Economic Implementation of the Organic Rankine Cycle in Industry

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ABSTRACT

An organic rankine cycle operates under the same principle as a steam rankine cycle, but with a lower operating temperature and pressure. These operating conditions are a result of substituting, into the closed loop system, a working fluid other than water. This allows a lower grade heat to act as a fuel for operation. The organic rankine cycle can be used in conjunction with a steam rankine cycle to recapture waste heat and improve overall system efficiency. A study was conducted in order to find feasible waste heat recovery applications and the industries which would benefit most from those applications.

This study shows calculations and quantitative results for theoretical organic rankine cycle operation. These calculations include energy generation of the system at variable waste heat temperatures. Additionally, economic cost calculations are supplied in order to demonstrate the simple payback period for various system sizes. Two potential applications are reviewed, demonstrating the need for year round operation. Furthermore, current technologies are evaluated to demonstrate the viability of organic rankine cycles in industries with reliable low-grade waste heat. Several examples of plug and play models are listed along with a variety of other models. Some of these plug and play models help emphasize the fact that implementation is not very complex and could easily be adopted.

Using numerical analysis, backed by several case studies, it is determined that an organic rankine cycle can be a useful and economical means of waste heat recovery.

Introduction

Power systems using steam have been around since the advent of the steam engine, powering pumps to lower the water tables in coal mines. The cost of the working fluid was minimal and the performance was limited – many of the early steam engines had efficiencies on the order of 10%. Improvements happened quickly with the invention of the condenser and advances in the engineering of pressure vessels. High input and low output temperatures improved efficiency but created their own problems. Modern steam power systems have high temperatures more than 1000°F requiring combustion in most cases. Also, in order to lower the temperature to near ambient (~130°F), the pressure in the condenser needs to be lowered to a few tenths of an atmosphere. Therefore in addition to just having a condenser, operational protocols require its pressure to be lowered significantly which normally results in long startup times and increased costs.

More recently, especially in geothermal power applications, cycles and hardware similar to that used in steam power systems have been combined with a different working fluid to create a power system better suited for low temperature applications. The rarity of geothermal resources suitable for power has led to slow development of these technologies for everyday applications. However, a significant amount of research has been done on various working fluids for various temperature applications creating a valuable resource.

Without much surprise, it has become obvious that fluids which work well as a refrigerant can also be used for power systems. Most refrigerants will change phase at normal pressures well below the boiling point of water (~212°F) and have high latent heats of vaporization. Since most of these fluids contain compounds including carbon, hydrogen and oxygen, they are generally referred to as organic power systems or, more correctly, organic Rankine cycles (ORC).

Taken to the next step, it was also likely that companies with expertise in chillers and refrigeration systems will have the skill sets to build high quality, high performance power systems based on these working fluids. Perhaps due to the political and programmatic difficulty in making distributed power, these companies have only recently begun to market a range of products which are both readily available, economic, and mostly "plug and play".

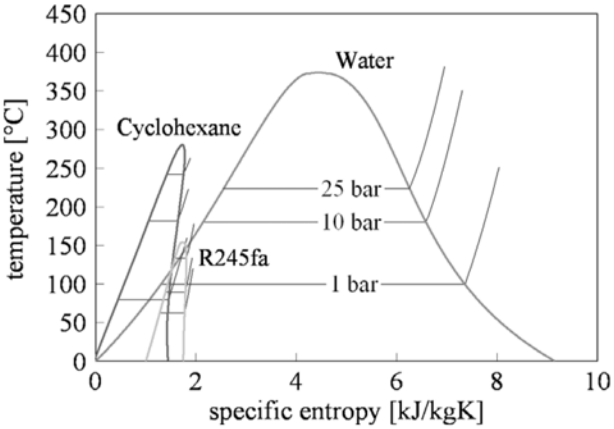
This paper reviews both the technology and current product offerings with an eye to two major applications – using the ORC as a bottoming cycle in combined heat and power (CHP) installations and as a single source waste heat utilizer. Where available, the current economics are discussed and case studies are referenced.

Details of the Technology

The organic Rankine cycle is a modification of the tradition steam Rankine cycle. This is a four stage thermodynamic cycle in which, first, a working fluid is pumped from a lower pressure to a higher pressure. Then the high pressure fluid enters a boiler where it is heated at a constant pressure until it becomes a dry saturated vapor. Next, this vapor expands through a turbine where mechanical work is converted into electrical energy. The wet vapor, then, enters a condenser where it is condensed back into a saturated liquid and the cycle starts again. In the case that we are interested in, the steam Rankine cycle is modified by swapping out its working fluid; water for a refrigerant.

