Thermal Efficiency from Organic Flash Cycle Commercial Analysis

2013

University of California, Berkeley

Organic Flash Cycles for Improved Power Production
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Technology

Background

As worldwide energy consumption continues to increase, the need for greater efficiency in energy production and usage becomes more critical. Maximizing the efficient conversion of heat to power in industries such as biomass, geothermal, solar thermal and industrial processes is one avenue that can be pursued to better address this growing demand for energy.

Large power plants that operate under high temperatures typically use a Rankine Cycle to convert heat to electricity. A Rankine Cycle is a closed cycle where water absorbs heat from an external heat source and is transformed to vapor. The water vapor is then expanded in a turbine to produce electricity. The Organic Rankine Cycle (“ORC”) is a Rankine Cycle that uses an organic fluid in place of water to convert some of this low temperature waste heat into electricity (see Figure 1.). Organic fluids are, in fact, “dry” fluids meaning that there is no risk, after expansion in a turbine, of formation of liquid droplets that could damage turbine blades and lower the system efficiency.

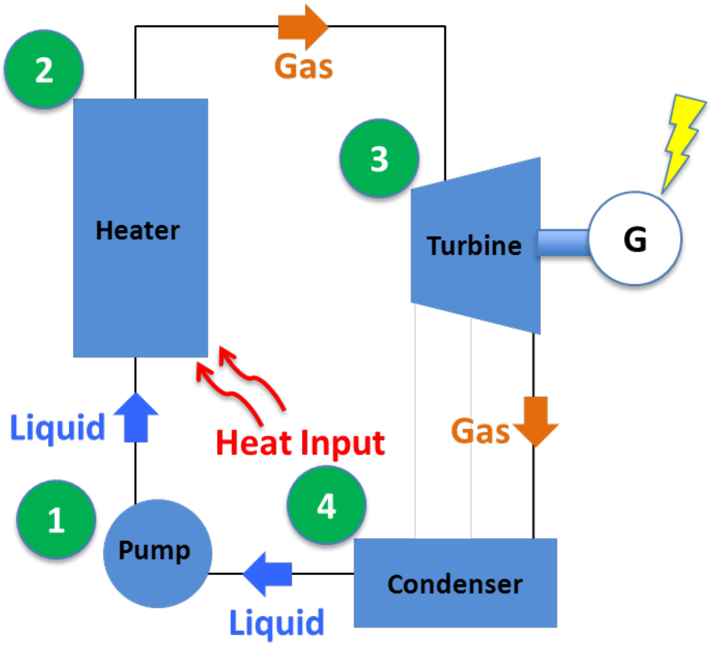

Figure 1. System Schematics for Organic Rankine Cycle

Innovations of the Organic Flash Cycle (OFC)

Scientists at Berkeley Lab and the University of California, Berkeley have designed a new variant of the ORC that results in better efficiency utilization of thermal resources. This new variant has been named the Organic Flash Cycle ("OFC").[1] The OFC increases exergetic efficiency with isentropic or "dry" aromatic hydrocarbons as working fluids that almost perfecty match the temperature of the thermal resource, reducing a major contributor of system energy conversion inefficiencies. Heat addition takes place completely in the liquid phase of the cycle with the working fluid vaporized during flash evaporation.

The OFC invention has several configurations, each suited to different conditions and cycle requirements. Figure 2 shows one of currently four variants of the OFC called the "Modified OFC". In this variant, turbine expansion is done in 2 stages. After the fluid is separated into liquid and vapor in the flash evaporator, the vapor goes through the first turbine. After expansion in this turbine, the vapor exhaust is mixed with the liquid from the flash evaporator in a mixer. In the mixer, the superheated vapor and saturated liquid produce a saturated vapor that can be used again in a second turbine. The liquid is condensed once it exits the second turbine and the cycle is completed. The additional components for the OFC are readily available in the marketplace and when used with aromatic hydrocarbons, can yield an incremental **9%-13%** efficiency over the basic ORC.

Another variation on the basic OFC replaces the throttling valve with a more efficient two-phase expander to reduce system irreversibility. The OFC outperforms the basic ORC with approximately 20% to 50% greater thermal energy utilization. It has approximately 90% heat addition efficiency compared to about 70% for basic ORC, about 75% for a zeotropic Rankine cycle with a binary ammonia-water mixture, and about 80% for a CO2 transcritical cycle.

