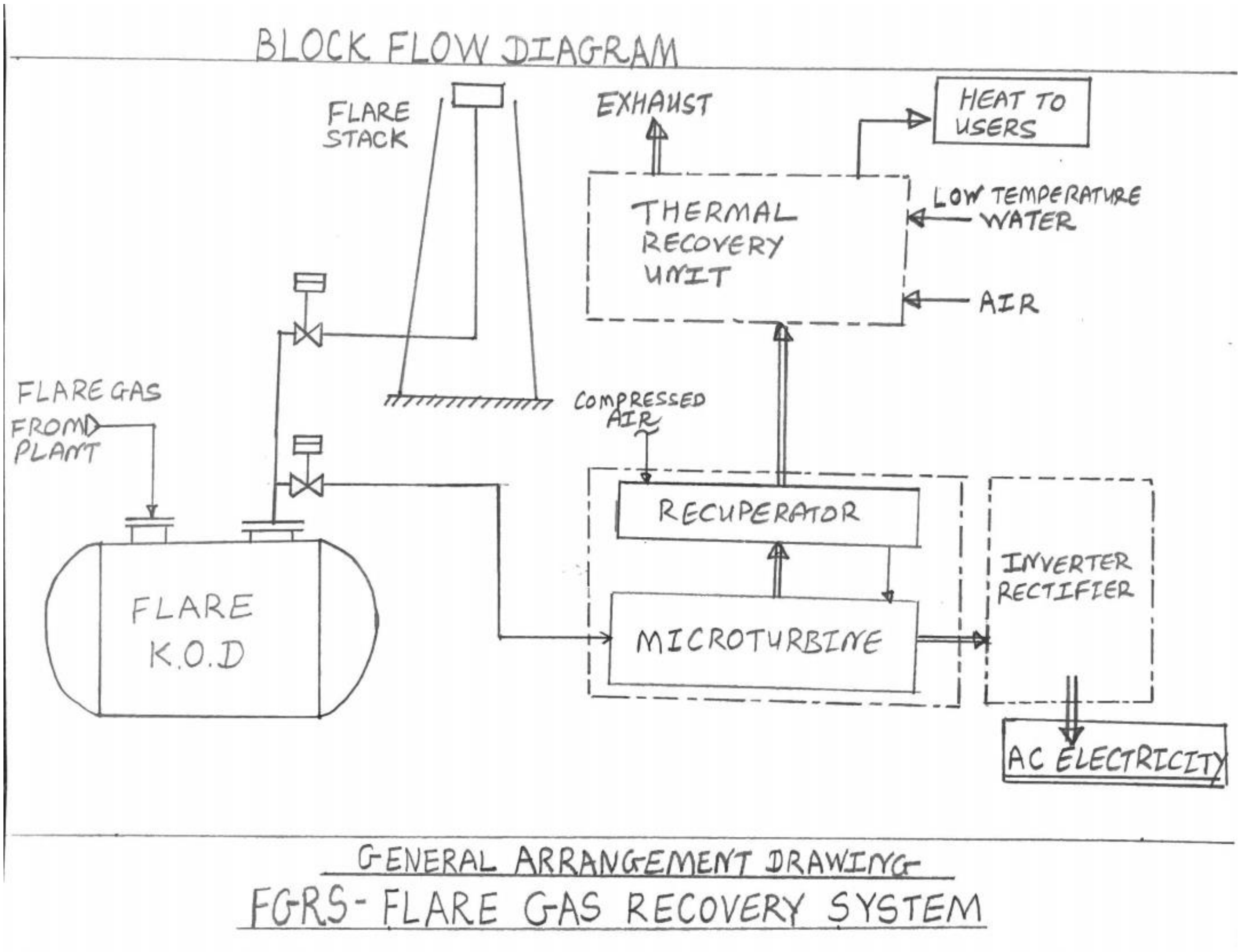


Figure 2: Flare Gas recovery with integrated Microturbine

Describe how the technology or application thereof is new, unique, and/or innovative.

