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Analysis of Alternative Cooling Options for a 1000 MW$_e$ Power Plant at Reduced Temperature Difference across Ultimate Heat Sink

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Abstract

Process heated water from most existing nuclear and fossil fueled power plants is discharged directly to the ultimate heat sink by once through system. This direct discharge increases the temperature of ultimate heat sink in the vicinity of the discharge which has worst biological and ecological effects, leading to legal actions by Environmental Protection Agencies (EPAs). In this paper, an analysis and comparison of alternative cooling options for a typical 1000 MWe Nuclear Power Plant is presented. Several alternative approaches are considered such as cooling canal, various types of cooling towers such as wet, dry and hybrid system, Heller system and cooling pond. The study is divided into three phases, thermal analysis, financial analysis and comparison of the above mentioned options. The quantitative analysis tool developed in MS Excel is validated by benchmarking the results against IAEA water management program (WAMP) tool kit. Financial analysis including investment cost and operation cost is done for each cooling option. Finally, a brief comparison of each technology is done against typical once through system. Results reveal that wet cooling towers are most economical alternative as compared to dry and hybrid cooling towers which high have investment and operation cost. Other alternatives including cooling canal, and cooling pond, also meet the requirement, but they require very large land area.

Keywords: *Heat sink, cooling tower, pond, evaporation, environment*

1. Introduction

The thermal efficiency of most power plants varies between 30 to 40 percent. This means that the process heat rejected from the power plants is 1.5 to 3 times the useful work output of these plants. This heat is thrown back to the ultimate heat sink by circulating water system. Circulating cooling water system is responsible for heat rejection from steam cycle to the environment. Most of the power plants, either nuclear or fossil fueled, utilize once through system for circulating cooling water.

In once through system, water is taken from the natural water body such as sea, river or a large lake and pumped through the condenser where it is heated and thrown back to the ultimate heat sink at higher temperature than the temperature of the reservoir. This is shown in the Figure 1 below.

In a typical once through system, discharged water is at higher temperature than the temperature of the ultimate heat sink. This has adverse effect on the biota and the eco-system of the receiving water body. Therefore it is important to explore other alternatives so that the water is discharged back to the sink at relatively cooler state which may prove to be environmental friendly and also economical.

2. Scope and Methodology

A nuclear power plant is a cleaner source of electricity as compared to other fossil fueled power plants such as a coal power plant. Life cycle assessment (LCA) was used to assess the environmental impacts of a coal power plant situated at United States by Ikpe et al [1]. Moreover, different governmental and non-governmental organizations introduce energy efficiency standards to encourage the reduction of environmental impact of different energy projects such as Gold Standard (GS) introduced by World Wide Fund (WWF) and other standards as discussed comprehensively in [2]. Research work in this paper mainly focuses on a 1000 MWe nuclear power plant with 30% efficiency. The ultimate heat sink will be the sea where the

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cooling water of open circulating water system will be discharged. The average weather conditions of Karachi Pakistan are considered and the temperature of intake water from the sea varies between 16 °C and 31°C depending on the time, tide and season. Cooling water will be drawn from the sea and will be passed through condensers and heat exchangers to cool the plant process equipment. Condenser range is 8 °C. Seawater cooling system is once-through and the heated seawater will be discharged back to the sea which will increase the temperature in the vicinity of the discharge. It is assumed that the local environmental regulations allow for a maximum temperature increase of 3°C to be attained within 100 m from point of discharge [3]. It means that the temperature of the sea, where the plant cooling water is discharged, must not rise above 3 °C on the average within 100 m radius from discharge. Therefore, some possible cooling options including the open cycle system, which is taken as the base case in the current study, have to be analyzed to select the optimum option in order to keep the discharge temperature within regulatory limits.

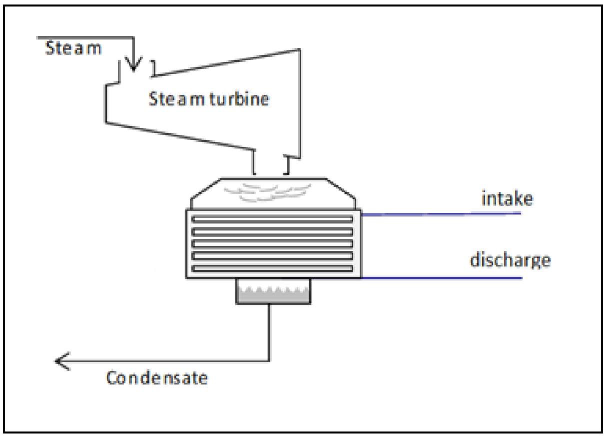

Figure 1: Once through system.

The alternative options to open cycle system include cooling canal, cooling pond and various types of cooling towers such as wet, dry and hybrid system in various configurations. Table 1 below shows the distribution of cooling technologies used in current nuclear power plants [4].

Table 1: Distribution of cooling system in NPPs

Once through system		Closed cycle	
Sea	Lake	River	Cooling tower
45%	14%	15%	26%

Although the requirements of water for once through system can be met, but environmental considerations sometimes limit the use of once through system if discharge water temperature exceeds the limit. For this purpose, alternative options must be used. Many methods are applicable throughout the world as mentioned before in this article.

A shallow water canal can be used to cool discharge water of the condenser by dissipating heat to the atmosphere by combination of convection and radiation heat transfer along with evaporative cooling.