There is no difference in thermodynamic structure between an organic Rankine cycle and those Rankine cycles used in power plants or other steam power systems. As a classic "heat engine" the second law of thermodynamics controls the efficiency seeking the highest temperature inputs and the lowest temperature exhausts. For most applications, the cycle includes a regeneration section to improve cycle efficiency. To appreciate the engineering challenges, two main differences with ORC's versus steam cycles are the thermodynamic properties of the working fluid and the typically smaller size of installations. Figure 1 shows the saturation lines for water and a common organic fluid – demonstrating both the different temperatures at which the fluid boils and positive slopes for saturated liquids and vapors for the organic fluid.

Figure 2. T-S Diagram for Water and Cyclohexane (from Schuster et al, 2010)



Over the years, many technologies have been developed to utilize geothermal energy. Due to its lower operating pressure and temperature, the organic Rankine cycle can effectively use this heat source. Hot water from a geothermal well is usually at temperatures between 225°F and 360°F which is hot enough to vaporize the working fluid and drive the power system (NREL, 2009). Since the system is completely closed the water from the well can be injected back into the ground where it will be heated and recirculated. In searching for viable organic Rankine cycle systems, it was found that most manufacturers are involved with geothermal applications, with some manufacturers currently only having case studies in geothermal units. There are numerous examples worldwide of geothermal applications which utilize the organic Rankine cycle, some even making use of heat sources as low as 165°F.

Modern Applications

Characterization of Waste Heat Opportunity

Clearly, in any review of applications, the waste heat source must be analyzed and characterized before a suitable ORC design can even be attempted. It is common to refer to the quality of the waste heat as its temperature without reference to flows or total energy. This is because the higher the temperature of the waste heat source, the more readily energy can be transferred from it. Unrecuperated flue gasses can have temperatures in excess of 600°F. Drying applications can have enormous energy flows but be only a few degrees above ambient. However, even with the small efficiencies achievable in these low temperature cases, in applications where the waste heat is being discarded the heat input to the Rankine cycle is essentially free.

Use as a Bottoming Cycle

Organic Rankine cycle systems can be an aid in heat recovery for gas turbines, offering advantages over the traditional steam bottoming cycles. A fairly recent application that is being explored as an appropriate implementation of an organic Rankine cycle, is using it as a bottoming cycle at cogeneration plants. By doing this, the system efficiency can be increased by as much as 15%. TransPacific Energy Inc. conducted a case study on a U.S. cogeneration plant that explored the option of replacing their steam condenser. By eliminating their facility's cooling tower, they were able to reroute that waste heat into an organic Rankine cycle, generating 294 kW of electricity. This resulted in a cost savings of $309,052; with electricity costs at $0.12 the payback period was 4.2 years.

Use for Recovery of Low Grade Waste Heat

It is believed that the organic Rankine cycle is most useful when applied to the recovery and use of waste heat. Two major applications are in Combined Heat and Power plants using biomass as fuel, and process waste heat applications. System sizing varies greatly, ranging from 10 kW units to as large as several megawatt units. Regardless of system size, the real importance of the organic Rankine cycle is that the system can convert low grade waste heat to power. Working examples or industrial waste heat recovery systems have been in place at several cement kilns and compressor stations since 1999 (Energy Services, Oct 2009). Whereas using the steam cycle to recover energy off low grade heat streams would be very expensive, using the organic Rankine cycle would make the process economically feasible and worthwhile. In fact, organic Rankine cycle engines are capable of effectively operating at temperatures as low as 158°F (Duffy, 2005). There is limited concern with the organic Rankine cycle competing with heat pumps, as heat pumps are limited in their maximum operating temperatures, roughly 200°F (Energy Services, Oct 2009).

Working Fluids Selection

Given that the ORC relies on a refrigerant as its working fluid, there is quite a selection to choose from and several important factors to take into consideration when choosing. Two main considerations must be taken into account: 1) its effect on cycle efficiency/cost and 2) its impact on the environment. The range of temperatures seen by an ORC system governs the type of working fluid that can be used. The chemical composition of refrigerants begin to break down at high temperatures and thus they must be chosen so that it remains stable at the system's highest temperature but have a freezing point well below the lowest temperature in the cycle. The fluid must have a high heat of vaporization and density to efficiently extract as much energy from the waste stream, as thermodynamically allowable. In addition, operating temperatures must be kept sufficiently low to keep equipment and personnel cost to a minimum. As for the environmental aspect, it should have a low ozone depleting potential as well as a low greenhouse warming potential. Non-corrosive, non-flammable, non-toxic and affordable are other important characteristics to look for when choosing a suitable working fluid (Quoilin, May 2007).

