Cost and Performance Analysis of Evaporative Cooling Enhancement for Condensers at Empire Energy Geothermal Plant

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Abstract

Cost and Performance Analysis of Evaporative Cooling Enhancement For Condensers at Empire Energy Geothermal Plant. DAVID M. COSTENARO (Washington University, St. Louis, MO, USA 63130). Chuck Kutscher (National Renewable Energy Laboratory, Golden, Colorado 80401).

Many of today's geothermal power plants are located in arid climates. With water at a premium, air-cooled condensers are often used instead of wet-cooling towers. During the hottest times of the day, plant performance suffers as the "cold sink" (the ambient air) rises in temperature. For summer peaking utilities, these are also the times when grid power demand is highest. To boost the performance of a particular plant in Empire Nevada during these problematic peak hours, we have explored four methods for enhancing air cooling using evaporative means: 1) spray cooling, 2) Munters packing media-cooling, 3) deluge cooling, and 4) a hybrid combination of spray and Munters. A detailed Microsoft Excel spreadsheet is used to evaluate the performance and cost characteristics of each system operating in the Empire environment. It is concluded that the deluge cooling system, despite potential scaling on the condenser tubes, is the most economical way to optimize the plant's performance. The danger of scaling is dealt with by adding a purified water rinse to wash away new-forming scale whenever the deluge system shuts down.

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Introduction

At Empire Energy in Empire Nevada, a proposed small-scale, 1-MW geothermal plant will extract hot water from underground aquifers. Entering the power plant at around 245ºF, the geothermal fluid will be used to heat a closed-loop secondary fluid (isopentane) with a relatively low boiling point. This working fluid boils and expands through the turbine, providing the work needed to generate electricity. This “binary cycle” also serves the purpose of keeping the mineral-laden geothermal fluid from coming into contact with the air and the valuable components of the turbine. After heat is extracted from the brine, it is reinjected into the aquifer so that the amount of water present underground is stable, and overall heat losses to the aquifer are minimized (Barbier, 1997).

The Empire plant, like any power plant, is based on a cycle in which work is produced from the thermodynamic driving potential between a hot sink and a cold sink. If the hot sink temperature is raised or the cold sink temperature is lowered, there is a greater thermodynamic driving potential, resulting in more work and higher cycle efficiency (Black, 1996). In Empire, the hot sink is the heat energy available in the brine. After this heat is transferred to the working fluid and used to obtain work, heat must be dumped out of the system so the cycle can be repeated. The condenser plays this role by rejecting the necessary heat into the cold sink: the surrounding environment. The condenser at Empire will consist of a series of tubes that the hot, working fluid flows through after work is extracted. These tubes, with fins attached to the outside for more heat transfer area, will have 15 fans inducing a cooling draft of air over them. The tubes run 60 feet in length, and the entire array is 90 feet wide and 12 feet off the ground.

Such an air-cooled condenser is one of two main types of condensers, the other being a wet-cooling tower. Wet cooling towers cool by generously evaporating water, which capitalizes on its high energy of vaporization. That energy is thus drawn out of the hot fluid very effectively, but with the need for a sizable supply of water. In an arid climate like Empire's, water is not readily available. The alternative, an air-cooled condenser, simply blows the free and readily-accessible ambient air over the condenser tubes to cool them. As a result, the cold sink is always the ambient air temperature (Kanoglu, 1998).

In warm, arid locations in the southwestern United States, such as Empire's, the use of air cooling poses a problem. When the ambient temperature rises on hot summer days, the cold sink temperature goes up as well, and plant efficiency is significantly reduced. At the same time, utility air conditioning loads result in a greater demand for grid power.

To combat this dilemma, it has been proposed to evaporatively cool using a minimal amount of water during these problematic peak hours to enhance the condenser's performance (Kanoglu, 1999). Understanding evaporative cooling requires an understanding of psychrometrics: the study of air and water-vapor mixtures. The ambient temperature as read from a conventional thermometer is the dry bulb temperature ("T_{db}") of the atmospheric mixture of air and water-vapor. Every atmospheric condition has a specific T_{db}, a specific humidity ratio ("ω"), and a specific wet bulb temperature ("T_{wb}"). The humidity ratio of an air- water mixture is the ratio of the mass of moisture contained in the mixture to the mass of dry air in the mixture. The wet bulb temperature is the resulting temperature of the air if the maximum amount of water vapor is evaporated into the mixture at those conditions. Therefore, if water is evaporated into the air, the humidity ratio is increased and the T_{db} will approach the cooler T_{wb} (Procell, 1993).

