



## ThermoHeart™ 25 kW<sub>e</sub> Advanced Materials Stirling Engine

Every day, all over the world, millions of dollars of valuable heat energy is wasted by being vented to the atmosphere. Sources of this wasted heat include drying and curing ovens, pollution control equipment, ceramic kilns, and engine exhaust across many different industries, including chemical manufacturing and refining. While good technologies exist to create value from these heat streams at the largest scales (hundreds of kW to MW), there are few good options for waste heat recovery (WHR) below 100kW. This situation leaves billions of dollars in clean electricity generation unrealized, causing unnecessary waste and pollution.

### **Cool Energy 25kW<sub>e</sub> Product Development Overview:**

One important solution to this challenge is Cool Energy's ThermoHeart™ Engine which converts low-temperature wasted heat into clean electricity. This engine has been developed by Cool Energy, Inc of Boulder, CO and has demonstrated high conversion efficiency and operating reliability. The ThermoHeart Engine differs from other Stirling engines because it can use lower temperatures for its heat input (100 °C to 400 °C) than typical heat engines. Harnessing heat from this lower and previously untapped temperature range opens an entire new set of efficiency and renewable applications for power generation. The 25kW output power of the ThermoHeart Engine enables distributed renewable power systems in applications such as waste heat recovery, solar thermal electric, and biomass power. Initial testing has begun on the 5th generation 25kW units, and has demonstrated over 30% thermal to electric conversion efficiency at 310°C. This remarkable efficiency level is the result of a historically novel engine design, advanced materials of construction, and high-effectiveness internal heat exchangers.



**The ThermoHeart® Engine – its applications and contributions to our energy needs:** The primary market application for the ThermoHeart engine, due to its rapid payback time, is the recovery of wasted and exhaust heat to produce electricity. Application environments include commercial and industrial facilities, remote and military generators, and ship engines, all of which can benefit from using the ThermoHeart Engine for electricity production. Aside from providing cost savings and reducing emissions from using less fuel and power, other advantages of the ThermoHeart Engine include reducing the need to transport fuel to remote and military locations, a process that is often expensive and logistically difficult (and for the military, often dangerous). Among the additional

applications for the ThermoHeart Engine are the use of **solar thermal, biomass, and geothermal sources** for powering homes and buildings.

Development of the ThermoHeart Engine began in 2006, and has been supported in part through grant awards from the US National Science Foundation, the Department of Energy, and the Environmental Protection Agency as well as contracts from the Dept. of Energy and Colorado Governor's Energy Office. Cool Energy has developed historically novel Stirling engines composed of high-surface-area heat exchangers, non-metallic self-lubricating piston/cylinder sets, and non-metallic regenerators. The design approach employed by Cool Energy has emphasized reduced cost and high reliability to minimize the total cost of ownership and hence the cost of the energy produced. Designed initially for operations at lower temperatures and moderate conversion efficiencies (10% to 25%) for waste heat recovery, conceptual designs have been generated to extended to higher temperatures in order to increase efficiency for use with concentrating solar power or biomass combustion. The fourth-generation prototype pictured on the top of the first page has demonstrated an output of 3.1 kW<sub>e</sub> at 300 °C input temperature and 20 °C rejection temperature with conversion efficiencies of over 22%. One of the fourth-generation prototypes was sold to Schneider Electric and delivered in 2011, where it is on a pilot test stand. Two of the fourth-generation prototypes are on test in Boulder, Colorado, where they have accumulated 9000 operating hours of power production between them.

### **Waste Heat Recovery applications for ThermoHeart® Engines<sup>1</sup>**

**The ThermoHeart® Engine can be used to recover low grade waste heat that has previously been uneconomical to recover, and boost operational efficiency of a power generator or process:**

The ThermoHeart Engine can be used with any heat source in the engine's optimal input temperature range of 100-300 °C (up to 400 °C for special applications). Whereas cost-effective waste heat recovery solutions at higher temperatures (over 500 °C) already exist, the ThermoHeart Engine offers a solution for low grade waste heat recovery from commercial and industrial processes, from remote and military generators, and from large-scale propulsion engines. This approach increases the efficiency of operations and reduces fuel consumption.

**The ThermoHeart Engine boosts the fuel efficiency of a diesel generator when recovering its waste heat:**

The ThermoHeart Engine can boost the output of a diesel genset by 5% to 10% when recovering the waste heat the generator exhausts. In remote and military settings where fully burdened diesel fuel can cost up to \$15/gal including transport costs, the payback period for the engine can be under one year. The reduced requirement for transport of fuel is a highly valuable benefit to the military, as a significant fraction of modern war-fighting casualties occur during resupply missions of water and fuel.

