

**ElectraTherm ORC Primer  
Series 4000 Green Machine**

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# ElectraTherm ORC Primer

## Series 4000 Green Machine



### Preface

The ElectraTherm ORC Primer is a reference guide created to give ElectraTherm's distributors and customers a high level understanding of the basic operation, frequently asked questions and application information as related to the ElectraTherm Series 4000 Green Machine. This document contains reference information only on the theory and operation of the Series 4000 Green Machine.

This document is not to be used for calculating the performance or the output of the Green Machine. As this document will cover, there are many different factors that will affect the output of our Green Machine, and almost everything from hot water temperature, condensing temperature and available heat will affect the Green Machine electrical output and performance. For a complete performance evaluation at your specific site, please visit [www.electratherm.com/pef](http://www.electratherm.com/pef), and fill out a "project evaluation form" to be reviewed and assessed by the ElectraTherm Engineering staff.

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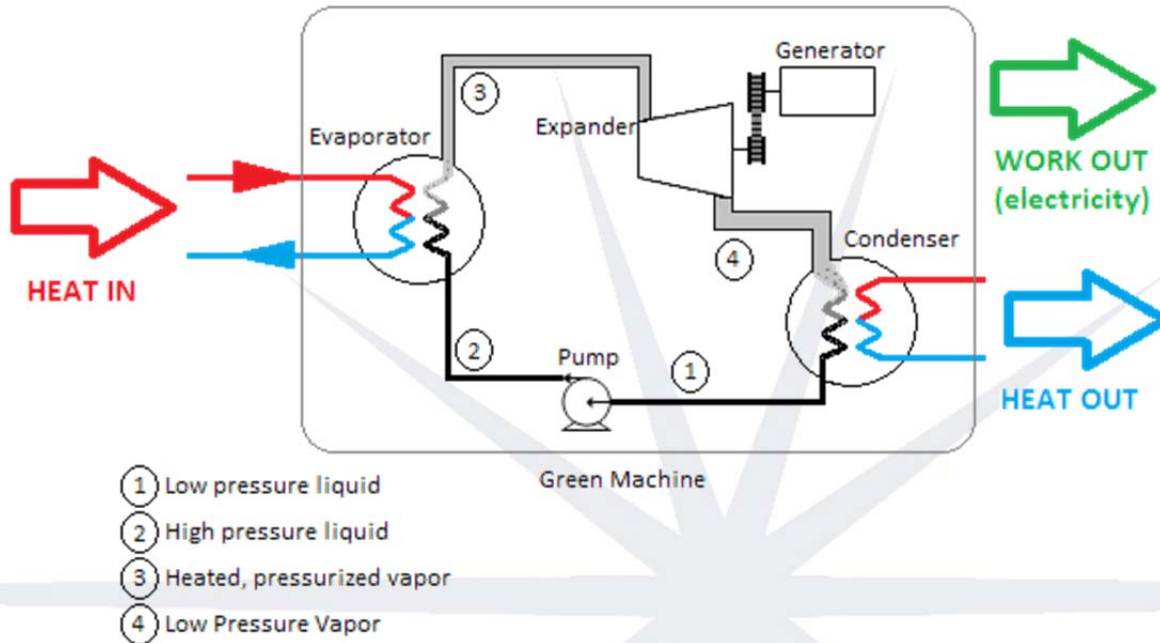
### Table of Contents

Preface .....	2
Table of Contents .....	3
What is an ORC? .....	4
The ElectraTherm ORC is a Heat Engine .....	5
The ElectraTherm ORC Component Breakdown .....	6
Heat Sources .....	9
Water Quality Specifications for the Green Machine for Hot and Cold Sources .....	9
Connecting Various Heat sources to an ElectraTherm Green Machine .....	10
Cooling / Condensing Sources .....	16
Conditions that Affect the Performance of the Green Machine ORC .....	20
Calculating Available Thermal Power .....	26
Cooling to Power Applications using the ElectraTherm Green Machine .....	28
Green Machine Controls and Remote Monitoring .....	28
Induction Generator FAQ .....	29
Green Machine Efficiency .....	31

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### What is an ORC?

The Organic Rankine Cycle (ORC) is a thermodynamic cycle which uses an organic fluid to convert low-temperature heat into mechanical work. That mechanical work can then be converted into electricity. An ORC thermodynamic process transfers the heat using an organic working fluid with a boiling point below that of water. The ElectraTherm Green Machine ORC process is shown below in Figure 1.



**Figure 1: ElectraTherm ORC**

- ①–② The low pressure, low temperature working fluid is pressurized by a pump to the inlet of the evaporator (heat exchanger).
- ②–③ Heat is transferred from the heat exchanger to the working fluid (sensible heat) and the temperature increases until the liquid flashes to a vapor. After vaporization, heat is still added to the vapor (latent heat) without a change in temperature. The high-pressure, heated vapor leaves the evaporator and travels to an expander.
- ③–④ The high pressure vapor turns a twin screw type expander, lowering the pressure and the temperature of the vapor. The work provided by the turning of the twin screw expander is coupled to a generator which produces electricity. The high pressure vapor leaves the expander as a cooler, low pressure vapor.
- ④–① The low pressure vapor enters the condenser, where heat is transferred from the vapor to a cooling source. Once the heat is removed from the vapor, it condenses back into a low pressure liquid, and begins the process over again.

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### The ElectraTherm ORC is a Heat Engine

The ElectraTherm Green Machine is a heat engine. Heat engines can use the Organic Rankine Cycle to convert thermal energy into mechanical work in order to produce electrical energy. The Green Machine uses waste heat (in liquid water form) and moves it from a hot source to a cold sink, while producing mechanical work, as shown in Figure 2.

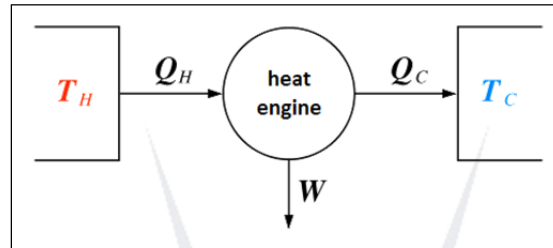


Figure 2: Heat Engine Diagram

In the case of the Green Machine, the mechanical work is produced through the movement of heat is used to drive an electrical generator. Some typical heat sources and condensing sources are shown below in Figure 3.

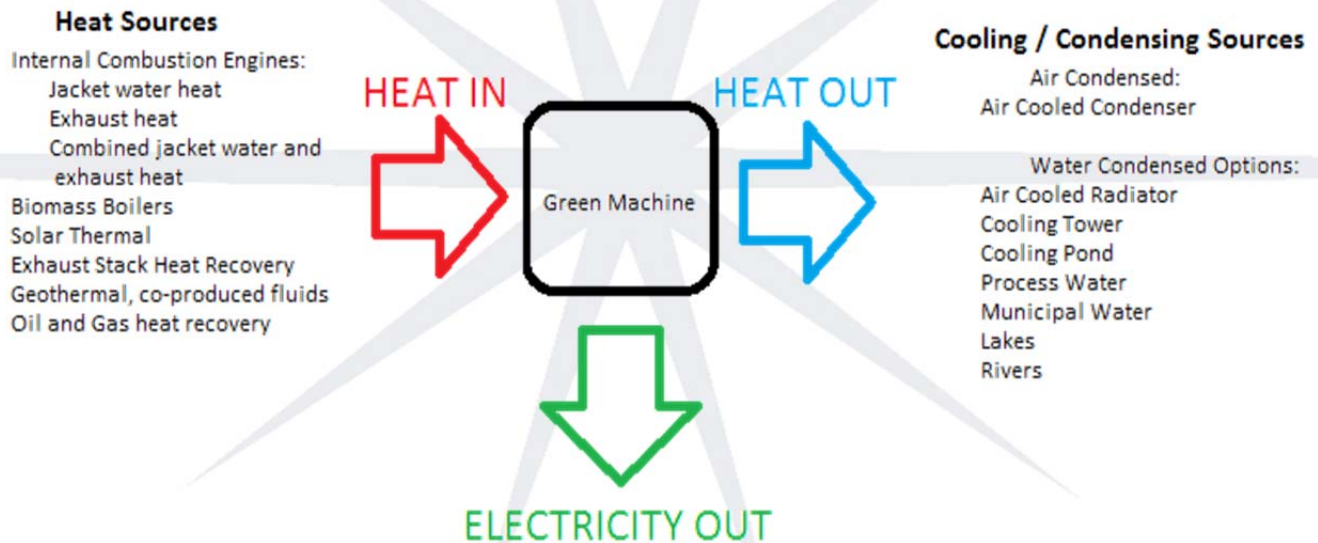
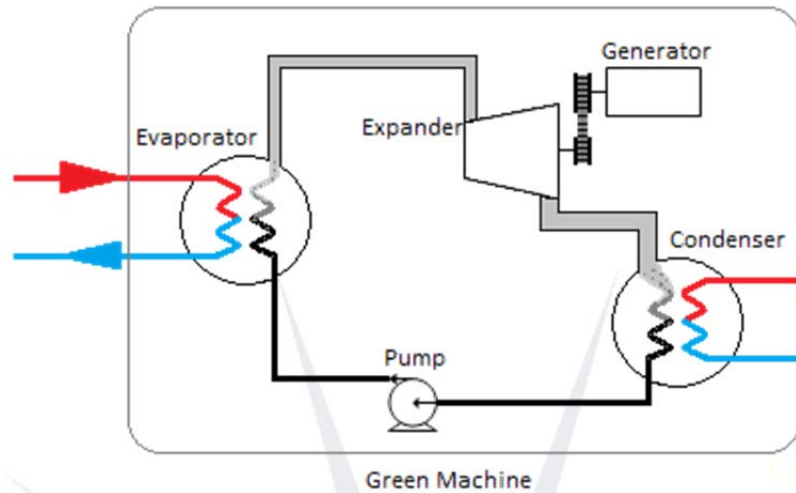


Figure 3: Possible Heating and Cooling Sources for ElectraTherm's Green Machine

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## The ElectraTherm ORC Component Breakdown



### Working Fluid HFC-245fa

HFC-245fa (1,1,1,3,3 pentafluoropropane) is an EPA-approved member of the hydro fluorocarbon (HFC) family of refrigerants, permitted under the Montreal Protocol. This non-flammable, low-toxicity, environmentally safe fluid boils at ~ 60°F (15.5°C) at atmospheric pressure. The Green Machine utilizes hot water to create pressure with the low boiling point attribute and that in turn runs our heat-to-power generating system. HFC-245fa is ozone safe and generally safe to handle.

### Working Fluid Lubrication

The POE oil used for lubrication is contained in the working fluid as part of ElectraTherm's proprietary in-process lubrication.

### Working Fluid Feed Pump

The feed pump is a multistage pump that is composed of a motor and a stack of impellers that force the working fluid in a given direction. The feed pump on the Green Machine is driven by a Variable Frequency Drive (from 0 to 60 Hz) and has a parasitic load ranging from 0-7 kW.



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### Evaporator/Pre-Heater

The pre-heater, evaporator and water condensers are all heat exchangers. The principle of the heat exchanger is to heat or cool one fluid by transferring heat between it and another fluid, while keeping the two from mixing.

Brazed plate heat exchangers, as used in ElectraTherm's Green Machine, are shown in the figure below. With the plates vacuum-brazed together, distinct flow channels are formed, effectively maximizing heat transfer in a compact package. ElectraTherm uses copper-brazed, stainless steel plate heat exchangers as pre-heaters, evaporators and condensers for the working fluid in its Organic Rankine Cycle (ORC).

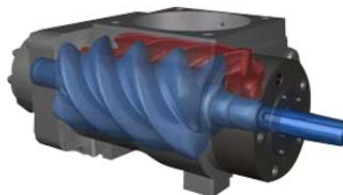


**Figure 5: Brazed Plate Heat Exchanger**

The pre-heater is used to raise the temperature of the working fluid before it goes through the evaporator. It uses the water exiting the evaporator to increase the efficiency of the system because this captures more heat from the water that would otherwise be wasted. The evaporator is used to heat the working fluid beyond the vaporization point increasing the pressure which drives the expander.

