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Gas Heat Pump RTU Cold Climate Performance Assessment

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Project Overview

With financial support from the New York State Energy Research and Development Authority [1], Utilization Technology Development NFP (UTD) and National Fuel Gas Co., The Levy Partnership, Frontier Energy and GTI conducted a field study of a unique natural gas engine-driven heat pump rooftop design (Blue Mountain Energy's model PGHP). This technology provides high-efficiency space conditioning (with optional water heating) for commercial buildings and offers potential economic and environmental benefits compared to conventional HVAC packaged rooftop technologies (RTUs).

Figure 1. Blue Mountain Energy's Packaged Rooftop Gas Engine-Driven Heat Pump (Model PGHP)

The PGHP design was originally introduced in 2011 to provide high-efficiency gas-fired cooling in extremely hot conditions, such as the Southwestern United States. The PGHP has a cooling capacity of 11 tons and heating capacity of 140 MBH. The design was successfully demonstrated at multiple sites, and 34 units continue to operate reliably in six states accumulating over 500,000 hours. Its rated heating efficiency (COPg > 1.0) exceeds the most efficient natural gas-fired furnaces along with non-energy benefits such as reduced peak electric demand, lower operating costs, and potential savings in greenhouse gas (GHG) emissions.

This field study was the first cold climate installation of the PGHP monitored to assess its installed performance and to identify design changes needed to optimize cold climate operation. This study quantified PGHP heating and cooling efficiency and peak electric demand. An economic assessment estimated annual energy cost savings and paybacks relative to other rooftop HVAC options. Reliability of the PGHP in cold climate operation and full-fuel-cycle GHG emissions were also evaluated.

The field site selected was the Allentown Trading Company in Buffalo, New York, a small gas station and grocery store with extended hours of operation providing long runtimes for the demonstration unit (Figure 2). It is a standalone historic building (pre-1980) and with internal cooling loads generated by a small bread oven and refrigeration cases. The PGHP replaced a conventional RTU with gas-fired heating and electric cooling. The site is located in a historic district listed in National Register of Historic Places. Since this was a like-for-like replacement, no special permitting was required.

1 NYSERDA Agreement #122717

Hours of Operation

Monday-Thursday: 6am-12am

Friday-Saturday: 6am-2am

Sunday: 8am-8pm

Figure 2. Allentown Trading Company, Buffalo, NY was selected for the PGHP demonstration (www.bflotradingstores.com).

Figure 3. A custom transition curb was to install the PGHP with the existing rooftop curb and interior ductwork.

Results

The PGHP design demonstrated potential to meet NYSERDA's NextGen HVAC Technology Challenge (2017 PON 3519) for a natural gas-fired system using a standard vapor compression cycle for small commercial (<100K s.f.) buildings in New York State. The PGHP water heating option was not demonstrated in this study and must be verified to meet NYSERDA's target of 2.0 COPg for combined space conditioning and water heating. Current incentives for electric demand reduction may also support applications or site-specific needs for this technology. The PGHP has the potential to reduce full-fuel-cycle GHG emissions compared to other rooftop technologies; however, this is highly dependent on the regional power generation fuel mix.

