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Challenges and opportunities of Gas Engine Heat Pumps – Two Case Studies

Ahmad Abuheiba[a,*], Isaac Mahderekal[b], Ayyoub Momen[a], Edward Vineyard[a]

[a]Oak Ridge National Laboratory, One Bethel Valley Road, Oak Ridge, TN 37831, USA
[b]IntelliChoice Energy, 6280 S Valley View Blvd Suite 240, Las Vegas, NV 89118, USA

Abstract

Gas engine driven heat pumps (GHP) currently hold a small share of the U.S. HVAC market. This share is considerably smaller than what the full potential of GHP technology can realize. One of the main benefits of GHP technology is their better primary energy utilization mainly due to the ability to recover the engine heat. However, development and market penetration of GHP technology have been challenged by various market and technical barriers. The main barriers are high initial cost, low awareness of the technology, and poor perception. On the other hand, several opportunities arise that the GHP technology can take advantage of to increase its market share. The most direct opportunity is the abundance of relatively cheap natural gas. This translates directly into monetary savings and higher return on investment (ROI). GHPs offer the advantage of reducing the peak demand by 80% compared to electric counterpart. From the point of view of utilities, this eliminates the need for lower-efficiency peaking power plants and over-expansion only to cover maximum peak times. From the point of view of renewable customers, GHPs eliminate the need to buy power from the grid at a high price. This is especially important in hot climates with high cooling loads. When built and operated as distributed generation, GHPs can improve the reliability of power delivery to consumers. The paper discusses the challenges and opportunities as seen during the development and commercialization of two different GHP products; a 35 kW (10-ton) packaged unit and 17.5 kW (5-ton) split unit.

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1. Introduction

Gas Engine Driven Heat Pumps (GHPs) can offer several advantages over their electric counterparts. Replacing the electric motor with an internal combustion engine reduces the electric power demand by about 80%. This reduction not only saves on utility bills, but can also in some cases eliminate the need for costly electrical infrastructure upgrades; panels, breakers, etc. besides electric power demand reduction, GHPs enable end use at higher primary energy efficiency when engine heat is recovered for auxiliary utilization such as water heating. Many studies have demonstrated these benefits. Sohn et al. [1] showed that using a 35 kW (10-ton) GHP achieved electric and gas combined utility savings. The study reported on a field demonstration of six units at six different U.S. Department of Defense (DoD) installations. Total energy cost savings ranged from $680 to $2,134

* Corresponding author. Tel.: +1-702-372-5689
E-mail address: abuheibaag@ornl.gov
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over a 12-month period. The study also showed that an estimated 990 m^3 of fresh water was saved at power plants due to the reduced consumption of electricity. In 2012, Mahderekal et al. [2] modeled an enhanced configuration of GHP. A desiccant wheel was integrated into the GHP to enhance dehumidification during cooling. Heat recovered from the engine was used to regenerate the desiccant. The study showed that heating COP can be improved by 25% by recovering heat from the engine into the suction line to the compressor. The study reported that using the desiccant wheel could lower sensible heat ratio to 40%. In 2012, the Building Technologies Office of the U.S. Department of Energy released a report [3] that estimated the energy saving potential of GHP technology in the residential sector to be 44 Terawatt-hour annually (0.16 EJ/year.) Despite their demonstrated benefits, GHPs currently have a very low share of the U.S. HVAC market. Economic and commercial challenges contribute to this low market penetration. There are also some technical barriers that GHPs have to overcome to improve their competitiveness. On the other hand, there are several opportunities that GHPs can exploit to increase their market share. This paper presents these challenges and opportunities as experienced during the development and commercialization of two different case studies GHP products; a 35 kW (10-ton) packaged roof top unit and a 17.5 kW (5-ton) split residential unit. At the end of the paper, the authors present some recommendations that could increase the competitiveness of GHPs.

2. Case Studies

2.1. Commercial Heat Pump

This is a packaged rooftop air-source unit. The design and the development of this unit were presented in [4]. The major specifications of the unit are summarized in Table 1.

Table 1. Main specifications of the commercial GHP.