Economic Considerations

As with most capital purchases, getting usable cost data for these types of devices and installations can be very difficult. Several case studies exist (including recently Bourji, et. al, 2010) but in almost all of these cases the data is presented in aggregate format with little in the way of direct costs.

In general, primary mover costs are doubled to estimate total implementation costs. Paybacks or ROI estimates improve when the cost of the purchased electricity which it is replacing is increased. Best case scenarios are for a four-year payback (ROI = 25%).

Figure 3. Case Study Graph from Bourji, et. al.

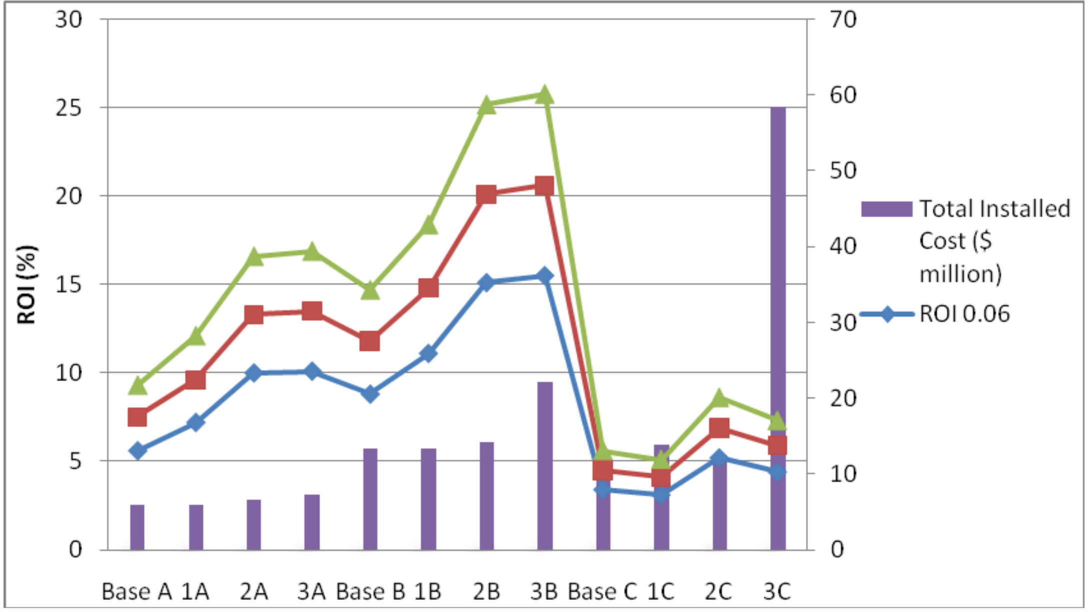


Table 2. Case Study from Brouji et. al.

	Scenario A				Scenario B				Scenario C			
	Base	1	2	3	Base	1	2	3	Base	1	2	3
Total Equipment Cost, $ million	$3.0	$3.0	$3.3	$3.7	$6.7	$6.7	$7.1	$11.4	$6.5	$7.0	$6.3	$29.3
Total Installed Cost, $ Million	$6.0	$6.0	$6.6	$7.4	$13.5	$13.5	$14.2	$22.7	$13.1	$13.9	$12.6	$58.6
Total Power Recovery, kW	707	899	1,364	1,549	2,484	3,102	4,455	7,308	916	892	1,364	5,367
ROI at $0.06/kWh	5.6%	7.2%	10.0%	10.1%	8.8%	11.1%	15.1%	15.5%	3.4%	3.1%	5.2%	4.4%
ROI at $0.08/kWh	7.5%	9.6%	13.3%	13.5%	11.8%	14.8%	20.1%	20.6%	4.5%	4.1%	6.9%	5.9%
ROI at $0.08/kWh	9.3%	12.1%	16.6%	16.9%	14.7%	18.4%	25.2%	25.8%	5.6%	5.1%	8.6%	7.3%

Table 2. Flow Rates and Temperatures from Brouji et. al.