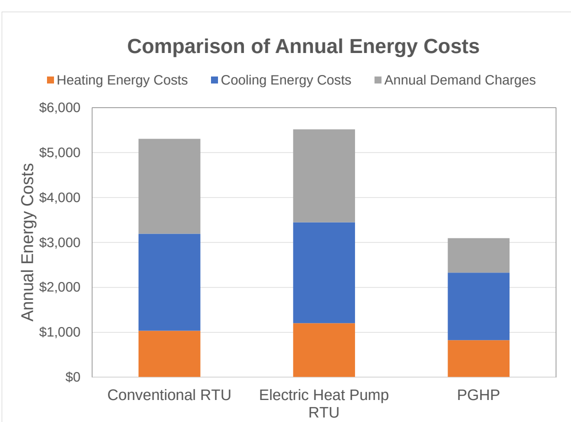
Cooling Performance: The PGHP demonstrated high cooling efficiencies ranging from 0.8 to 1.7 COPg. Seasonal average efficiencies were 1.19 COPg for Summer 2020, and 1.12 COPg for Summer 2021 with an increased ventilation load. Installed cooling performance aligned well with rated efficiencies of 1.12-1.24 COPg under full-load conditions at 95°F ambient. Part-load operation had minimal impact on the cooling efficiency reflecting effective control strategies to minimize cycling losses. Second-stage cooling operation increased cooling capacity, but with slightly lower efficiencies, resulting in lower overall efficiency during the second year. Sizing best practices can minimize second-stage cooling and optimize cooling efficiency. Power measured during cooling operation averaged 2.38 kW with 4.38 kW peak demand, a significant decrease (76%) from the summer peak demand associated with a conventional RTU using natural gas heating and electric cooling (18 kW). For this field site, an electric heat pump RTU would generate an even higher peak demand during heating, over >22 kW excluding the use of supplemental heating at low temperatures.

Heating Performance: Average power measured during heating operation was 3.22 kW with 4.68 kW peak demand. Average heating efficiency from September-December 2020 was 0.96 COPg and the seasonal average was 0.78 COPg, much lower than the rated efficiency of 1.4 COPg based on laboratory measurements at full-load and 47°F ambient.

While the measured field efficiency was typically lower than rated steady-state performance under controlled conditions, some heating performance issues were discovered at lower ambient temperatures; not unexpected for the first cold climate demonstration. As noted, a key objective of this study was to identify design changes needed to optimize PGHP heating performance and effectively implement this design in colder climates. It was found that during first-stage heating, air flow was reduced but that gas consumption remained as high as second-stage full-load operation, resulting in lower heating efficiency; this issue requires further investigation by the product design team. In addition, cycling operation adversely impacted heating efficiency. During longer heating cycles with steady-state operation (>20 minutes), the PGHP heating performance approached rated specifications (COPg >1). Another issue was identified during the coldest months, when the supplemental gas heater operated frequently despite adequate rated heating capacity. The project team suspected a malfunction of heat recovery coolant valve during colder ambient conditions, but the issue resolved itself in the spring with warmer temperatures and could not be replicated or confirmed.

Reliability: During the 18-month demonstration, four outages were reported and quickly resolved. These were primarily due to various component failure (e.g., PLC controller, wire harness). No reliability issues were related to the natural gas engine operation.

Economic and Environmental: A summary of the economic assessment is shown in Table 1. The PGHP estimated energy costs, based on rated efficiencies, were 42% to 44% lower than a conventional electric cooling/gas heating RTU or an electric heat pump RTU, respectively (Figure 4). Based on field site measured performance, with lower than expected seasonal heating efficiencies (0.78 COPg heating; 1.12 COPg cooling), PGHP energy costs were 36% lower than a conventional RTU, and 39% lower than an electric heat pump RTU. These energy cost savings are driven by the use of low cost natural gas for cooling and reduced demand charges. The PGHP significantly reduced peak electric demand compared to the other RTU technologies. This translates into lower electric demand charges and potential to qualify for demand response programs or initiatives.



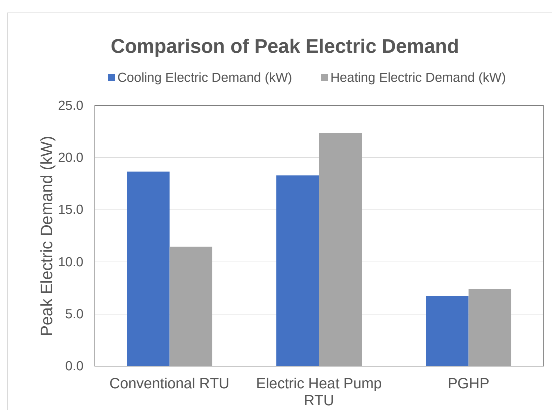


Figure 4 PGHP had lower energy costs and peak electric demand compared to Conventional RTUs and Electric Heat Pumps

