

SBIR Phase I Final Report
DOE Contract Number DE-SC0008215
“Low Temperature Stirling Engine for Geothermal Electricity Generation”
Cool Energy, Inc.
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Purpose of Research: With the rapid growth of hydro-fracking in oil and gas production, there are small-scale (up to 200kW) distributed power generation opportunities in heated liquids that are co-produced with the main oil and gas products. Since 2006, Cool Energy, Inc. (CEI) has designed, fabricated and tested four generations of low-temperature (100°C to 300°C) Stirling engine power conversion equipment. The electric power output of these engines has been demonstrated at over 3kW_e and over 22% thermal conversion efficiency for an input temperature of 300°C. This power conversion approach has great promise for geothermal applications, especially at low power capacities where current technology sees performance degradation, and this grant was used to explore the feasibility of Stirling power generation for distributed geothermal.

Research Performed: In Phase I, Cool Energy and CSU analyzed thousands of oil and gas wells for electric power generation potential, and modeled the performance of electricity generation in oil and gas production system using heat from co-produced liquids to drive a Stirling engine. In addition, Cool Energy customized the design of a 20kW_e low-temperature electricity generation engine specifically for the geothermal application by optimizing engine performance and customer value for the temperature ranges supplied by co-produced liquids. The 20 kW_e design uses novel approaches of self-lubricating, low-wear-rate bearing surfaces, non-metallic regenerators, high-effectiveness, low-cost heat exchangers, and a rotary transmission to transfer the mechanical work of the engine to the built-in electrical generator in the engine housing. A Stirling approach has several advantages over the current products used in these applications: smaller opportunities can be addressed, part-load performance is excellent, and Stirling engines do not use the environmentally hazardous organic fluids found in incumbent technologies.

Research Findings: Up to 330MW of generating capacity exists in US oil and gas production operations, and perhaps double that worldwide. Harnessing this potential could avoid 1.8 million tonnes of CO₂ emissions each year, and additional SO_x and NO_x emissions. A 20kW_e Stirling engine optimized for this application was designed with a software gradient descent engine analysis tool. This engine was simulated in operation at certain specific geothermal wells on an hourly basis, and showed the potential to generate 95 MWh of electricity per year. In volume production, this could produce customer payback times of 2-3 years before subsidies.

Potential Applications: If commercialized, a 20kW_e Stirling engine customized for the geothermal power generation application could produce economical clean power from geothermal sources, as well as other sources of low-grade heat, such as engine exhaust, industrial waste heat, and flared natural gas.

Introduction and summary: Many active oil and gas wells produce heated liquids in addition to the oil and gas production at the well. These liquids are separated from the petroleum products and either pumped back into the ground, or evaporated in surface pits, but in either case the thermal energy they contain is often wasted. The potential exists to operate a low temperature heat engine using these fluids, and several operating pilots have been installed in the US and China using organic Rankine cycle machines. Of the 825,000 active wells in the US, it has been estimated that there is enough heat flow to generate 3GW of clean geothermal power. This work describes an assessment of the potential in Texas and Montana utilizing publicly available data sets. An optimization routine was developed to maximize the net power production from a Stirling engine powered by heat in the co-produced fluids at active oil and gas wells. The power production net of parasitic losses is the objective function maximized by the routine, over a range of ambient temperatures, co-production flow rates, and co-production fluid temperatures, to produce a map of the optimized system performance. The maps produced from the optimization were then used to estimate the net electric energy produced over a year using ambient temperature data and co-production data for a single well in Texas. Hourly power production and system temperatures are plotted. The net electric energy potential from well API 42479406730000 over the one year data period is 94.4 MW-h.

Phase I Technical Objectives and Accomplishments

1. **Objective:** Geothermal heat sources, especially oil and gas wells drilled into “hot rocks,” will be analyzed to determine whether they can produce economically significant amounts of electric power based on resource quality and the resulting levelized-cost-of-electricity (LCOE).

Accomplishment: To assess resource quality, published data for oil and gas wells in Texas and Montana were examined for borehole temperature and flow rates of the hydrocarbon product and co-produced water.

Texas data:

Borehole temperature data, compiled by the Texas Bureau of Economic Geology for oil and gas wells, were downloaded from the National Geothermal Data System (<http://www.geothermaldata.org>). Each temperature observation is accompanied by a well API number as the primary identifier of each unique well. The data set includes open producing wells, temporarily abandoned wells, dry holes, and plugged bores. The production data were collected for individual wells from the Railroad Commission of Texas (RRC) specific lease query (<http://webapps2.rrc.state.tx.us/EWA/specificLeaseQueryAction.do>). Because Augustine and Falkenstern¹ report that “Oil wells in Texas were considered to be too shallow and therefore at too low a temperature to be used for electricity generation,” only gas wells were queried in the Texas data. Because Texas operators do not report co-produced water production, it was estimated from the gas production for each individual well, using a water-to-gas ratio (WGR) of 511 bbl/MMCF.

Since the temperature data set is extremely lengthy (13539 temperature observations) and the production data must be queried individually, a statistical approach was used to sample wells within the temperature data set and reduce the number of queries required. This approach ensures the samples have been randomly selected with no bias toward temperature, flow rate, or a particular basin or RRC district. The statistical approach follows:

¹ Augustine, C. and Falkenstern, D. (2012), “An Estimate of the Near-Term Electricity Generation Potential of Co-Produced Water from Active Oil and Gas Wells,” Geothermal Resources Council Transactions, 36, 187-200.

- Wells with borehole temperatures less than 125 °F were not considered hot enough and were removed from the data set. The remaining 12739 wells were then binned by temperature, such that one quarter of the population occupied each bin.
- Within each quartile, 120 wells were selected at random.
- The RRC Public GIS Map Viewer (<http://gis2.rrc.state.tx.us/public/startit.htm>) was used to locate the well bores by API, and the “Identify Wells” map tool used to open the well attributes table. A link in the attributes titled “Operator/Wellbore/PDQ” opens another table that describes whether the well is open or plugged, producing or abandoned, and contains a link titled “Production Data Query (PDQ)” if the well is open.
- The PDQ link was used to open the specific lease query results for the specific well selected by API number in the Pubic GIS Map Viewer. The total gas produced in one reporting year was then recorded.

The data set resulting from the production data queries is presented in Figure 1 and summarized in Table 1, by temperature and annually averaged co-production flow rate.

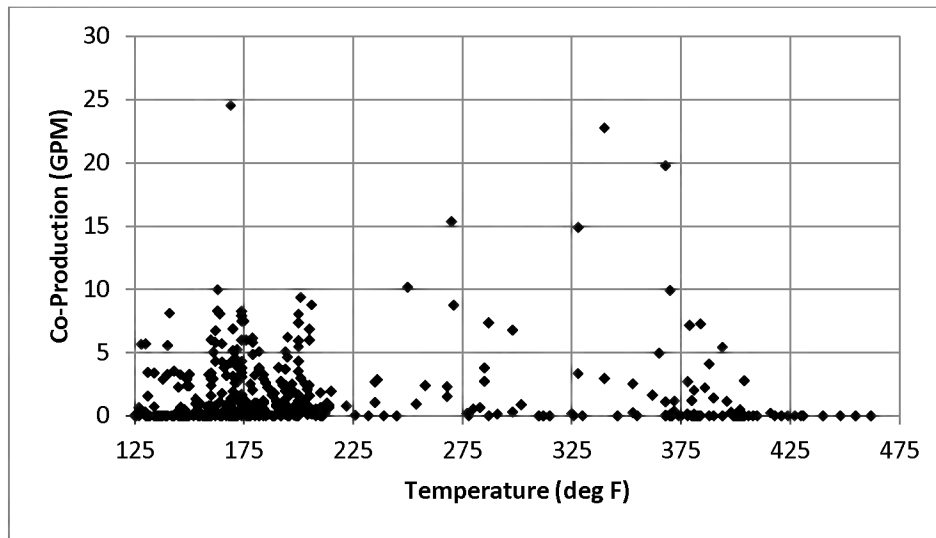


Figure 1) Queried data by temperature and co-production flow rate, 296 producing wells.