Cooling lakes or ponds are one of the oldest heat rejection systems. Heat is dissipated to the pond by combined action of evaporation, convection and radiation during night. Cooling lakes has very low cooling effectiveness and thus very large area is required. Area between 4000 to 8000 m^2 is required per megawatt of the plant output [5]

In Florida, a cooling canal was evaluated by Leffler et al [6], who showed that 4.7 GW of heat can be rejected by 32 canals, each one 8390 m long and 90 m wide with a cooling area of 17.7 x 10^6 m^2.

A spray pond is a large pond using fountains that emit water in air inside the pond. Here heat is rejected from water by spraying it through spray nozzles into the air by virtue of evaporation and convection. In United States, spray ponds have been used in a number of geographic locations for nuclear power plants [4].

The cooling towers reject heat to the environment either directly (wet) or indirectly (dry). In wet cooling towers, cooling is mainly through evaporation where air interacts directly with water. 3-5 % water is consumed and make up water must be added to meet water requirements [4].

Dry cooling towers are used in water deficient areas in close loop. In this system no water is lost to atmosphere. South African power utility Eskom uses dry cooling towers at many of its power plants. Kendal power station is the world's largest dry cooled power plant [4].The table below summarizes the above discussion.

Table 2: Heat exchange mechanism for cooling systems

Cooling Type	Turbine/Condenser Heat Transfer	Heat Sink Heat Transfer
Wet cooling	Steam/water HX	Water/air (direct contact)
Dry cooling	Steam/water HX	Water/air HX
Cooling pond	Steam/water HX	Evaporation, Convection
Cooling canal	Steam/water HX	Evaporation. Convection

In order to propose an economical and environment friendly alternative to the existing once through system, the following procedure was used:

1. Analysis of once through system was carried out. Its capital and operational costs were determined.
2. Similar procedure was followed to find capital and operating costs of the alternative options.
3. Analysis results were compared with respect to technical issues and cost. Finally, an optimized and economical option which met the regulations of local environmental protection agency (Sind Environmental Protection Agency) (EPA) was suggested. Optimized in this context means an option with lowest total evaluated cost, which is the sum of capital cost and operational cost and a technically viable option.

The calculations were performed using MS EXCEL. These results are also calculated by Water Management Program (WAMP) tool kit available on IAEA website [7].

3. Characteristics

As already mentioned above, our analysis mainly focuses on 1000 MW power plant. The plant is AP1000 which is a Westinghouse design designed for 60 years operation. The thermal power of the plant is 3415 MWe. The hot leg temperature is 321.11 °C [8]. Table 3 shows some design parameters used in calculation.

Table 3: Power plant design parameters

	Value	Unit
Thermal Power	3415	MW_t
Plant Efficiency	30	%
Heat Rejected	2390	MW
Hot leg temperature	321.11	°C

The calculations are performed for the coastal areas of Karachi, Pakistan. The site characteristics are shown in Table 4.

Table 4: Site characteristics

Parameters	value	Unit
Dry Bulb Temp, DBT	26.3	°C
Wet Bulb Temp, WBT	21.2	°C
Sea Water Temperature	31	°C
Relative Humidity, RH	64	%
Wind Speed, V	3.45	m/s

4. Results and Discussion

4.1. Once Through System

For the once through system, the condenser range is 8 °C. Pump Head required is 19.7 m and pump efficiency at the given flow rate is assumed as 92 %. Using the data available, the results obtained are shown in Figures 2 to 4.

As the condenser range is increased, the water flow rate through the condenser is decreased as shown in Figure 2. Flow rate is mainly dependent on two parameters, the cooling load and range of the condenser. Optimized water flow rates in the condenser provide saving in capital and operating cost. It is evident from the energy balance formula across the condenser.

$$Heat\ rejected = m'C_p(T_2 - T_1) \quad (1)$$

here

m' is water mass flow rate in kg/s.

C_p is specific heat of water in KJ/Kg-C

T_1 and T_2 are water inlet and outlet temperature across the condenser respectively in °C.

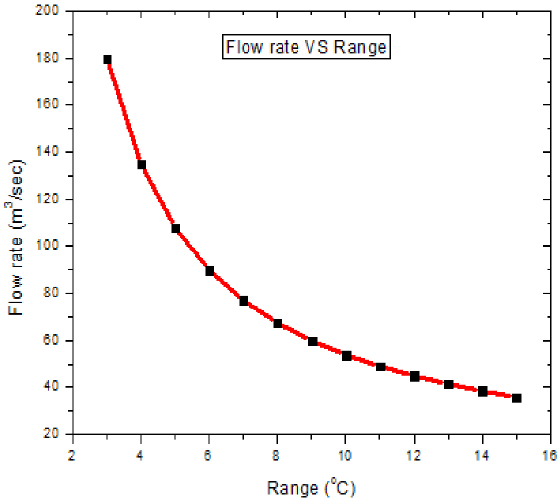

Figure 2: Variation of Flow Rate with Condenser Range

Pump power requirement decreases with the increase in condenser range because condenser range varies inversely with flow rate as shown in Figure 3. At lower range, flow rate is high and thus power demand is high. . Pump power is determined by

$$Power(kW) = \frac{Q(m^3/hr.) \times H\ (m) \times (SG)}{(366 \times \eta)} \quad (2)$$

where Q is water volume flow rate in m^3/s, SG is Specific Gravity and H is pump head in meters.