Application of Technology:

The application of this technology is considered new. The reason being the prescribed advantages are real. It has been noticed that the technology has been deployed throughout the world in various sectors however deployment of the same in Oil and Gas sector is found rare.

The use of high-capacity turbines is common in Oil and Gas sector; however, use of micro turbine is not so common.

So far if we are correct, hardly any Oil and Gas operators in Alberta have taken initiatives to implement this technology.

The uniqueness of the technology is that it is almost available in any size, can be deployed at remote locations and is capable of processing sour gas.

The other uniqueness of this technology is when deployed counts toward ZERO GHG emission.

The technology or process presented is considered innovative because.

- If we are correct, this would be the first of the kind deployment if implemented in Alberta
- Development of this combination of process is product of our thought process and experience
- We also propose the deployment of this technology at well head or oil rig facility where acid gases are vented to the flare because recovery of gas is not feasible

- As per our knowledge this technology is not yet deployed at well head or oil rig facilities in Alberta
- It is considered innovative because we came up with a combination of the process where the GHG emission will count to a net zero.

Describe the positioning of the technology within the competitive landscape, including the gap(s) that it addresses and its advantages relative to incumbent solutions.

- Positioning of this technology is considered competitive and cost effective and energy efficient. The payback period for the initial investment is not so long, which makes it competitive
- The main advantages relative to incumbent solution or in other words, it fulfills the purpose of incumbent by reducing or capturing the GHG emission and allows operating the facility methane emission free.
- The real benefit of deploying this arrangement is that it counts toward net zero emission of GHG.
- The equipment is proven and operates almost maintenance free or longer period of maintenance and with high reliability and high availability. Above all these, it is also cost effective with short term payback period.
- Further advantages are described in above sections.

iii. Project Implementation

Provide a description of the overall objectives, work scope, deliverables, and the scale of prototype/demonstration for the proposed project.

SCALE OF PROTOTYPE[4]:

The technology readiness is identified at level 7, which is “Prototype ready for demonstration in an appropriate operational environment”.

iv. Environmental Benefits - GHG and Non-GHG Benefits

GHG EMISSION REDUCTION:

The baseline scenario is that the flare gas comprised of purge gas, seal vent gas and other minor sources is being flared and burned at the tip of the flare to convert high climatic potent gas methane to a lower potent gas of carbon dioxide and other GHGs.

MECHANISM FOR EMISSIONS REDUCTIONS:

Implementation of technology will liberate 1100 kW of energy which when utilized in terms of electricity and heating (building, steam) will result in reduction of equivalent fossil fuel consumption.

This reduction in fossil fuel consumption will lead to total negative GHG emission when compared to a base case scenario.

[4] Ref: https://www.ic.gc.ca/eic/site/080.nsf/eng/00002.html

CALCULATION:

Assumption: assumed that the flare header is 24 inch in size and 0.1m/s of purging velocity.

- Natural gas purging @0.1 m/s velocity through 24”(ID=23.25”) header will yield flowrate of 98.6 Am3/h ~130 Nm3/h
- Assuming net calorific value of 36 MJ/m^3 will yield 3550 MJ or 1096 kWh

COST BENEFIT ANALYSIS:

- Assuming electricity cost of $0.4 per kWh, yields to $438 saving per hour
- Total estimated savings = 3,840,384 per year. (2,880,288 based on 75% efficiency)

POTENTIAL IMPACT OF TECHNOLOGY:

- Firstly, implementation of this technology will yield net negative emission effect
- Secondly, Implementation of this technology is considered one step forward in the direction of Repsol’s goal of achieving emission free facilities
- Thirdly, as per cost benefit analysis, short period of payback, after that operations will have net positive cash flow. May benefit from government’s Carbon Offset Credit grants. It will also help in minimizing the Carbon emission Tax.