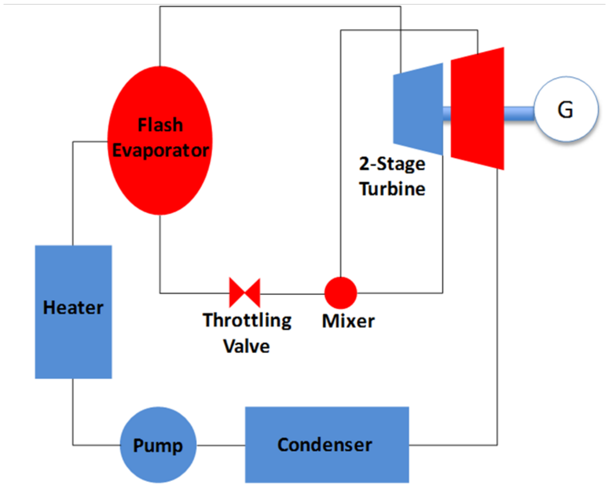

Figure 2. System Schematics for the Modified OFC

Applications

Within each of the primary applications (geothermal, biomass, industrial heat recovery, and solar thermal), there are specific installation opportunities. In addition to these four primary applications, additional opportunities can be envisioned in other areas, such as transportation. The following table includes a nearly comprehensive list of potential installation types.

Table 1 - Potential Applications for Organic Rankine Cycle

Geothermal	**Heat Recovery**	**Transportation**
• High grade geothermal[2] • Conventional hydrothermal[3] • Geothermal and hydrocarbon co-production[4] • Geopressured systems[5] **Biomass** • Pulp and paper[6] • Biomass boilers[7] • Pellet manufacturing[8] • Fiberboard manufacturing (MDF/OSB) [9] **Solar Thermal** • One-axis concentrated solar thermal[10] • Solar desalination units[11]	• Food and beverage[12] • Metallurgy[13] • Cement production[14] • Ceramics[15] • Oil refining[16] • Gas turbine/combined cycle plants[17] • Landfill biogas[18] • Glass industry[19] • Steel industry[20] • Non-ferrous furnaces[21] • Refineries[22] • Vegetable oil/biodiesel[23] • Biogas-fuelled internal combustion engines (agriculture/farming)[24] • Fuels cells (polymer electrolyte membrane, solid oxide)[25] • Gas-cooled nuclear power plant[26] • Chemical plants[27] • Compressor station[28]	• Transportation vehicles[29] • Ship engines **Energy** • Cogeneration plants[30] • Small combined cycles (paired with a reciprocating engine)[31] **Remote Power** • Onshore (telecommunications/oil & gas)[32] • Offshore (unmanned platforms)[33] • Complete integrated power solutions (Trans-Alaska pipeline)[34] • Bottoming cycle of micro gas turbines[35]

Market

The existing market for the ORC serves as an excellent proxy in analyzing the potential OFC market given the close similarities. The two technologies overlap in terms of function (heat to power conversion), working fluid (aromatic hydrocarbons and siloxanes), heat source temperature (50-350°C), and power output (<7MW).

The latest research estimates that installations of ORC systems can generate over 1.3 GW_{el} in total power output.[36] This output can be broken down into four primary applications: geothermal, biomass, industrial heat recovery, and solar thermal.

The figure below illustrates the percentage of the total power output produced by ORC systems for each application type and the estimated number of ORC systems per power and temperature range, respectively.[37]