			Temperature Bin (°F)				Grand Total
			1	2	3	4	
			125 < T < 162	162 < T < 180	180 < T < 214	T > 214	
Production Bin (GPM)	0	Not Producing	78	29	18	63	188
	1	V < 0.36	4	15	23	14	56
	2	0.36 < V < 0.95	11	15	26	7	59
	3	0.95 < V < 2.03	4	22	23	10	59
	4	2.03 < V < 3.90	16	14	17	12	59
	5	3.90 < V < 24.5	7	25	13	14	59
Grand Total			120	120	120	120	480

Table 1) Data count within each temperature and production bin.

Montana data:

Borehole temperature data, compiled by the Montana Bureau of Mines and Geology for oil and gas wells, were downloaded from the National Geothermal Data System (<http://www.geothermaldata.org>). Each temperature observation is accompanied by a well API number as the primary identifier of each unique well. The data set includes open producing wells, temporarily abandoned wells, dry holes, and plugged bores. The production data were collected for individual wells from the Montana Board of Oil and Gas Conservation online production data query system, located at <http://www.bogc.dnrc.mt.gov/WebApps/DataMiner/Production/ProductionByWell.aspx>. Montana operators report co-produced water, as well as gas and oil production, for each well.

Since the temperature data set is lengthy (4285 temperature observations) and the production data must be queried individually, a statistical approach was used to sample wells within the temperature data set and reduce the number of queries required. This approach ensures the samples have been randomly selected with no bias toward temperature, flow rate, or a particular basin. The statistical approach follows:

- Wells with borehole temperatures less than 125 °F were not considered hot enough and were removed from the data set. The remaining 2975 wells were then binned by temperature, such that approximately one quarter of the population occupied each bin.
- Within each quartile, 100 wells were selected at random.
- The Montana Board of Oil and Gas Conservation online production data query system was then used to query the well bores by API.
- The production data in one reporting year was averaged and recorded.

The resulting data set included only a single well that potentially produced greater than 5 kWe electric power. Due to this observation, the remaining wells from the top temperature quartile were queried in hopes of finding more wells with higher potential.

The data set resulting from the production data queries is presented in Figure 2 and summarized in Table 2, by temperature and annually averaged co-production flow rate. The temperature bin limits in Table 2 were selected to produce an equal population of 100 in each bin, except for the hottest bin, which contains all wells in the highest temperature bin.

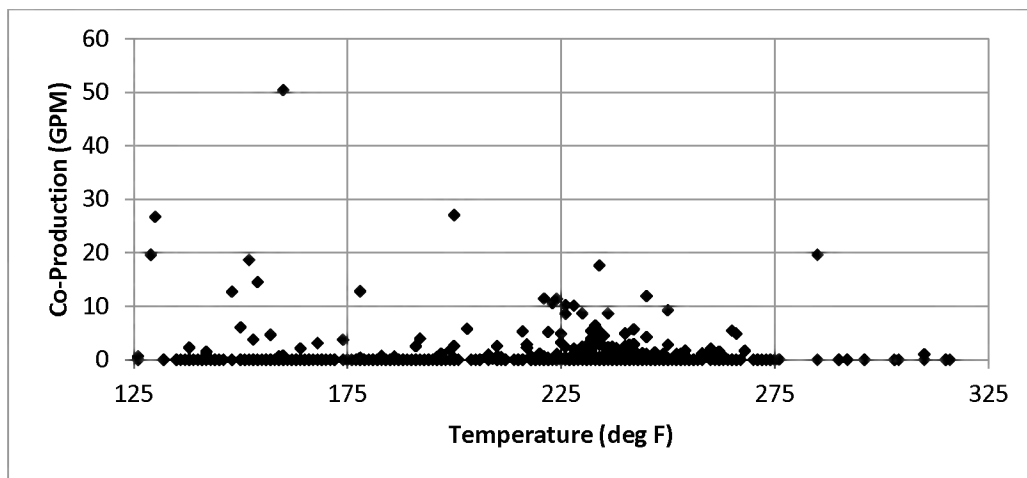


Figure 2) Queried data by temperature and co-production flow rate, 216 producing wells

			Temperature Bin (°F)				Grand Total
			1	2	3	4	
Bin Range			T>220	220>T>185	185>T>159	159>T>125	
Production Bin (GPM)	1	V>2.55	36	6	4	8	54
	2	2.55>V>1	46	7	1	2	56
	3	1>V>0.36	44	6	2	2	54
	4	0.36>V>0	47	2	1		50
	5	Not Producing	556	79	92	88	815
	Grand Total			729	100	100	100

Table 2) Data count within each temperature and production bin.

Electric Power Generating Potential:

The temperature and flow rate data of the ten wells in each state having the highest potential were examined in the preliminary analysis for their potential to generate electricity. No heat loss was assumed between the borehole and surface temperatures of the products and co-products. During extraction, however, expansion of dissolved gas may cause a non-trivial decrease in temperature that should be further investigated.

Incorporating the basic engine performance maps developed in Objective 4 below, the preliminary analysis determined the number of Stirling engines, or fraction thereof, that maximizes the electric power generated from the heat supply stream for each well, with the temperature of the heat rejection heat transfer fluid entering the Stirling engine's cold side fixed at 25 °C, and using heat recovery heat exchangers having a constant effectiveness of 0.80. The preliminary analysis models two system configurations, the single-stage and the dual-stage. In the single-stage configuration, the co-produced water passes through a heat exchanger that transfers some of the geothermal heat into an intermediary fluid stream, that in turn supplies heat to one Stirling engine. In the dual-stage configuration, the co-produced water passes sequentially through two heat exchangers that transfer some of the geothermal heat into two, separate intermediary fluid streams. The temperature of the intermediary fluid in the heat exchanger through which the co-produced water first passes is thus higher than the temperature of the intermediary fluid in the heat exchanger through which the co-produced water subsequently passes. The intermediary fluid streams in turn supply heat, separately, to two Stirling engines, which necessarily operate at different hot temperatures. Details of the motivation and advantages of the dual-stage configuration are discussed in the Phase I grant application, in the section Analysis of Cascade Application to Multiple Stirling Engines.

The ten Texas wells with the highest potential for generating power are shown in

API	Well Temperature (°C)	Co-Production Estimate (GPM)	# of 1-Stage	1-Stage Power (kWe)	# of 2-Stage	2-Stage Power (kWe)
42479406730000	187	19.8	2.6	23.6	3.6	33.3
42283322260000	171	22.8	2.6	20.5	3.6	29.0
42247320270000	188	9.9	1.3	12.0	1.8	17.0
42479407860000	164	14.9	1.6	11.7	2.2	16.5
42311337180000	196	7.3	1.0	10.1	1.4	14.1
42247320320000	193	7.1	1.0	9.4	1.4	13.2
42311337370000	201	5.4	0.8	8.1	1.1	11.4
42427327750000	198	4.1	0.6	5.8	0.8	8.2
42247320740000	185	5.0	0.6	5.8	0.9	8.2
42505330910000	132	15.3	1.0	5.0	1.4	7.2

Table 3.

API	Well Temperature (°C)	Co-Production Estimate (GPM)	# of 1-Stage	1-Stage Power (kWe)	# of 2-Stage	2-Stage Power (kWe)
42479406730000	187	19.8	2.6	23.6	3.6	33.3
42283322260000	171	22.8	2.6	20.5	3.6	29.0
42247320270000	188	9.9	1.3	12.0	1.8	17.0
42479407860000	164	14.9	1.6	11.7	2.2	16.5
42311337180000	196	7.3	1.0	10.1	1.4	14.1
42247320320000	193	7.1	1.0	9.4	1.4	13.2
42311337370000	201	5.4	0.8	8.1	1.1	11.4
42427327750000	198	4.1	0.6	5.8	0.8	8.2
42247320740000	185	5.0	0.6	5.8	0.9	8.2
42505330910000	132	15.3	1.0	5.0	1.4	7.2

Table 3) Top ten electric power potential estimates from Texas data query.