QUANTITATIVE ESTIMATES[5]:

The GHG reduction is estimated at 252 kg/h or 6048 kg/d when the technology is integrated to utilize maximum energy liberated.

NON GHG BENEFITS:

Following are the major non-GHG benefits:

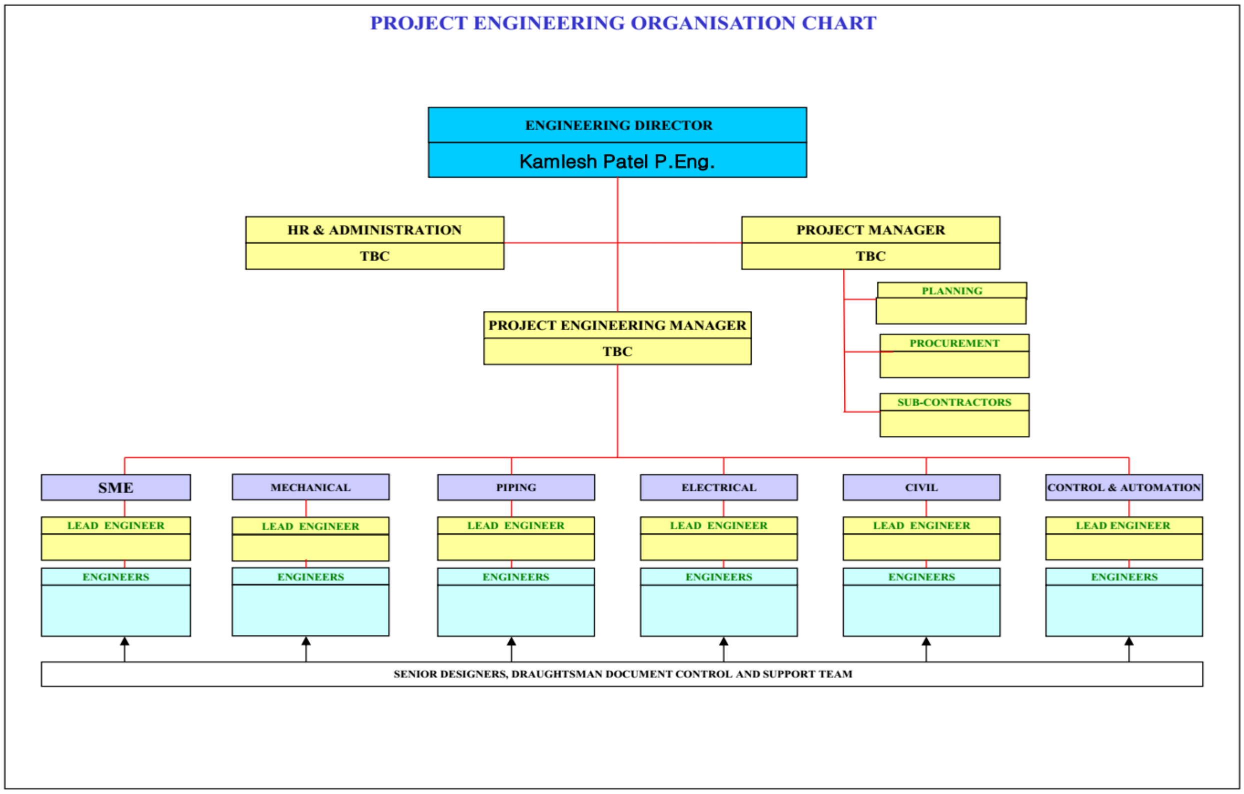
1. Enhanced combustion efficiency
2. Convenience in capturing carbon
3. Increased operational economics

Estimate the potential annual reductions (GHG and Non-GHG) that could be achieved by market adoption of the technology by 2030 and 2050, and indicate any assumptions made for market penetration rate.