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<sup>1</sup> Certain information about waste heat recovery presented in this section has been acquired from the website of the U.S. Department of Energy Intermountain Clean Energy Application Center – Waste Heat Recovery

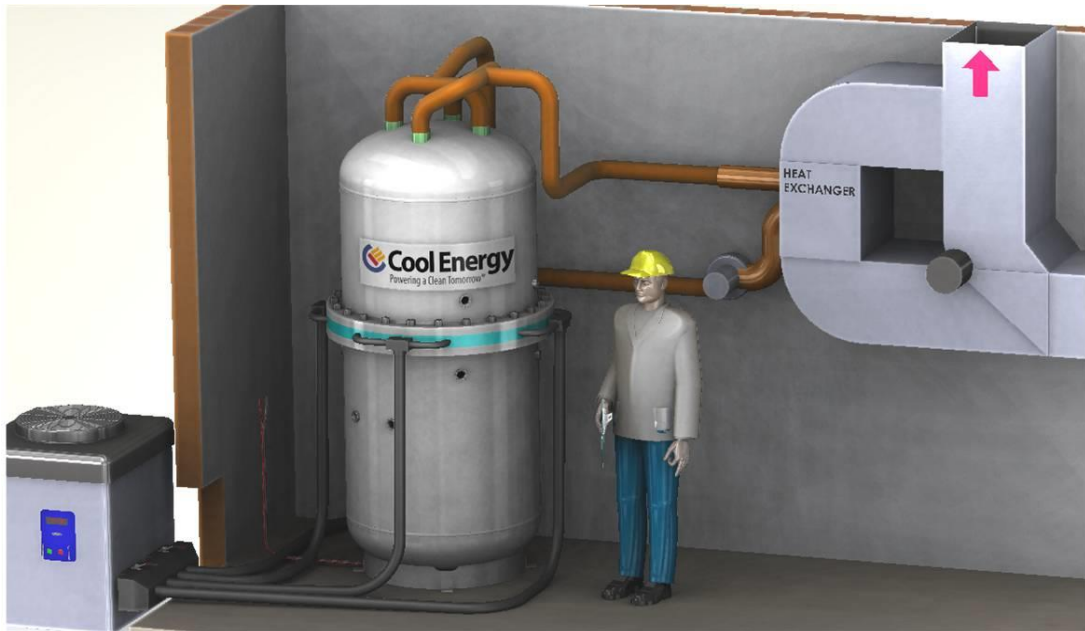


Figure 1) Rotary-drive 25 kW<sub>e</sub> Stirling engine shown in an example waste heat recovery application. The source of hot gas flowing through the engine heat exchanger could be a reciprocating engine exhaust stream, or waste from an industrial process or pollution control equipment. Gas temperatures up to 600°C can be used, even though the heat transfer fluid used to deliver thermal energy to the engine will not exceed 400°C.

An illustration of the ThermoHeart Engine configured to capture waste heat from a genset is included below.

