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An Alaska case study: Organic Rankine cycle technology

Ben Loeffler and Erin Whitney
Alaska Center for Energy and Power, University of Alaska Fairbanks, P.O. Box 755910, Fairbanks, Alaska 99775-5910, USA

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Organic Rankine cycle (ORC) technology is mature for larger-scale power generation, but ORC systems appropriate for smaller-capacity generators, typical of Alaska village and other Arctic community power plants, are still new to the market or in the prototype phase. Many villages are being approached by product developers to invest in this new technology, and there is a significant value in the dissemination of the real world performance and costs of existing systems. In this analysis of ORC installations across Alaska, capacity factors ranged from 33% to 52%. Low utilization levels are attributed to insufficient waste heat resources (in Unalaska and Cordova) and to higher than expected maintenance costs in a prototype pre-commercial model (in Tok). Significant annual fuel savings have been realized for each installation, with annual demonstrated savings of \$70 000 in Unalaska and projected annual savings of over \$300 000 in Cordova. Modifying existing generation for an ORC system has proven to be challenging and expensive. Project cost data indicate that Alaska projects should expect total capital expenditures to be two to three times the cost of the ORC unit itself. Some systems have been highly reliable and cost-effective, while other installations have been neither. The most cost effective ORC system may be best implemented with a ground-up new generator design and install. Of the installations in Alaska, only the Unalaska Green Machines have achieved reliable operation beyond a few weeks. The smallest reliable system, which operates in Unalaska, has a 50 kW nameplate capacity and requires 500 kW of waste heat, indicating that this technology is best suited for communities with 1 MW or more of diesel generation. *Published by AIP Publishing*. https://doi.org/10.1063/1.4986583

INTRODUCTION

Diesel generators are the main source of electrical generation in remote Alaska communities. The best diesel generator systems convert roughly 40% of the diesel fuel energy content into electricity, with the rest of the fuel energy converted to heat. This heat, if not captured by heat recovery devices, is lost to the atmosphere through the exhaust and cooling systems. The most efficient use of waste heat is for direct heating of adjacent building spaces or domestic water. When such a direct use of engine waste heat is precluded by geographic or infrastructure constraints, this heat energy can be used to generate additional electricity through Organic Rankine Cycle (ORC) technology.

The Rankine cycle is a thermodynamic cycle that converts heat into mechanical work, such as spinning an electrical generator. An organic Rankine cycle uses an organic fluid with a boiling point lower than that of water to convert waste heat from the cooling jackets and exhaust stacks of generators into electricity. The ORC is utilized as a waste heat to power (WHP) system to generate electricity that is supplied to the grid. This study evaluated four ORC units implemented in communities in Alaska.

The potential for waste heat recovery through a Rankine cycle is dependent on the temperature of the waste heat source. Exhaust stack gases can reach high temperatures (over 1000 °F), while cooling jacket water is a lower temperature (as low as 165 °F). Cooling jacket water is an appealing waste heat source, as an ORC can often be plumbed with the engine's existing coolant lines. Exhaust stack heat recovery offers the potential for higher ORC fluid temperatures

(300 °F or more) and increased ORC efficiencies but requires the additional capital costs of adding a heat exchanger to the engine's exhaust system. In addition, the presence of the exhaust heat exchanger can change the exhaust gas composition and may not be compatible with emission controls.

Working fluid choices can affect the operating efficiency of the ORC unit. All ORC units in Alaska use either R-245fa (pentafluoropropane) or ammonia as the working fluid. Other proven working fluids include pentane, propane, CO_2, benzene, toluene, and *p*-Xylene. Polar molecules such as water, ammonia, and ethanol (due to strong hydrogen bonds) are not the most appropriate working fluids due to larger vaporizing enthalpy (Liu *et al.*, 2004). Organic Rankine cycle working fluids should also have high decomposition temperatures and high critical and condensing temperatures and be chosen to work within the temperature range of available waste heat and cold resources (Bourji *et al.*, 2010). ORC system manufacturers select working fluids based on anticipated waste heat temperatures and hardware compatibility.