Of the 480 unique wells queried, 5 (1.04%) produce enough heat to generate 10 kWe in a single-stage Stirling engine system, 2 (0.42%) of which produce enough heat to generate greater than 20 kWe. Assuming the queried data is representative of the complete temperature listing of 13539 wells listed in the Texas borehole temperature workbook from the National Geothermal Data System, approximately 141 wells (1.04%) will produce enough heat to generate greater than 10 kWe, of which approximately 56 wells (0.42%) will produce over 20 kWe.

The ten Montana wells with the highest potential for generating power are shown in Table 4.

API	Well Temperature (°C)	Co-Production Estimate (GPM)	# of 1-Stage	1-Stage Power (kWe)	# of 2-Stage	2-Stage Power (kWe)
25083210800000	140.6	19.6	1.7	10.0	2.4	14.2
25083211530000	112.2	17.6	0.9	3.3	1.3	4.7
25083050180000	118.3	11.9	0.7	2.9	1.0	4.1
25083216760000	121.1	9.3	0.6	2.5	0.8	3.6
25083218290000	129.4	5.5	0.4	2.0	0.6	2.8
25083217570000	130.0	4.9	0.4	1.8	0.5	2.6
25085212130000	113.3	8.6	0.5	1.7	0.7	2.4
25091213060000	108.9	10.1	0.5	1.6	0.7	2.3
25085050370000	106.7	11.4	0.5	1.6	0.7	2.3
25091216990000	107.8	10.2	0.5	1.5	0.7	2.2

Table 4) Top ten electric power potential estimates from Montana data query.

Of 1029 unique wells queried, 1 (0.1%) produced enough heat to generate 10 kWe in a single-stage Stirling engine system. Production data for every well within the top temperature quartile (729 individual wells) listed in the Montana borehole temperature workbook from the National Geothermal Data System were queried, of which 175 wells (24.0%) were actively producing, and only a single well produced a combination of temperature and flow rate sufficient to generate greater than 10 kWe. Although it is possible that the power potential could be increased during the winter months when the ambient temperature is lower than that used in the analysis, the power potential will also be reduced during the summer months when the ambient temperature is warmer. The data suggests many Montana oil and gas wells do not produce enough water at a high enough temperature to power a 20 kWe system.

It was found that the increase in the amount of electric power produced by the dual-stage system is nearly proportional to the increase in the number of Stirling engines (or fraction thereof) by which the dual-stage system is larger than the single-stage system. Thus, the dual-stage system would have a cost-per-watt nearly equal to that of the single-stage system, yet, in all of the test cases examined, produce consistently 40% more electric power.

2. Objective: For hydrothermal systems, models will be developed of water or steam flow rate, pumping pressure (including an acceptable pressure drop imposed by a heat recovery heat exchanger), pumping cost, geothermal fluid stream temperature and pressure, acceptable enthalpy drop in the stream during heat extraction, equipment requirements (particularly for handling corrosion and scale), and heat rates for the most promising classes of opportunities.

Accomplishment: Very little data was found for hydrothermal resources not already developed and fully dedicated to generating electric power. It was therefore concluded that searching for new ones would not be feasible within the scope and objectives of this project. Geothermal heat originating as an inherent byproduct of oil and gas production, however, from wells already drilled, incurs no further cost to develop, and would likely be the better economic opportunity on that account alone. Because much more data has been reported and published on existing oil and gas wells, there will also be a higher degree of confidence in the assessments made of the availability of this source of geothermal heat and its potential for electric power production.

3. Objective: For oil and gas wells, models will be developed of the product or co-product flow rates, acceptable pressure drop imposed by a heat recovery heat exchanger, acceptable enthalpy drop in

the product or co-product stream during heat extraction, and heat rates for the most promising classes of opportunities.

Accomplishment: As described in Objective 1 above, because the databases were large and required manual intervention to sort, the models manifested as a statistical survey, from which was derived an estimate of the number of wells that could generate economically sufficient amounts of electric power.

The acceptable pressure drop imposed by a heat recovery heat exchanger was not considered, as the co-produced fluid is water and likely already pressurized at the wellhead.

The acceptable enthalpy drop in the product or co-product stream during heat extraction was addressed only to the extent that the pinch point temperature in the heat recovery heat exchanger not be too small, as discussed in Objective 6 below. Maintaining some minimum temperature, so as to prevent precipitation of salts, paraffin, or soluble minerals, requires specific knowledge of the composition of the product and co-product streams, which not only is different for every well, but also changes over time. To the extent that solid matter is separated from the product or co-product stream by cooling it, however, the heat removed during the cooling process is nonetheless of geothermal origin, and would be applied to the hot side of the Stirling engine system.

As described in Objective 1 above, heat rates for the most promising classes of opportunities were found for a sample population of oil and gas wells, with an estimate made for how many such wells are in the total population of wells from which the sample was extracted.

4. Objective: New and/or existing models will be developed and refined of the performance of Stirling engines optimized for the temperature ranges and thermal power input possibilities determined from the models in Objectives 2 and 3 above. Engine performance maps will be extracted.

Accomplishment: The model used in the Stirling engine analysis program was refined to include the use identical aluminum finned heat exchangers for each the hot and cold heat exchangers (for cost savings), while optimizing the design to minimize pressure vessel cost, which was used as a proxy for system cost.

The design point criteria of the Stirling engine are:

Electric power: 20 kWe, net of engine's share of parasitic electric power

Number of Stirling cycles: 4

Working fluid: Nitrogen

Charge pressure: 500 psig

Hot heat transfer fluid: Marlotherm N

Hot heat transfer fluid inlet temperature: 190 °C

Hot heat transfer fluid flow rate, nominal: 643 L/min

Cold heat transfer fluid: 30% Dowfrost in water

Cold heat transfer fluid inlet temperature: 25 °C

Cold heat transfer fluid flow rate, nominal: 364 L/min

Optimization strategy: The engine design was optimized to minimize the cost of the pressure vessel at a hot heat transfer fluid temperature of 165 °C, subject to the constraints (among others) that the fraction of Carnot efficiency, taken at the mechanical output of engine and net of engine's share of parasitic mechanical power, is 0.51, and that the engine produce 20 kWe net electrical power at a hot heat transfer fluid temperature of 190 °C.

The Stirling engine analysis program can simulate the operation and optimize the design of two Stirling cycle machines simultaneously, through the use of a generalized reduced gradient optimization algorithm. The Stirling cycle machines can be completely independent, or coupled and constrained arbitrarily. For the 20 kWe engine, both of the simulated Stirling cycle machines are configured as mechanically identical engines, with the temperature of the hot heat transfer fluid powering the first engine being 165 °C, and that powering the second being 190 °C. When the optimization routine runs, dimensions and other parameters are varied, in this case, to minimize an objective function that is the modeled cost of the pressure vessel that contains the Stirling engine and electric generator. Varying the dimensions and other parameters of the first engine automatically varies the same dimensions and parameters of the second engine so that they always remain equal. This method allows the engine to be optimized at the hot temperature of 165 °C, where it is most likely to be operated, while upholding the 20 kWe electric power performance specification at the rating temperature of 190 °C. Since this modeling was completed, the optimization code has been extended to minimize the levelized cost of energy (LCOE) produced by the Stirling engine, given certain operating assumptions about component costs in the engine as a function of native characteristics. An example is the number of tubes in an internal heat exchanger. In a gradient descent algorithm, a version of an engine may be assessed that increases the number of tubes in the engine heat exchangers, increasing performance but also increasing cost. With a merit function defined related to LCOE, the optimization algorithm will calculate whether the change improved or degraded the LCOE performance, and move the optimization in the direction of improved LCOE. In this way, thousand of engine configurations are tested in each optimization run, arriving at designs that trade off the many variables in the engine design such that customer value is maximized.