Engine	Water-cooled, 4-stroke, 3 cylinder, 9.5 kW rated output
Engine speed	1600 to 2400 rpm
Fuel type	Natural gas
Compressor	2 x 60.5 cc/rev, open-drive, belt-driven scroll type
Compressor Speed	2720 to 4080 rpm
Refrigerant type	R410A
Design Cooling rating	35 kW (120,000 Btu/hr or 10 ton)
Design Heating rating	43 kW (147,000 Btu/hr or 12.25 ton)
Design cooling gas COP	1.2 at 35ºC (95ºF) outdoor temperature
Design heating gas COP	1.6 at 8.3ºC (47ºF) outdoor temperature
Electrical power requirement	3 kW
Maintenance interval	10,000 hours

The results of an economic and reliability field test of 6 of this unit were presented in [1] and its laboratory performance was presented in [5]. Since 2010, a total of 70 units have been installed and operated. These 70 units have aggregated over 400,000 hours of running time. One of the installations was fueled by propane and the rest were fueled by natural gas. Currently there are 32 field installations. More than half of them have accumulated more than 10,000 hours of runtime. One unit has accumulated 29,000 hours. In addition to the 32 field installations, one unit served an office building in Las Vegas, NV for 6 years during which it accumulated 27,000 hours. Overall, the units operated satisfactorily. There were no major reliability issues even with the units with the highest runtimes.

Currently, this unit is planned to undergo a final design revision by a large US HVAC equipment manufacturer. Cost analysis of each component and subsystem will be performed to meet market feasibility. High sales volume is very important in lowering first costs; production volumes of 2000-3000 units per year are required for mature market pricing. A network of air conditioning system distributors will be developed to achieve effective market coverage in each targeted area, and to build the sales, installation and service infrastructure required to support the growth of the business. Specific incentives will be created to attract highly qualified and reputable distributors who will become the primary sales channel. Key distributors in each

area will be consulted on local market development activities and will be invited to participate in local demonstration projects. The project team will work with natural gas and propane distributors to encourage local promotional activities, highlighting the advantages of this commercial GHP and providing referrals of interested customers. It is also anticipated that large dealers will participate in the selection, construction, operation of certain demonstration sites, as well as ongoing performance monitoring required to confirm benefits.

2.2. Residential Heat Pump

The development of this unit was completed in 2015. It is a split air-source heat pump. The laboratory performance of this unit was presented in [6]. The major specifications of this unit are summarized in Table 2.

Table 2. Main Specifications of the residential GHP.

Engine	Water-cooled, 4-stroke, 1 cylinder, 6 kW rated output
Engine speed	1200 to 3400 rpm
Fuel type	Natural gas
Compressor	1 x 60.5 cc/rev, open-drive, belt-driven scroll type
Compressor Speed	1350 to 3825 rpm
Refrigerant type	R410A
Design Cooling rating	16.5 kW (56,400 Btu/hr or 4.7 ton)
Design Heating rating	20.2 kW (69,000 Btu/hr or 5.75 ton)
Design cooling gas COP	0.99 at 35ºC (95ºF) rating condition
Design heating gas COP	1.33 at 8.3ºC (47ºF) rating condition
Electrical power requirement	1.750 kW maximum
Target Maintenance interval	10,000 hours

Twenty-two units of this residential GHP have been installed and operational for since May 2014. Twenty-one units have accumulated over 23,000 run hours. The collected field data provided valuable information on the performance of the unit. Some minor engine reliability issues are yet to be tackled. Currently, there is a cooperative research and development agreement between the US DOE, represented by ORNL, and a private investor to finalize the development and to commercialize this residential GHP.

3. Challenges

The main challenges can be classified into three major categories; technical, economical, and commercial. Each will be detailed in the following paragraphs.

3.1. Technical challenges

Finding suitable engine. Operating and maintenance requirements of GHPs impose unique requirements on the engine to be used in the GHP. The engine needs to be able to run reliably for extended periods of time, 10,000 hours or more, without periodic maintenance, e.g. oil change and spark plugs replacement. The engine also needs to be water-cooled to enable coolant-to-refrigerant or coolant-to-water heat recovery. If water heating feature is included, the combustion temperature needs to be relatively higher to maximize water heating effect. Due to these requirements, ideally the engine has to be designed specifically for GHP. Due to the limited demand on GHPs, suitable engines are limited and are expensive. This is especially true for smaller size engine as in the case of the residential GHP.

In the commercial GHP, the engine was imported from Japan. The same engine is used in a Japanese 28 kW (8-ton) multi-zone GHP [7]. It is well matured in terms of performance, reliability, and price. The engine used currently in the residential GHP is U.S. made. It is produced in small quantities and requires design changes to increase its reliability and better its performance.