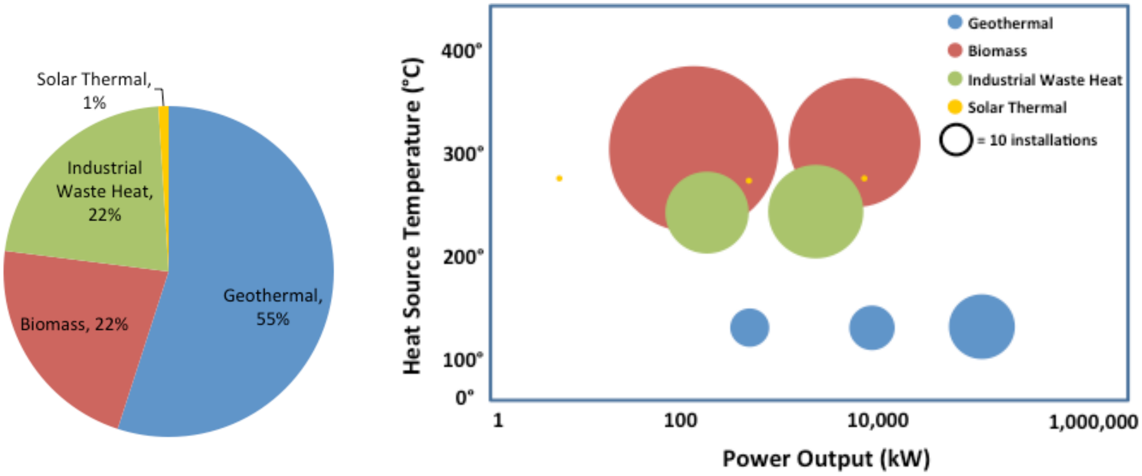

Figure 3. Market Breakdown by Application Type and by Temperature / Power Output

Geothermal

The global geothermal industry is expected to grow from 11 GW currently installed, to over 31 GW installed by 2020, representing annual power plant investments of $20 billion.[38] A sizeable portion of this industry will be open to low-grade heat recovery technology, whether as a way to develop underutilized lower temperature geothermal resources, or as a way to increase the overall efficiency of higher temperature geothermal resources. ORC units can produce electricity from geothermal heat sources, which can range from 90 to 300+°C.[39]

Biomass

Biomass is a primary generation source across the world, comprising over 60 GW of power capacity[40], with nearly 20 GW of capacity in the United States and in Europe. For biomass applications, cogeneration plants with ORC can produce heat and electrical power in the range of 200kW to 2.5 MW.[41] Biomass can be sourced from agricultural or industrial waste streams (e.g. wood), and is used primarily for onsite power generation.

Solar Thermal

In solar thermal applications, ORC units can convert heat collected by solar thermal collectors to power. Traditionally, parabolic dishes and solar towers have been coupled with the steam Rankine cycle to generate power. However, steam cycles need high installed power (high temperatures and pressures) to be profitable. Since the ORC is well suited for lower temperatures, it can be used in smaller solar plants and the total installed power can be reduced to the kW scale.[42]

Industrial Heat Recovery

ORC recovers low-grade waste heat from industrial processes, reciprocating engines, and gas turbines. These heat sources can be converted to electrical power in the range of 400kW to 5 MW.[43] It is estimated that 20% to 50% of all industrial energy input is lost as waste heat, from hot exhaust gases, cooling water, and heat lost from hot equipment and surfaces. Considering that in the United States, industrial energy accounts for 33% of all energy used (equivalent to approximately 30,000 TBtu per year), there is a significant waste-heat opportunity within this sector. Of all industrial waste heat, 60% is estimated to be low temperature waste heat. While only a portion of waste heat has the potential to be converted into electricity, as some cannot be captured and some will be used directly for heat, estimates have shown that a minimum of 600 TBtu per year (equivalent to 175,000 GWh) could be recovered from low temperature heat-to-power applications in the U.S. alone.[44]

Economics

The vast majority (80% - 85%, from a cost perspective) of the components in the OFC are the same as in the ORC. As such, development and maintenance considerations should be fairly similar between the two technologies. The four additional components in the OFC include a flash evaporator, a two-stage turbine, a throttling valve, and a mixer – all of which are commercially available.

For a 1 MW system that uses toluene as the working fluid, the OFC has the potential to achieve a 5% reduction in total equipment costs when compared to the ORC. A high-level snapshot of the differences in costs between the OFC and the ORC is illustrated in Figure 4. Similarly, a detailed comparison of component costs is shown in Table 2.