The goal of adding ORC products to an existing generator system is to convert some waste heat into additional electricity generation, increasing the overall generating efficiency of the power plant. While ORC technology is mature for larger-scale power generation, ORC systems appropriate for smaller-capacity generators typical of Alaska village and other Arctic community power plants are still new to the market or in the prototype phase. Many villages are being approached by product developers to invest in this new technology, and there is significant value in the dissemination of the real world performance and costs of existing systems.

This review of ORC technology in Alaska is a result of Alaska Senate Bill (SB) 138. In this bill, the Alaska State Legislature created an uncodified section of law entitled: "Plan and Recommendations to the Legislature on Infrastructure Needed to Deliver Affordable Energy of the State to Areas That Do Not Have Direct Access to a [proposed] North Slope Natural Gas Pipeline." To support the Alaska Energy Authority (AEA) in its development of an Alaska Affordable Energy Strategy, the Alaska Center for Energy and Power (ACEP) contracted with AEA to document technology development needs specific to Alaska with regard to renewable and sustainable energy technologies. The intention was to identify targeted energy technology development solutions than can be implemented in Alaska to make energy more affordable in the Alaska Affordable Energy Study area. While the focus was on technology research solutions, other factors such as logistics, labor, and training were also addressed. Drafts of technology reviews were vetted by expert roundtables in late February and early March 2016.

These reviews are not meant to be exhaustive discussions of energy technologies in Alaska or proper designs for each technology, and they should not be used as guides for the choice and installation of specific systems. As such, not all possible issues with power production and each technology are addressed. Data for each technology were collected from surveys and publically available databases. Only projects with clearly reported or projected data were included in each technology analysis. These distinctions and descriptions of data sources are included in each technology review.

METHODS

Alaska ORC installations

This paper evaluates four ORC generator systems that have been or are being installed in different parts of Alaska. Each system is evaluated based on the publically available cost and performance data. A summary of the installations is shown in Table I.

In Cordova, a Renewable Energy Fund (REF) grant enabled the installation of a new 3.6 MW diesel generator and a dedicated ORC waste-heat recovery system. The installation was completed in March 2013, and the generator and the ORC system ran for approximately 2 months before being shut down for economic reasons. The diesel generator is too often supplanted by hydroelectric generation, and the air coil cooling tower design for the ORC proved to be insufficient (Cordova Electric Cooperative, 2008a,b,c).

In Unalaska, three ElectraTherm 4200 50 kW stand-alone ORC modules were installed to capture waste heat off three of the powerhouse's diesel generators. The city considered the

TABLE I. Summary of Alaska ORC installations.

Installation location	Manufacturer	Model	Heat source	Cold source	Nameplate capacity (kW)	Number units	Total capacity (kW)
Cordova	Pratt and Whitney	PureCycle 280	Cooling jacket	Air coil	260	1	260
Kotzebue	Energy Concepts[a]	Ammonia Power Cycle	Exhaust stack	City water and air cooler	162	1	162
Unalaska	ElectraTherm	Green Machine	Cooling jacket	Sea water	50	3	150
Tok	ElectraTherm	Green Machine Block 1[b]	Cooling jacket	Well water	50	1	50

[a] Kotzebue Renewable Energy Fund (REF) application data are for an Energy Concepts ORC, but a General Electric brand system was actually purchased.

[b] Block 1 machine was a prototype, pre-commercial model.

ORC systems of more than a dozen manufacturers before selecting the ElectraTherm units. The Unalaska ORC installation was completed in October 2014, and the units are still in operation, requiring only routine maintenance. As of March 2016, the ORC system has offset 44 501 gallons of fuel usage, saving the city $101 686.

Kotzebue recently completed the installation of a waste-heat recovery system to use waste heat from the exhaust stack of its largest generator. The system is being installed simultaneously with district heating upgrades and a new absorption chiller system that produces ice for the local fishing industry. The Kotzebue ORC system has not yet been commissioned.

The ORC system in Tok was initially installed at the ACEP Power Systems Integration Laboratory for testing. The system was then moved to the Tok power plant, where it ran continuously from October 2, 2013, to November 19, 2013, when an expander failure shut down the system. The manufacturer stated that it was aware of the problem and implemented design and lubricant changes in subsequent models. In Tok, the ORC expander was not rebuilt, and the system was and remains bypassed.