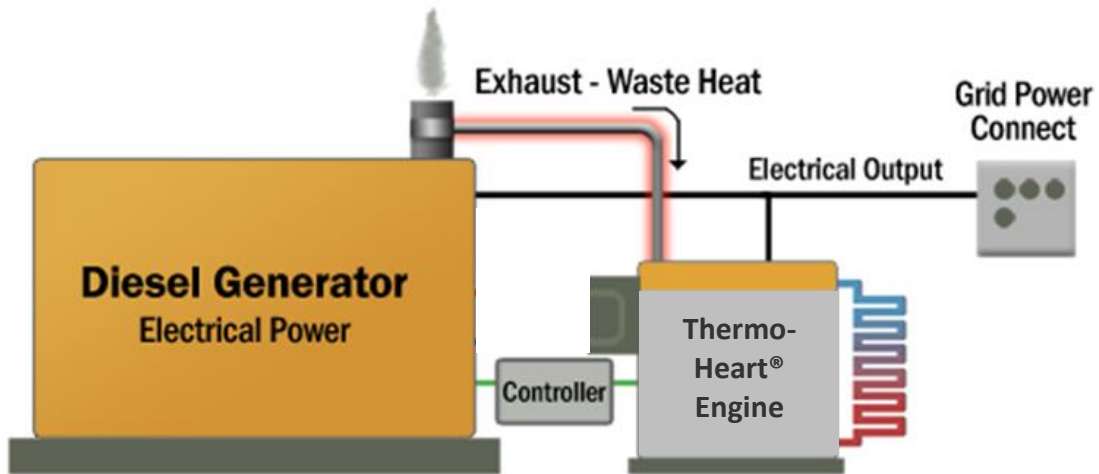
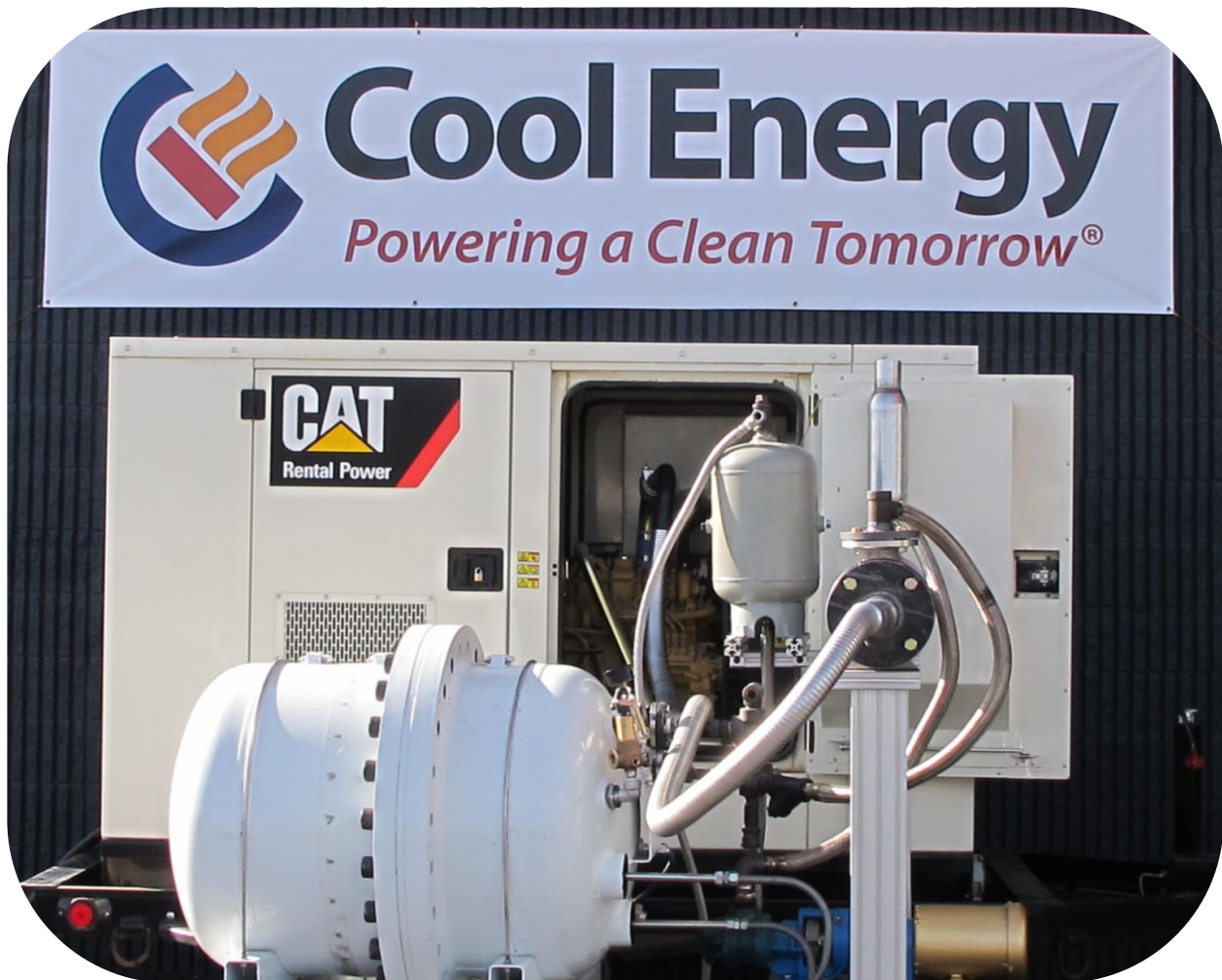


Fig 2) ThermoHeart® Engine configured to recover genset exhaust waste heat

**The ThermoHeart® Engine is efficient and simple in its operation**

Cool Energy, Inc. • 5541 Central Ave, #172 • Boulder, CO • 80301 • tel (303) 442-2121 • fax (303) 442-0820  
[www.coolenergyinc.com](http://www.coolenergyinc.com)

The ThermoHeart target operating temperature range enables materials to be used in the engine components that minimize thermal losses and reduce weight and cost relative to typical engines operating at high temperatures. Advantages the Stirling engine has over organic Rankine cycle machines include excellent part load performance, a wide operating temperature range not constrained by temperature restrictions of the working fluid, and high performance at both constant and variable rates of waste heat production.