### Twin Screw Expander

The Green Machine uses a twin screw expander as its power block; which effectively is a compressor in reverse. The working fluid comes in at high pressure forcing the screw to spin allowing the working fluid to expand creating a pressure drop at the exit. The twin screw expander design is robust and simple. The operating speed of the Green Machine is low, and does not require a gearbox. The twin screw can also run in a "wet" condition meaning the refrigerant does not have to be 100% vapor. This is an advantage over traditional turbine-based expansion devices.



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## Electrical Generator (Induction Type)

The ElectraTherm Green Machine uses an induction generator for electrical power production. An induction generator is asynchronous in operation, and does not require synchronization to the grid. Voltage regulation and frequency regulation are provided from the existing connection to the power grid. Because induction generators are not self-excited and have no magnetization or terminal voltage prior to coming on-grid, synchronization is rendered meaningless. (Often users confuse the induction generator with a synchronous generator or alternator which has stand-alone terminal voltage when it rotates, and requires synchronization before being placed on-grid). For further information, and frequently asked questions regarding induction generators, reference the section of this document labeled [Induction Generator FAQ](#).



### Heat Sources

#### Hot Water Heat Source

The Green Machine requires water as the input medium. The heat exchangers inside the Green Machine are designed to be used with water. Ethylene glycol and propylene glycol are suitable for use in the ElectraTherm Green Machine hot water input loop. When glycols are used with water, it is recommended that the percentage of glycol to water does not exceed 40-50%, as the heat transfer decreases with increased percentages of glycol.

#### Exhaust Stack or Flue Gas as a Heat Source

Exhaust gas or exhaust stack heat will require an exhaust gas heat recovery heat exchange loop to transfer the heat from the gaseous waste heat source to a hot water loop for input into the Green Machine.

#### Thermal Oils

The ElectraTherm Green Machine is not directly compatible with thermal oils as the heat input source. Thermal oils have approximately half the heat capacity and heat transfer capabilities of water, and would require twice the flow rate through the heat exchangers as would be required with water. At 200% of the rated flow rate, the pressure drop incurred through the heat exchanger, as well as viscosity and velocity limitations through the heat exchanger in the Green Machine simply will not work with thermal oils. In many situations, a secondary hot water loop heated by thermal oil is easily feasible.

#### Other Liquid Waste Heat Sources

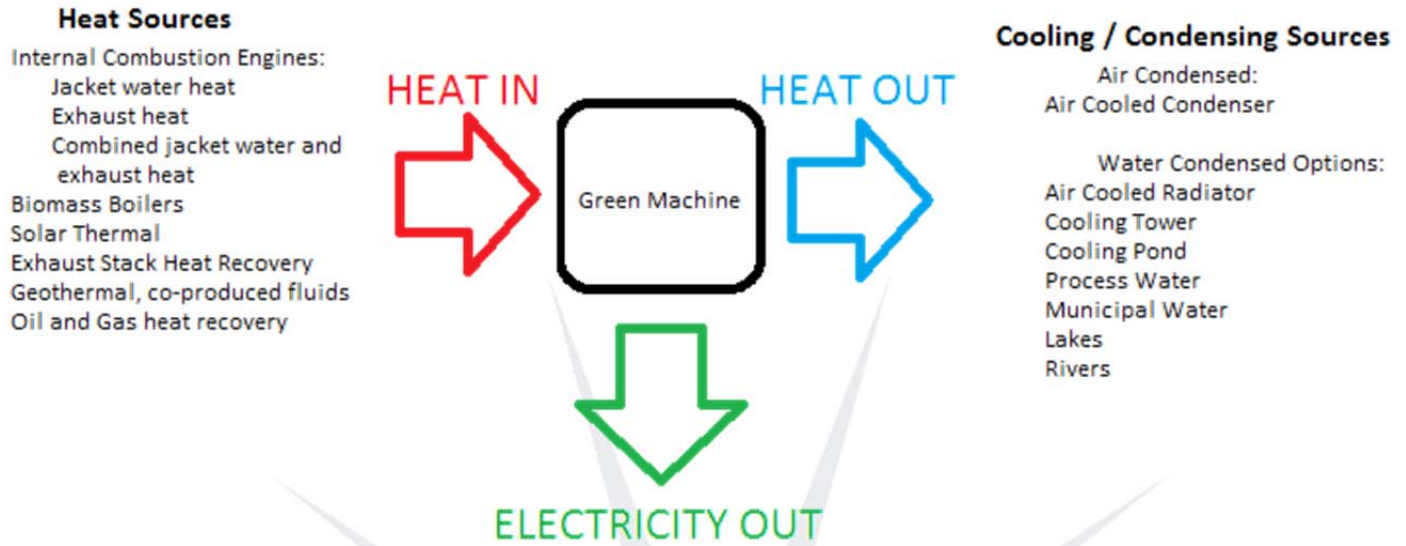
Caustic water, oils, chemicals, salt water or anything liquid not meeting the water quality requirements listed below will all require a secondary heat exchange loop to transfer the heat from the waste heat source to a hot water loop for input into the Green Machine.

#### Water Quality Specifications for the Green Machine for Hot and Cold Sources

The fluid used to heat the evaporator/pre-heater is clean water with the following general specs:

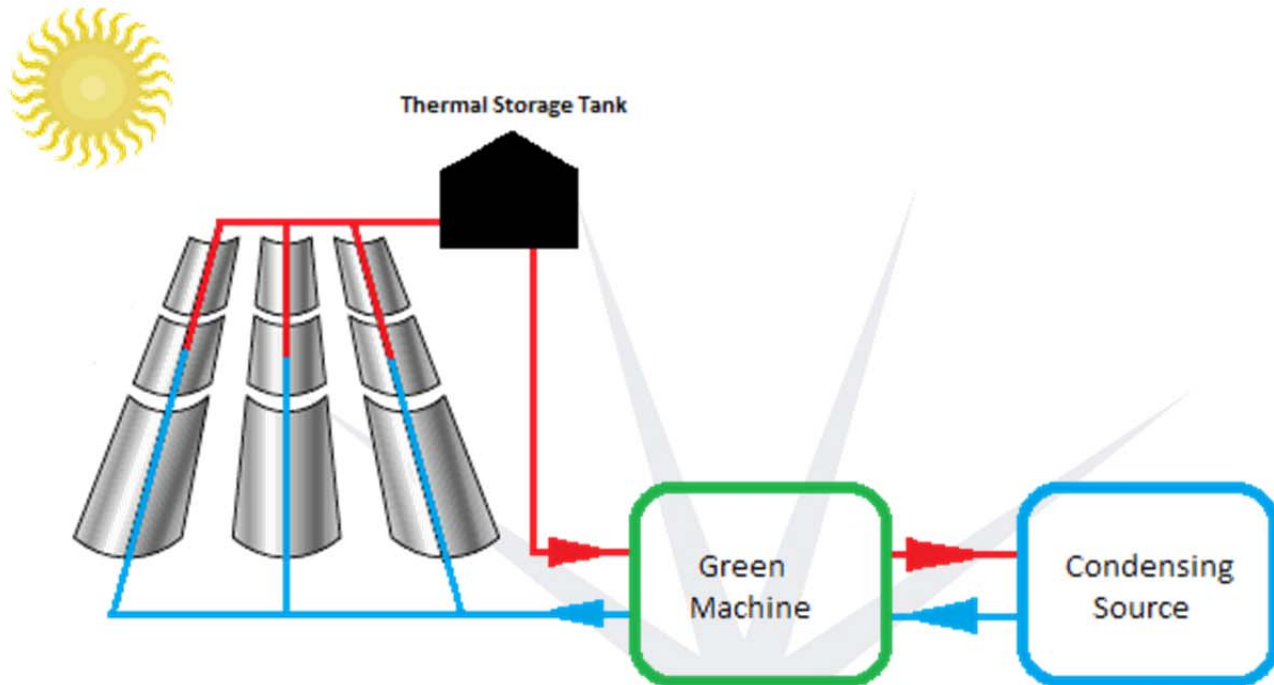
- Water should be neutral to slightly alkaline PH (7-8.5).
- Water should be free of abrasive material that will abrade and wear down the heat exchanger plates.
- Water should have little to no dissolved solids, as scaling on the heat exchanger plates reduce heat transfer capability, and reduce flow rate / increase pressure drop through the heat exchangers.
- The heat exchangers are made of stainless steel with copper brazing; chemicals that cause corrosion of stainless steel or copper should not be present in the hot water source.
- For complete water quality guidelines, please contact ElectraTherm.

## Connecting Various Heat sources to an ElectraTherm Green Machine



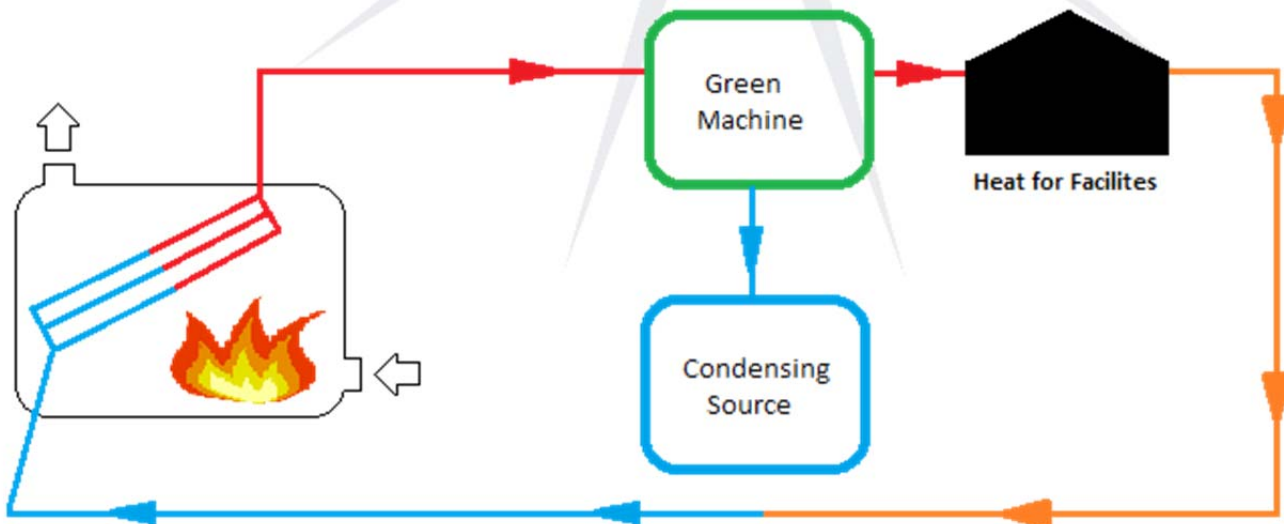
**All Green Machine applications require the waste heat input to be in a liquid hot water form. The examples on the next few pages are diagrammatic and demonstrative in nature, and do not represent all possible configurations.**

## Solar Thermal



Solar thermal arrays will need thermal storage and have limited hours of operation depending on daylight hours. If the solar thermal array uses a medium other than a water-glycol mix, a heat exchanger system will be needed.