Scenario	Flow Rate, MMscfd	Temperature, °F
A	66.2	1,000
B	1,135	350
C	1,728	225

In the search to develop an accurate ROI chart, it has been discovered that typical installed costs range from $1,800 to $3,000 per kilowatt. However; the cost can be as low as $1,300 per kilowatt for HVAC-derived units. The HVAC-derived units may be among the latest in development, but that is a promising sign of reduced system installed costs (Energy Services, Oct 2009). An HVAC-derived low-cost 200kW system has been developed by PureCycle. This system consists of parts from standard 350 ton air-conditioning equipment and was first introduced in the PureCycle 200 in 2004 (Brasz, et. al., 2005).

Figure 1: Installed ORC Power Generator

A completed ORC installation requires more than just the unit itself. The ORC unit interface items include, but are not limited to, inlet and outlet flanges, power terminals in the switch gear panel and parallel breaker, signal terminals in the control panel, and a concrete supporting plate. Most of these systems are modular and skid-mounted, about 20 to 40 feet in length depending on system rating. A typical ORC package will come with the following items: drawings, wiring schemes, turbo-generator, organic working fluid, computer interface, installation supervision, technician instruction courses, and manuals. The customer will also need to provide the following: local grid connection devices, transformers, grid protections, adequate ventilation for the ORC, packaging, transport, necessary unloading and positioning equipment for the ORC, and permitting, to name a few.

Maintenance and operating costs are said to be reduced, as compared to a similar sized fossil-fuel generator, mostly due to the limited moving components in the system and the lower operating pressures. In fact, these costs tend to be only a fraction of comparable fossil-fuel generators. This is a result of the organic Rankine cycle systems operating at lower speeds, being closed loop, and having few moving parts. The skid mounted, packaged units make for easier installation and operation. Maintenance activities are rather similar to standard industrial equipment maintenance: replace filters, maintain oil, lubricate parts, and recharge working fluid. The additional benefit to the organic Rankine cycle is that the lower operating pressure generally eliminates the need for an operator to monitor the unit. Most units come with computerized remotely monitored control units (Energy Services, Aug 2009).

Available Products

Much of the work on ORCs involves modeling behavior and optimization. Unfortunately, the end-user must select from a limited array of products and fluids. This is a developing field with many innovations in the pipeline – however many companies are trying to deliver commercially ready products. In the following tables, various manufactures will be listed as well common fluids for various applications.

Simple Cycle Systems

Table 1. Organic Rankine Cycle System Manufactures

Manufacturer	Product Line	Size Range	Minimum Temperature	Estimated Nominal Cost Per kW
Turboden	Heat Recovery Units	400kW-5MW	500˚F	NA
Tri-O-Gen	Tri-O-Gen ORC	60kW-165kW	662˚F	NA
Energetix	Kingston	1kW	NA	NA
Infinity	Infinity Turbine ORC Power	10kW-280kW	175˚F	$2,260/kW
Ormat	Ormat Energy Converter	250kW-20MW	195˚F	$1,800-2,000/kW
United Technologies	Pure Cycle	280kW	165˚F	$2,857/kW
Electratherm	Green Machine	50kW	400˚F - Gas 190˚F - Water	$2,530/kW
Calnetix	Clean Cycle	100kW-150kW	250˚F	NA
Cryostar	Lo-C	1MW-15MW	212˚F	NA
Barber Nichols	Waste Heat Recovery Systems	500kW-2MW	240˚F	NA

Table 2. Working Fluids for Various Applications

Source	Refrigerant
Geothermal	RE134, RE245, R600, R245fa, R245ca, R601, Ammonia, Propylene, R227ea
Waste Heat Recovery	Benzene, Toulene, n-pentane, R123
Solar	R152a, R600, R290
Biomass	AlkylBenzenes

ORC Combinations

Some applications are already considering the use of ORC technologies with other devices in plug-and-play configurations. Namely, GE has a line of gas fueled reciprocating engines, made by GE's Jenbacher line, for power generation. These units are starting to be paired with containerized ORC's in order to capture exhaust gas for additional power generation. Heat Recovery Solutions, formerly part of Calnetix was bought by GE to produce the ORC's for the GE Jenbacher gas engines (Streiter, et. al., 2010). Currently the new division has created a 125kW heat recovery generator to be used on various types of engines and biomass boilers (GE Power).

Case Studies

For demonstration purposes two potential sites have been analyzed. The two sites chosen are a Biopolymer Plant in Delaware and the Rutgers Cogeneration Facility in New Jersey. These represent two of the most common applications of ORCs. The biopolymer plant has enormous drying operations with lots of very low quality waste heat but continuous operation. Rutgers' CHP facility has a waste heat source with a much higher driving temperature, but is available for bottoming cycle operations for only a few months out of the year.