The following variables were optimized:

- Hot heat transfer fluid flow rate
- Cold heat transfer fluid flow rate
- Cylinder diameters
- Piston stroke
- Gas side fin length
- Gas side fin height
- Gas side fin thickness
- Gas side fin spacing
- Liquid side fin height
- Liquid side fin thickness
- Liquid side fin spacing
- Length of regenerator
- Diameter of regenerator (equal to diameter of hot and cold heat exchangers)
- Thickness of regenerator film
- Spacing of regenerator film

The resulting optimum engine design was used to make the basic engine maps used in the preliminary analysis described in Objective 1 above. These maps calculate heat input rate and electric power generated, as functions of the hot and cold heat transfer fluid temperatures at fixed but optimum volume flow rates, and engine speed. The same optimum engine design was then used to make enhanced maps, which calculate heat input rate, heat rejection rate, electric power generated, hot side fluid pumping pressure drop, and cold side fluid pumping pressure drop, as functions of the hot heat transfer fluid temperature and flow rate and the cold heat transfer fluid temperature and flow rate. Engine speed was not included this time, as it is expected that an engine well-matched to the geothermal heat source would run at maximum speed most of the time. The functions in the engine maps have at most ten coefficients, and were produced with the aid of Eureqa, a data-mining software tool for discovering mathematical relationships in data. The outputs and inputs of these enhanced engine maps were needed for the system

model developed by CEI's research colleagues at CSU, so that operation of the Stirling engine and its ancillary systems could be optimized for maximum net power production over the range of expected inputs.

Work loops predicted by the Stirling engine analysis program at the rated design of 20 kWe electric output power are shown in Figure 3 below.

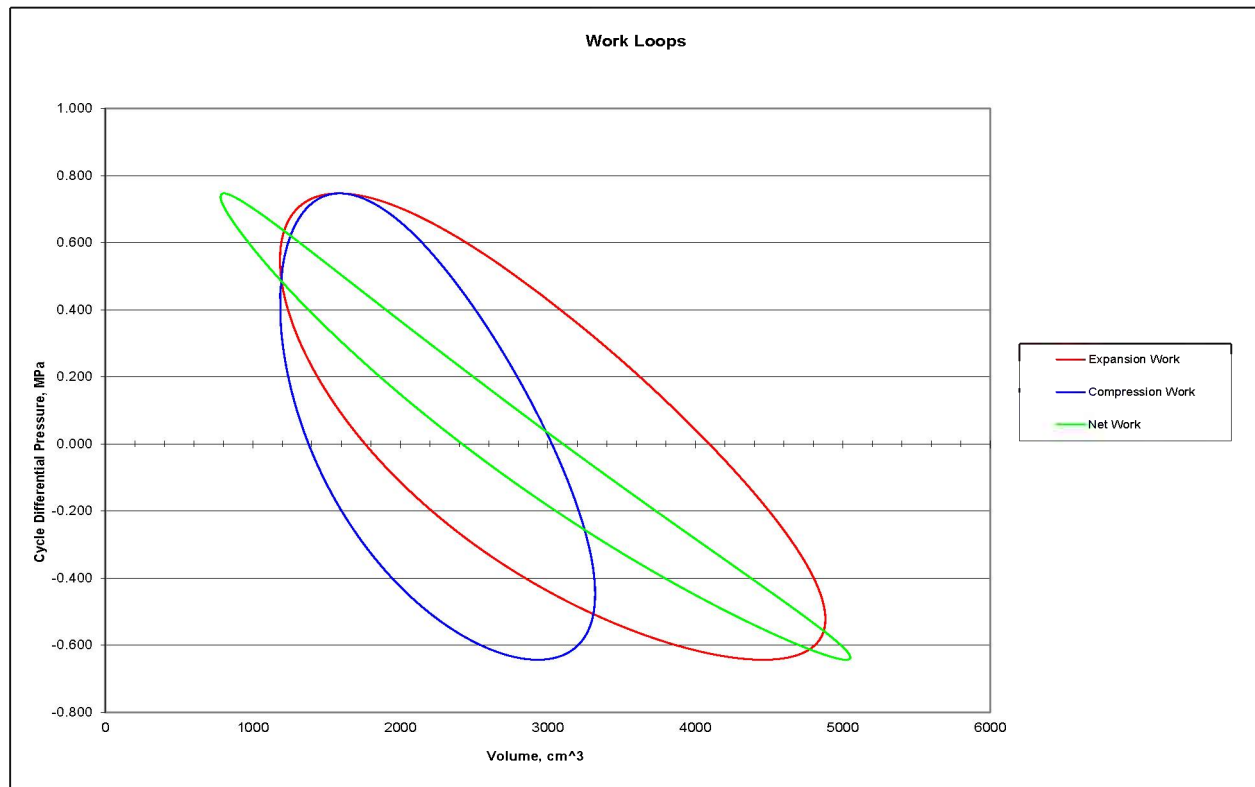


Figure 3) Predicted expansion, compression, and net work loops, for 190 °C hot temperature, 25 °C cold temperature, 500 psig charge pressure, and 600 rpm. Predicted net work per cycle is 611 J.

Predicted distribution of losses are shown in Figure 4 below.

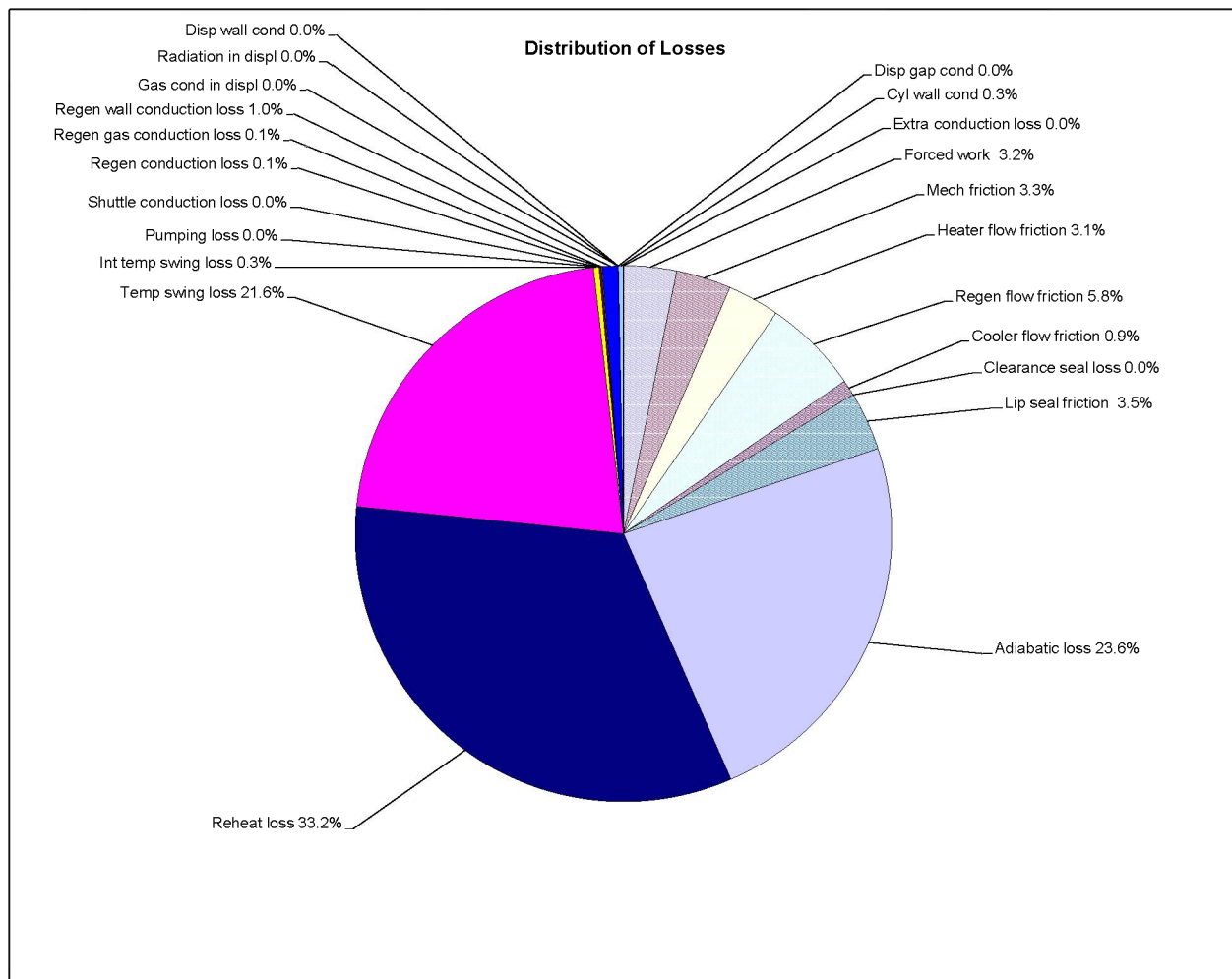


Figure 4) Predicted distribution of losses for 190 °C hot temperature, 25 °C cold temperature, 500 psig charge pressure, and 600 rpm.