## Biomass/Biogas Boiler

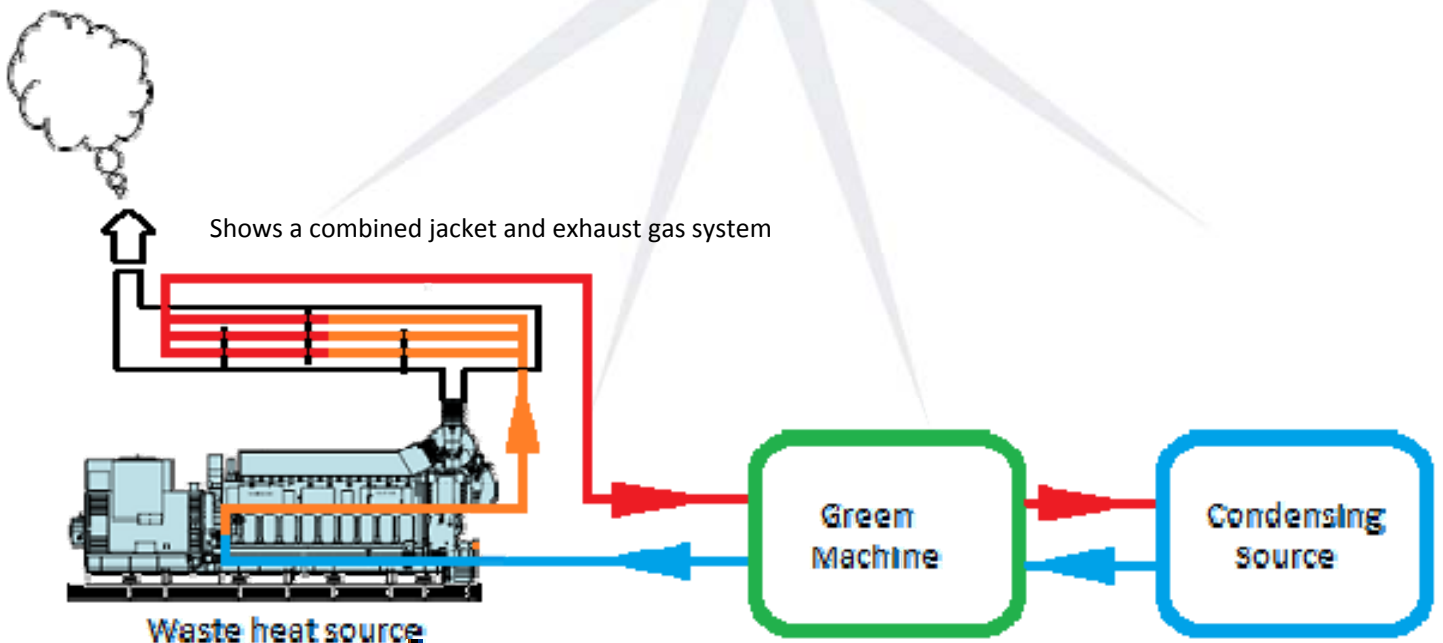


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### Internal Combustion Engines (ICE)

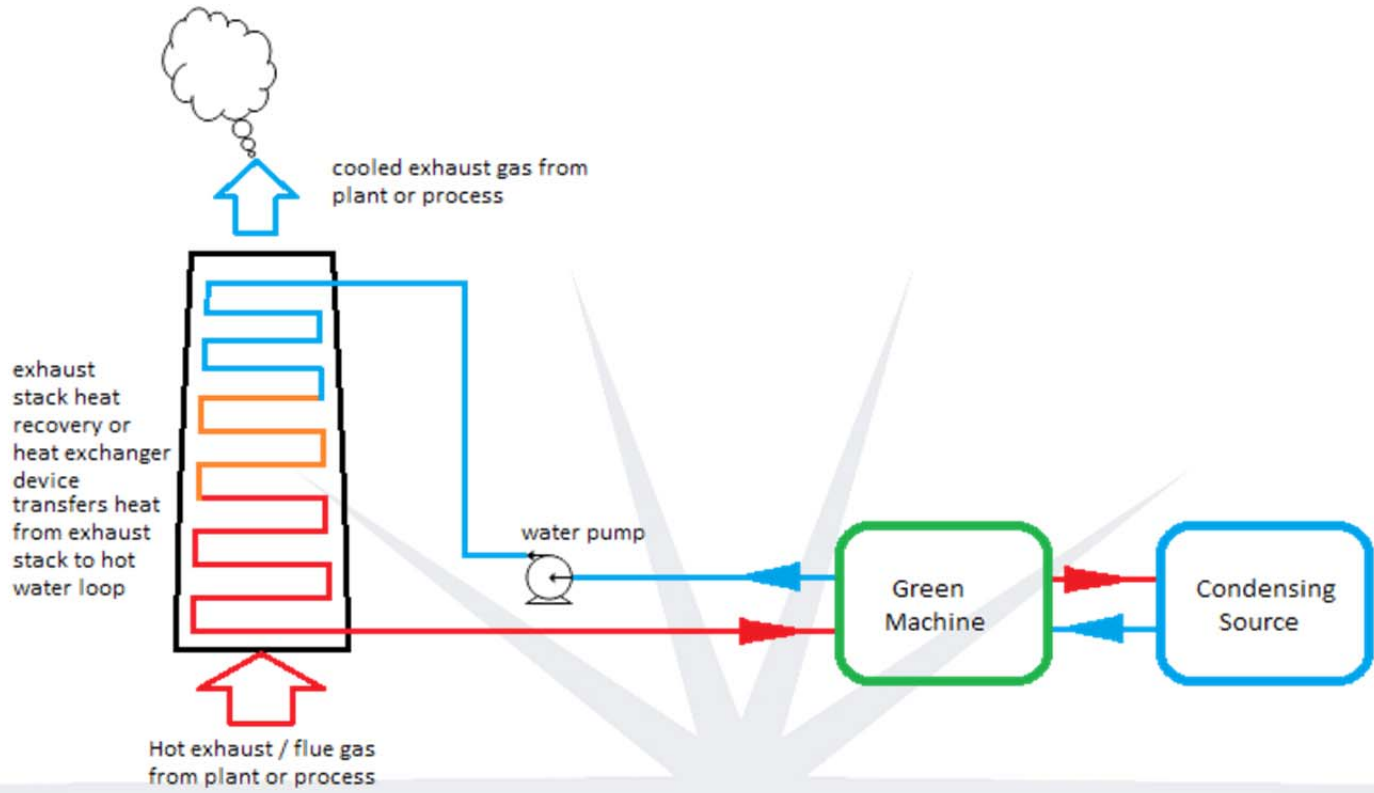
Given that most internal combustion engines are only 30-40% efficient thermally means that of all the thermal heat put into an engine through fuel input, 30-40% of the fuel input becomes mechanical work, and the other 60-70% of the fuel input leaves the engine as waste heat through the jacket water cooling circuit, the exhaust stack and other cooling circuits. Capturing the heat from the jacket water circuit, the exhaust or combining the exhaust heat with the jacket water heat are easy options to convert the waste heat from an internal combustion engine into electricity as well as providing other heating requirements. When fuel costs are high, and the internal combustion engine is used for electrical production, the ElectraTherm Green Machine will save fuel costs by allowing the engine to operate at a lower fuel input rate to maintain the same electrical output as supplemented by the Green Machine. Also, installing a Green Machine reduces the amount of heat that the radiator previously had to reject. A reduction in heat rejected at the radiator is equal to reduced electrical consumption by the radiator. Not only is the Green Machine producing electricity from the jacket water heat, but the effective net output of the entire engine increases because of the reduced electrical load on the radiator.

The waste heat from the engine jacket water is combined with the waste heat that is going out the exhaust. Heat is added to the water in the engine, raising the temperature. The heated water then passes through an exhaust gas heat exchanger, where heat is transferred from the high temperature exhaust into the heated water, increasing the temperature more. The waste heat rejection for this example would include the Green Machine, building heating and anaerobic digester loads, as well a radiator to remove excess heat if necessary. The diagram on the next page shows the hot water heat source flow using both the jacket water heat and exhaust gas heat.



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## Exhaust Stack Heat Recovery

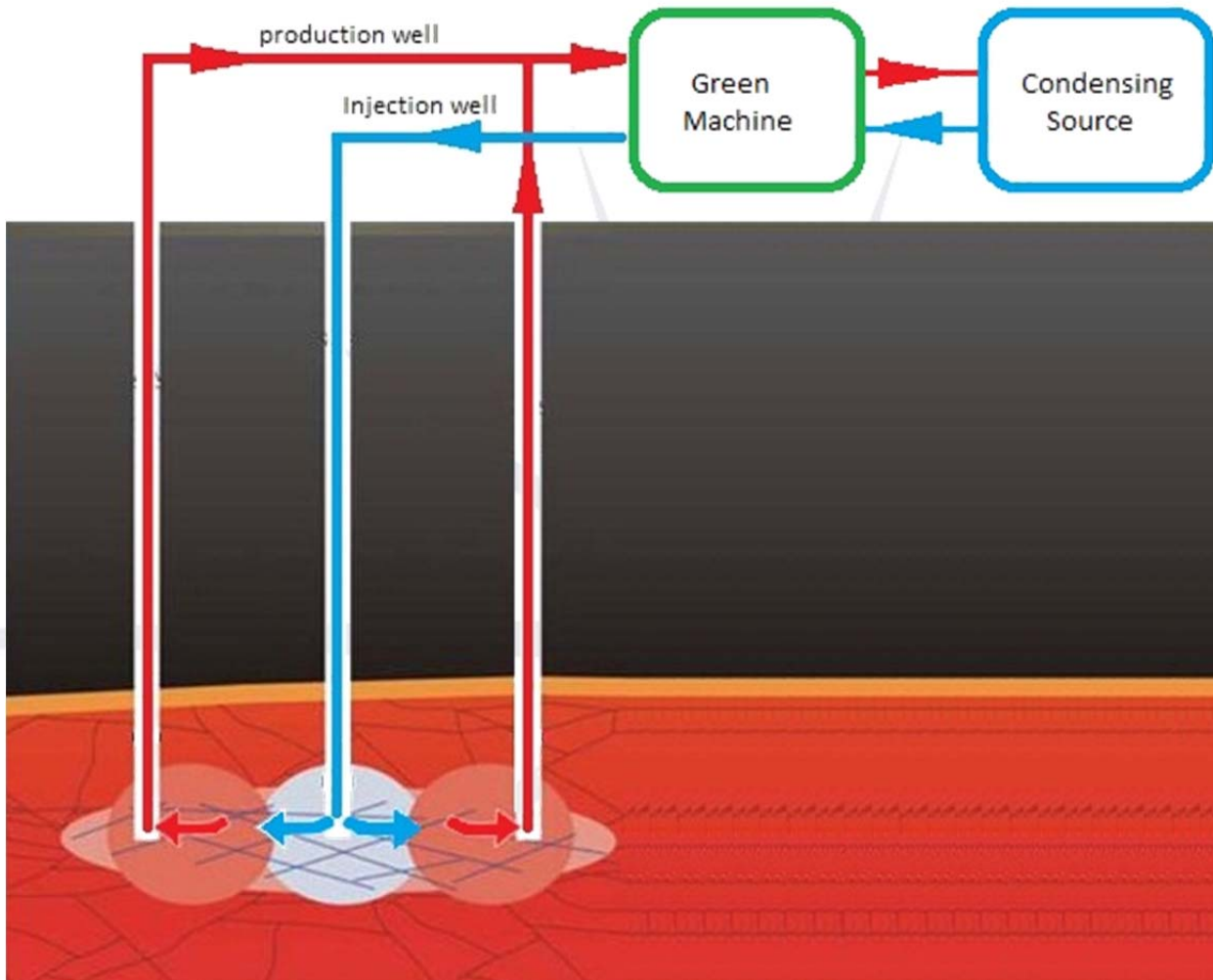


*Stack heat recovery heat sources require an exhaust stack heat exchanger.*



## Geothermal and Co-Produced Fluids

Many oil wells also produce hot water, like the geothermal sites. The hot water is extracted from the ground and re-injected after the heat is removed.