Evaporative cooling of the mixture will produce a path like that shown on the psychrometric chart in Figure 1.

Evaporative cooling is an inexpensive and effective way to improve condenser performance during peak hours. In this study of the Empire Plant, the effectiveness and cost of four methods of condenser enhancement by evaporative cooling are investigated and compared using a detailed Microsoft Excel Spreadsheet. These methods are summarized briefly as follows:

1) **Spray cooling** - The intake air gains moisture before entering the condenser by passing through a mist pumped from an array of spray nozzles.
2) **Cooling with Munters packing** - Intake air gains moisture before entering the condenser by passing through wetted Munters evaporative-cooling media.
3) **Deluge cooling** - Air blows through the condenser just as usual, except the tubes are deluged by pumped water that drips down from above. Evaporative cooling occurs directly on the tubes.
4) **Hybrid cooling** - A less sophisticated array of spray nozzles is aimed at a thinner piece of Munters packing. Intake air gains moisture by passing through the spray nozzles and the Munters packing.

Materials and Methods

Much of the information in this study was obtained through working closely with Dr. Chuck Kutscher, Principal Engineer at NREL. An extensive literature search of reports, articles, and books dealing with relevant issues provided a great deal of background information. Experts in the power industry, such as Larry Green at Empire Energy and Bob Sullivan at Mammoth Power, as well as experts in the research community, such as NREL Principal

Engineer Dr. Desikan Bharathan, were consulted frequently for scientific advice. Also, several manufacturers were contacted for pricing and general information.

As data and theoretical models for the four evaporative systems were developed, they were integrated into a Microsoft Excel Spreadsheet. The spreadsheet was designed to be generalizable so that values in yellow-highlighted, input boxes could be altered and the rest of the spreadsheet would adjust to them. Conditions specific to Empire such as elevation, condenser intake area, and yearly Nevada weather profiles were input, and the given parameters of each system yielded their performances at said conditions. Most calculations were performed by spreadsheet formulae, using named variables for clarity like “Elevation” or “Intake_area” as opposed to cell indices like “A42” or “C17” (Person, 1997). Some of the more detailed calculations requiring algorithms and iterations were done by embedding Visual Basic macros into the spreadsheet.

The cost analysis of each system included determining the capital costs of equipment and installation as well as routine maintenance and ongoing costs, e.g., water consumed. These costs were weighed against the value of the additional electricity the plant could produce with each system installed. Performance and cost data for each system were collected and evaluated using five key economic indicators: total life-cycle cost (TLCC), net present value (NPV), levelized cost of energy (LCOE), simple payback years (SPB), and internal rate of return (IRR).

Results

I. SYSTEM MODELS

The baseline condenser system at Empire consists of 15 induced-draft fans drawing air through ten, 60-foot-long tube bundles. Aspen Simulation Software was run for the entire

Empire plant and used to find out how net output was affected by the ambient temperature. This produced the linear correlations shown in Figure 2. As the ambient temperature is decreased, plant performance rises. The enhancement systems were all modeled so that the plant would behave as if the ambient temperature was the temperature resulting from the cooling hardware. The corresponding performance was then determined from this curve. The plateau in the graph shows that only a finite amount of enhancement is possible. Once the condenser reaches a certain low temperature, physical restraints on the pressure drop through the turbine limit additional power available from the cycle.