A map of predicted thermal-to-electrical efficiency is shown in Figure 5 below.

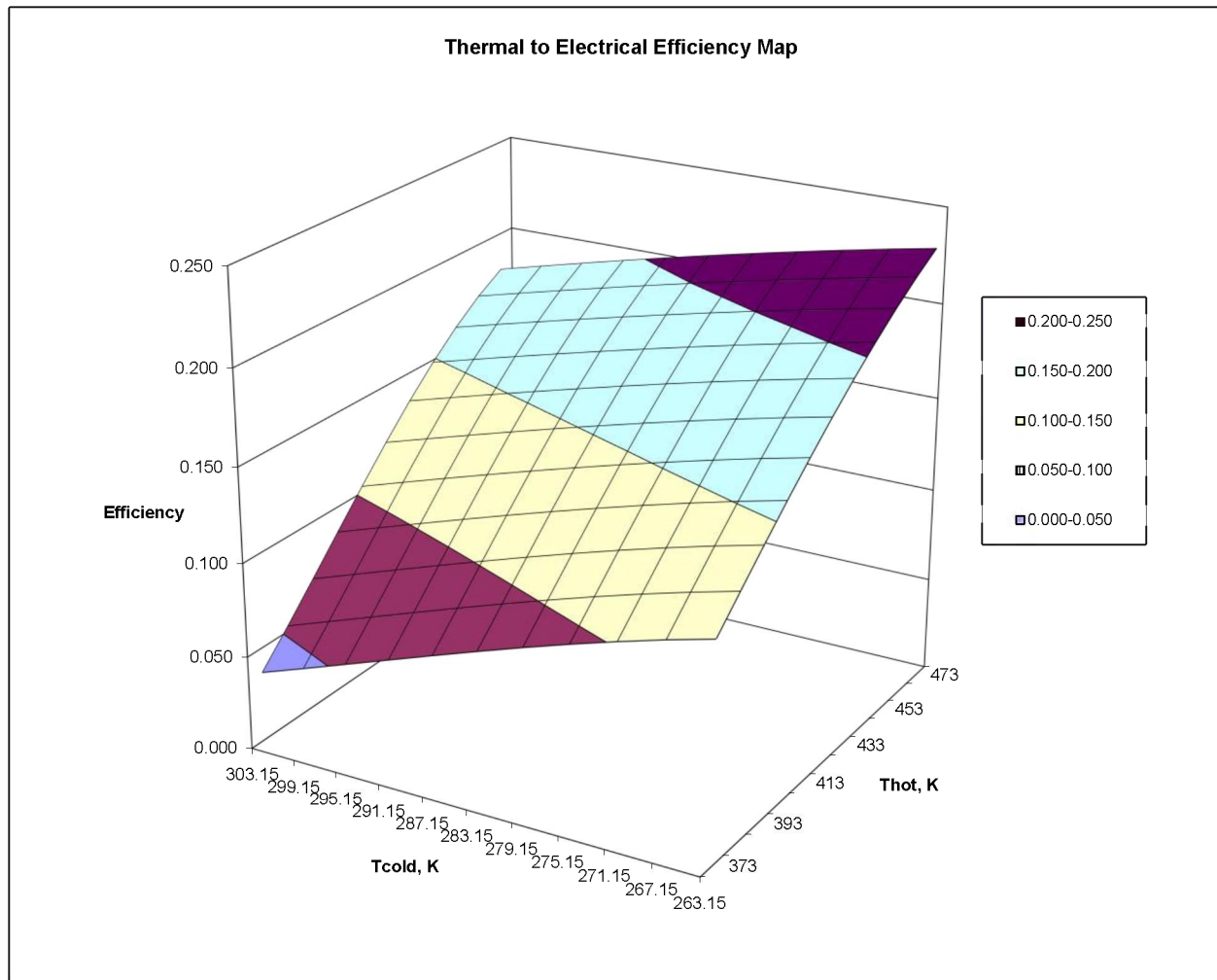


Figure 5) Map of predicted thermal-to-electric efficiency versus hot and cold heat transfer fluid temperatures.

In addition to optimizing the thermodynamic design of the engine, a detailed mechanism design was performed on a rotary transmission which provides kinematic linkages between the thermal cycles to achieve the relative phase relationship necessary between each cycle's hot and cold pistons. This mechanism has to bear the forces delivered from the hot and cold pistons, and is designed using sealed and shielded bearings to eliminate circulating lubricants in the engine. Hence, the bearing design for reliable operation is of great importance. A further function of this rotary mechanism is to transform the linear motion of each piston into rotary motion to turn a permanent-magnet generator. A complete dynamic engine mechanism model was assembled for two alternate versions of the rotary mechanism, one with a barrel cam and wheeled-carriage design, and a second with a Watt linkage and swashplate design. Each of these alternatives have advantages and disadvantages, but from the standpoint of simplicity and lowest cost, the Watt-linkage/swashplate design is superior. The dynamic mechanism modeling also revealed that not only is the bearing count lower for the Watt linkage by about half, but the sizes required of the bearings is also lower. After completing this design analysis, the 20 kWe Watt linkage mechanism coupled with a new shell-and-tube heat exchanger design was selected as the best thermo-mechanical layout for low-to-medium temperature geothermal applications. The barrel-cam/carriage mechanism version of a 20 kW geothermal engine is shown at left in Figure 6, and the Watt-linkage/swashplate version is shown on the right.

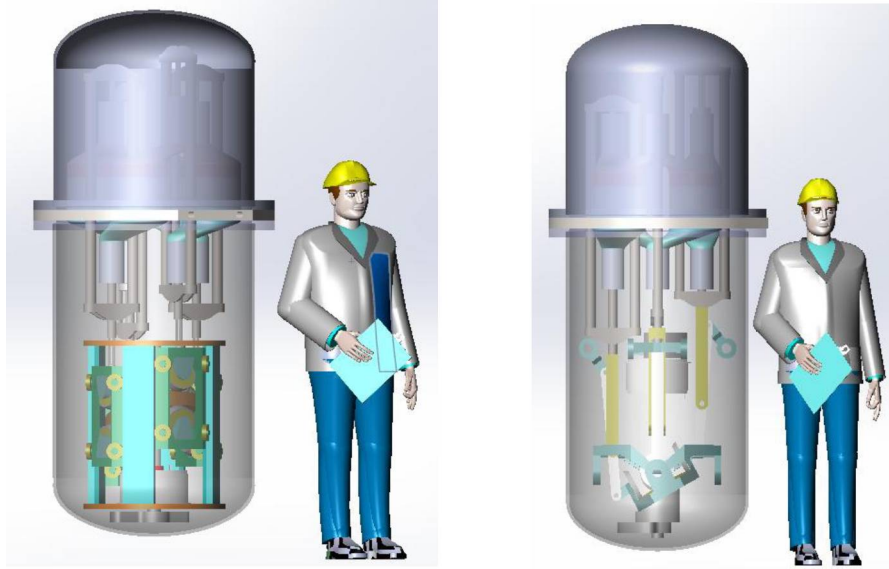


Figure 6) Left - CAD model of barrel-cam/carriage kinematic linkage for 20 kW Stirling engine; right- CAD model of Watt-linkage/swashplate kinematic linkage for 20 kW Stirling engine.