ANALYSIS

Utilizing available data and projections, each of the four Alaska ORC installations considered in the report were analyzed for system performance, capital and O&M costs, and economic impact.

Capacity factor

Every energy system is expected to perform below peak capacity in the real world. The capacity factor is defined as the actual ORC system electrical output as a percentage of the system nameplate capacity. The Kotzebue application projects a capacity factor of 96%, but the real-world performance of the other three systems indicates that 30%–50% is a more realistic expectation. Table II shows the demonstrated power, energy output, run time, and capacity factor of the ORC systems in Alaska. The estimated values are in italics.

Capital costs and operation and maintenance costs

The capital costs for each installation were calculated for both nameplate and demonstrated average power outputs. Capital costs represent the total "overnight" expenses incurred prior to the first production of electricity. The annual operation and maintenance (O&M) costs were calculated based on the nameplate and demonstrated annual energy output.

The Cordova installation coincided with a new diesel generator installation, and the Kotzebue installation coincides with a new absorption chiller and district heating loop installation. To the extent possible, the ORC system costs were isolated from the total project costs for Cordova and Kotzebue.

TABLE II. Summary of ORC power output and energy production in Alaska (estimated values in italics).

	Power output			Energy production		
Location	Name-plate (kW)	Average demonstrated (kW)	Total demonstrated runtime (h)	Name-plate (kW h/yr)	Average demonstrated (kW h/yr)	Capacity factor (%)
Cordova[a]	260	134.0	382	2 265 120	*1 167 408*	52
Kotzebue[b]	162	*154.7*	…	1 411 344	*1 348 164*	*96*
Unalaska[c]	150	57.4	30 000	1 306 800	500 064	38
Tok[d]	50	16.6	1138	435 600	*144 619*	33

[a] Cordova performance from the 2013 ACEP case study.
[b] Kotzebue performance based on 2008 REF application estimates.
[c] Unalaska performance data submitted through March 2016 by the City of Unalaska.
[d] Tok performance data from 2013 ACEP report field data.

Table III compiles the system total capital and O&M costs on a nameplate and actual performance basis. The nameplate figure represents the system running at nameplate capacity 363 days a year (2 days offline for maintenance). Estimated and projected figures are identified in Table III in italics.

The data from Table III are plotted in Fig. 1 for comparison. The nameplate quantities are represented with triangles, and the demonstrated quantities are represented with circles. The quantities for each installation are connected by color-coded lines.

A 2015 report from Oak Ridge National Labs (ORNL) (Elson *et al.*, 2015) predicts an installed cost for ORC systems between 50 and 500 kW capacity of 4500 \$/kW. ElectraTherm quotes turnkey prices for three of their ORC modules ranging from 35 kW to 110 kW. In Fig. 2, the capital costs of the Alaska installations are plotted with the ORNL and ElectraTherm values for comparison.

Installed costs by major components

Capital costs were compared on a per-kilowatt nameplate basis and broken into categories of ORC units, materials, labor, shipping, and other costs. In Table IV, the nameplate capital costs of each project category are compiled. The ORC unit itself accounted for 34%–53% of the total capital costs, indicating that projects in Alaska should expect total capital expenditures to be two to three times the cost of the ORC unit itself. Capital costs per kW are graphed in Fig. 3. Kotzebue's numbers are based on expected costs and performance from their REF application, with actual installed costs expected to be higher and actual performance expected to be lower.

TABLE III. Capital costs and O&M costs of ORC systems installed in Alaska (estimated values in italics).

	Capital cost			O&M costs		
Location	Capital cost (USD)	Nameplate (\$/kW)	Actual ($\$/\text{kW}_{\text{avg}}$)	Annual O&M (\$/yr)	Nameplate (\$/kW h)	Actual (\$/kW h)
Cordova[a]	\$1 934 376	\$7440	\$14 436	\$17 555	\$0.00775	\$0.01504
Kotzebue[b]	*\$1 056 042*	*\$6519*	*\$6824*	*\$20 222*	*\$0.01433*	*\$0.01500*
Unalaska[c]	\$1 889 381	\$12 596	\$32 916	\$1200	\$0.00092	\$0.00240
Tok[d]	\$280 500	\$5610	\$16 898	*\$7600*	*\$0.01745*	*\$0.05255*

[a] Cordova capital costs from the REF application cost worksheet; O&M costs projected based on the ACEP case study.
[b] Kotzebue costs from REF application estimates.
[c] Unalaska capital costs from REF application. Unalaska O&M actual costs reported by the City of Unalaska.
[d] Tok capital costs based on installation of the pre-production module at the ACEP Power Systems Integration Laboratory; O&M costs estimated by the ACEP study.