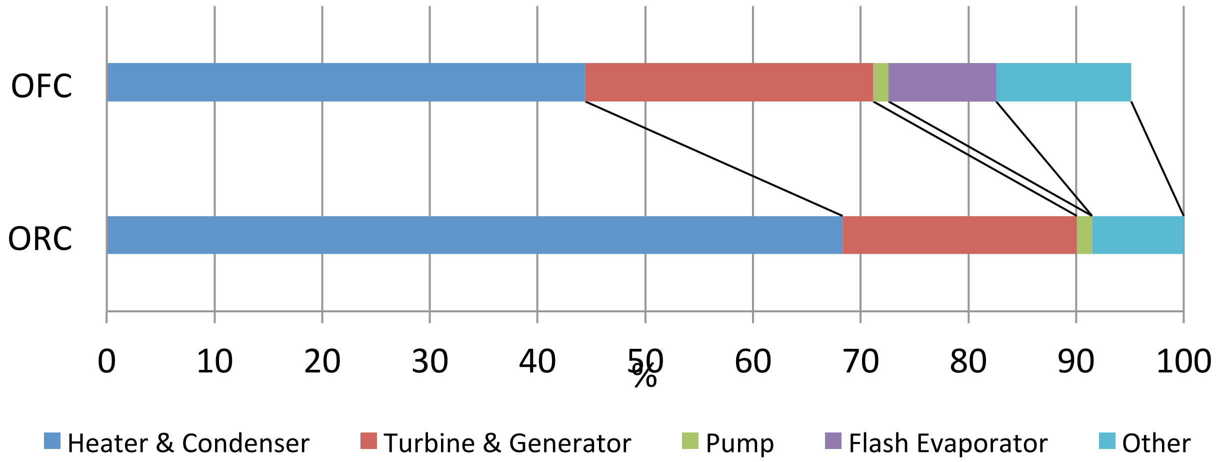

Figure 4. Total System Cost Breakdown by Using Toluene as Working Fluid

	ORC Component Price ($)		%	OFC Component Price ($)	%
Heater & Condenser	Preheater	$228,349			
	Evaporator	$413,114			
	Regenerator	$105,722			
	Condenser	$133,450			
	Total	$880,635	68.33	$572,545	44.43
Turbine & Generator		$280,286	21.75	$344,722	26.75
Pump		$18,193	1.41	$18,193	1.41
Flash Evaporator		$0	0.00	$128,872	10.00
Other		$109,608	8.51	$161,157	12.51
Total ($)		$1,288,722	100.00	$1,225,489	95.09
Total ($/kW)		$1,289		$1,225	

Table 2. 1MW System Cost Comparison between ORC and OFC Using Toluene as Working Fluid[45]

Competitive Landscape

Figure 5 shows the efficiency gain from the OFC compared to a traditional ORC system for various fluids. Both the OFC and ORC can use various fluids as working fluids. Dr. Ho analyzed two main families of fluids, hydrocarbons and siloxanes, in his research. He observed that for all aromatic hydrocarbons, the Modified OFC has an efficiency gain over the ORC in the range of 9% -13%. at a 5% lower cost.

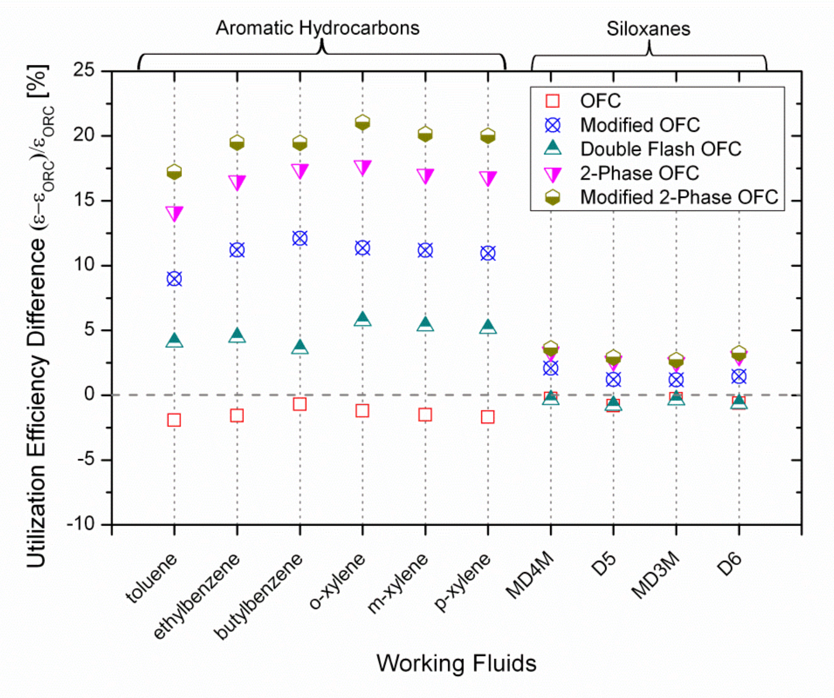

Figure 5. OFC Efficiency Gain vs. ORC Using Different Working Fluids

There may be some technologies that may be more advanced and efficient than the basic ORC and be competitive with the potential gains achieved by the OFC. Some already exist today, such as the Kalina Cycle, while others are under development, such as piezoelectrics.[46] The following paragraphs identify existing technologies that are potentially competitive to the OFC.