As estimated above, the GHG reduction per day is estimated at 6 t/d.
The cumulative GHG reduction per annum is anticipated at 2,190 tonnes.
The cumulative GHG reduction till 2030 is anticipated at 19,710 tonnes.

ORGANIZATIONAL STRUCTURE:

[5] Ref: https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references


PROJECT ENGINEERING ORGANISATION CHART
ENGINEERING DIRECTOR
Kamlesh Patel P.Eng.
HR & ADMINISTRATION
TBC
PROJECT MANAGER
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PLANNING
PROCUREMENT
SUB-CONTRACTORS
PROJECT ENGINEERING MANAGER
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PIPING
ELECTRICAL
CIVIL
CONTROL & AUTOMATION
LEAD ENGINEER
ENGINEERS
SENIOR DESIGNERS, DRAUGHTSMAN DOCUMENT CONTROL AND SUPPORT TEAM

REFERENCE SPECIFICATIONS

1. CHP TECHNOLOGY FOR FGRS

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Combined Heat and Power Technology Fact Sheet Series

Microturbines

Microturbines are relatively small combustion turbines that can use gaseous or liquid fuels. While large gas turbines (described in a separate fact sheet[1]) have been used for CHP applications for several decades, microturbines emerged as a CHP option in the 1990s. Individual microturbines range in size from 30 to 330 kilowatts (kW) and can be integrated to provide modular packages with capacities exceeding 1,000 kW. **Table 1** provides a summary of microturbine attributes.

Microturbine CHP installation at a commercial facility.
Photo courtesy of Capstone Turbine Corporation

Applications

Microturbines are used in distributed generation applications due to their flexibility in connection methods, their ability to be stacked in parallel to serve larger loads, their ability to provide stable and reliable power, and their low emissions compared to other technologies. Microturbines are well suited to be used in CHP applications because the exhaust heat can either be recovered in a heat recovery boiler, or the hot exhaust gases can be used directly. There are over 360 sites in the United States that currently use microturbines for CHP. These microturbine sites represent over 8% of the total number of CHP sites in the United States, accounting for 92 MW of aggregate capacity.[2] Sites that use microturbines for CHP include hotels, nursing homes, health clubs, commercial buildings, food processing plants, and small manufacturing operations. In CHP applications, thermal energy from microturbine exhaust is recovered to produce either hot water or low pressure steam. The temperature of microturbine exhaust also allows for its effective use with absorption cooling equipment that is driven either by low pressure steam or by the exhaust heat directly. Microturbine systems that provide both cooling and heating can be used in a variety of commercial and institutional applications. Microturbines can burn a variety of fuels, making them useful for resource recovery applications, including landfill gas, digester gas, oil and gas field pumping, and coal mine methane use.

Table 1. Summary of Microturbine Attributes

Size range	Available from 30 to 330 kW with integrated modular packages exceeding 1,000 kW.
Thermal output	Microturbines have exhaust temperatures in the range of 500 to 600 °F, and this exhaust can be used to produce steam, hot water, or chilled water (with an absorption chiller).
Part-load operation	The electrical generation efficiency of microturbines declines significantly as load decreases. Therefore, microturbines generally provide best economic performance in base load applications where the system operates at, or near, full load. An exception is modular packages where one or more individual microturbines can be shut down while the remaining microturbines operate at or near full load.
Fuel	Microturbines can be operated with a wide range of gas and liquid fuels. For CHP, natural gas is the most common fuel.
Reliability	Microturbines are based on the design principles used in larger capacity combustion turbines and, like combustion turbines, microturbines have high reliability.
Other	Microturbines have low emissions and require no cooling. Individual units are compact and can be easily shipped and sited in confined spaces.