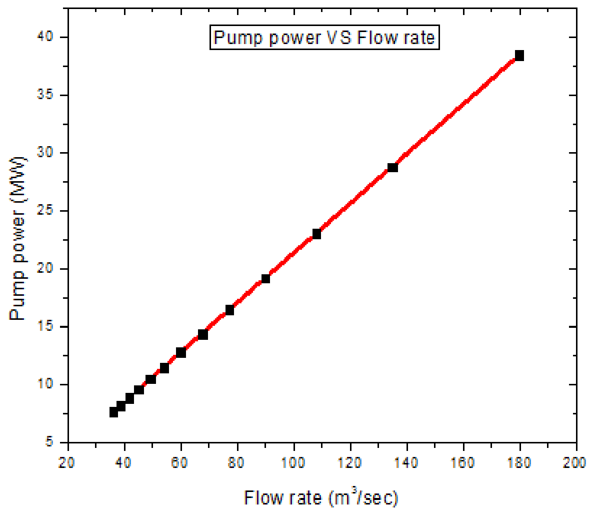

Figure 3: Variation of Pump Power with Condenser Range

On the other hand pump power varies linearly with the flow rate. At very high flow rate, the pumping power increases tremendously. It is shown below in the Figure 4.

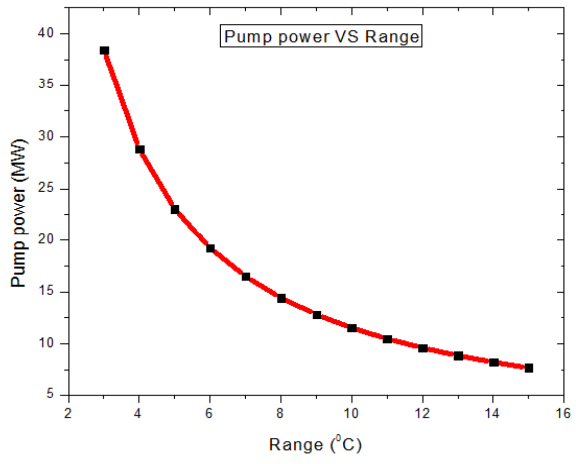

Figure 4: Variation of Pump Power with flow rate

4.2. Cooling Canal

Cooling canals are an integral part of the once through system in many cases to carry away the discharge water back to the sea. On the passage, if the flow channel is open, some heat may be rejected from warm water to the environment by evaporation and convection. Discharge water from power plant is at 39 °C as we have inlet water at 31 °C and condenser range is 8 °C. This water temperature at discharge should reach to 34 °C to meet the regulations of environmental agency [1]. Therefore an analysis of the existing system is done. Length of the canal is varied from 0 to 6000 m where the required temperature is achieved. The depth of water should be shallow in order to dissipate heat uniformly from bulk of water. The energy balance across the canal is given by equation 3 as

$$m_i' h_i - m_{i+1}' h_{i+1} + Q_{solar} = Q_{evap} + Q_{conv} \quad (3)$$

$$Q_{solar} = A\left[\alpha_{solar} G_{rad} - \varepsilon\sigma T_s^4 - T_{sky}^4\right] \quad (4)$$

$$Q_{conv} = hA(T_s - T_\infty) \quad (5)$$

$$Q_{evap} = m_{evap}' * h_{fg} * A \quad (6)$$

Evaporation from the water surface depends on the following factors [9]

1. Air velocity above the surface
2. Water temperature
3. Air temperature
4. Humidity ratios

Where mass flow rate (kg/sec) is given by [9]

$$m_{evap} = \frac{\emptyset * A * (Xs - Xw)}{3600} \quad (7)$$

where

$$\emptyset = (24 + 19V) \quad (8)$$

Φ is evaporation coefficient (kg/m^2.h), X_s is specific humidity at saturation, X is specific humidity, and A is the area.

Solar radiation incident on earth is 1.38 KW/m^2 [9]. All solar radiation is not absorbed. Some are reflected back as well. Also operation at night doesn't receive solar radiation. So roughly 70 percent is not available to water. Similarly evaporative heat transfer and convective heat is determined from their respective equations. Our analysis mainly focuses here to find the length of the canal for the required temperature drop.

Increasing the length of the channel decreases the outlet discharge temperature because surface area increases for convection and evaporation heat transfer. This is shown in Figure 5. But this option has large land area requirement. So to achieve outlet temperature of 34 °C, approximately 6 km long channel with 6 m width is required. This has an area of 36000 m^2.

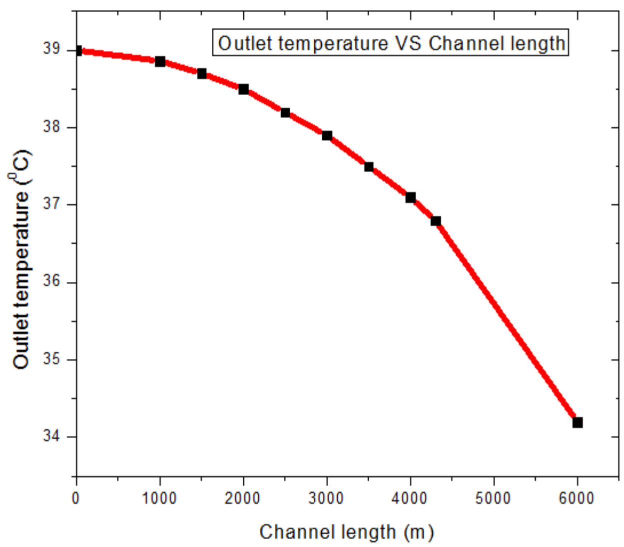

Figure 5: Variation of Outlet Temperature with Length of Channel

4.3. Cooling Towers (Open Mode)

In open mode system, some intermediate cooling system is installed which will reduce condenser load and thus an expected decrease in pumping power. A cooling device is used between the sea and the condenser. The cooling system may be cooling tower, cooling pond. We will analyze open loop cooling system with cooling tower first, which may be either natural draft or forced draft. Open mode is advantageous in a sense that it reduces water flow rate across the condenser which ultimately reduces pumping power. This is only possible by increasing the condenser range from 8 °C to some higher values. As already found for existing system, the range should be maximum for minimum pumping power. So we select condenser range of 14 to 15 °C.