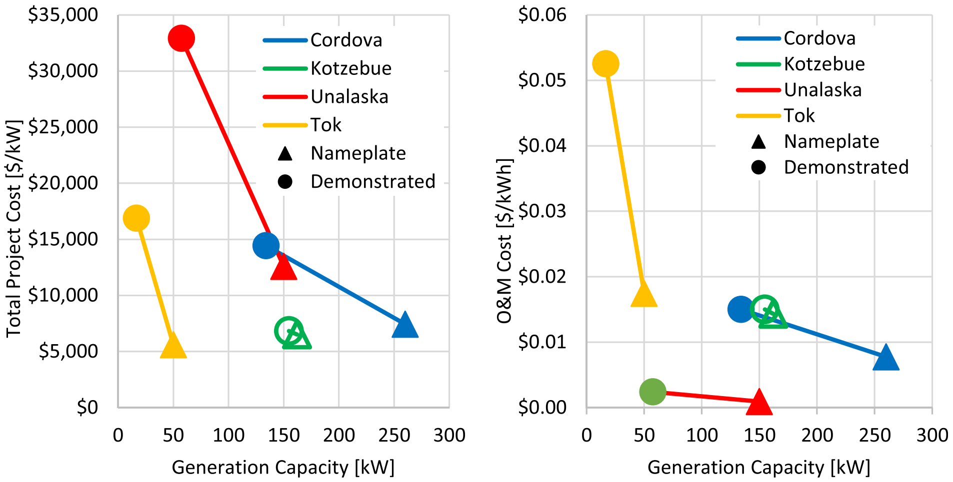

FIG. 1. Alaska ORC capital and O&M costs. The nameplate quantities are represented with triangles, and the demonstrated quantities are represented with circles. The quantities for each installation are connected by color-coded lines.

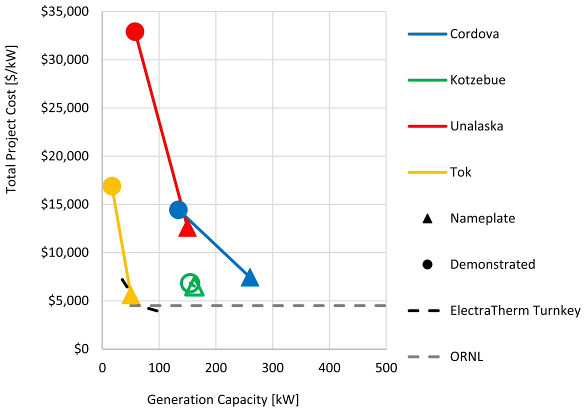

FIG. 2. Alaska ORC capital costs compared with commercial expectations in the Lower 48. Elevated nameplate costs can be attributed to higher costs of shipping, labor, and materials in Alaska's remote areas.

TABLE IV. Capital cost breakdown based on nameplate capacity. Kotzebue's numbers are based on expected costs and performance from their REF application, with actual installed costs expected to be higher and actual performance expected to be lower.

		Cordova	Kotzebue[a]	Unalaska	Tok
ORC unit	$/kW	$3961	$2932	$4256	$2388
	% total	53%	45%	34%	43%
Materials	$/kW	$0[b]	$1533	$4615	$1439
	% total	0%	24%	37%	26%
Labor	$/kW	$3452	$1080	$2089	$1780
	% total	46%	17%	17%	32%
Shipping	$/kW	$28[c]	$753	$500	$0
	% total	0%	12%	4%	0%
Other	$/kW	$0	$220	$1135	$3
Total	$/kW	$7440	$6519	$12 596	$5610

[a] Based on expected costs and performance.
[b] ORC unit costs not separated from other materials.
[c] Shipping from Whittier to Cordova only.