1 U.S. Department of Energy, Combined Heat and Power Technology Fact Sheet Series – Gas Turbines, 2016.

2 U.S. DOE *Combined Heat and Power Installation Database*, data compiled through December 31, 2015.

ADVANCED MANUFACTURING OFFICE

Technology Description

Microturbines operate on the same thermodynamic cycle (Brayton Cycle) as larger combustion turbines and share many of the same basic components. In the Brayton cycle, atmospheric air is compressed, heated by burning fuel (e.g., natural gas), and then used to drive an expansion turbine that in turn drives both the inlet compressor and a drive shaft connected to an electrical power generator. **Figure 1** shows a schematic of the basic microturbine components, which include the combined compressor/turbine unit, generator, recuperator, combustor, and CHP heat exchanger.

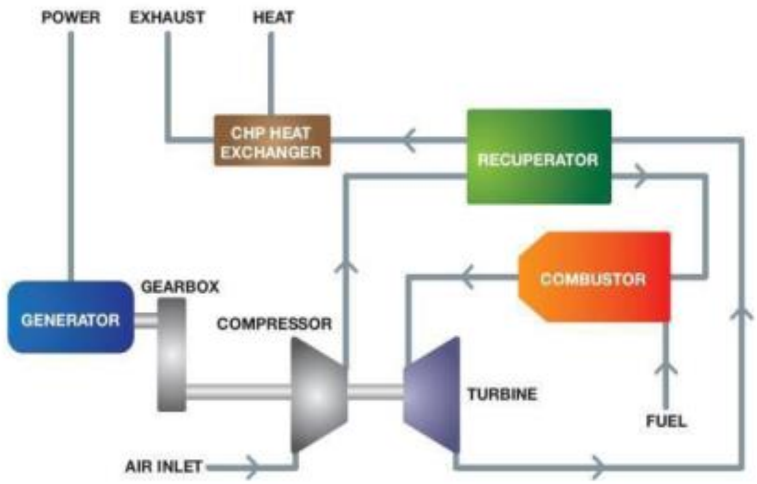

Figure 1. Microturbine configuration for CHP.
Graphic credit Flex Energy.

Figure 2 shows an illustration of a microturbine. The heart of the microturbine is the compressor-turbine package (or turbocompressor), which is commonly mounted on a single shaft along with the electric generator. The shaft, rotating at upwards of 60,000 rpm, is supported on either air bearings or conventional lubricated bearings. The single moving part of the one-shaft design has the potential for reducing maintenance needs and enhancing overall reliability.

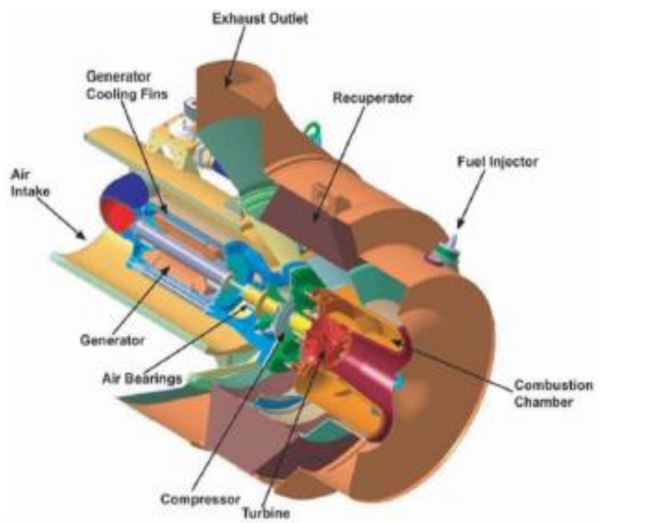

Figure 2. Microturbine illustration.
Graphic credit Capstone Turbine Corporation.