Table 5 below shows results for mechanical draft wet cooling tower in open mode.

Here the fan power is given as

$$P_{fan}(HP) = \frac{\text{cfm} \times \text{PD}}{33000 \times \eta\eta} \quad (9)$$

where, cfm is air flow rate in cubic feet per minute, PD is pressure drop in inches of water and η is fan efficiency.

Table 5: Results for open mode Mechanical Draft Tower

	Value	Unit
Evaporative Losses	0.56	m^3/sec
Blow Down Losses	0.06	m^3/sec
Make Up Water Needed	0.62	m^3/sec
Air Flow Rate	40.15	m^3/sec
Fan Power	0.28	MW
Total Power(Fan +Pump)	**8.97**	**MW**

On the other hand Natural draft tower have advantage of saving fan power but they are very costly. In natural draft tower, air flow rate is enhanced due to the height of the tower and its hyperbolic design. The driving pressure is applied by the difference in density of the inlet and outlet air. Air at the outlet is almost saturated. The driving pressure is given as

$$\Delta P_d = (\varrho_{out} - \varrho_{in}) \times H \times \left(\frac{g}{g_c}\right) \quad (10)$$

Where H is height of the tower, $\boldsymbol{\varrho_{out}}$ is density of air at exit, $\boldsymbol{\varrho_{in}}$ is density of air at inlet to tower. We assume tower height of 100 m.

The densities are calculated by

$$\varrho_{out} = \left(\frac{P-P_{v1}}{R_a T_1}\right) + \left(\frac{P_{v1}}{R_v T_1}\right) \quad (11)$$

$$\varrho_{in} = \left(\frac{P-P_{v2}}{R_a T_2}\right) + \left(\frac{P_{v2}}{R_v T_1}\right) \quad (12)$$

where 1 and 2 refers to inlet and outlet points and R_a and R_v refer to gas constant of dry air and water vapor, respectively. Also

$$P_v = P_{sat} \times \Phi \quad (13)$$

Results are shown in Table 6.

Table 6: Results for Natural Draft in Open Mode

Parameters	Value	Unit
Atmospheric Pressure,	1	atm
Outside Air Density	7.94	kg/m^3
Inside Air Density	6.37	kg/m^3
Driving Pressure	0.22	Psi

4.4. Cooling Tower (Close Loop)

In close loop system, the pumping head is less than that in open mode because here water circulates in closed mode and it has to be pump from tower fill instead of sea. The total power is less than once through system and open mode system. The condenser range is kept similar to that in once through system to decrease cooling tower load. In this case we are again at advantage as per the pumping requirements. This is clear from the results given below in table 7.

Table 7: Results for Close Loop Mechanical Draft

Parameters	Value
Water Flow Rate (m^3 /sec)	71.34
Pump Power (MW)	7.72
Evaporation (m^3 /sec)	0.87
blow down losses (m^3 /sec)	0.09
make up water (m^3 /sec)needed	0.97
air flow rate (m^3 /sec)	52
Fan power (MW)	0.27
Total power (fan +pump)	**8.00**

Table 8 show results for natural draft tower operated in close mode.

Table 8: Results for Natural Draft Tower in Close Mode

Parameters	Value	Unit
Atmospheric Pressure	1	Atm
Outside Air Density	7.94	Kg/m3
Inside Air Density	6.18	Kg/m3
Driving Pressure	0.25	Psi

4.5. Dry Cooling Towers

The most important parameter to define the dry cooling towers id Initial temperature difference (ITD). It is given as

$$ITD = T_{hot} - T_{air,dbt} \quad (14)$$

where, $\boldsymbol{T_{hot}}$ is the temperature of the hot water entering the tower and $\boldsymbol{T_{air,dbt}}$ is the dry bulb temperature of air.

In most cases ITD ranges from 10 to 16 °C. Whether used in direct mode or indirect mode, heat dissipated by the dry cooling tower is proportional to product of ITD and surface area of the cooling tower, other thing being equal. As air temperature is constant, increase in load will cause increase in ITD and thus temperature of circulating water entering the condenser. This will increase back pressure of the turbine. Fans with high flow rates of air will be required to carry away the condenser heat. We will evaluate dry system for three different ITDs. Make sure that heat dissipation required is approximately 2390 MW. So the circulating water pump requirements are similar to once through system. Remember that there are no evaporative or drift losses on this case.