Both engine assemblies, for the residential and the commercial GHP, cost approximately the same, about $4500. This represents 22% of the cost of the commercial GHP and 32% of the cost of the residential GHP,

making it the single most expensive component of either system. Less expensive engine options should be identified to help bring the cost of GHP down to competitive level.

Low frequency noise. This issue presented itself in the residential GHP. The noise originated from sound-generating vibrations derived from the combustion in the cylinder and the corresponding pressure waves in the intake and exhaust systems. They are all keyed to the engine's rotational speed; as the engine speed rises or falls, the pitch goes up or down. Measures to dampen the sound waves this issue were costly and only partially effective especially for the longer wavelength portion of the wave spectrum. A better design of the intake and the exhaust manifolds was needed to reduce noise. Also better engine mounts, or mounting configuration, could reduce vibration.

3.2. Economic challenges

Cost premium. The high initial cost is a major challenge. Currently, the cost of production per unit is $14,000 and $24,000 for the residential and the commercial GHPs respectively. Although value engineering could reduce the cost, the reduction would be minimal. The two main drivers for the high cost are the low volume of production and the cost of engine assembly. The low volume of production drives the cost up in two ways; cost of custom components and cost of manufacturing.

The cost of custom components, such as the outdoor coil, increases exponentially as the supplied quantity decreases. For example, the unit cost of the outdoor coil of the residential unit increases from $500 for quantities of 1000 units to $1000 for quantities between 1 and 10 units. On the other hand, at low volumes of production, the manufacturing and assembly processes rely mainly on manual labor in most of the manufacturing and assembly steps. This considerably increases the cost of production.

Despite the difference in size, both engine assemblies in both models of GHPs cost about $4500. This equates to approximately 32% and 22% of the cost of the residential and the commercial GHPs respectively. The engine in the residential GHP, although smaller in size, is produced in relatively small quantities and thus has a high cost of unit production. In both cases, the engine assembly consists of the engine, controls, and coolant-to-exhaust heat exchanger. This heat exchanger in both cases cost about $1000. This amounts to nearly 22% of the cost of the engine assembly.

The current *cost of manufacturing* for both the residential and the commercial GHPs are 2 to 3 times the *retail price* of their conventional (electrical) counterparts. This places the GHPs at an extremely disadvantageous competitive position. Although cost could be reduced, we expect that it will always be higher than conventional counterparts, at least in the foreseeable future. Therefore, more emphasis needs to be put on valuation of the benefits of GHP through its life cycle.

3.3. Commercial challenges

Low awareness. Although GHPs have been commercially available in the U.S. market for over a decade, the technology is still largely obscure. Most of the publications about GHPs have been scientific in nature with a lot less focus on the general public. A broader campaign is needed to target end-users, developers, and builders to educate them about the availability of the technology and about its benefits.

Market acceptance. Aside from few early adopters, customers are hesitant to specify GHPs for their applications. Because of the limited, or lack of, knowledge of the technology, concerns arise. Some concerns are founded such as cost premium and added maintenance requirements, e.g. oil change and lack of GHP service contractors. Some other concerns are merely the result of the customers' perception of GHPs. Due to the low awareness and low market penetration of the GHPs, customers associate them more with the automotive industry rather than with HVAC. This creates a perception that GHPs will require the same annual maintenance expense that cars need. This in turn deters customers from adopting GHPs. The low acceptance level is sometimes the result of a past failed GHP experience. In the early 2000s a GHP unit called Triathlon was rolled out by York. It suffered from reliability issues and the product line was discontinued.

Lack of infrastructure. The authors see this as the most major economic barrier to wide adoption of GHP technology. From experience, end users put as much emphasis on the life cycle of equipment as they place on upfront cost. Currently, in the US, there are no service representatives nor sales channels in each state. To establish GHP sales and service channels in each state is impractical for most manufacturers at the current low sales volume.

4. Opportunities

We can classify the drivers for GHP installation into two: the benefits that can be quantified financially and the ancillary benefits that impact marketability. The quantifiable benefits are "spark spread," system efficiency, and government incentives and regulations. The ancillary benefits include such things as environmental and operational advantages.