Existing Technology:

1) Kalina Cycle: The Kalina Cycle is a variant of the Rankine Cycle, where a mixture of ammonia plus water is used instead of water only. The use of this mixture can increase the efficiency up to 25%. However, the Kalina Cycle brings a great amount of complexity and despite the fact that it was developed in the 1980s, it is still far from being competitive in the market compared to simpler heat to power technologies. Since the Kalina Cycle has been in the market for a long time but few installations exist today, rapid market adoption is not expected in the near-term[47].

2) Cascade ORC: Cascade ORC consists involves coupling multiple ORC systems together. The exhaust of one ORC system is used as the heat source for another ORC system. In this way the overall system efficiency is increased. However, this cycle can be quite expensive given the added systems, and is typically used only in select cases where the economics can justify the additional costs.[48]

The advantage of the OFC compared to the aforementioned technologies is simplicity; relative to the others, the OFC's modifications compared to a traditional ORC are minor. Specially, using an OFC system can actually decrease capital costs, whereas the cost for the Kalina Cycle and Cascade ORC is more significant. Likewise, the technological complexity of the OFC is far less than both nascent thermoelectric and piezoelectric technologies.

Driving Forces

Two primary types of influencers exist in the ORC market today: government agencies and trade organizations. Historically, both have had an impact on the market landscape and appetite for ORC technology, as well as the broader heat conversion to power space.

Government

As with many discussions around energy technologies, subsidies that help reduce the cost (and payback time) of these technologies play a particularly important role in adoption. In the United States, the federal government provides a tax credit for renewable energy production and ORC system costs can be included as part of a larger installation for power generation. The table below provides a list of resource types where ORC can be utilized.[49]

Resource Type	**In-Service Deadline**	**Credit Amount**
Closed-Loop Biomass	December 31, 2013	2.2¢/kWh
Open-Loop Biomass	December 31, 2013	1.1¢/kWh
Geothermal Energy	December 31, 2013	2.2¢/kWh
Landfill Gas	December 31, 2013	1.1¢/kWh
Municipal Solid Waste	December 31, 2013	1.1¢/kWh

Table 3. Federal Incentives/Policies for Renewables & Efficiency (A Subset)

Similar in fashion to tax credits for renewables like wind and solar power, federal legislation has been introduced in the United States with the goal of passing a federal tax credit for waste heat systems to promote further use.[50]

In the United States, incentives also exist on a state-by-state basis. For instance, in Miami-Dade County, Florida, a commercial property owner using ORC for waste heat recovery may qualify for PACE financing[51] under the Voluntary Energy Efficiency and Renewable Energy Program.[52] Furthermore, 11 states have allowed industrial waste heat recovery to be included in their calculation of renewable portfolio standards.

Trade Organizations

A number of trade organizations have been created to advocate on behalf of the heat-to-power and ORC industry. The primary goal of these groups is to push for legislation and policy that promotes the adoption of these systems. In the United States, the *Heat is Power Association* ("HIP") represents ORC companies like GE, Calnetix, United Technologies, ElectraTherm, and TAS Energy and supports "the efficient, industrial use of emission-free electricity generated through Waste Heat to Power processes."[53] As part of its platform, HIP aims to recognize waste heat as a renewable equivalent and is lobbying to update Sections 45 and 48 of the U.S. tax code.[54]

Intellectual Property

A Provisional patent application has been filed in the U. S.

Licensing Strategy

The most viable option for commercialization of our technology is the licensing of the intellectual property. In this arrangement, the licensee would most likely be an incumbent in the ORC space looking to benefit from the unique configuration of the OFC that yields increased efficiency at a lower overall system cost. Examples of incumbents include General Electric, Ormat Technologies and TAS Energy. Berkeley Lab researchers may be available for further development of the technology.

Next Steps

Companies interested in licensing this technology may contact ttd@lbl.gov or call 510-486-6457.

Endnotes

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