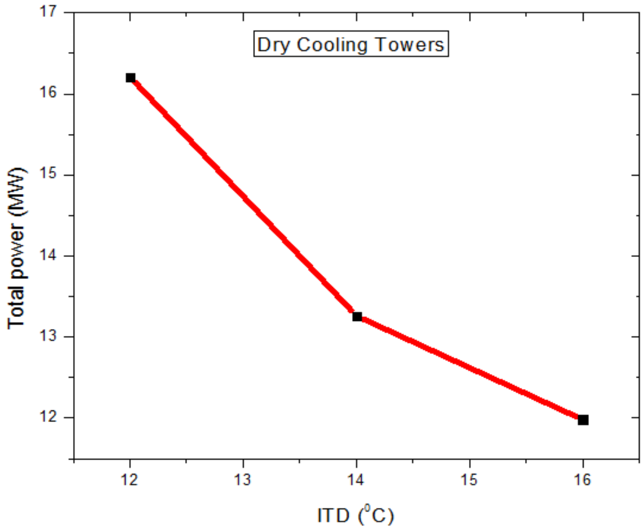

Figure 6: Dry cooling tower results

Total power requirements decrease with increasing ITD because it has inverse effect on the water flow rate. Also fan's horse power decreases with increasing ITD due to lower L/G ratio. L/G ratio is the ratio of water flow rate and air flow rate. This is shown in figure 6. The following formulae can be used to determine L.G ratio.

$$\frac{L}{G} = \frac{(h2-h1)}{(T1-T2)} \qquad (15)$$

Where:

T_1 = hot water temperature (°C)

T_2 = cold-water temperature (°C)

h_2 = exit air enthalpy

h_1 = inlet air enthalpy

Table 9: Dry cooling system results

Parameters	**12 °C ITD**	**14 °C ITD**	**16 °C ITD**
Tower Inlet Temp C	39.30	41.30	42.30
ITD	12.00	14.00	16.00
Heat Dissipated MW	2390	2390	2390
Fan Power (MW)	1.55	1.45	1.22
Pump Power	13.49	10.87	9.91
Total power (MW)	16.20	13.26	11.98

4.6. Cooling Pond

Cooling ponds can operate in two ways in circulating water system. It can either be open mode or closed loop. In open loop, it is just like a once through system and hence no effect on the pumping power and flow rate. Surface area required is less than the close loop. But in close loop, water has to be cooled to inlet water temperature, so large pond area will be required. Here also pumping power and flow rates are similar.

Figure 7 below shows the results for close loop cooling pond. Here 2.6 Km^2 land area is required for cooling pond operation to cool water to the desired temperature. Water flow rate is almost similar to once through because condenser range is not altered. For open loop system, evaporation rate can be calculated similar to that of a canal. It is given by

$$m_{evap} = \frac{\emptyset \times A \times (Xs - Xw)}{3600} \qquad (16)$$

here Φ is a function of velocity of air given as

$$\emptyset = (95 + 0.425\, V) \qquad (17)$$

As m_{evap} is known, we can calculate area of the pond. In this case the area required is 17160 m^2. Figure 8 show results for an open loop system of cooling pond.

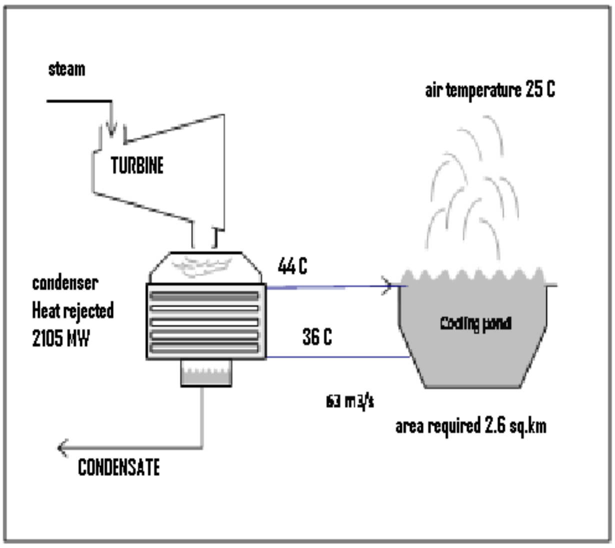

Figure 7: Results for cooling pond close loop

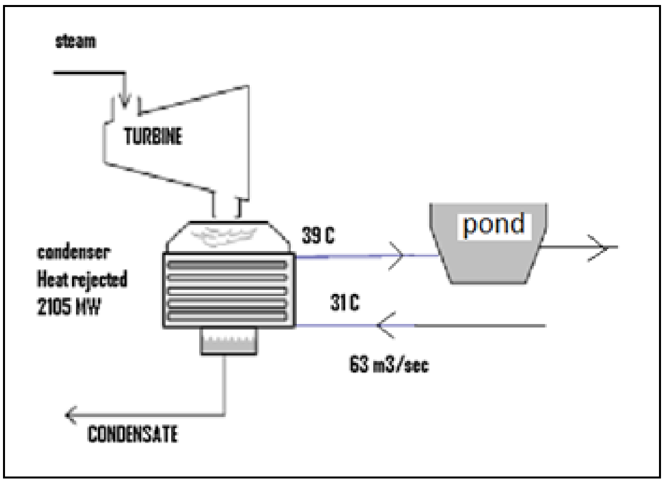

Figure 8: Once Through with Cooling Pond.

5. Financial Analysis

In order to propose an economical and environmental friendly alternative option for cooling system, an estimate of cooling cost of each option is necessary. Making final comparison will be very difficult as each system has its pros and cons. Also cost estimate with 100% precision is impossible because these cost vary from region to region. Also the operating cost varies from time to time in different regions. So a generalized cost estimate is very difficult.