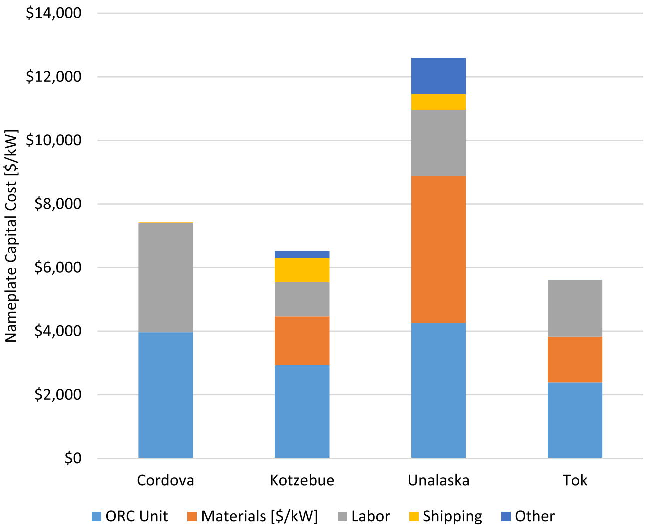

FIG. 3. ORC nameplate capital cost per kilowatt by cost category.

From the Unalaska and Kotzebue estimates, it appears that shipping constitutes 4%–12% of the capital costs of an ORC installation in Alaska. Available shipping information is shown in Table IV.

Diesel offset

The magnitude of the diesel offset is dependent on the generating efficiency of the existing diesels, the ORC capacity factor, and the efficiency of the ORC system, which is dependent on the temperature of the waste heat and the proper sizing of the system. The total annual savings is the cost savings from the diesel offset minus the ORC O&M expenses. Diesel and cost savings data are compiled in Table VI with estimated or projected values in italics.

Levelized cost of energy

The estimated cost of energy of each system over a 20-year life was calculated using the National Renewable Energy Laboratory's Energy Analysis Calculator (http://www.nrel.gov/analysis/tech_lcoe.html). The simple levelized cost of renewable energy (sLCOE) reflects the average cost of energy over 20 years from a renewable system and is calculated assuming a 3% discount rate. Table VII presents the specific capital and O&M costs along with the capacity factor and 20-year sLCOE.

DISCUSSION

ORC real world performance

While a 20-year design life (Venables, 2014; ElectraTherm, 2015) is the industry standard for commercial ORC generators, of the installations in Alaska to date, only the Green Machines

TABLE V. Transportation costs for systems to communities in Alaska.

Cordova	$7220	Barge: Whittier to Cordova
Unalaska	$75 053	Land: Reno to Seattle (706 mi) Barge: Seattle to Unalaska (1951 mi)
Kotzebue	$122 000	Unknown
Tok	Costs were not separated out	Land/Barge: Reno to Tok (2700 mi)

TABLE VI. Alaska ORC annual diesel offset and cost savings.[a] Estimated and projected figures are given in italics.

		Cordova	Kotzebue	Unalaska	Tok
Annual diesel generation[b]	Diesel cost ($/gal)	$3.87	$5.20	$2.28	$5.00
	Annual generation (kW h)	11 490 065	20 300 000	45 719 844	9 776 160
	Diesel consumption (gal/yr)	841 763	1 400 000	2 921 748	698 297
	Electricity fuel price ($/kW h)	$0.28	$0.36	$0.15	$0.36
	Diesel efficiency (kW h/gal)	13.82	14.5	15.69	14
ORC Output	Average power (kW)	134	*155*	57	17
	Annual energy (kW h)	*1 167 408*	*1 348 164*	500 064	*144 619*
ORC annual impact	Diesel offset (gal/yr)	*84 472*	*92 977*	31 872	*10 330*
	Fuel savings ($/yr)	*$326 908*	*$483 480*	$72 667	*$51 650*
	Fuel savings (%)	*10*	*6.6*	1.1	*1.5*
	Combined efficiency (kW h/gal)	*15.04*	*15.46*	15.82	*14.21*
	Annual savings (Fuel–O&M) ($/yr)	*$309 353*	*$463 258*	$71 467	*$44 050*

[a] Fuel prices and savings calculated utilizing costs reported for the period of evaluation.
[b] Annual generation information from REF applications.

located in Unalaska have achieved reliable operation beyond a few weeks. The City of Unalaska reports show that their ORC modules have required only normal maintenance.