The microturbine produces electrical power either via a high-speed generator turning on the single turbo-compressorshaft or through a speed reduction gearbox driving a conventional 3,600 rpm generator. The high-speed generator single-shaft design employs a permanent magnet and an air-cooled generator producing variable voltage and high-frequency AC power. This high-frequency AC output (about 1,600 Hz for a 30 kW machine) is converted to constant 60 Hz power output in a power conditioning unit. The recuperator is a heat exchanger that uses the hot turbine exhaust gas (typically around 1,200°F) to preheat the compressed air (typically around 300°F) going into the combustor, thereby reducing the fuel needed to heat the compressed air to the required turbine inlet temperature. In CHP operation, microturbines offer an additional heat exchanger package, integrated with the basic system, that extracts much of the remaining energy in the turbine exhaust, which exits the recuperator at about 500-600°F. Other than the size difference, microturbines differ from larger combustion turbines in that they typically have lower compression ratios and operate at lower combustion temperatures. In order to increase efficiency, microturbines recover a portion of the exhaust heat in a heat exchanger called a recuperator. The recuperator increases the energy of the gases entering the expansion turbine thereby boosting efficiency. Microturbines operate at relatively high rotational speeds, often reaching 60,000 revolutions per minute.

Table 2. Microturbine Performance Characteristics

Description	System				
	1	2	3	4	5
Rated Power (kW)	65	200	250	333	1,000
Parasitic Load for Gas Compressor (kW)	4	10	8	10	50
Net Electric Power (kW)	61	190	242	323	950
Fuel Input (MMBtu/hr, HHV)[3]	0.84	2.29	3.16	3.85	11.43
Useful Thermal (MMBtu/hr) [4]	0.39	0.87	1.20	1.60	4.18
Power to Heat Ratio[5]	0.53	0.75	0.69	0.69	0.77
Electric Efficiency (%, HHV)	24.7%	28.4%	26.1%	28.7%	28.3%
Thermal Efficiency (%, HHV)	46.9%	38.0%	38.0%	41.6%	36.6%
Overall Efficiency (%, HHV)	71.6%	66.3%	64.0%	70.2%	64.9%

Note: *Performance characteristics are average values and are not intended to represent a specific product.*

Performance Characteristics

Table 2 summarizes technical performance characteristics for microturbine CHP systems ranging in size from 65 to 1,000 kW. The values in the table are based on systems connected to low pressure (< 5 psig) natural gas. Microturbines typically require an inlet fuel pressure near 75 psig, and most microturbines include an onboard gas compressor to provide the required gas pressure. The net power shown in **Table 2** represents the maximum power available after the parasitic compressor load has been subtracted. As indicated, the overall CHP efficiency for the five representative microturbines ranges from 64% (System #3) to slightly under 72% (System #1). The power to heat ratio ranges from 0.53 (System #1) to 0.77 (System #5).

Table 3. Microturbine Capital and O&M Costs[6]

Description	System				
	1	2	3	4	5
Net Electric Power (kW)	61	190	242	323	950
Complete Microturbine Package[7]	$2,120	$2,120	$1,830	$1,750	$1,710
Construction and Installation	$1,100	$1,030	$870	$800	$790
Installed Cost ($/kW)	$3,220	$3,150	$2,700	$2,560	$2,500
O&M, not including fuel (¢ /kWh)	1.3	1.6	1.2	0.8	1.2

Note: *Costs are average values and are not intended to represent a specific product.*

Capital and O&M Costs

Table 3 provides cost estimates for microturbine systems used in CHP applications that produce hot water at 140 °F. Thermal recovery in the form of cooling can be accomplished with the addition of an absorption chiller. The basic microturbine package consists of the microturbine and power electronics. All commercially available microturbines offer basic interconnection and paralleling functionality as part of the package cost. Most microturbine CHP systems offer an integrated heat exchanger with the basic package. As indicated, installed capital costs range from $3,220 to $2,500 per kW and decline with increasing capacity. The total plant

3 Fuel consumption and efficiency values are based on the higher heating value (HHV) of natural gas unless noted otherwise.