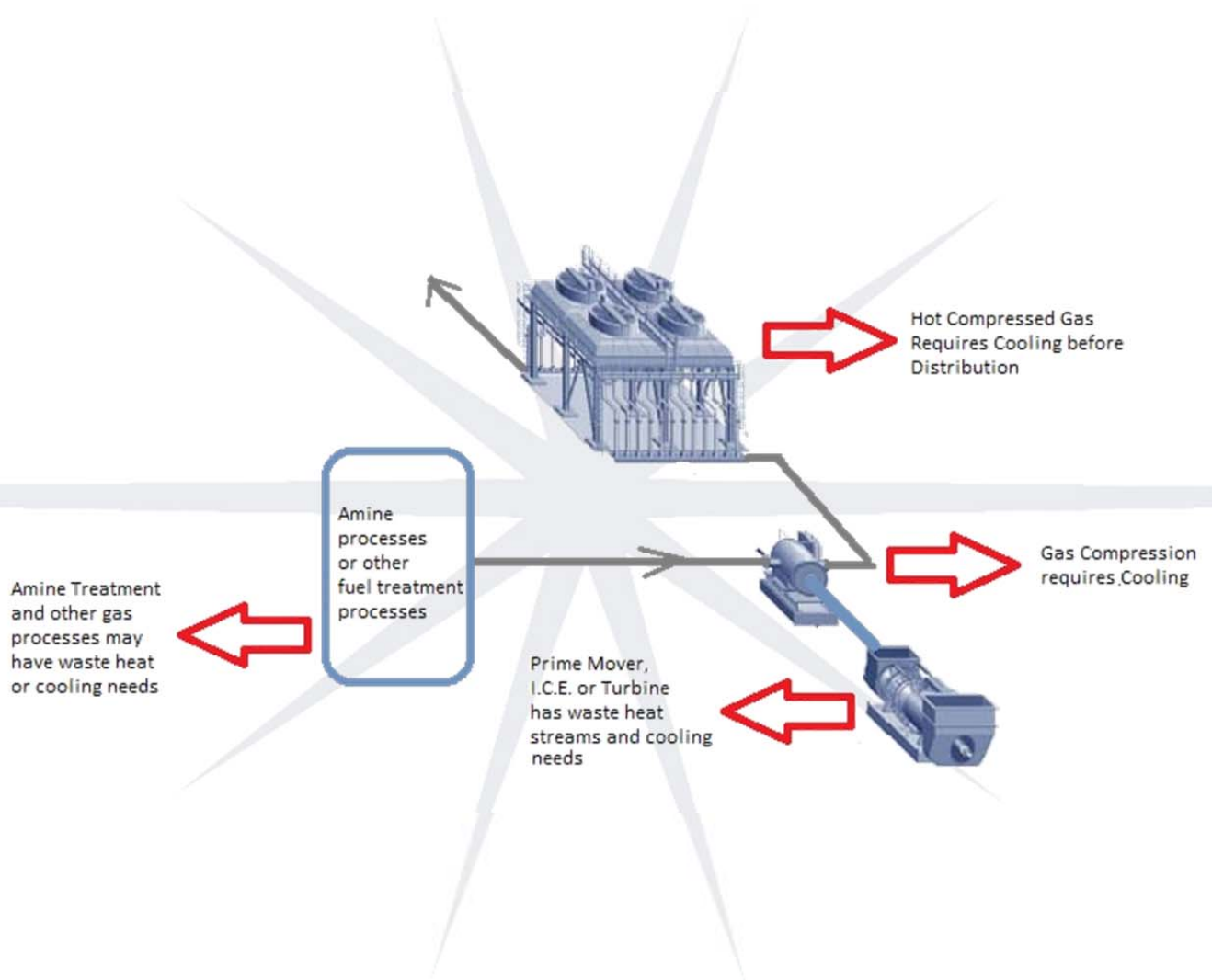


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## Oil and Gas Heat Recovery

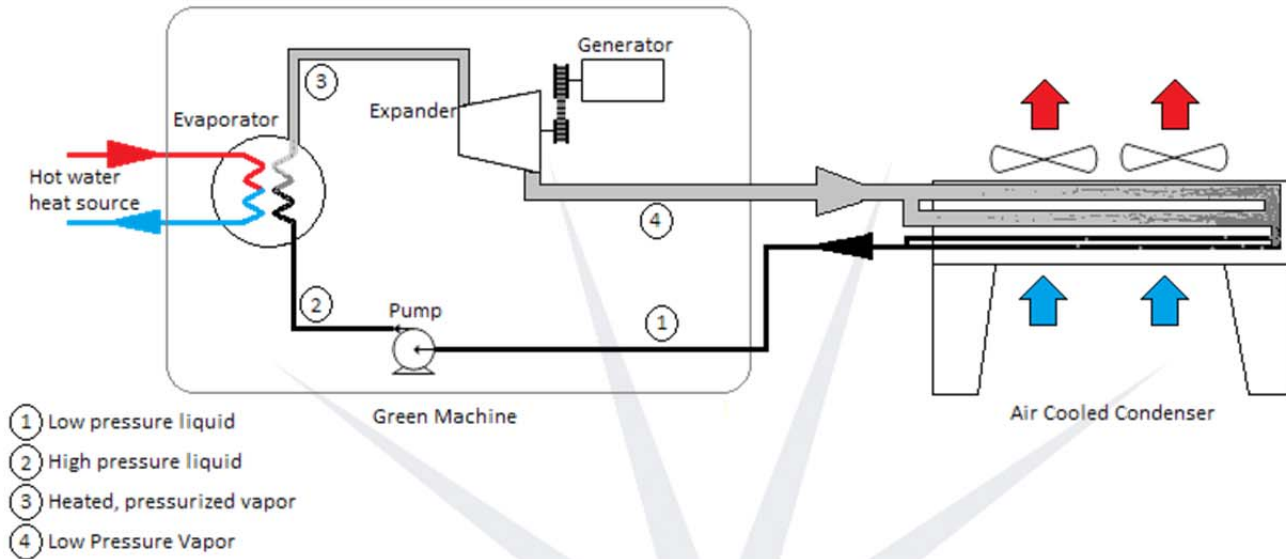
Refining processes, gas compression and other industrial processes create a lot of waste heat. As shown below, a typical gas compression station has many sources of heat, and some of those sources of heat need to be cooled, so there is a double benefit of both producing electrical power from the heat and reducing the cooling power loads on the existing system.



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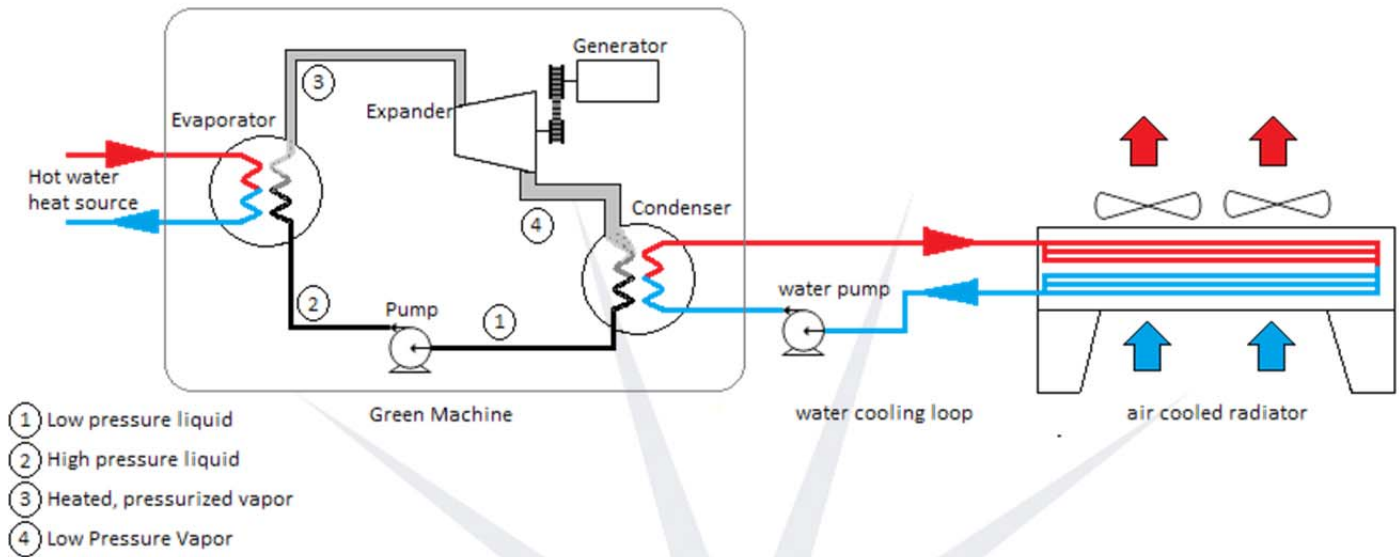
## Cooling / Condensing Sources

### Green Machine with an Air Cooled Condenser



When using air cooled condensing, the working fluid is condensed outside the Green Machine, in an air cooled condenser. The heat that is removed from the low pressure vapor (4-1 in the above diagram) is rejected directly to the air through the use of an air cooled condenser. The air cooled condenser used in conjunction with the ElectraTherm Green Machine is specified by ElectraTherm, and can be procured through ElectraTherm. Although the nomenclature is similar, the Green Machine air cooled condenser is very different in operation when compared to a traditional air conditioning condenser.

## Green Machine with a Water Cooled Condenser



When a water cooled condenser is used, the working fluid is condensed in the water cooled condenser located inside of the Green Machine. The heat that is removed from the low pressure vapor(4-1 in the above diagram) is transferred to a water cooling loop, and the heat in the water cooling loop is then rejected to the air through the use of an air cooled radiator or cooling tower. There are many advantages and disadvantages for the cooling method used for the water. Listed below are some common items to consider when looking at cooling towers vs. an air cooled radiator.

### Cooling Towers

Depending on the difference between wet bulb and dry bulb temperatures, a cooling tower can typically offer better water cooling performance than a closed loop radiator. This is mainly true in dry climates. Cooling towers continuously consume water. Water is lost through evaporation, water is lost through drift out of the cooling fan and water needs to be drained out to remove minerals and solids that are left behind as they do not evaporate. Condensing water must be treated to avoid the growth of bacteria and algae. These items need to be accounted for and weighed accordingly when deciding which condensing source is best per each application.

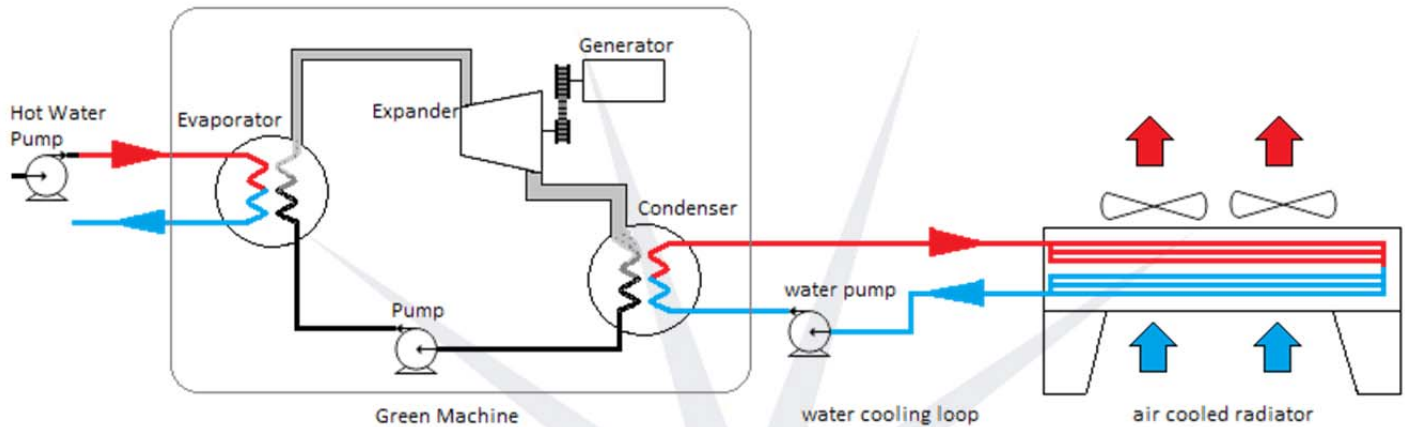
### Closed loop water radiator

A closed loop water radiator uses electric fans to reject heat from the hot water to the atmosphere. A closed loop water radiator should not consume any water during normal operation.

### Water Cooled Condensers

The water cooled units use a brazed plate heat exchanger similar to those used for the pre-heater and evaporator. The cold water may come from a variety of sources. Ensure that the water quality meets the standards stated in the water quality section.