The major areas of cooling cost considered in this report are as under.

1. Initial cost of the equipment and installation cost.
2. Annual operating cost of pumps and other water treatment and maintenance cost.

Operation cost can be determined by

$$C_{opr} = P\ (KW) \times t(years) \times 365 \times 24 \times A_f \times C \qquad (18)$$

where P is total power, t is life of plant, A_f is availability factor and C is cost per KWh

It should be noted that operation cost also include other cost than energy consumption cost such as maintenance cost, labor cost, environmental cost and plant down time cost. We ignore all these except plant downtime cost as it has huge impact. This has been considered in the calculations.

Table 10: Life time total cost of cooling technologies

Technology	Capital Cost (M$)	Operation Cost (M$)	Total Cost (M$)
Once through system	30	1212	1242
Wet cooling (close mode):			
a) Natural draft	94	331	426
b) Mechanical draft	57	898	955
Wet cooling (open mode):			
a) Natural draft	59	406	465
b) Mechanical draft	32	968	1001
Dry cooling	164	1265	1429
Hybrid cooling system	147	1140	1287
Cooling pond:			
a) Once through	72	1212	1285.
b) Close loop	103	1212	1316.
cooling canal	60	1212	1273
Spray canal	81	1212	1294

6. Overall Comparison

Figure 9 show a brief comparison of flow rate required through each cooling technology. It is clear that all open mode require the least flow rate because of higher condenser range achievable. While in close loop, flow rate is similar to once through system because here condenser range is kept 8 °C. This high flow rate is compensated by low pump head required in close loop. Flow rate has direct effect on pumping power. Dry cooling system also has less flow rate but it is not feasible owing to high fan power required to cool the hot water. Flower rate through the canal and pond can be reduced but these are not feasible options because more heat will have to be dissipated and thus large land area will be required. About 6000 m length of canal is required to obtain temperature drop of 5 °C. Increase in temperature drop will further increase channel length so we cannot decrease flow rate from 65 m^3/sec. The same is case with cooling pond.

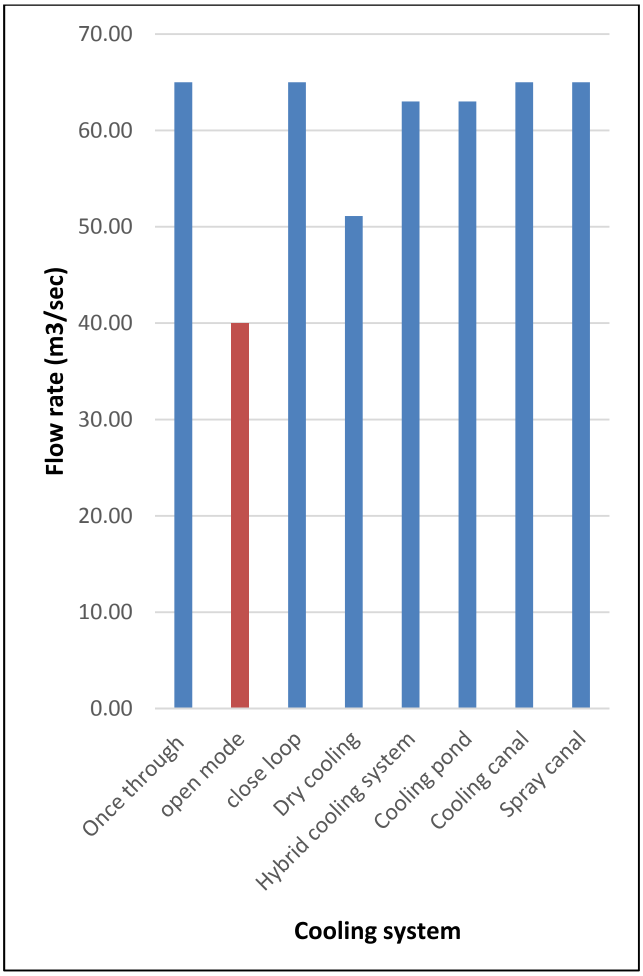

Figure 9: Flow Rate Comparison

Figure 10 shows power comparison for different options. As power is directly related to flow rate of water through the pump as well as the pump head, so close loop cooling system has least power requirement beside the fact that it has maximum flow rate. This is because of low pumping head required. Dry cooling has maximum power requirements because of very high air flow rate along with pumping power in closed loop. So this option is not feasible as it will have high operating cost and also very high capital cost of the equipment. Power requirement through once through, cooling pond and canal system is almost same because of similar head and flow rates.