The **spray cooling** method operates by having a high pressure water pumping system hooked up to an array of strategically-placed, atomizing nozzles that mist the air as it enters the condenser. (See Figure 3.) With only a thin network of pipes and nozzles, the air flow into the condenser is not significantly impeded, and so the pressure drop and fan power required are not adversely affected. The water droplets, split by impaction pins on the special nozzles, have diameters on the order of microns and evaporate very quickly and effectively. The incoming air can thus be cooled 95% and more from the T_{db} to the T_{wb} (This is referred to as 95% saturation efficiency). Manufacturers, such as Mee Fog Inc and Munters, claim that evaporation is so effective that there is no danger of water droplets impinging on the downstream condenser tubes. Water making contact with the tubes is a serious issue, because even small amounts of it can leave significant chemical deposits on the tubes over time, greatly impeding heat transfer (Smith, 1972). Also, no return-water loop is necessary, because there are not appreciable amounts of unevaporated water. Depending on the chemistry of the water, however, deposits on the nozzles may require cleaning.

The **Munters cooling** method involves covering the intake area with an evaporative cooling media and running the system like a typical evaporative or “swamp” cooler. (See Figure 4.) Water is pumped at ordinary pressures to a distributing cap that spreads the water over the top of this honeycomb-like, porous media. As the water drips down and through it, air passes through, perpendicular to the media, and absorbs moisture. Munters Corporation makes a product specifically for this purpose called CELdek. A pan collects the excess water and recirculates it. As the water evaporates, though, it leaves deposits and minerals behind. To prevent this from building up, Munters recommends that water be bled off from the cycle at (depending on the water chemistry) between 10 and 50% of the amount of water that is evaporated. Therefore, the water that must be supplied is equal to the amount of water that is evaporated plus 10 to 50% of that again for the bleed-off stream.

Saturation efficiencies can range from around 60 to 98% as the media thickness increases. Pressure drop, and consequently fan power required, also increases as thickness increases, so the proper balance must be struck. A mist eliminator is placed downstream of the Munters packing to prevent any droplets picked up by the air-flow from impinging on the condenser tubes and scaling or corroding them. When the system is not in use, it is advantageous to have some sort of bypass for the air flow to avoid the pressure drop associated with the packing. Complete systems like this, called Combinaire systems, can be purchased from Hudson corporation (Smith, 1972).

The **deluge cooling** method is fundamentally different from the previous two methods in that evaporative cooling occurs directly on the condenser tubes, rather than in the air before it reaches the tubes. Consequently, the thermal resistance associated with air boundary layer is effectively eliminated. Also, much more heat can be transferred to the air stream because the air gets saturated as it goes through the condenser. In the other cases, the air gets saturated before it enters the condenser, and so it approaches the wet bulb temperature then. For example, the ambient air may be 77ºF, which is saturated and cooled by the spray or Munters method to around 57ºF before it enters the condenser. After this point, no more water is added to the air stream. Using the deluge method, however, the air may rise from 77ºF to 82ºF while it goes through the condenser, picking up moisture all the while. Saturated air at 82ºF can hold significantly more moisture than saturated air at 57ºF. The deluge method draws the additional heat needed to evaporate that water directly out of the condenser tubes.

Water is pumped up at ordinary pressures and sprayed onto the tubes from above. (See Figure 5.) It drips down and much of it is evaporated as it does so. The water that does not evaporate is recirculated. In studies done in the 1980s at Pacific Northwest National Laboratories, very large increases in heat transfer rates were observed using this method. Using these studies as a model, an expression for the thermodynamic driving potential was correlated to the enhancement ratio. The enhancement ratio was defined as the ratio of the amount of heat transfer when deluged to the amount of heat transfer when dry, and was routinely between 3 and 7. These results were obtained using a finned-tube heat exchanger similar to the condensers under consideration (Hauser, 1982).

With water directly contacting the condenser tubes, scaling and deposition are a significant concern. When the system is shut down, the water that is still on the tubes will evaporate and leave deposits behind. To use deionized or purified water at all times is extremely expensive. It has been proposed to implement a small, reverse-osmosis purifier to accrue a tank-full of clean water over the course of the day. Whenever a system is shut down, the condenser tubes will be rinsed with the pure water, greatly reducing the amount of scaling. This rinse system would require a separate piping and pumping system. Also, with the high heat transfer rates available, only one out of fifteen condensing units needs to have the equipment installed. If this is the case, the system could be rotated between units of the condenser bank so that any scaling that did occur would be spread out over the whole condenser field.