### Water Cooled Green Machine Configuration



**Gross kWe** is the power produced from the generator.

**Internal feed pump parasitic kWe** is the power consumed from the Green Machine feed pump.

**Air cooled condenser parasitic kWe** is the power consumed by the fans on the Air Cooled Condenser.

**Hot water pump parasitic kWe** is the power consumed by the hot water pump (not always necessary).

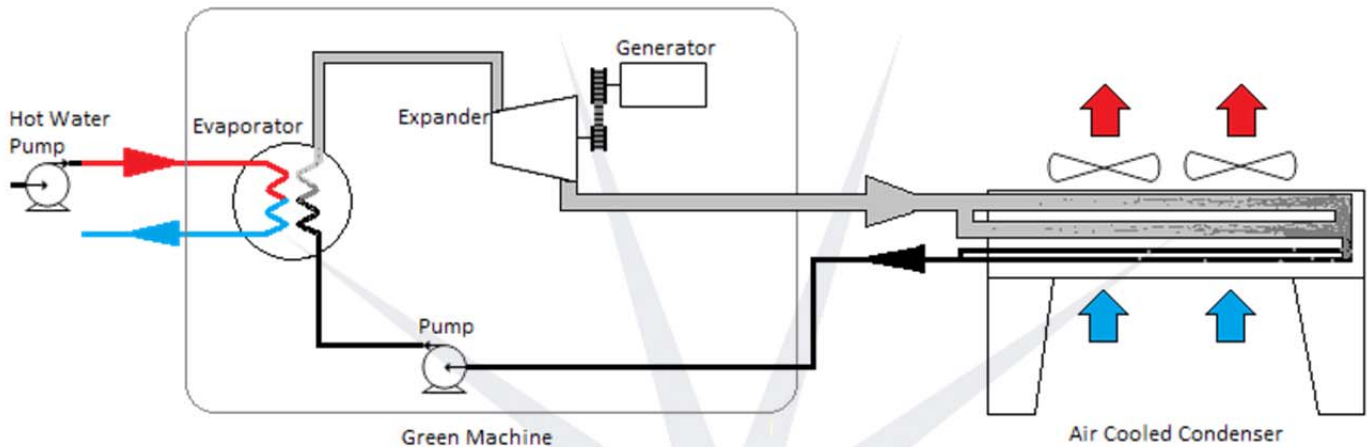
**Water cooling loop pump kWe** is the power consumed by the cooling water pump.

**Net kWe** is the Gross kWe produced by the generator less all of the parasitic loads necessary for the operation of the Green Machine.

## Air Cooled Condensers

Air condensed Green Machines do not have water cooled condenser, as the working fluid is condensed to a liquid through an air cooled condenser located outside of the Green Machine.

### Air Cooled Condenser Green Machine Configuration



**Gross kWe** is the power produced from the generator.

**Internal feed pump parasitic kWe** is the power consumed from the Green Machine feed pump.

**Air cooled condenser parasitic kWe** is the power consumed by the fans on the air cooled condenser.

**Hot water pump parasitic kWe** is the power consumed by the hot water pump (not always necessary).

**Net kWe** is the Gross kWe produced by the generator less all of the parasitic loads necessary for the operation of the Green Machine.

### Conditions that Affect the Performance of the Green Machine ORC

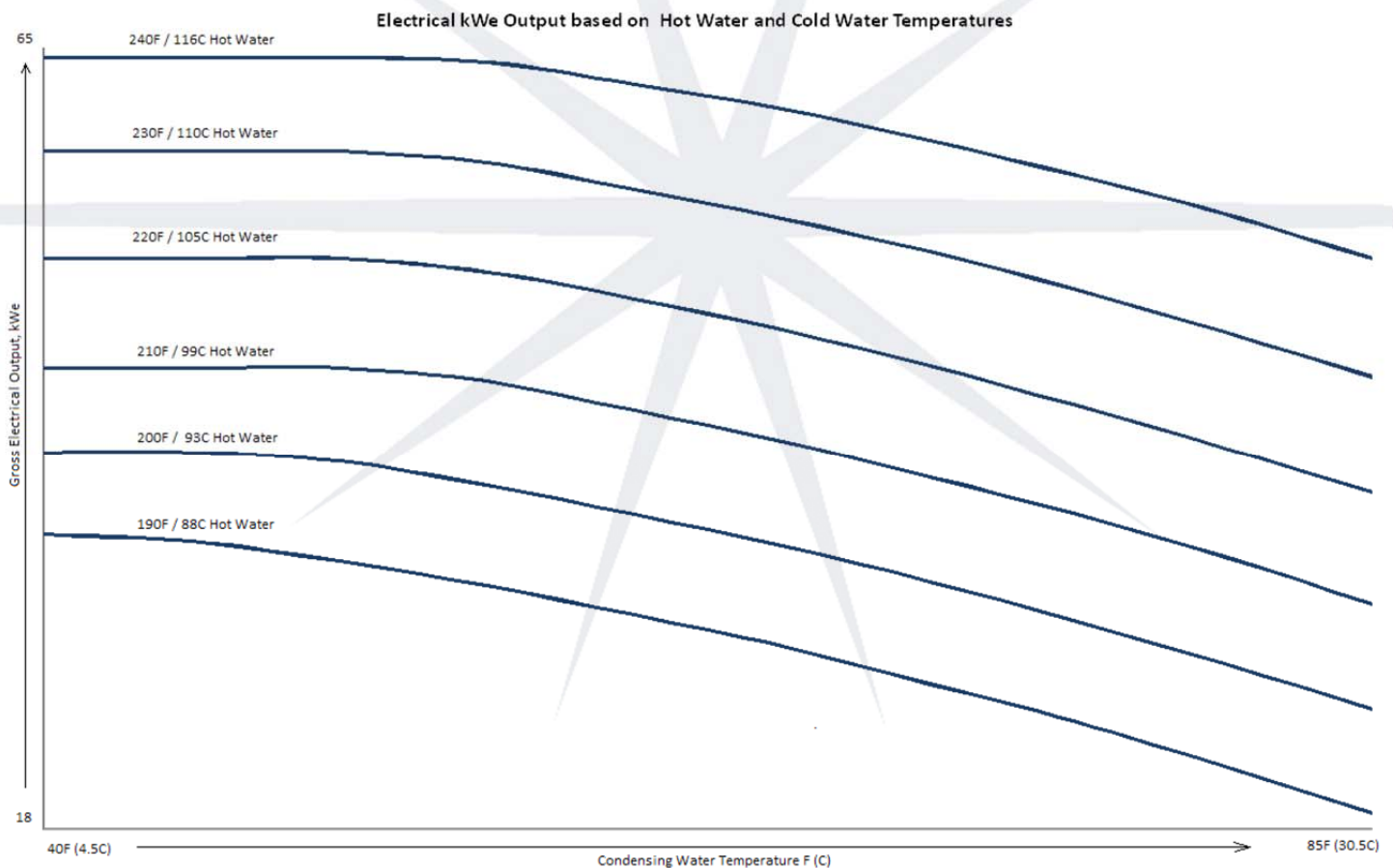
#### Condensing Temperature (Ambient)

The ability to condense the working fluid from a low pressure vapor to a liquid is related to the ambient temperature. When a water cooling source is used to condense the working fluid, the water temperature is related to the ambient temperature, as it is cooled with air through a cooling tower or radiator. When an air cooled Green Machine is used, the air is used to directly condense the refrigerant in and air cooled condenser.

#### Hot Water Source Temperature

With proper flow rates, and enough available heat, the hot water source temperature is the primary driving force for maximizing the amount of electrical output that can be produced by the Green Machine. Higher temperature hot water sources produce higher electrical output with the same condensing conditions.

See figure below for electrical output curves relative to Hot Water and Cold Water temperatures.



\*Drawing is representative only, Do not scale drawing, or collect data from this graph for performance evaluation

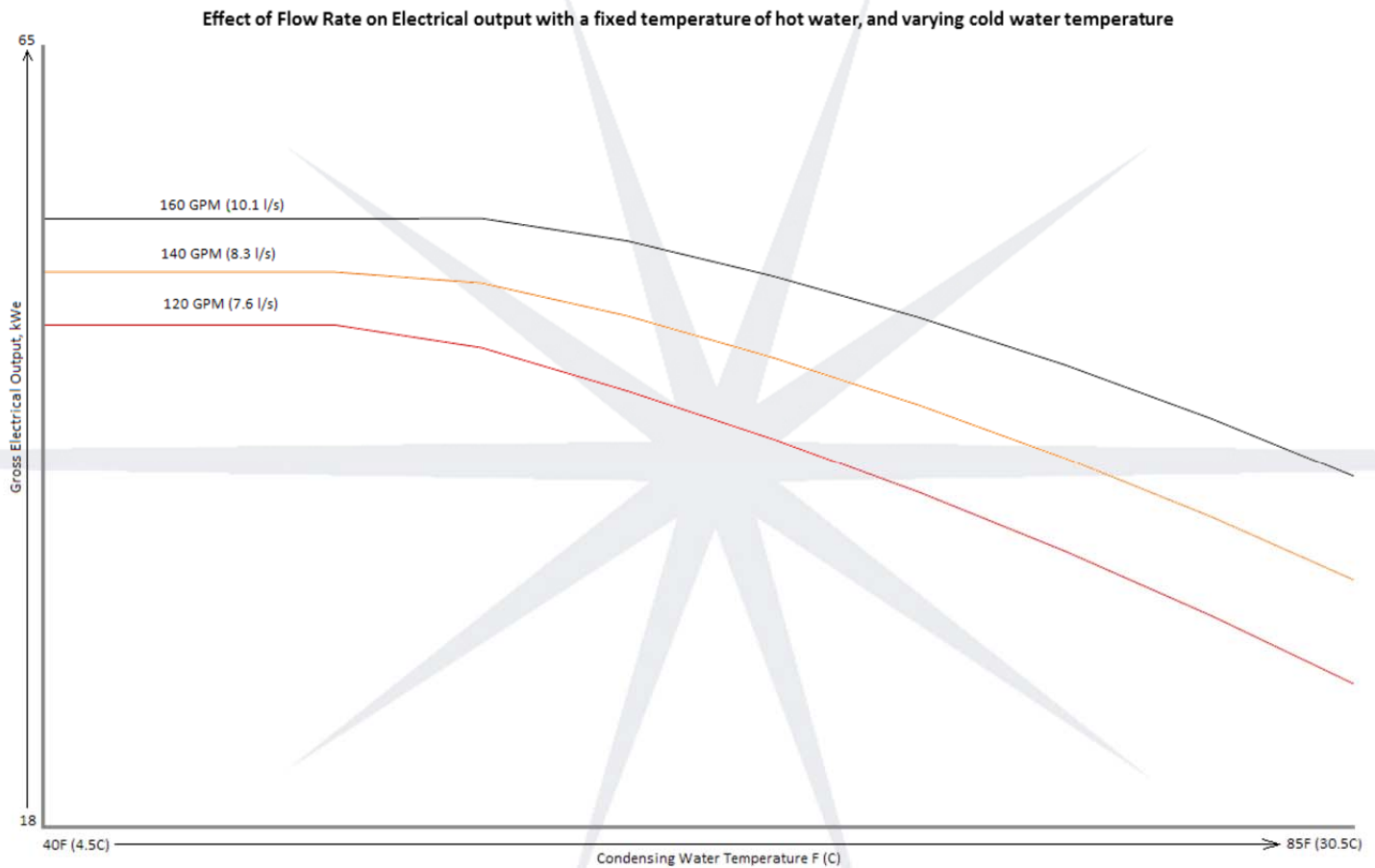
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## Flow Rate of Hot and Cold Water Source

The evaporator and heat exchanger are designed to optimally work with hot water flow rates in the range of 120-200 GPM (7.6-12 l/s). Lower flow rates have a lower ability to transfer heat from the hot source into the working fluid. Power output from the Green Machine decreases when the flow rate is reduced. The required flow rate on the condensers is between 180 – 220 GPM. Performance of the heat exchangers (used as condensers) will decrease as flow rate is reduced on the cold water side.