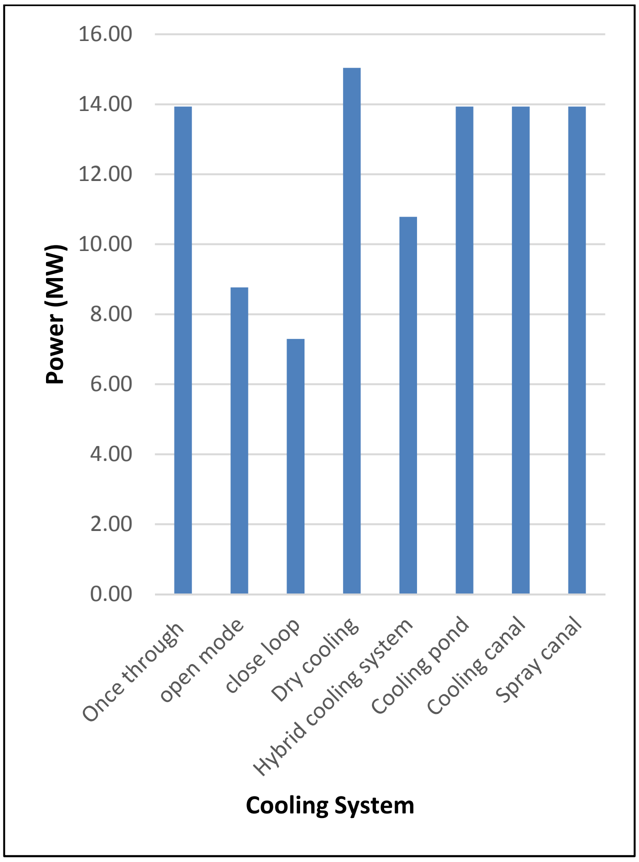

Figure 10: Power Comparison

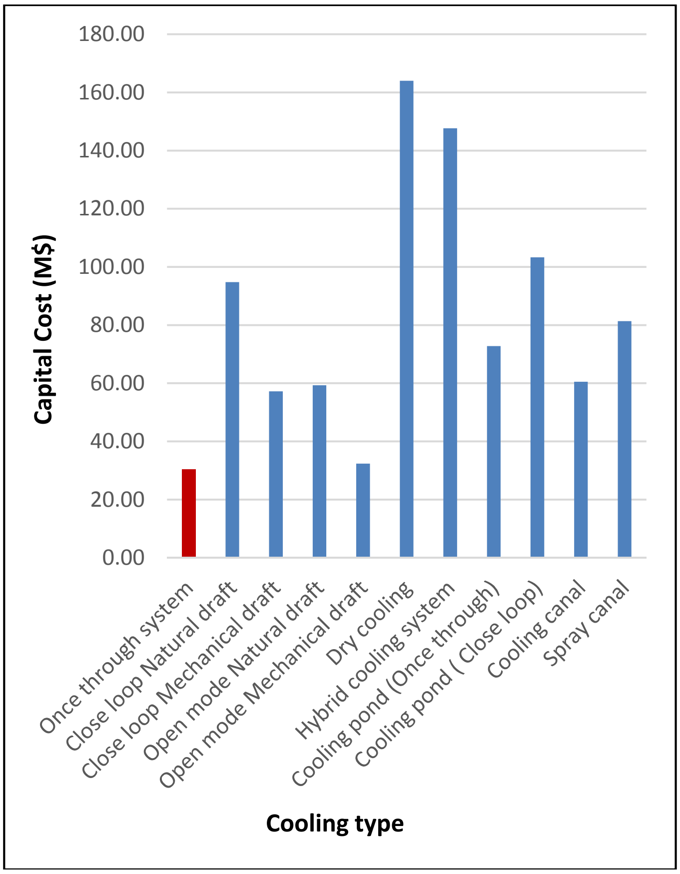

Figure 11: Capital Cost Comparison

Capital cost of each technology varies greatly from one another. So it will have an overall effect on the final selection of the most feasible alternative option for cooling system. Figure 11shows that capital cost of the once through system is least. But once through system has to be replaced because it does not fulfil the environmental regulations. Open mode has the second least cost even though cooling towers has to be installed but due to less pumping power requirement which is major contributor to the cost of the system, open mode capital cost comes out to be least among other option because of higher rating pumps required in other options. Cost of natural draft is maximum among both cooling tower options because it has huge structure and height is much higher than mechanical draft tower. Hybrid and dry towers has maximum capital cost because of close circuit operation and huge piping requirements. Cost of cooling canal is also in acceptable limits but as already mentioned, land area requirement is a major problem. Only capital cost cannot determine which option is most economical. It must also be counter checked with operating cost and then total cost will be used to select the most feasible option.

Figure 12 shows a comparison of the operating cost of each cooling option. Operating cost mainly include energy cost and downtime cost neglecting labor and maintenance cost. Operating cost throughout the life of the plant supersedes much more than its capital cost and thus has major contribution in overall total cost. Also, Figure 12 shows that natural draft towers have least operating cost because it has negligible down time cost and only energy cost is taken into account. Mechanical draft is second most economical option as shown in figure. Dry cooling system is the most expensive option with regards to operational as well as capital cost. Hybrid tower have somewhat less operating cost than dry because of less operation of dry system during normal operation time. These both options are nullified if there is no shortage of water at the site. Operating cost of rest of the options is almost same because pump power and flow rate are same in all cases.

Adding capital and operating cost give overall cost associated with each system. It is clear from Figure 13 that among all options, only cooling towers seems most economic because it dissipate heat easily through evaporation of water through air while other options require huge surface areas as well as pumping power. So the overall cost of once through, cooling canal, cooling pond and dry and hybrid system are higher than wet cooling tower. Among the towers, natural draft are most economical options.