The **hybrid cooling** method combines aspects of the spray cooling and the Munters cooling methods. (See Figure 6.) A less sophisticated array of spray nozzles, with water at a lower pressure, heavily mists the intake air. The droplets are not atomized to the small diameters of the spray method, and so, are not evaporated as completely. The water that isn't evaporated here, though, impinges onto a thin layer of Munters packing. As the air passes through the Munters packing, it becomes more saturated, while experiencing a lower pressure drop than the pure Munters method because the packing is thin. The water is recirculated in a manner similar to the pure Munters cooling scheme. Interestingly, this method was pioneered for use in the poultry industry to keep chickens cool.

II. System Performance

After calculating the estimated costs and performance of each system over the plant's lifetime, it was immediately apparent that the Munters cooling had the lowest performance boost and the highest capital cost. Both the spray and the hybrid schemes performed fairly well in enhancing the plant performance, but neither of them broke even economically. The net present values of both systems after the life-cycle cost analysis were negative, with the spray being slightly less costly than the hybrid. The deluge system increased plant output the most, and also delivered a return on money invested with a positive net present value. Results are tabulated in Figure 7.

Discussion and Conclusion

The following conclusions are derived from the spreadsheet analysis with the site-specific data for the Empire Energy plant:

The **spray cooling** method produces a substantial amount of cooling at a fairly reasonable system price. Fan power is not significantly impacted because pressure drop remains virtually the same. Some negative points, however, are that the high water pressures required to atomize the droplets create the need for a robust piping system and a pump with more parasitic power-draw. Also, nozzles must be cleaned, maintained, and occasionally replaced as scaling and deposits may clog them over time.

The **Munters cooling** method yields the lowest system enhancement capabilities at the highest capital cost. Maintenance is not a serious issue after initial installment, aside from an occasional replacement of the CELdek media. The boost in plant performance is not enough, though, to offset the costs. Also, the fan power must rise to draw air through the increased pressure drop caused by the media. When compared to the other methods outlined here, Munters cooling is an unattractive and uneconomical option.

The performance with the **deluge cooling** system is very impressive, allowing the plant to run at almost full capacity at all times. The system is quite simple as well, in that it merely pumps water up and dumps it on the tubes. A comparatively huge amount of water, is necessary for this system, and so its feasibility is very much driven by the price of water. Also, it may require a more sophisticated control system than the other methods which could turn deluge sections on or off as needed and switch between deluge and rinse cycles. Scaling and build-up on the condensers from the direct water contact is of paramount concern. Addition of the clean rinse-water subsystem to wash new-forming scale when a section is shut off would drastically reduce scaling and build-up. Under the conditions at Empire, the deluge system is the only option that renders a positive economic return. This, coupled with the very high performance increases, makes it the most favorable candidate for installment.

The **hybrid cooling** method, as might be expected, has performance and cost characteristics right between those of its constituents: the spray and Munters methods. The sophistication of the nozzles, pumping, and piping in the spray method are eliminated because the droplets do not need to be atomized as well. The significant pressure drop of the Munters method is reduced because only a thin sheet of it is needed. In addition, the Munters packing acts as a mist eliminator, catching large droplets from the nozzles so they do not impinge on the condenser tubes. The hybrid cooling method is a simple and attractive option, but it does not quite pay for itself economically.

In conclusion, for the proposed Empire Energy plant in Empire Nevada, Munters cooling is not a viable enhancement option. Installation of a spray cooling system or a hybrid cooling system would increase plant performance significantly, but are not financially advantageous. A deluge system, in spite of the looming issue of scale deposition, is an effective and economic method by which plant performance could be enhanced during troublesome peak hours. The rinses with purified water should neutralize this threat, making deluge the recommended system for the job.