As with many emerging technologies, PGHP first costs are much higher than more mature technologies due to small volume initial production runs. The design incorporates a long-life engine rated for 30,000 to 60,000 hours runtime. When initially introduced, PGHP equipment lifetime was reported as 30,000 hours deferring to Aisin's conservative estimates for the VRF system using the same engine. Field demonstrations of the PGHP were initiated in 2009 in multiple warm climate locations and several units are still operating after 10 years with runtimes approaching 70,000 hours. Based on their experience with actual installations, the PGHP manufacturer has extended the maintenance interval to 10,000 hours and is confident the PGHP can achieve equipment lifetime 60,000 hours or 20 years with proper maintenance. In addition, the PGHP is required to meet same longevity standards as conventional RTUs or electric heat pumps for ETL certification and a similar equipment lifetime is a key design goal for this unit.

For this field site, based on measured data, the weather-normalized runtime hours were 2,971 hours per year. For the economic assessment, we assumed 3000 hours/year runtime and a 20 year equipment life for all three options. The PGHP engine requires additional maintenance such as oil changes or belt replacement, similar to an automobile. In some cases, a service contract is used to cover the cost of any extra maintenance removing any uncertainty for the owner.. Other maintenance such as filter replacement are similar for all three RTU technologies. Based on manufacturer maintenance costs provided for 60,000 hours total runtime, GTI estimated annualized incremental maintenance costs $358/year.

Table 1. Summary of Economic Assessment of PGHP Compared to Conventional RTUs

	PGHP	Conventional RTU	Electric Heat Pump
Cooling Energy Costs	$1,503	$2,159	$2,243
Heating Energy Costs	$826	$1,036	$1,205
Incremental demand (kW)		11.9	11.5
Annual Demand Charges	$765	$2,111	$2,070
Annualized Incremental Maintenance	$358		
Annual O&M Savings		**$1,854 (35%)**	**$2,066 (37%)**
First Costs	$69,375	$31,326	$27,534
First Costs: $/ton	$5,200	$2,311	$2,087
PGHP Incremental First Costs		**$38,049 (121%)**	**$41,841 (152%)**
Simple Payback (years)		**20.5**	**20.3 3**

Assumptions: 20-year equipment life for all equipment
PGHP annualized incremental maintenance costs $358 per manufacturer estimates for 60,000 hrs total runtime and 3000 annual runtime hours.
Natural Gas $0.770/therm; Electric $0.1500/kWh; Electric Demand $9.43/kW

The project team understands that Blue Mountain Energy plans to make value engineering and cold climate performance improvements for this design to incorporate recent technology improvements in controls, compressor technologies, and engines. The rooftop configuration minimizes installation costs with a like-for-like retrofit of existing RTUs. Table 2 presents a scenario where first costs are reduced by $2000/ton through cost engineering and/or demand response incentives. For this case, assuming optimized heating and cooling performance, the PGHP can achieve paybacks of 8.6 years and 9.4 years, relative to a conventional RTU and electric heat pump, respectively.

Table 2. Economic Scenario for Reduced PGHP First Cost

		Conventional RTU	Electric Heat Pump RTU
PGHP Annual O&M Savings		$1,854	$2,066
PGHP Incremental First Costs		$38,049	$41,841
GHP Incentive or Cost Reduction ($/ton)	**$2,000**		
Simple Payback (yrs)		**8.7**	**9.6**

GHG Emission Assessment: The PGHP 16.6 hp engine is certified per EPA Emission Standards for Natural Gas-fueled Nonhandheld Engine Class II to not exceed maximum emission limits; however, engine emissions are typically much lower than the certification limit. For this study, authors were unable to obtain specific emissions data for the PGHP engine, so emission factors were estimated based on measured emissions for a similar engine type, normalized by GHP capacity (58.65 CO2e lb/MMBtu). For this assessment, PGHP emissions include both engine emissions and upstream full-fuel-cycle GHG emissions.