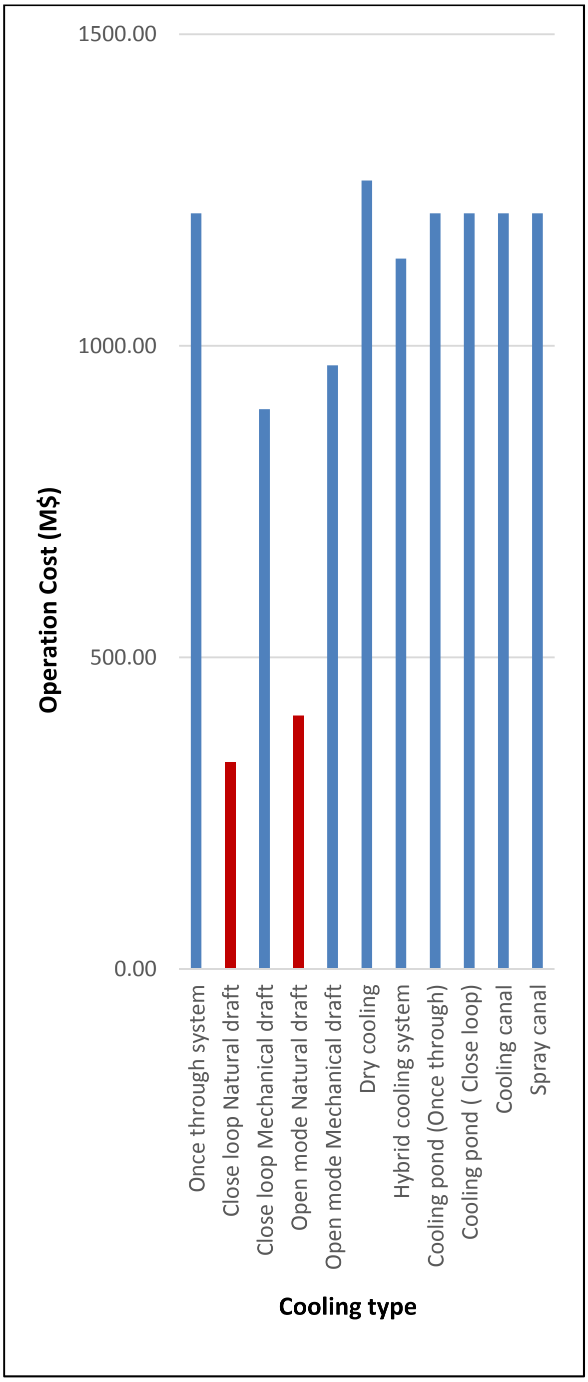

Figure 12: Operation Cost Comparison

7. Conclusion

Five alternative cooling options and their operation in different modes are thoroughly studied and results were calculated for each option in MS Excel and WAMP. The work was divided into three phases. First phase was to explore alternative cooling options to the once through system which was taken as the base case. In the second phase, all these options were analyzed both technically and economically. An overall comparison was done in third phase which is shown in the previous chapter.

After careful evaluation of all the alternative options, it is concluded that close loop natural draft wet cooling towers have the least overall life time cost. Also there is another advantage of close loop that there is no impingement of foreign debris into the condenser which will solve fouling problems in condenser. The total head is also less as compared to open mode operation so less pumping power is required. Hybrid cooling and dry cooling are the most expensive options and they are not recommended. Cooling canal and cooling pond options are also more expensive than the once through system because of very large land area required. So we propose close loop natural draft tower option as the most feasible option.

There are some other alternative options which are not analyzed in this work but they should be analyzed in future. The heat rejected from the discharged water is dissipated to the environment. This heat can be utilized for some useful purposes which will further save some money. According to [6], there are some alternatives methods which are helpful from the perspective of enhanced plant efficiency and reduced environmental impact. They include:

1. Green house heating during wintertime
2. Multi-port diffuser can also be used to control temperature rise of sea water. This option must be analyzed.

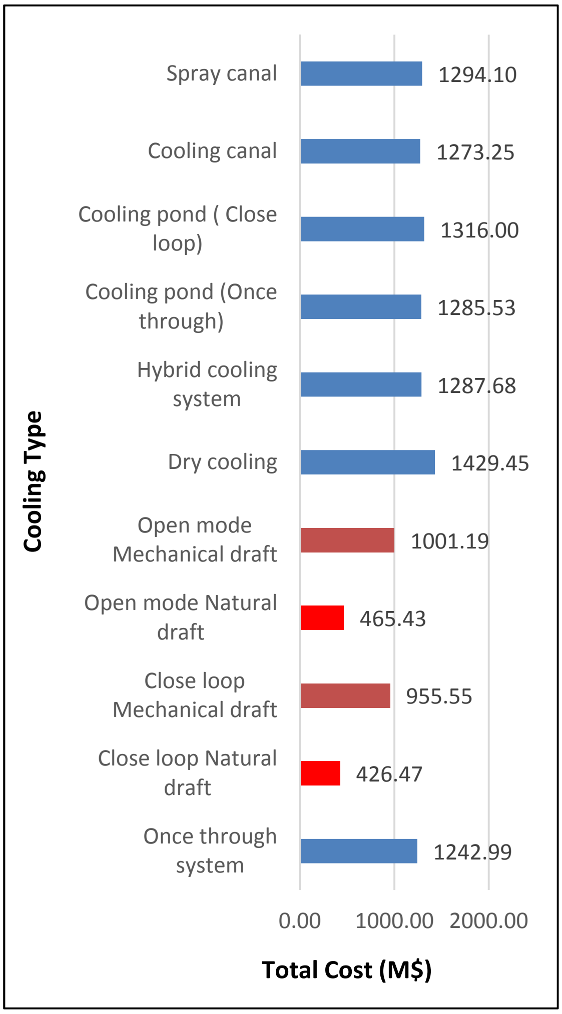

Figure 13: Overall Cost Comparison

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