5. Objective: How the tradeoff between the temperature drop imposed on the geothermal heat stream, the cost to pump the geothermal heat stream, the size of the Stirling engine system, the number of cascaded cycle stages (if so configured), and engine efficiency impacts the electric power produced will be determined.

Accomplishment: A Stirling engine assumed to be installed at an active well and powered by the geothermal heat in the co-produced water stream was examined, in the single-stage configuration shown in Figure 7 below. The co-produced water enters Heat Exchanger A, where it provides heat to the hot heat transfer fluid at a rate of $\dot{Q}_{in}$. The hot heat transfer fluid leaves Heat Exchanger A at temperature T_h and enters the engine. The cold heat transfer fluid leaves Heat Exchanger B at temperature T_c and enters the engine. Heat Exchanger B rejects heat at a rate of $\dot{Q}_{out}$ to air convected across Heat Exchanger B by a fan.

The net power output of the system is the gross electric power output of the Stirling engine minus the parasitic electric power necessary to run the pumps and fan, and is given by

$$\dot{W}_{net} = \dot{W}_{elec} - \dot{W}_{hot} - \dot{W}_{cold} - \dot{W}_{air}, \text{ where}$$

$\dot{W}_{net}$ = Net electric power output of system, W

$\dot{W}_{elec}$ = Electric power generated by Stirling engine, W

$\dot{W}_{hot}$ = Electric power required to pump hot heat transfer fluid, W

$\dot{W}_{cold}$ = Electric power required to pump cold heat transfer fluid, W and

$\dot{W}_{air}$ = Electric power required to convect air through Heat Exchanger B, W.

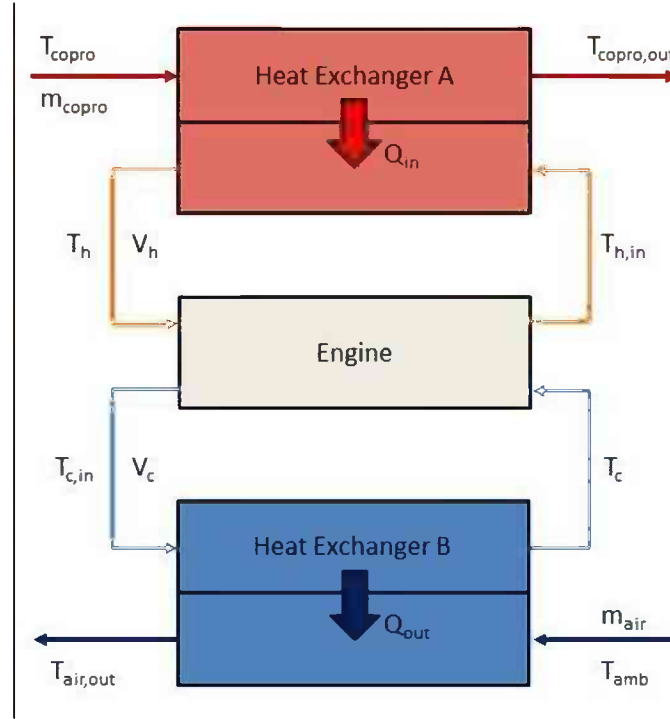


Figure 7) Schematic of single-stage Stirling engine system.

$\dot{W}_{elec}$ is a function of the hot and cold heat transfer fluid temperatures, T_h and T_c respectively, and volume flow rates, V_h and V_c respectively. T_h and T_c are functions, directly or indirectly, of V_h and V_c respectively, the co-produced fluid temperature T_{copro} and volume flow rate V_{copro} , and the ambient air temperature T_{air} and mass flow rate through the heat rejection heat exchanger $\dot{m}_{air}$. Thus, $\dot{W}_{net}$ is a function of the independent variables T_{copro} , V_{copro} , T_{air} , $\dot{m}_{air}$, V_h , and V_c . Because T_{copro} , V_{copro} , and T_{air} are externalities and thus are not changeable by the system, the only variables available to search over in maximizing $\dot{W}_{net}$ are $\dot{m}_{air}$, V_h , and V_c .

6. **Objective:** With the results of objective 5 above, the temperature conditions, power outputs of the engine and each stage (if so configured), the engine design(s), and engine cost will be determined.

Accomplishment: The optimization was performed for the 20 kWe engine design described in Objective 4 above, characterized mathematically by the enhanced performance maps. The density and specific heat of the hot and cold heat transfer fluids were also characterized mathematically, by curve-fits of property data.

Thermal models of Heat Exchangers A and B, the pressure drop model of the ambient air being convected across Heat Exchanger B, and the MATLAB optimization program to maximize $\dot{W}_{net}$ were developed by CEI's colleagues at CSU. Because the enhanced engine performance maps were constructed over specific ranges of the input variables T_h , T_c , V_h , and V_c , the input variables were constrained to be within these ranges during optimization. The models used for Heat Exchangers A and B both identify a "pinch point" temperature, which is the difference between the temperatures of the two fluid streams at that point in the heat exchanger where this difference is the minimum. The pinch point temperatures of both heat exchangers were constrained to be not less than 5 K during optimization.

The system performance map is a hyper-surface, assumed to be continuous, that maps T_{copro} , V_{copro} , and T_{air} onto the optimal $\dot{m}_{air}$, V_h , and V_c that maximize $\dot{W}_{net}$. With enough points found on this hyper-surface to allow accurate interpolation between them, the hyper-surface can be represented by explicit functions in T_{copro} , V_{copro} , and T_{air} curve-fit to the points. The functions thus provide a fast, not-iterative way to calculate the system's optimal performance over the range of allowable inputs. Individual points were obtained by maximizing $\dot{W}_{net}$ over the variables $\dot{m}_{air}$, V_h , and V_c , subject to the constraints above, for given T_{copro} , V_{copro} , and T_{air} at each point. 3696 such points were generated by systematically varying T_{copro} , V_{copro} , and T_{air} , each over the following ranges, respectively:

T_{copro} , from 110 °C to 160 °C in increments of 5 °C
 V_{copro} , from 5 gpm to 120 gpm in increments of 5 gpm
 T_{air} , from -25 °C to 40 °C in increments of 5 °C

7. **Objective:** With the results of objectives 4, 5, and 6 above, operational models will be developed of geothermal Stirling-based power plants, including annual hourly power generation profiles, hourly efficiency profiles, startup and shutdown procedures, LCOE, and return on investment.

Accomplishment: One operational model of the geothermal Stirling-based power plant was developed, based on running opportunistically as much as possible while being optimally managed in accordance with the system performance map described in Objective 6 above. The operational model was validated in a simulation using the borehole temperature and flow rate of the co-produced hot water (calculated from actual monthly production data) of a Texas, high-output natural gas well, and hourly ambient air temperature in the vicinity of the well (from climate data collected by the National Climatic Data Center), over the course of a year. The system performance map receives as inputs the temperature and flow rate of the co-produced water and the ambient air temperature, and then calculates the hot heat transfer fluid volume flow rate, cold heat transfer fluid volume flow rate, and heat rejection radiator air mass flow rate to be used in each hour of the simulation. Previously determined during construction of the system performance map, these three flow rates are the optimums that maximize the net electric power output for the particular inputs in a given hour. The total energy potential for this well over the course of the year was 94.4 MW-h.

The top well listed in Table 3, API 42479406730000, was selected for this analysis. This well had the highest electric potential of all producing wells from the Texas data queries.

Production data was collected on a monthly basis from the Texas RRC Production Data Query Tool for the months of December 2011 until November 2012. Because the co-production flow rate is not reported in the public data, it was estimated from the gas production using a water-to-gas ratio (WGR) of 511 bbl/MMCF. The co-production flow rate was assumed constant for each month, due to the unavailability of hourly data in the gas production rate.