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Figures

Figure 1. Psychrometric Chart Showing Path of Evaporative Cooling

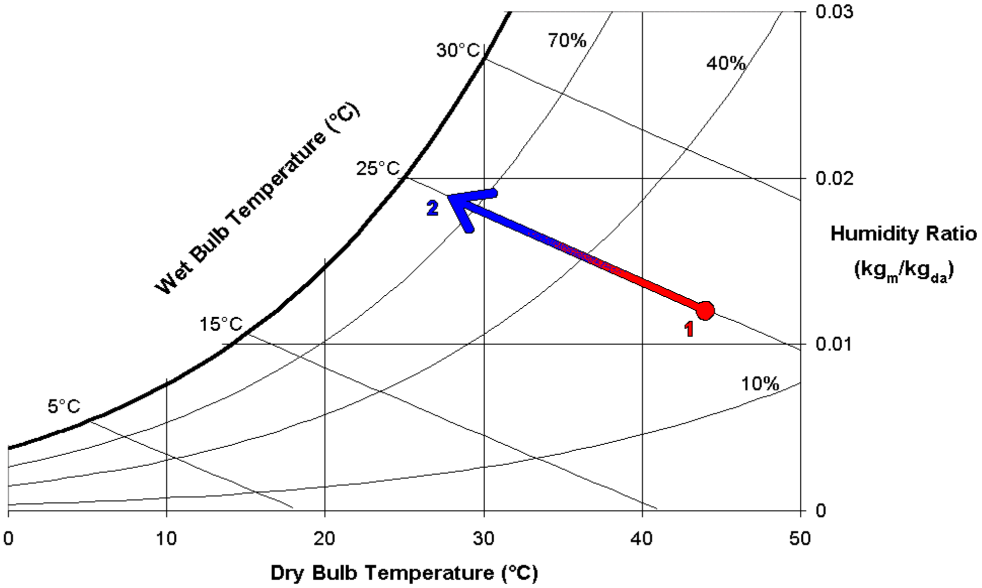


Figure 2. Plant Net Output vs. Ambient Temperature

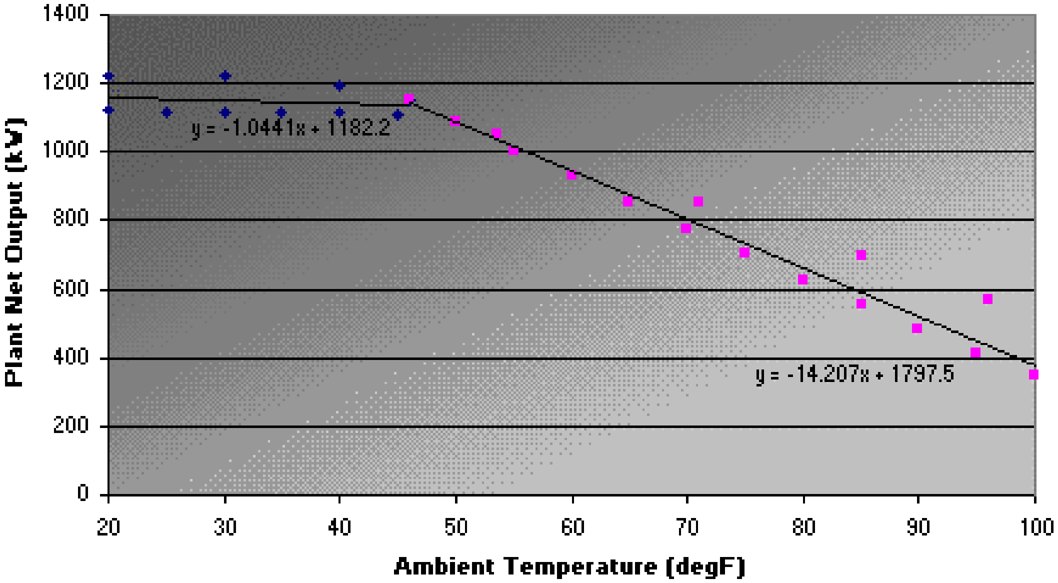


Figure 3. Spray Cooling System

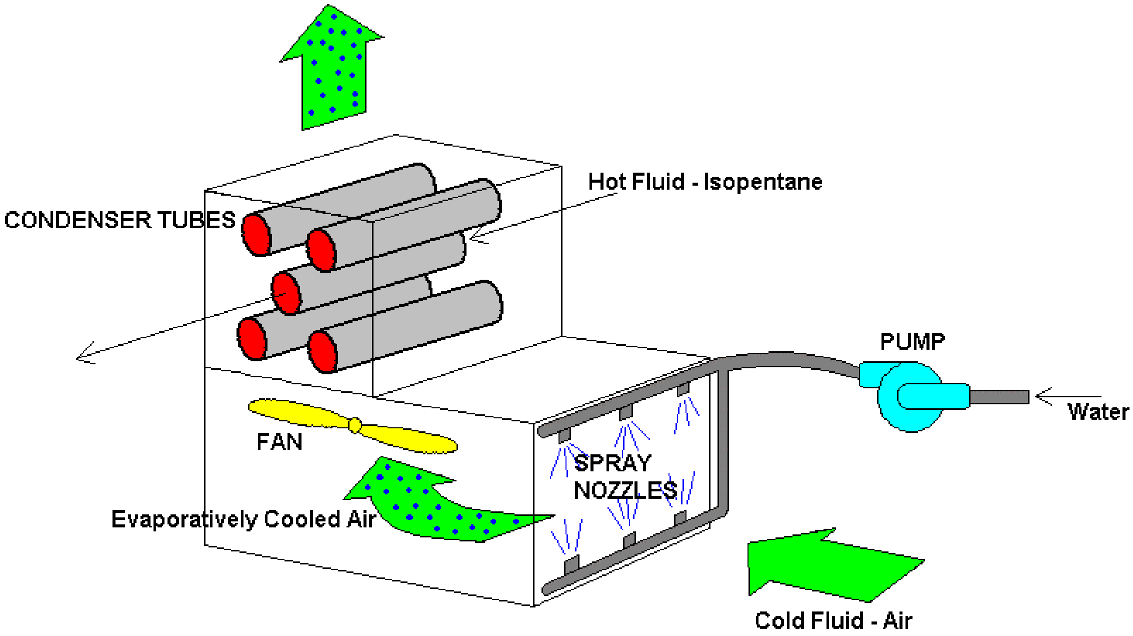


Figure 4. Munters Cooling System