4 Useful thermal energy is based on producing hot water at a temperature of 140 °F.

5 Power to heat ratio is the electric power output divided by the useful thermal output. The ratio is unit-less.

6 Costs are based on vendor data, installation estimates, and information provided by project developers.

7 The complete package includes the microturbine engine, fuel gas compressor, and heat recovery hardware. The package does not include the cost of an absorption chiller for applications that produce chilled water.

cost consists of all equipment costs plus installation labor and materials (including site work), engineering, project management (including licensing, insurance, commissioning, and startup), and financial carrying costs during a typical three-month construction period. The costs shown are representative estimates and can vary significantly depending on the scope of the plant equipment, local emissions requirements, and other site specific requirements.

Non-fuel operation and maintenance (O&M) costs are also shown in **Table 3**. Maintenance costs vary with size, fuel type, and technology (air versus oil bearings). As indicated, maintenance costs for microturbines range from 0.8 to 1.6 ¢/kWh (includes fixed and variable maintenance based on 6,000 hrs/yr of operation).

Table 4. Microturbines Emission Characteristics

Description	System				
	1	2	3	4	5
Electric Capacity (kW)	61	190	242	323	950
Emissions (ppm at 15% oxygen)[9]					
NOx	9	9	5	5	9
CO	40	40	5	5	40
VOC	7	7	5	5	7
Emissions (lbs/MWh)[10]					
NOx[11]	0.46	0.40	0.24	0.22	0.40
CO[12]	1.24	1.08	0.15	0.13	1.08
VOC[13]	0.12	0.11	0.08	0.08	0.11
CO_2 Emissions (lbs/MWh)					
Electricity only	1,613	1,406	1,529	1,392	1,407
CHP w/ thermal credit[14]	667	739	804	668	764

Note: Emissions are average values and are not intended to represent a specific product.

Emissions

Microturbines are designed to meet state and federal emissions regulations, including more stringent state emissions requirements in California and some other states. **Table 4** shows maximum NOx, CO, and VOC emissions as reported by vendors. All systems have no emissions control hardware.[8] As indicated, maximum NOx, CO, and VOC emissions are 9, 40, and 7 ppm, respectively. These emission values are measured in the exhaust stack and corrected to 15% oxygen. Table 4 also shows NOx, CO, and VOC emissions in units of lbs/MWh. These values are based on the electric power production and do not include a credit for thermal recovery.

Table 4 shows CO_2 emissions for CHP systems based on the electric power output and on the complete CHP system. For the complete CHP system, CO_2 emissions are calculated with a thermal credit for natural gas fuel that would otherwise be used by an on-site boiler. With this credit, CO_2 emissions range from 667 to 804 lbs/MWh. For comparison, a typical natural gas combined cycle power plant will have emissions of 800-900 lbs/MWh, and a coal plant will have CO_2 emissions near 2,000 lbs/MWh. ■

8 The microturbines for Systems #3 and #4 use a lean premixed swirl-stabilized combustor to achieve low emissions with no after treatment.

9 NOx, CO, and VOC emissions are maximum exhaust emissions at full load ISO conditions.

10 NOx, CO, and VOC emissions expressed in units of lbs/MWh are based on electric output and do not include a thermal credit.

11 NOx conversion: NOx [lbs/MWh] = NOx [ppm @ 15% O2] / 271 / electrical efficiency [%, HHV] X 3.412.

12 CO conversion: CO [lbs/MWh] = CO [ppm @ 15% O2] / 446 / electrical efficiency [%, HHV] X 3.412.

13 VOC conversion: VOC [lbs/MWh] = VOC [ppm @ 15% O2] / 779 / electrical efficiency [%, HHV] X 3.412.

14 The CHP CO_2 emissions include a thermal credit for avoided fuel that would otherwise be used by an onsite boiler. The boiler is assumed to operate on natural gas with an efficiency of 80%.

U.S. DEPARTMENT OF
ENERGY
Energy Efficiency &
Renewable Energy

For more information, visit the CHP Deployment Program at energy.gov/CHP
or email us at CHP@ee.doe.gov

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