The Biopolymer Plant

A very common industrial process is the wet formation of powders. Following any chemistry and other forming actions, a large, low temperature drying operation must take place. With upper temperatures very limited due to the nature of the biopolymers, large amounts of modestly heated air is used and then typically discarded. In the case in question this amounted to about 9.7 MMBtu/hr of air typically 140°F above the ambient.

If it is assumed that the ORC heat exchangers can capture 90% of this waste heat and utilize a cycle with 10% efficiency, the electrical output would be about 250 kW.

Using vendor information, both the pure cycle and infinity turbines would be good choices although the driving temperatures are still a bit low. At $1,500/kW for the device and another $1,500/kW for installation, capital costs would be $750k. At the max, the system would run 8,000 hours per year which would save $300k (assuming $0.15/kWh) per year for a two and a half year payback.

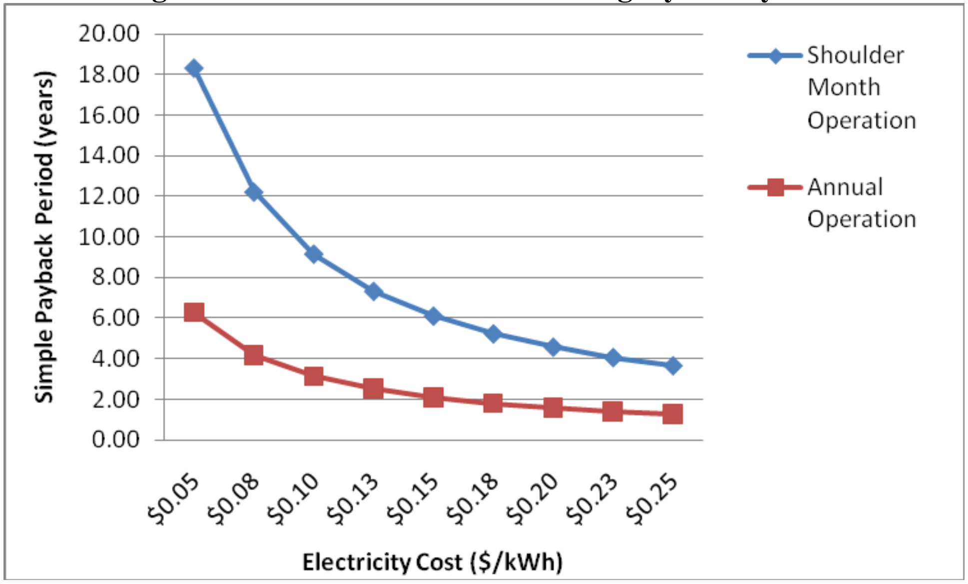
Rutgers Cogeneration Facility

This is a classical university type implementation with a high pressure hot water system used for space heating in the winter and in support of an absorption refrigeration cycle in the summer. For about four months out of the year little or no utilization of waste heat occurs and an opportunity exists to install a bottoming cycle using ORC technology.

In this case the recoverable energy is about 30 MMBtu/hr and the working temperature of the waste heat would be about 360 °F with a 200 °F drop in temperature in the main heat exchanger. Achievable efficiencies would be about twice that for the drying case discussed above reaching, perhaps, 16%.

Output from an appropriately sized ORC would be about 1.25 MW with a total installed cost of $3.45 million. Assuming this system would run, at most, 3,000 hours per year which would save $562,500 (assuming $0.15/kWh) per year for a six year payback.

Figure 4. CHP Plant ORC Bottoming Cycle Payback



As seen in the graph above, by varying the cost of electricity and the operating hours per year, the payback of a 1.25 MW ORC system for use as a bottoming cycle on the Rutgers Cogeneration Facility varies largely. Ideally, if this system were run constantly throughout the year the average payback period would decrease by more than one half. In its current set-up, the heat generated at Rutgers CHP plant is already depended upon in the heating and cooling months. This reduces the availability of the waste heat and, in turn, significantly, spikes the length of the payback period.

Conclusions

The organic Rankine cycle system is a useful technology for waste heat recovery. There are multiple systems commercially available worldwide. At this time it appears that ORC systems are best suited for low grade waste heat recovery. There is no debate on the usefulness and benefits of organic Rankine cycles; however there is still delay on wide-spread implementation in the US. These systems have taken off, rather quickly, in Europe due to high electricity rates resulting in short payback periods. Currently, due to the relatively low cost of electricity in the US, there tends to be a requirement for year round operation of the ORC in order for it to be economically feasible.

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