Full-fuel-cycle GHG emissions for these three HVAC rooftop technologies were compared using regional emission factors for Upstate New York. As shown in Figure 5, the eGRID NYUP region has 75% baseload power generated by low carbon sources, while the non-baseline power generation mix is about 90% natural gas. Non-baseload power generation represents the flexible peaking power generation capacity used during periods of seasonal peak demand such as high cooling loads, or potentially high heating loads due to growing number of policies supporting building electrification. Non-baseload power generation also can modulate to offset variability in renewable sources such as wind or solar.

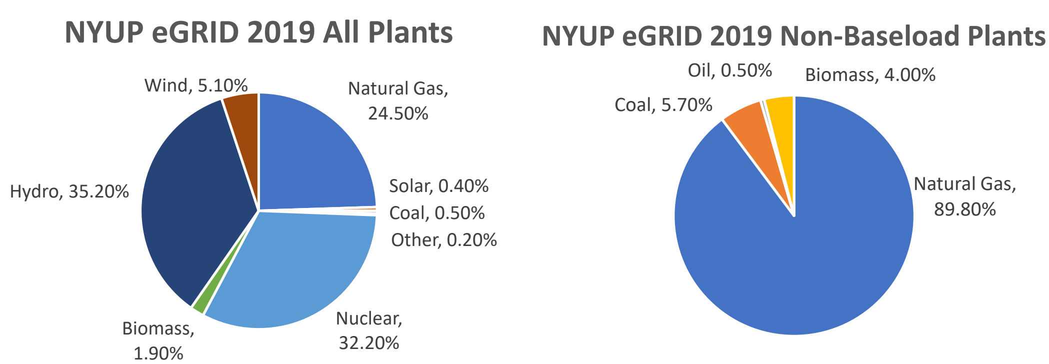
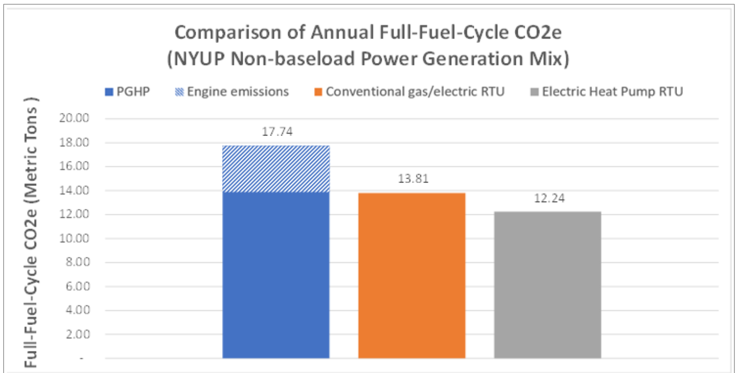


Figure 5. Upstate New York eGRID 2019 fuel mix for baseload and non-baseload power generation.

For energy efficiency calculations, non-baseload power generation mix is typically used to determine the impact on full-fuel-cycle emissions since the non-baseload power generation is the most likely to be reduced with the use of alternative technologies. Based on the non-baseload emission factors, Figure 6 shows PGHP upstream emissions are similar to the conventional RTU and the electric heat pump; however, the onsite engine emissions account for an additional 26% GHG emissions. This highlights the need for an engine design that can optimize performance while also minimizing GHG emissions.

Note, this comparison assumes the actual installed performance of the electric heat pump matches the performance ratings at all operating conditions. Electric heat pumps often require supplemental electric resistance or gas-fired heating to deliver adequate heating capacity during the coldest conditions which would increase its GHG emissions.