An important metric in evaluating an ORC's real world operation is the system's capacity factor. Real world capacity factors frequently fall short of design values due to maintenance downtime or reduced or intermittent waste heat availability. For the three systems that have operated in Alaska, the Cordova PureCycle briefly demonstrated 52% capacity, the Unalaska ElectraTherm units are achieving 38% capacity, and the Tok ElectraTherm unit demonstrated 33% capacity.

The data used in this analysis do not include real time data that could be used to attribute reduced capacity factors to either systems being offline for repairs and maintenance or reduced outputs due to insufficient heat resources. The percentage of waste heat that can be converted into mechanical work for electricity generation is limited by the thermodynamic availability of the energy in the system, as defined by the Carnot efficiency equation:

$$\eta = 1 - (\mathrm{T_c}/\mathrm{T_h}).$$

Maximum possible ORC system efficiency, η, is dependent on both the waste heat temperature, $\mathrm{T_h}$, and the available cold temperature resource, $\mathrm{T_c}$ (generally the ambient air temperature or natural cold-water sources), where the temperature units are in Kelvin. Typical waste heat to power systems achieve a Carnot efficiency of around 1/3 (Elson *et al.*, 2015).

Waste heat and power output data were available for all three operating ORC systems. The average waste heat temperatures and calculated operating efficiencies achieved by these systems are shown in Fig. 3, along with a curve of 1/3 Carnot efficiency (assuming a 40 °F cold source temperature). Based on waste heat temperatures noted in the available reports, we can see that

TABLE VII. Alaska ORC specific costs and 20-year sLCOE.

Location	Nameplate capacity (kW)	Capital costs ($/kW)	O&M costs ($/kW h)	Capacity factor (%)	20-yr sLCOE ($/kW h)
Cordova	260	$7440	$0.00775	52	$0.117
Kotzebue	162	$6519	$0.01433	96	$0.066
Unalaska	150	$12 596	$0.00092	38	$0.254
Tok	50	$5610	$0.01745	33	$0.130

only the Unalaska system operated near the expected efficiency (Fig. 4). Data on the waste heat stream in Unalaska indicate that the waste heat flow was not sufficient to operate the ORC system at full rated output. Tok and Cordova appear to have produced electricity at a rate below what would be expected for their waste heat resource, reducing their capacity factor. It was noted in the Green Machine report (Lin, 2014) that the amount of waste heat available in most communities may not be enough to run an ORC unit at full capacity year-round, as waste heat availability in summer in some communities may decrease, reducing the operational period of the ORC to 7.5 months, or less, a year.

ORC real world economics

Nameplate capital costs for Alaska projects are greater than those predicted by ORNL and Electratherm data. Elevated nameplate costs can be attributed to higher costs of shipping, labor, and materials in Alaska's remote areas. Demonstrated capital costs in Alaska are up to seven times greater than expected capital costs in the Lower 48. Much of this difference can be attributed to the Alaska installations operating with relatively low capacity factors, which likely are the result of either maintenance/reliability-related downtime or improper system sizing. Improper sizing can result in an ORC that requires more heat to operate at rated output than that can be supplied or inefficient performance due to ineffective cooling on the cold side of the ORC.

The ORC presence in Alaska is not sufficient to comment on cost changes over time. The installation in Unalaska, which is a newer version of the ElectraTherm pre-production ORC system in Tok, has exhibited improved reliability and decreased O&M costs.

Technology trends

Organic Rankine cycle system performance is highly dependent on the quantity and temperature of available waste heat, the availability of a low-temperature heat sink, and the properties of the working fluid. New systems are being developed that use efficient working fluids better suited to particular waste heat source temperatures. Exhaust heat captured from diesel generators allows elevated cycle temperatures but may conflict with tightening emission restrictions, as the heat exchangers can interfere with exhaust composition. The ORC offers the potential to combine multiple waste heat sources of different qualities or to incorporate solar thermal and biomass heat sources.