See figure below for a representation of hot water flow rates as they affect the electrical output of the Green Machine.



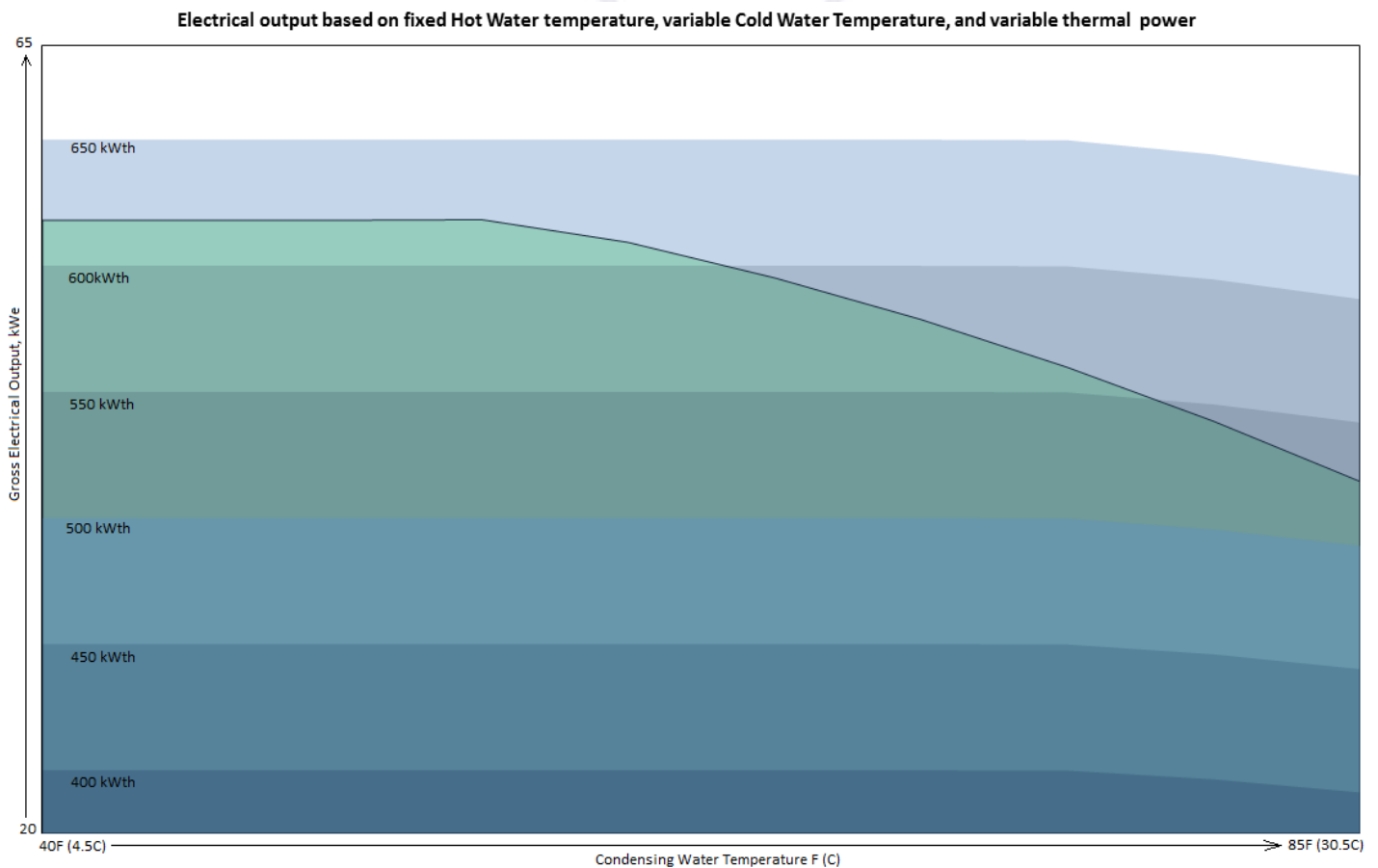
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### Available Heat/Thermal Power

Available thermal power is the rate of BTU's/hr or KWth that is continuously produced by the waste heat source that is available to be consumed by the Green Machine. Available thermal power affects the performance of the Green Machine because the Green Machine converts thermal power into electricity. Simply put, less thermal power equates to less electrical output.

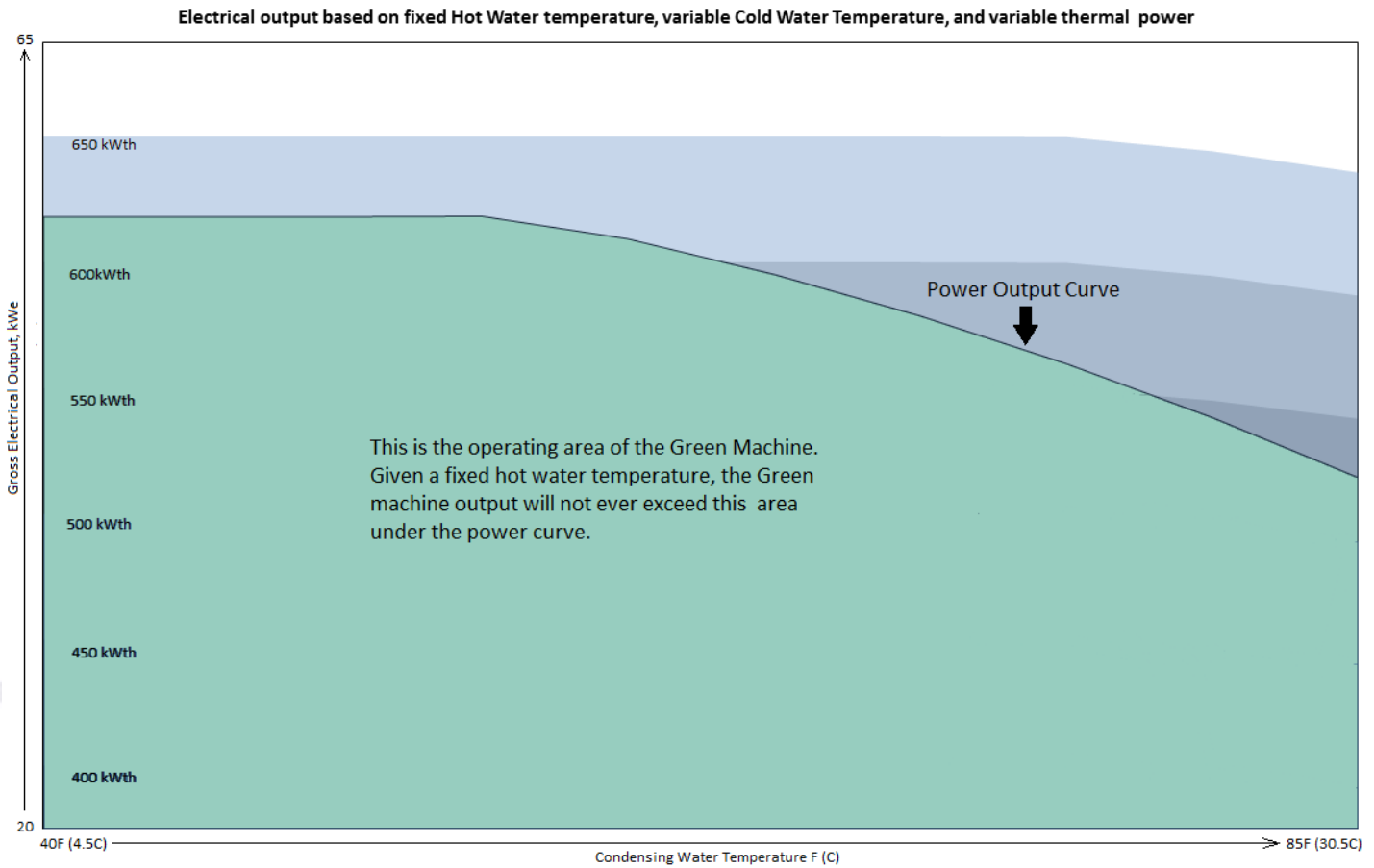
Given a specific set of input conditions (flow rate, hot water temperature and condensing temperature), the Green Machine will have a specific "appetite" for the amount of thermal power that it will consume to produce electrical output. Examples of the relationship between electrical output and thermal power consumed are shown on the following diagrams. In the example diagrams, a fixed hot water temperature and flow rate are used to demonstrate the relationship.



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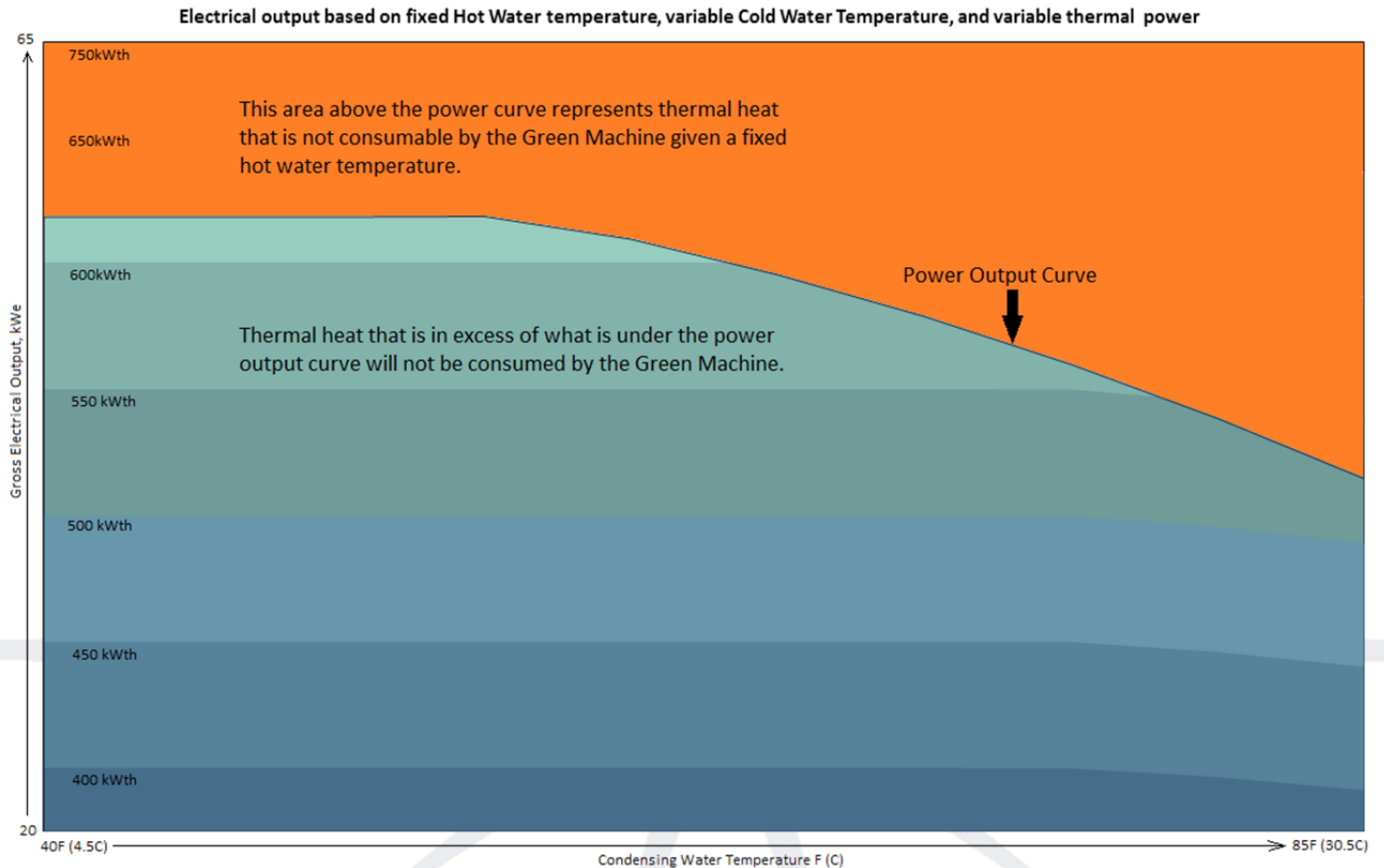
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Reference the figure below for the operating curve when given a specific hot water temperature.