Energy Form	CO_2	SO_2	NOx	CH_4	N_2O	CO_2e
Electricity (metric tons/MWh)	0.490421508	0.000310709	0.000391448	0.0014719	3.1751E-06	0.532560019
Natural Gas (Building Used, metric tons/MMBtu)	0.059075562	1.31541E-05	7.80175E-05	0.000238588	1.3608E-06	0.066069919

Reference: eGRID 2019; assume 100% conversion efficiency for renewable energy

Figure 6. GHG Emissions for three rooftop HVAC technologies based regional baseload power generation fuel mix.

Summary and Recommendations

This field study quantified the heating and cooling efficiency, the economic and environmental benefits, and the reliability of the packaged natural gas engine-driven heat pump rooftop unit (PGHP) for high-efficiency space conditioning for commercial buildings in cold climates. Key findings were:

- This field study validated high cooling efficiencies along with significant reductions (76%) in peak electric demand, which may qualify for electric demand response programs or non-wire initiatives.
- Although the PGHP has demonstrated high heating efficiencies in laboratory testing (rated efficiency of 1.4 COPg at full-load and 47°F ambient), the average measured heating efficiency in this field test was lower than expected (0.96 COPg from September-December 2020). As the first cold climate demonstration of the PGHP, originally designed for extremely hot conditions (e.g., U.S. Southwest), this study identified multiple design changes needed to optimize this technology for cold climate applications.
- In total, the PGHP has potential to reduce energy costs up to 44% compared to conventional and electric heat pump RTUs due to high efficiency operation, the use of low cost natural gas, and reduced demand charges.
- Based on regional (NYUP) non-baseload power generation mix, the PGHP upstream emissions were similar to conventional and the electric heat pump RTUs, but onsite engine emissions account for an additional 26% GHG emissions. This highlights the need for an engine design that can optimize performance while minimizing GHG emissions.
- Reliability of the PGHP unit was good, with only four outages during the monitored period which were quickly resolved. These were primarily due to various component failure (e.g., PLC controller, wire harness), and there were no reliability issues related to the natural gas engine operation.

As next steps to leverage these results, the project team understands that Blue Mountain Energy plans to incorporate value engineering and cold climate performance improvements identified in this study for its next iteration of its PGHP design in order to further reduce first costs, optimize efficiency, and enhance reliability. These efforts will include to incorporate more recent technology improvements in controls, compressor technologies, heat recovery, and natural gas engines. Based on this study, first costs should be reduced by approximately $2,000/ton to achieve paybacks within 10 years relative to conventional RTUs.

This field study did not evaluate the heat-recovery water heating option in the PGHP unit, and solely analyzed space conditioning thermal loads. Future field studies should include assessment of the revised PGHP design with economizer and water heating options to meet NYSERDA target of average annual COP >2.0 for combined space conditioning and water heating. Cold climate demonstrations of the revised PGHP in higher heating load applications, such as an office building or school, will highlight the energy and economic benefits of its high efficiency heating. Onsite measurements of PGHP engine GHG emissions are needed to accurately compare the environmental impact of RTU technologies. Future designs should investigate options to reduce GHG emissions for engine-based designs by incorporating exhaust treatment, renewable natural gas, hydrogen blends and/or carbon capture.

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List of Acronyms

Acronym	Description
Btu	British Thermal Unit
COPg	Coefficient of Performance defined by heating or cooling output divided by gas consumption input; comparable to a furnace Annual Fuel Utilization Efficiency (AFUE) rating
eGRID	Emissions & Generation Resource Integrated Database
GHG	Greenhouse Gas emissions (CO2e)
GTI	Gas Technology Institute
HVAC	Heating Ventilation and Air Conditioning
kW	Kilowatts
kWh	Kilowatt-hours
NYSERDA	New York State Energy Research and Development Authority
NYUP	Upstate New York eGRID region
PGHP	Model name for Blue Mountain Energy's Packaged Gas engine-driven Heat Pump
RTU	Packaged rooftop unit for heating and/or cooling commercial buildings
UTD	Utilization Technology Development NFP