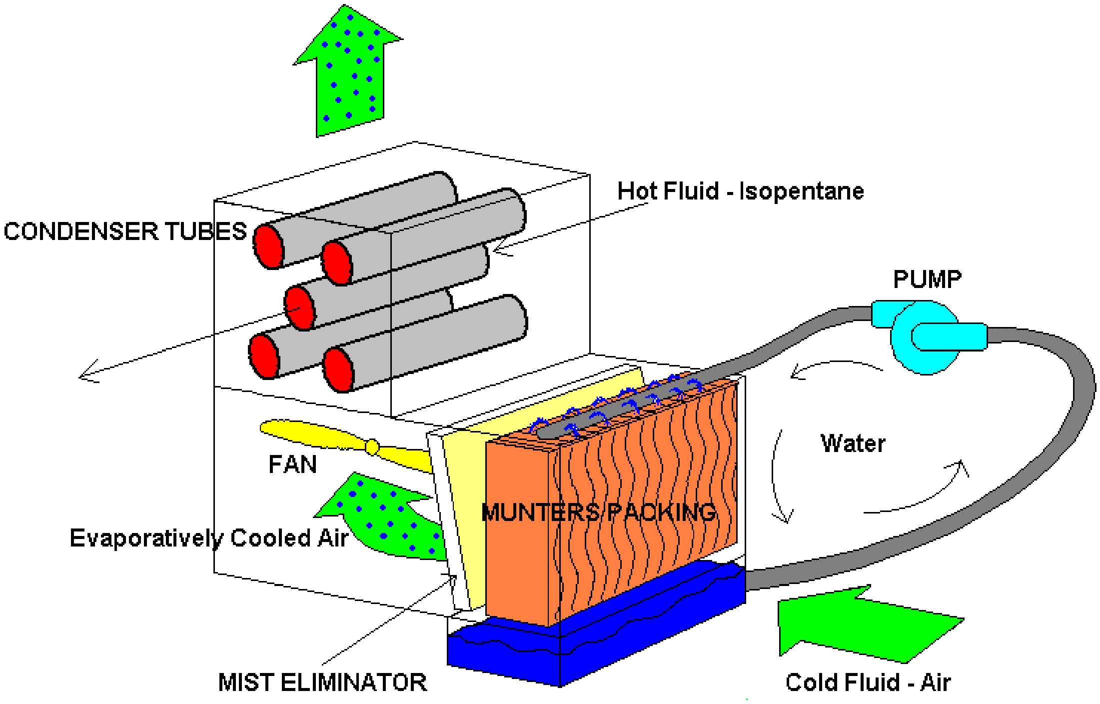


Figure 5. Deluge Cooling System

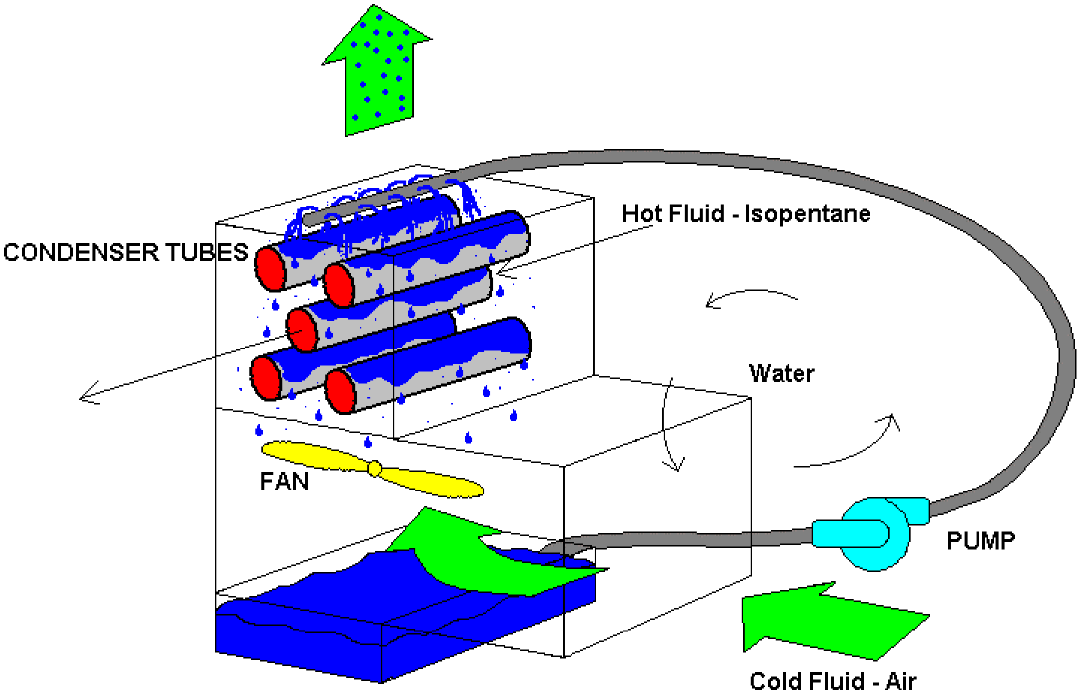
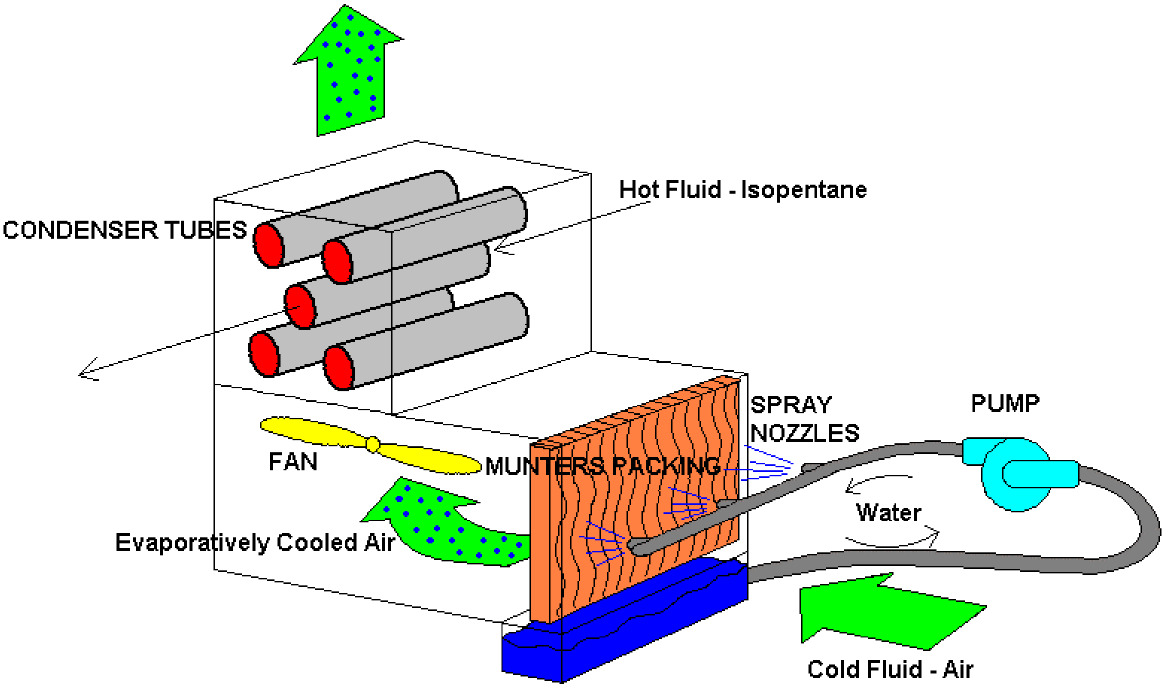
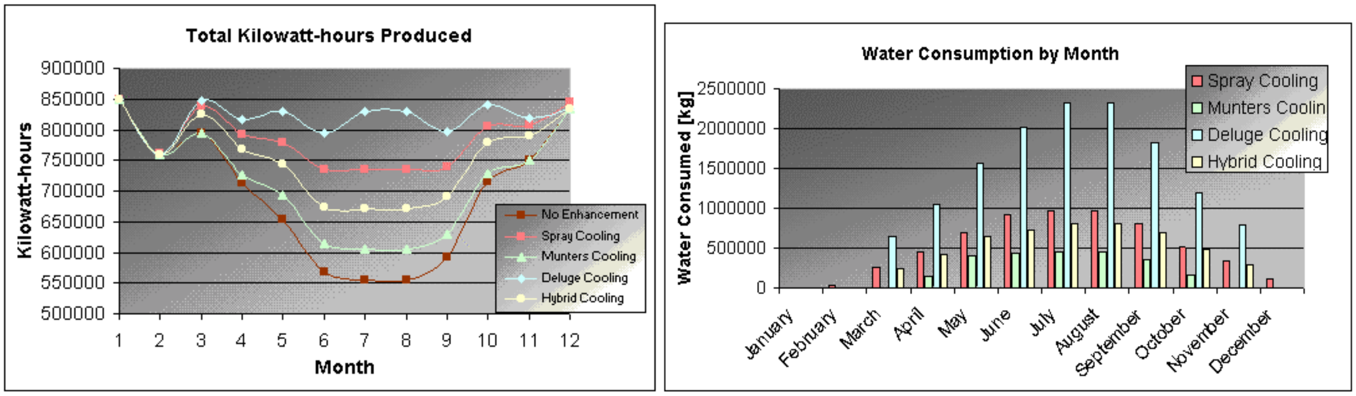


Figure 6. Hybrid Cooling System



<u>**Figure 7. Results of Spreadsheet Analysis**</u>



Key Economic Indicators

	System 1 - Spray Cooling	System 2 - Munters Cooling	System 3 - Deluge Cooling	System 4 - Hybrid Cooling
Total Capital Cost [$]	$155,977	$215,491	$37,139	$134,911
Additional kWh produced per year with system [kWh]	1,078,240	247,259	1,501,902	713,071
Total Value of Additional Electricity [Present Value $]	$453,124	$149,534	$641,731	$315,940
TLCC - Total Life-Cycle Cost [Present Value $]	$481,387	$361,008	$575,382	$355,102
NPV - Net Present Value [Present Value $]	-$28,264	-$211,474	$66,348	-$39,162
LCOE - Levelized Cost of Additional Energy [Additional Cost per year / kWh gained per year]	$0.0691	$0.2259	$0.0593	$0.0770
SPB - Simple Payback Years	10	Investment Will Not Pay For Itself	5	11
IRR - Internal Rate of Return	12.6%	0	29.4%	10.8%