The difference between the cost of electricity and natural gas is called the "spark spread" and the profitability of employing a GHP is improved with a higher "spark spread." Spark spread is a common metric used to estimate the cost effectiveness of a power plant by showing the difference between the electricity price and the price of the natural gas needed to produce that electricity. A GHP should be installed where the cost of electricity is relatively high and cost of natural gas is relatively low. High electricity costs provide a justification for the additional costs required to install and operate a distributed power source such as GHPs rather than use power from the grid. In addition to a high cost of electricity, the business case for GHPs is improved if the cost of its fuel is low. This business case assumes that GHPs operate using natural gas. Unlike electrical costs, which have seen a slow but steady increase over the last decade, natural-gas prices have dropped to their lowest levels in nearly a decade, and have declined every year for the last 5 years. Although gas prices are expected to moderate upwards in coming years, prices will remain relatively low, improving the business case for GHPs.

The spark spread accounts only for the GHP shaft power generation. GHPs also provide heat as a usable by-product. As a result, if the particular application can also use the heat that is generated, the energy savings potential of the technology is further improved. To benefit from the higher system efficiency of the GHP and realize this larger spark spread, steady heat usage is required. Such usage would include both continuous heating requirements over the course of a day and throughout the year. The market that uses the largest fraction of hot water relative to space-conditioning demand throughout the year is lodging (e.g., hotels, dormitories, etc.). These types of facilities operate 24 hours-a-day, which leads to higher continuous hot water usage. Similar to hotels and dormitories with their high energy usage, multifamily residential buildings are alternative candidates for GHPs based on their large hot water and space-conditioning demands.

Government incentives are designed to support penetration into the market by new technologies that have societal benefits (e.g., environmental benefits) when the costs are not yet economic for the consumer. There are different types of incentives designed to encourage deployment of both distributed generation systems generally in the United States (e.g., corporate tax credits, federal grant programs, federal loan programs, etc.).

Market and policy observers generally agree that some form of future carbon tax (tax on CO_2 emissions) can be expected in the United States. This tax will target emissions from fossil fuel combustion, most typically exemplified in transportation and fossil-fuel-fired electricity generating plants. One outcome of imposing such a tax likely would be a noticeable increase in electricity prices as utilities pass the effects of the tax on to their customers. Again, this will improve the business case for GHPs.

In addition, companies with shareholders, customers, or competitors interested in sustainability would benefit from environmentally friendly power production. These companies may also be interested in renewable power. The use of GHPs to provide baseload (handling cooling and heating demand) can help further establish renewable sources such as solar and wind.

In summary, while the business case for GHPs may not be made now for all locations and applications, based on the current utility prices, available government incentives, and fuel cell costs, the business case will continue to improve. With the increased growth and advancements expected from GHP research and development, the manufacturing cost of GHPs is expected to continue to decline while the reliability and efficiency the systems are expected to increase. Within the next few years, the business case for these systems is expected to continue to strengthen.

5. Recommendations

Though GHPs can provide numerous benefits to a consumer, there are a number of factors that restrict its

deployment. The most significant barrier to deployment is high capital costs. However, a number of other market and regulatory barriers persist, limiting further deployment. These barriers include incomplete valuation of the full benefits that GHP can provide, and regulatory and utility business model barriers (uncertainty risk). Valuation issues can be addressed through further research and model development, as well as more transparent pricing of energy-system services and control technologies to end users. The current regulatory landscape is moving towards a treatment of GHP (distributed generation) as either providing solely regulated services (in which case the cost can be rate based) or having to recover all of its costs through the market. A hybrid treatment of GHP that can better capture market and non-market services, such as unbundling, can provide more efficient GHP development. Government support, such as the use of investment tax credits, can help mitigate the riskiness of this technology, improve project economics, and lower deployment barriers. Utilities and end users may also avoid or reduce risk by contracting energy services to third party service providers, which then assume any associated risk. Tying GHP to renewables is another means to promote the product. Moreover, many of the non-technical issues that limit GHP deployment are likely to raise similar barriers to the competing solutions. Thus, to the extent that addressing these issues can make the proposed technology more attractive, it will often improve the economics of these competing technologies. It will require continued engagement with regulators, policy makers, market operators, utilities, and manufacturers to mitigate identified barriers.
As a new technology in the early stages of adoption, GHPs are currently more expensive than alternative technologies. As the technology gains a foothold in its target markets and demand increases, their costs will decline in response to improved manufacturing efficiencies, similar to trends seen with other technologies. However, at this early stage, collaboration among GHPs manufacturers is needed to increase the market share of the technology. Such collaboration helps reduce the capital each manufacturer would need to invest to establish their own distribution channels and service networks.

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