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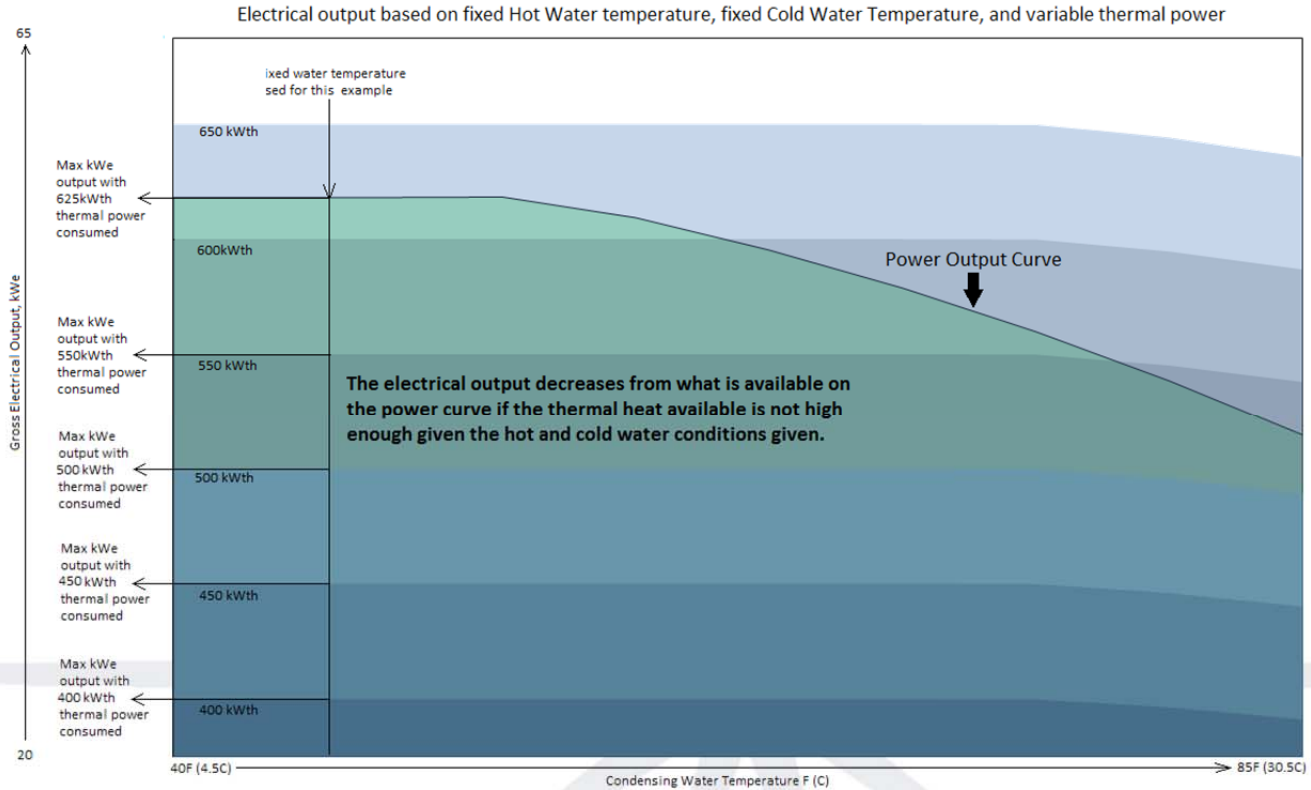
See figure below for circumstances when more heat is available for consumption than the Green Machine has an appetite for.



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See figure below for electrical output considerations for situations when the thermal heat available for the Green Machine is less than the appetite of the Green Machine based on specific hot and cold water conditions.



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### System Delta T ( $\Delta T$ )

The system Delta T is the difference between the hot source and the cold source. The Delta T correlates to the overall efficiency of the ORC system. Within the limits of hot and cold resource, as well as the working fluid itself, a higher Delta T will give a higher efficiency of an ORC system. The Green Machine system is Delta T temperature limited because of the physical properties of liquid water. Reference the [Green Machine Efficiency](#) section of this document for further information regarding efficiency and the ElectraTherm ORC.

### Calculating Available Thermal Power

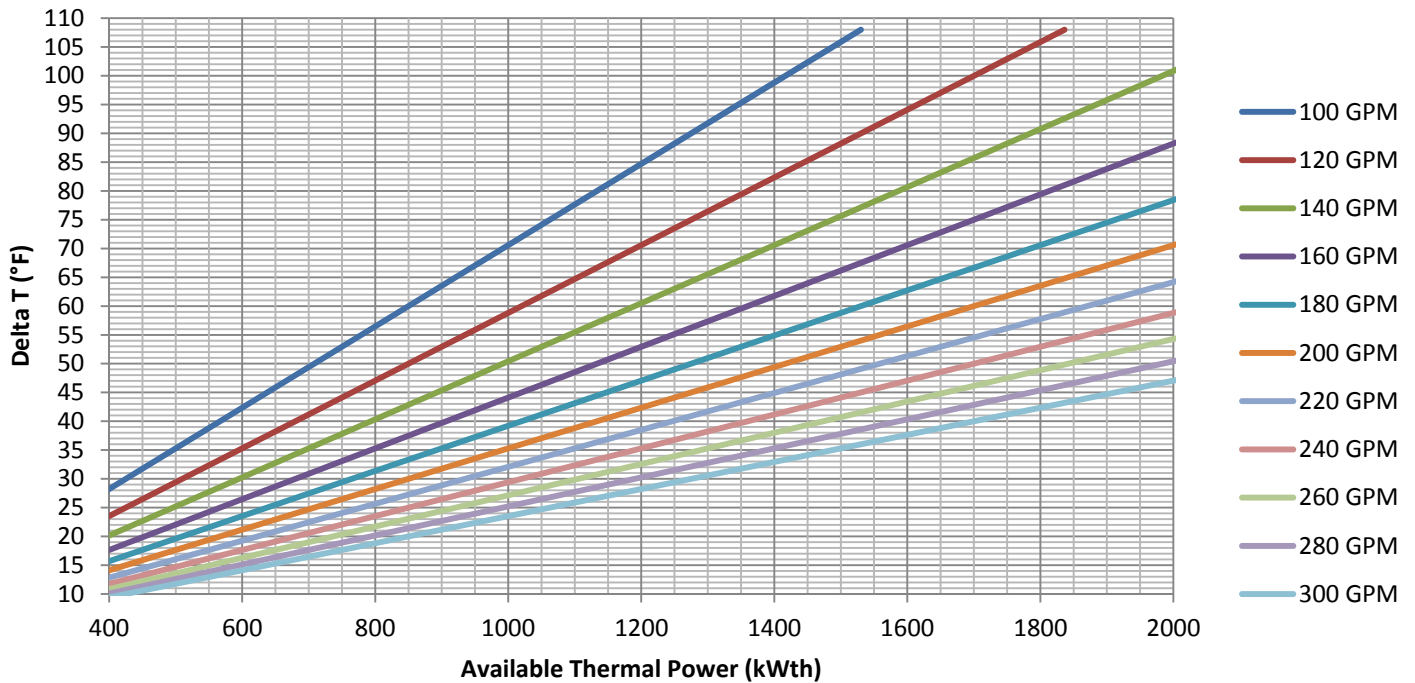
The charts in the next slide will help estimate the available thermal power for pure water waste heat streams.(this graph does not work for glycol/water mixes, or fluids other than water such as thermal oil).

- Calculating available thermal power.
- The available thermal power is calculated using the mass flow rate of the fluid, specific thermal properties of the fluid, and temperature difference between the hot exit temperature and cooler return temperature (Delta T) from the heat source. This is not the system Delta T. It is the Delta T in temperature difference between the hot water as it exits and returns to the heat source. For instance, if an internal combustion engine with a jacket water exit temp of 95°C and a return temp of 75°C combined with a 7.6 l/s flow will have about 600 kWth available thermal power. This is found on the graph by using the Delta T between exit and return (95°C-75°C = 20°C) and the 7.6 l/s flow line.

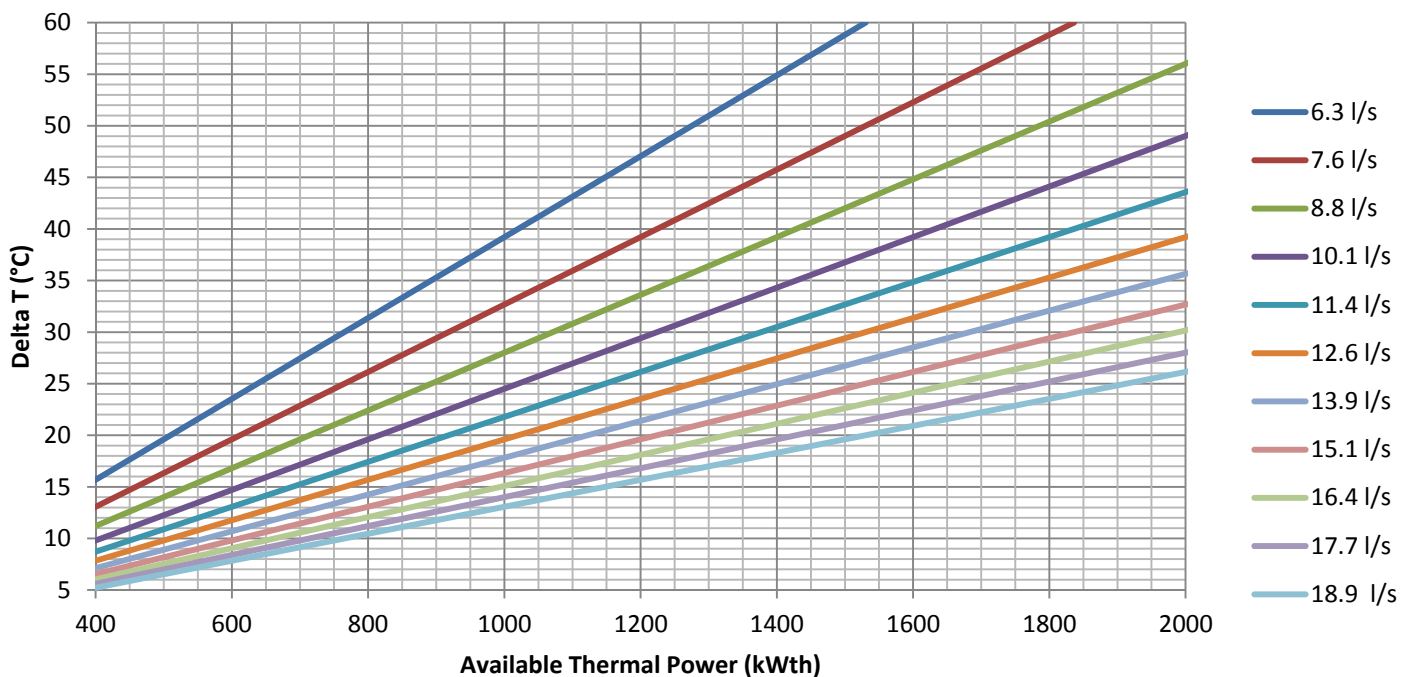
See the two graphs on the following page for estimating thermal power of a liquid water waste heat source. Please note that this is for pure water, and it does not account for any glycols that may be mixed with the water.