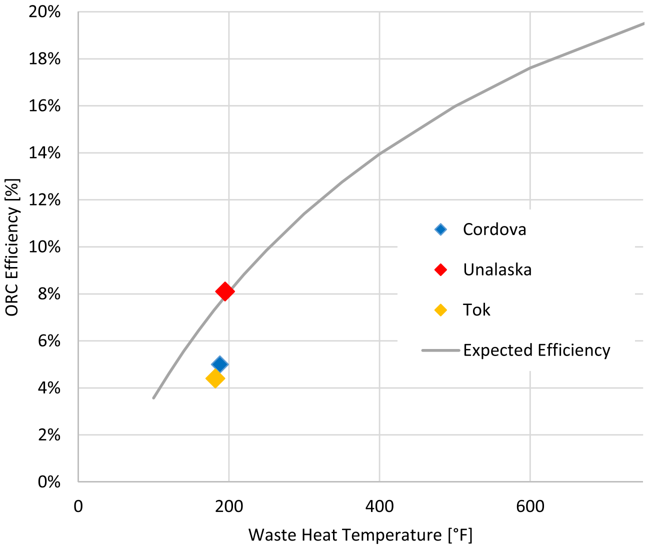

FIG. 4. ORC efficiency as a function of waste heat temperature. Expected efficiency assumes a cold source temperature of 40 °F and achievement of 1/3 Carnot efficiency.

Tech-specific storage systems

The energy generated by the ORC unit is integrated into the main power plant electric generation grid. The heat used to generate power through the ORC comes from the power plant directly as waste heat. Some systems use thermal storage when combined with other renewable energy sources such as solar photovoltaic power.

CONCLUSIONS

Capacity factors range from 33%–52% for installations that have already been installed. Low utilization levels are a result of insufficient waste heat rather than inefficient ORC operation (in Unalaska), as well as the use of a prototype pre-commercial model (in Tok). While operation and maintenance costs vary, significant annual fuel savings have been realized for each installation, with annual demonstrated savings of $70,000 in Unalaska and projected annual savings of over $300 000 in Cordova. A 20-year design life is the industry standard for commercial ORC generators although of the installations in Alaska, only the Unalaska Green Machines have achieved reliable operation beyond a few weeks.

Modifying existing generation for an ORC system has proven to be challenging and expensive. Project cost data indicate that Alaska projects should expect total capital expenditures to be two to three times the cost of the ORC unit itself. Some systems have been highly reliable and cost-effective, while other installations have been neither. The most cost effective ORC system may be best implemented with a ground-up new generator design and installation. Of the installations in Alaska, only the Unalaska Green Machines have achieved reliable operation beyond a few weeks. The smallest reliable system, which operates in Unalaska, has a 50 kW nameplate capacity and requires 500 kW of waste heat, indicating that this technology is best suited for communities with 1 MW or more of diesel generation.

Organic Rankine cycle generators are most efficient with higher-temperature waste heat sources. The choice of working fluid is also a factor in efficiency. All ORC units in Alaska use either R-245fa (pentafluoropropane) or ammonia. Looking forward, new ORC systems are being developed that use efficient working fluids better suited to particular waste heat source temperatures. An ORC offers the potential to combine multiple waste heat sources of different qualities or to incorporate solar thermal and biomass heat sources.

Heat capture from diesel generator exhaust allows elevated ORC temperatures and increased efficiencies but may conflict with tightening emission restrictions, as heat exchangers can interfere with the exhaust composition. There is also difficulty in receiving performance guarantees from ORC manufacturers. Installations that are more efficient require approved rate adjustments to recover debt and cost; however, rate proceedings are very expensive and time-consuming.

The ORC unit itself accounts for a third to a half of the total capital costs, indicating that Alaska projects should expect total capital expenditures to be two to three times the cost of the ORC unit itself. Shipping is less than 10% of the cost in all installations.

Table VIII compares the projected sLCOE for the ORC systems with the existing cost of diesel generated electricity. All installations except for Unalaska projected ORC sLCOE representing a savings over current diesel generation costs.

TABLE VIII. Comparison of ORC sLCOE with the existing Diesel generation electricity cost.

Location	ORC 20-yr sLCOE ($/kW h)	Existing generation fuel cost ($/kW h)
Cordova	$0.117	$0.28
Kotzebue	$0.066	$0.36
Unalaska	$0.254	$0.15
Tok	$0.130	$0.36

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