*Fig 3) 3 kW<sub>e</sub> ThermoHeart® Engine boosting genset output by 5% to 7%.*

**Other Useful Information about Cool Energy and the ThermoHeart® Engine**  
**More about Stirling engines:**

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Cool Energy has developed the ThermoHeart® Engine which is a heat engine based on the Stirling cycle (invented in the early 1800's by Robert Stirling) and for which no internal combustion is required. The Stirling engine is a heat engine that operates by expansion and compression of air or other gas (called the working fluid), at different temperature levels such that there is a net conversion of heat energy to mechanical work. The ThermoHeart Engine uses air as the working fluid, and is driven by relatively low temperatures (100 °C-300 °C). The mechanical work generated drives a generator built inside the engine that creates electrical power.

**The ThermoHeart Engine is quiet:**

Because the ThermoHeart Engine operates at a relatively low speed (600 rpm), has no internal combustion or explosions and is fully balanced, the engine is extremely quiet and low in vibration. The metal housing adds acoustic and thermal insulation.

**Reliability of the ThermoHeart Engine:**

The ThermoHeart Engine is designed for a 20,000 hour service interval – 3 years at 80% operating time. The anticipated lifetime of the engine is over 100,000 operating hours. There is no internal lubrication required as all bearings are sealed and the moving seals are self-lubricating. Two 3kW units are being evaluated for reliability on a continuous-operation test stand. One runs continuously, while the other is torn down and the key components are measured to determine wear rate and estimate component lifetime. One engine has 5000 hour of run-time (180,000,000 revolutions), while the other has 2800 hours of run-time.



*Fig 4) left: 25kW ThermoHeart® Engine. The penetrations in the upper pressure vessel are the thermal heat transfer oil inlets and outlets. The heat rejection fluid is circulated through the center aluminum plate.*

**25 kW<sub>e</sub> ThermoHeart Engine preliminary specifications:**

Operating speed: 600 RPM

Engine weight: 8700 lbs

Engine dimensions: 52" dia. x 105" tall

Lifetime: 180,000 hours, with service interval every 20,000 hours

Operating Ambient Temperatures: -40C to 80C

Output Voltage: up to 350V-dc

Operating parameters: see table below

Expected Operating Parameters for a Cool Energy 25 kW<sub>e</sub>, 400°C ThermoHeart® Engine with a 20°C rejection environment. Lower rejection temperatures will produce higher powers and efficiencies.

Hot Side Inlet Temp, °C	Oil Flow Rate, L/min	Hot Side Outlet Temp, °C	Input Heat Rate Required, W	Rejection Heat Rate Required, W	Gross Generator Output Power, W	Thermal to Electrical Conversion Efficiency
150	115	131	67505	60363	7201	10.7%
150	170	137	67883	60236	7712	11.4%
150	250	141	68112	60153	8042	11.8%
150	380	144	68216	60086	8277	12.1%
200	115	179	74245	61864	12439	16.8%
200	170	186	74576	61724	12915	17.3%
200	250	190	74773	61631	13221	17.7%
200	380	194	74847	61549	13438	17.9%
250	115	228	79724	62798	16981	21.3%
250	170	235	79996	62639	17417	21.8%
250	250	240	80158	62536	17698	22.1%
250	380	243	80222	62456	17899	22.3%
300	115	277	84698	63768	20981	24.8%
300	170	284	84940	63613	21383	25.2%
300	250	289	85084	63512	21643	25.4%
300	380	293	85136	63434	21828	25.6%
350	115	325	89157	64725	24482	27.5%
350	170	333	89386	64578	24863	27.8%
350	250	339	89215	64263	25000	28.0%
350	380	343	88561	63659	25000	28.2%
400	115	376	83222	58247	25000	30.0%
400	170	384	82316	57343	25000	30.4%
400	250	389	81742	56782	25000	30.6%
400	380	393	81299	56384	25000	30.7%

### **About Cool Energy, Inc.:**

Cool Energy is a privately held corporation, based in Boulder, Colorado.

To date, Cool Energy has been backed primarily by angel and venture capital investment and has received several SBIR grants from the National Science Foundation and the Environmental Protection Agency, as well as a Department of Energy subcontract and a Colorado Governor's Energy Office grant. Cool Energy is currently raising its Series B round of capital for the purposes of beginning volume manufacturing.

For more information about the company, please contact Sam Weaver, CEO at [spweaver@coolenergyinc.com](mailto:spweaver@coolenergyinc.com) or 303-442-2121.

The dimensions, drawings, typical illustrations, weights, materials, and details of construction included herein, while representing the best information available at the time of the issuance of this Proposal, may vary from that set forth during the development of the final design under terms of contract. Such drawings as are included in this Proposal are intended only to illustrate the arrangement of equipment and are not to be construed as defining the extent and scope of the material Cool Energy proposes to furnish.

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