Quality-controlled local climatological data were downloaded from the National Climatic Data Center (at <http://cdo.ncdc.noaa.gov/qclcd/QCLCD>) to determine the ambient temperature on an hourly basis for the corresponding months of gas production. The station COTULLA-LA SALLE CO ARPT was selected, as it is in the vicinity of the well. Data were filtered by averaging the temperature from all records for each hour. Linear interpolation was used to fill hours where data gaps existed.

The co-production temperature was assumed constant at 160 °C over the course of the year, as a better approximation was unavailable from the data. This value was selected to account for some cooling of the fluid as it rises through the borehole and traverses to the heat exchanger. It is also the upper limit of the range for which the optimized solution was calculated to create the system performance map.

The inputs T_{copro} , V_{copro} , and T_{air} are plotted in Figure 8 below, for each hour in the year.

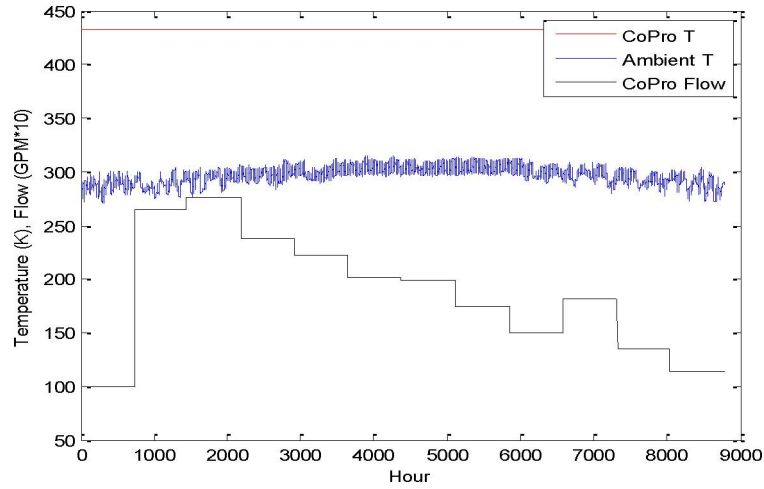


Figure 8) Inputs at each hour in the year.

The net power produced and the system temperatures are shown below in Figure 9, left and right respectively, both over the course of the year. The temperature of the co-produced fluid leaving Heat Exchanger A is strongly dependent on the flow rate, as seen by comparing the coproduction outlet temperature in the right of Figure 9 to the co-production flow rate in Figure 8. The left graph in Figure 10 shows the net power and ambient temperature over a two-day period, and shows that as the ambient temperature rises, the net power production decreases. The right graph in Figure 10 shows the system temperatures over the same two-day period. The temperatures of Heat Exchanger B track the ambient temperature. The temperatures in Heat Exchanger A are steady since the co-production flow rate and temperature are more steady. Startup and shutdown procedures were not addressed, as the system ran full time in the simulation.

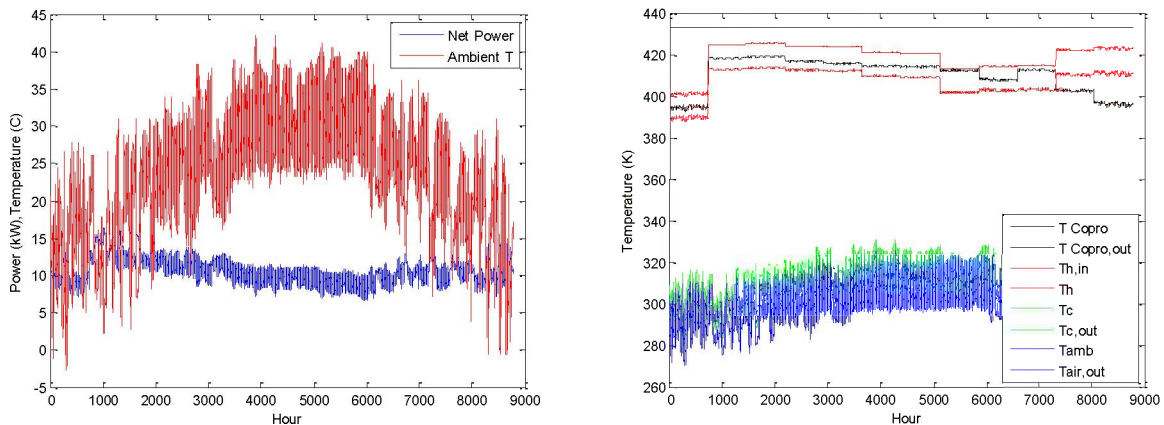


Figure 9) Left - hourly net power and ambient temperature; right - hourly system temperatures

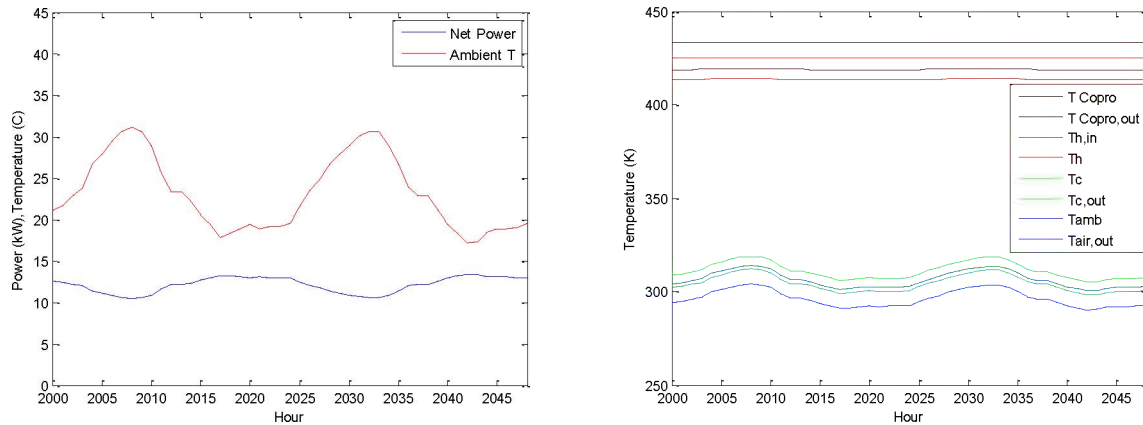


Figure 10) Left - power production over 48 hours; right - system temperatures over 48 hours

In addition to advantages due to the modular nature of the Cool Energy approach, the native economics of the system have extremely promising prospects. The variables that determine customer returns include the initial cost of the system, the maintenance costs of the system, discount rate, interest rate, capacity factor of system utilization, and payment rate for generated electricity. Two cases were examined for customer value: Use of electricity to avoid diesel fuel use, and use of the electricity to avoid retail electricity consumption in the field. In both cases, for a given capacity factor the levelized cost of energy (LCOE) produced is the same, while the user revenue (avoided costs) depends on the avoided electricity rate. Figure 11 shows the LCOE as a function of capacity factor given the expected production costs of a 20 kWe Stirling engine system operated at its maximum output. Assumptions include cash purchase of the engine with all necessary balance of system components and installation for \$50,000, 10 years of operation, \$0.01/kWh operations and maintenance costs, and a 7% discount rate.