### Imperial Chart



### Metric Chart



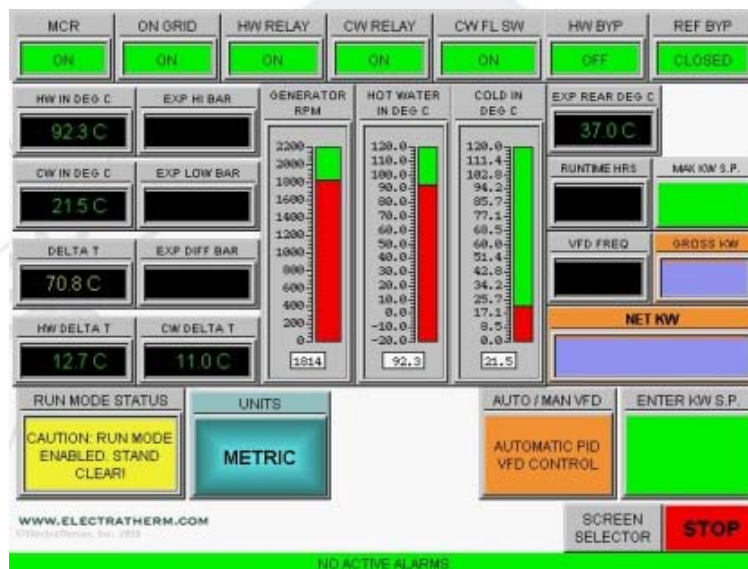
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## Cooling to Power Applications using the ElectraTherm Green Machine

Not all waste heat is “free”. Some heat produced in processes needs to be cooled. Cooling processes cost money, as cooling processes typically consume electricity to cool when cooling is provided by fan coolers or cooling towers. If the heat source or process being cooled is suitable for use by the Green Machine, there is a double effect when using the Green Machine. In addition to the electrical output produced by the Green Machine, the existing cooling loads are reduced as well, increasing the actual output of the Green Machine higher than what the Green Machine produces on its own. For example, if an 800 kWe internal combustion engine produces 500 kWth heat that has to be rejected in a water loop radiator, electricity is required to operate the fans that cool the radiator loop to reject that heat. Installing a Green Machine reduces the amount of heat that the radiator previously had to reject. A reduction in heat rejected at the radiator is equal to reduced electrical consumption by the radiator. Not only is the Green Machine producing electricity from the jacket water heat, but the effective net output of the entire engine increases because of the reduced electrical load on the radiator. In the above example, if the Green Machine produced 35 kWe of electricity from the jacket water heat source, and the Green Machine reduced the existing radiator fan parasitic load by 5 kW, then the effective output of the system increased to 40 kW.

## Green Machine Controls and Remote Monitoring

The Green Machine can be controlled both remotely and from an LCD panel touch-screen located on the front of the machine. The machine has two different running modes, automatic and manual. In auto mode the unit starts and runs automatically. The machine will optimize power output on its own; also temperature differentials for auto stop and auto start in this mode are set at the factory but can be adjusted using the set up screen. Manual mode is for trained and authorized personnel only and can only be accessed by a password.



The machine may be accessed and controlled remotely using the required internet connection. The machine will send its run data to ElectraTherm every day where it is monitored and analyzed to ensure that the machine is running properly and to help the customer optimize power output.

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### Induction Generator FAQ

#### What is an Induction Generator?

An induction generator is electro-mechanically similar to an induction motor. In the case of the Green Machine, our induction generator is based on a 70-100 horsepower (about 50-75 kW) squirrel cage motor with some optimizations to the internal construction to make it more efficient as a generator.

#### Why does ElectraTherm use an Induction Generator?

Induction generators have significant advantages over other devices. Similar to industrial motors, they are inexpensive, robust and proven, employing no brushes, commutator, slip rings, exciter, regulator, synchronizer or other complex parts. For the amount of power we produce, the induction generator provides a good solution.

#### How does an Induction Motor/Generator Work?

An induction motor draws power when running below its synchronous speed, and generates power above synchronous speed. Typical synchronous speeds would be 1,500 RPM for 50 Hz and 1,800 RPM for 60 Hz. At exactly those speeds, the motor theoretically neither consumes nor generates power (some small amount of power is consumed due to friction, etc.). To reach full electrical output, the induction motor/generator typically must turn less than 2.5% over the synchronous speed (1,840 RPM for 60 Hz, 1,530 RPM for 50 Hz applications are typical).

#### Does the Induction Generator need a Synchronization Device?

No. Voltage regulation and frequency regulation are provided from the existing connection to the power grid. Because induction generators are not self-excited and have no magnetization or terminal voltage prior to coming on-grid, synchronization is rendered meaningless. (Often users confuse the induction generator with a synchronous generator or alternator which has stand-alone terminal voltage when it rotates, and requires synchronization before being placed on-grid).

#### Does the Green Machine Require Further Grid Protections?

In principle, no, but to back up onboard protections built into the Green Machine, operators may choose to add grid and generator protection features such as over-current, phase imbalance, and voltage & frequency excursion monitoring via a Beckwith unit, or similar device. Requirements may vary per utility company or municipality; ElectraTherm engineering can advise you on any particular requirement.

#### How does the Green Machine go Online?

Upon startup, the onboard feed pump sends working fluid (liquid refrigerant) to the evaporator and starts building system pressure. The twin screw expander turns, accelerating the generator. When the unit approaches synchronous speed, a contactor (switch) closes and connects the un-excited motor/generator to the line. An inrush current flows to magnetize the unit (just as it would when starting the motor conventionally) but since it is already up to speed, no large acceleration current is required. As working fluid flow increases, the motor then transitions into generation and power

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output gently ramps up. Power output continues to increase until the limit of available heat is reached or the unit achieves rated output.

### **Does Operating the Generator beyond the Synchronous Speed Stress the Rotor and Bearings?**

No. Our purpose-built generators are designed for this service.

### **Does Raising or Lowering Speed Change the Voltage and Frequency of the Output?**

No. The only thing that varies significantly is the torque going out from (motor mode) or into (generator mode) the device. The power grid establishes voltage and frequency regulation and the induction generator just follows along. This is distinctly different behavior than that of a synchronous generator (alternator).

### **What Happens if the Grid Goes Down? Will the Induction Generator Island?**

No. The Green Machine cannot operate as a stand-alone generator. In the event of a loss of grid, the unit will automatically shut down, and cannot be re-started until line conditions return to normal. The only possible exception is if there is a large amount of capacitance (surplus reactive power) in the local grid, and loads were less than the output of the Green Machine. In this case, the unit could remain online for a few seconds until the associated rise in voltage or frequency tripped internal alarms and initiated shutdown. Alternatively, the recommended grid/generator protective relay could initiate shutdown as soon as parameters started to drift.

### **What about Ramp Rate, Harmonics, Flicker and Power Factor? How Clean is the Power?**

Green Machine electronics control ramp rate. Our power output range (30-65 kW) is very small by power plant standards; many of the questions you may face on interconnect agreements are geared toward much larger facilities and won't apply.

Induction generators are not a significant source of harmonics, and the voltage output is a near perfect sine wave. We have never observed flicker or noise problems. Computers and other sensitive equipment operate fine on circuits fed by Green Machines.

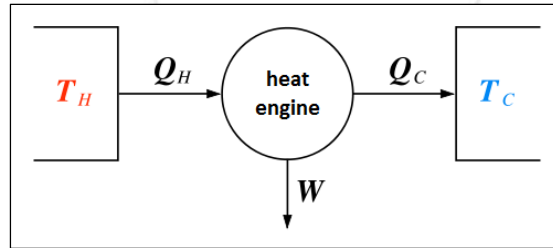
### **What is the Power Factor using an Induction Generator?**

ElectraTherm Green Machines use integral power factor correction capacitors to improve the inherently low power factor of the induction generator to a value from 0.90 to unity, depending on load. See separate ElectraTherm FAQ on power factor.

### Green Machine Efficiency

The laws of thermodynamics limit the efficiency of any ORC technology. Fundamental efficiency limits, dictated by physics, as well as engineering realities result in the low conversion efficiency of low temperature ORCs.

Consider a heat engine operating between a heat source ( $T_H$ ) and cooling source ( $T_C$ ). In order for the engine to run, heat ( $Q$ ) must flow through it. For heat to flow from the heat source to the cooling source there must be a difference in temperature between the heat source ( $T_H$ ) and the cooling source ( $T_C$ ). Some of the heat flow ( $Q$ ) converts to useful work ( $W$ ), and the rest dissipates at the cooling source ( $T_C$ ) as illustrated in the figure below:



Experience shows that all conceivable engines, regardless of design, must accept that their maximum theoretical efficiency will be limited by the Carnot efficiency ( $\eta$ ), defined to be:

$$\eta = \frac{W}{Q_H} = 1 - \frac{T_C}{T_H}$$

#### Where:

$W$  is energy exiting the system as work, or in our case, electricity.

$Q_H$  is heat put into the system.

$T_C$  is the absolute temperature of the cold reservoir (the cooling source temperature).

$T_H$  is the absolute temperature of the hot reservoir (the hot water supply temperature).

To calculate the Carnot efficiency, all temperatures are given with respect to absolute zero, i.e. for Celsius temperatures you must add 273.15 to convert to Kelvin scale. For Fahrenheit, you must add 459.67 to convert to Rankine scale. A maximum theoretical efficiency of 1, or 100%, is mathematically obtainable if ( $T_C$ ) is absolute zero (0°K), or ( $T_H$ ) is infinitely large. Clearly, these conditions are impossible to achieve in real world applications.

The temperature ranges for  $T_H$  and  $T_C$  that low grade heat ORC systems typically operate in will dictate lower efficiencies than high grade heat ORC systems because of the higher heat source temperature  $T_H$ .

***This Carnot efficiency is the absolute maximum efficiency physics allows for any engine, regardless of size, complexity, money spent or the amount of time allowed for the engine to do the work.***



Using this Carnot efficiency baseline, efficiency is influenced primarily by the *difference* in temperature between the heat source ( $T_H$ ) and the cooling source ( $T_C$ ) through the equation  $1 - T_C/T_H$ . A higher difference in temperature between  $T_H$  and  $T_C$  ( $\Delta T$ ) will yield a higher efficiency. The efficiency is also the ratio  $W/Q_H$  of produced work output ( $W$ ) relative to the heat flow input ( $Q_H$ ).

### Green Machine Efficiency

Green Machine efficiencies may seem low; however, in cases where the heat source is currently going to waste, such as an engine's jacket water, or a process oven's hot exhaust stack, **the thermal efficiency without a Green Machine is zero**. In many cases, this waste heat is just released to the surrounding environment, which makes converting even a small amount of this waste heat to electricity valuable and worthwhile.

### Are There Ways to Increase the ORC System Efficiency?

Indirectly, there are ways to increase the efficiency. In practice, increasing the efficiency of an ORC will eventually cost more than the dollar value of the additional output. However, there are many indirect ways to increase the efficiency of the system as a whole in ways that aren't easily recognizable through analysis of just the ORC.

### Maximize Efficiency by Increasing your Overall Delta: $T (\Delta T) = T_H - T_C$ .

The larger this number, the higher the efficiency limit will be. Usually, it is difficult to decrease the  $T_C$ , as this is driven by environmental factors, such as air temperatures, cooling body temperatures, etc.  $T_H$ , on the other hand, is often subject to adjustment. Techniques like exhaust gas heat exchangers on engines, radiator thermostat changes, operating a hot water boiler under pressure or insulating pipes can all raise the hot source temperature,  $T_H$ .

### Reuse Condensing Heat ( $Q_C$ ), since over 90% of the Original Heat ( $Q_H$ ) ends up There.

There's no law of physics that says this heat must be wasted, only that it must be used at a temperature reduced by the work conducted by the ORC. Numerous "cascading" applications are suitable to low grade (lower temperature) heat. These uses, provided by the "free" waste heat from the ORC, can be correlated to savings in heating costs.

## Examples of “Cascading” uses for Green Machine Condensing Heat ranging up to 49°C (120°F):

- Digester heating for biogas and/or agricultural/wastewater treatment;
- Fuel drying for biomass;
- Preheat (temper) make-up air to building ventilation systems;
- Radiant floor heating;
- Swimming pool heating;
- Preheat (temper) of domestic hot water;
- Driveway or roadway ice melting;
- Cattle trough warming and other agricultural uses;
- Aquaculture with tropical species (tilapia and largemouth bass, for example);
- Boiler feed water preheating.