The value proposition for the two customer application scenarios considered – offsetting diesel electricity, and offsetting retail electricity – is markedly different. Assuming that the Stirling engine units in these scenarios will operate at 90% capacity factor on the co-produced liquids from the operating well, the first scenario will avoid electricity at about \$0.35/kWh from field generation, and the second class will avoid electricity at about \$0.10/kWh. These avoided rates do depend on geography and diesel fuel pricing, but are based on median US prices. These are also native costs, and do not include the 10% Federal Investment Tax Credit for heat recovery equipment, nor any renewable power production incentives that are available federally and in some states. Simple payback and internal rates of return (IRR) for the two scenarios are below:

Avoided diesel fuel consumption simple payback: 0.93 years
Avoided diesel fuel consumption IRR: 107%

Avoided retail electricity simple payback: 3.5 years
Avoided retail fuel consumption IRR: 25.4%

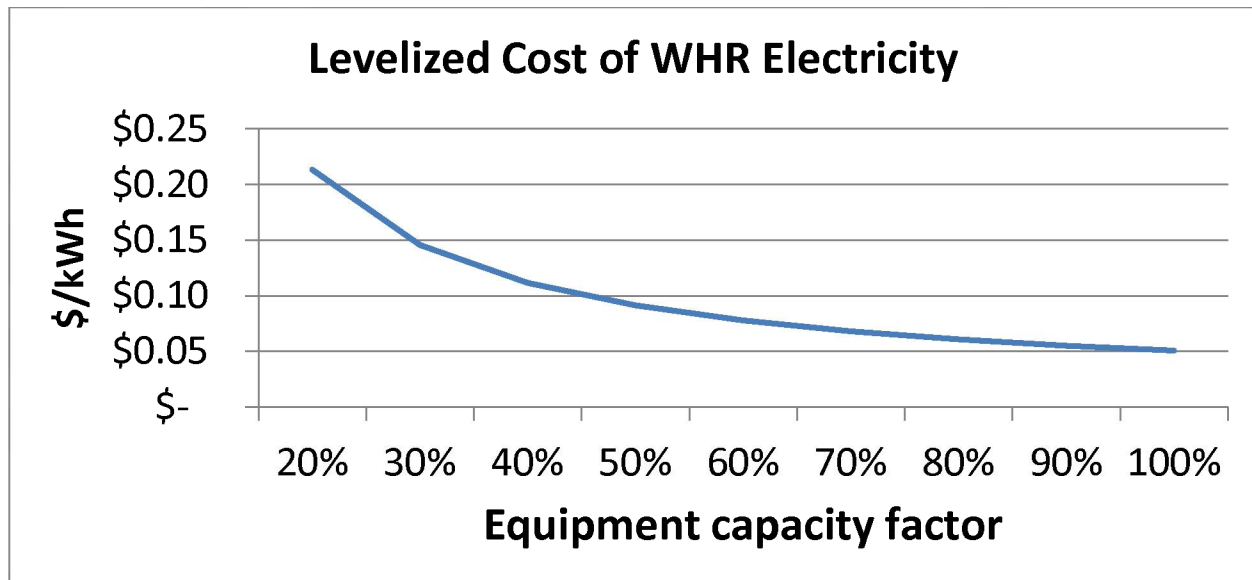


Figure 11) The projected levelized cost of generating electricity using a Stirling engine system as a function of the capacity factor. The installed system cost is expected to be \$2500/kW in manufacturing volumes of a few hundred per year.

Economic and Market Analysis:

An important part of the Phase I effort was to quantify the opportunities for power generation using the geothermal heat flows from active wells using borehole data from 480 sampled wells. The overall conclusion was that around one percent of active wells could produce meaningful power levels (>10 kWe). While this sounds like a small number, this analysis is most accurate for single wells in isolation, because the methods to assess multiple nearby opportunities in a given field were limited, and this analysis does not take into account the potential from fields that have steam injection processes to stimulate production. Conservatively, the two latter points (as well as analysis of geographies in addition to Montana and Texas) could double the number of wells to which geothermal heat recovery would be meaningful to 2% of the total 825,000 producing wells in the US.² This represents 16,500 opportunities, and the median well production of those considered practical was 20 kWe in the Texas analysis, for a total practical US capacity of 330 MW of power generation from co-produced fluids. At an economic cost of \$1500/kW to \$2500/kW depending on well characteristics and engine production volume, the total market for power generation from co-produced fluids using a Stirling engine system is \$500M to \$800M. Adding the rest of the world could perhaps double this entire market to \$1B to \$1.5B total, since there are about as many wells in the rest of the world as there are in the US. This is the total size of the niche market in geothermal power production that Cool Energy will address in the Phase II commercialization effort. The 330 MW represents clean baseload power generation that prevents the combustion of diesel or coal to generate. According to the EPA, a single megawatt hour (MWh) of electricity generated from geothermal water (rather than grid electricity) will reduce carbon dioxide emission by 705 kg. Over the course of a single year, assuming 90 per cent capacity factor, 5560 tonnes of CO₂ emissions are avoided for each MW of installed geothermal capacity. If the full 330 MW of potential generating capacity were realized through the Stirling engine co-produced fluids approach, 1.8 Mtonnes of CO₂ emissions would be avoided each year, as well as additional SO_x and NO_x emissions from stationary power plants.

² US Energy Information Administration, United States Distribution of Wells by Production Rate Bracket, 2009

Another important part of the Phase I effort was to produce and analyze candidate designs for a 20 kW Stirling engine operating at co-produced fluid temperatures of 100 °C to 200 °C. Both the thermodynamic optimization and the mechanical design and analysis were performed for a four-cylinder, low-temperature 20 kW engine based on the components used in the operating 3 kW Stirling engines at Cool Energy. In order to minimize the size and cost of the engine, a rotary kinematic linkage was chosen to couple the single-acting alpha thermodynamic configuration to the electrical generator. Two different rotary mechanisms were modeled and analyzed: A carriage/barrel-cam design, and a Watt-linkage/swashplate design. Each engine design was analyzed for expected performance, bearing lifetime, piston ring lifetime, and expected cost. Estimates received for volume manufacturing of the 3 kW units, and scaling these to the size and weight of the 20 kW units, produces a cost estimate of \$20,000 for the Stirling engine, with a sales price of \$30,000 in manufacturing volumes of 250 per year. The remaining balance of systems for extracting the heat from the co-produced liquids, delivering it to the Stirling engine, rejecting heat from the Stirling engine, controlling the Stirling engine, installing the system, and coupling the electricity to the local grid amount to an additional \$20,000. For a full 20 kW installation, the cost would be \$50,000, or \$2500/kW. For larger capacity sites, multiple engines will be connected on a single heat transfer manifold, and the balance of system components will be spread over multiple Stirling generators, reducing the system cost significantly. Higher volume manufacturing would also reduce the Stirling engine cost to \$1000/kW, so the expected system cost could be as low as \$1500/kW for larger field sites and higher manufacturing volumes.

Products Developed: While no publications were produced during the Phase I projects, a paper is planned to be authored on the results during the second half of 2012. The collaboration between Colorado State University and Cool Energy was the first such joint work between these organizations. A portion of this work is also likely to be included in the doctoral thesis of Clay Bell. Techniques were developed for exporting an engine map from Cool Energy's Stirling engine simulation software into MATLAB, where CSU researchers coupled the engine map into models of the heat flows from co-produced liquids to simulate hourly performance of geothermal power generation.

Conclusion: This Phase I study showed that it is clearly technically and economically feasible to produce electricity using a low-temperature Stirling engine driven by the thermal energy found in co-produced fluids from oil and gas operations in Texas and elsewhere. A 20 kW engine has been designed and analyzed for performance and reliability, and cost estimates for the installed power system ranging from \$1,500/kW to \$2,500/kW were produced. The levelized cost of energy for each individual well will depend on the well capacity factor and liquid temperatures and flow rates, but can range from a low of \$0.03/kWh in a field with multiple well sources at higher temperatures and capacities, to a high of \$0.10/kWh in a field with a single lower-temperature source and only a 50% capacity factor. Payback times for the operators of such systems can range from six months to 5 years, depending on the type of electricity displaced. The study also showed that there are about 330 MW of practical power generation available from small-scale, low-temperature co-produced liquid wells. Harnessing these opportunities will avoid diesel, coal, and natural gas combustion and their associated pollution emissions. If the full 330 MW of potential generating capacity were realized through the Stirling engine co-produced fluids approach, 1.8 Mtonnes of CO₂ emissions would be avoided each year, as well as additional SO_x and NO_x emissions from stationary power plants.