Chapter Six{ TC "Chapter Six" \l 1 }

System Simulation

In the previous chapters models of the components of the cooling cycle and of the power plant were introduced. The TRNSYS model of the power plant is used to study the performance of the cooling cycle under various operating conditions. The effect of ambient conditions on the system is examined. The alternatives that exist to change the system, including operation mode of the towers, deepening the pond, and adding system components, are examined to find the optimum operation point with respect to fuel costs. Equipment costs are not included in the calculation and it is left to the plant operators as to whether an investment can be justified by the fuel savings obtained.

6.1 Selection of input data for the simulation{ TC "6.1 Selection of input data for the simulation" \l 2 }

As the most critical period for plant operation is the summer only summer months will be used for the simulation. There are several weather data sources available as was outlined in section 3.1. TMY weather files and actual data for the year 1988 are available in a suitable format; therefore weather data for 1988 are used instead of data for 1995 as 1988 is also considered to be a bad year with respect to plant operation.

Simulations are run for the month of July. Figures 6.1 and 6.2 show solar radiation and ambient dry- and wetbulb temperatures for July obtained from TMY files and for the year 1988, respectively. The charts do not allow one to immediately distinguish the two weather data sets or to decide, which weather conditions are worse with respect to plant operation.

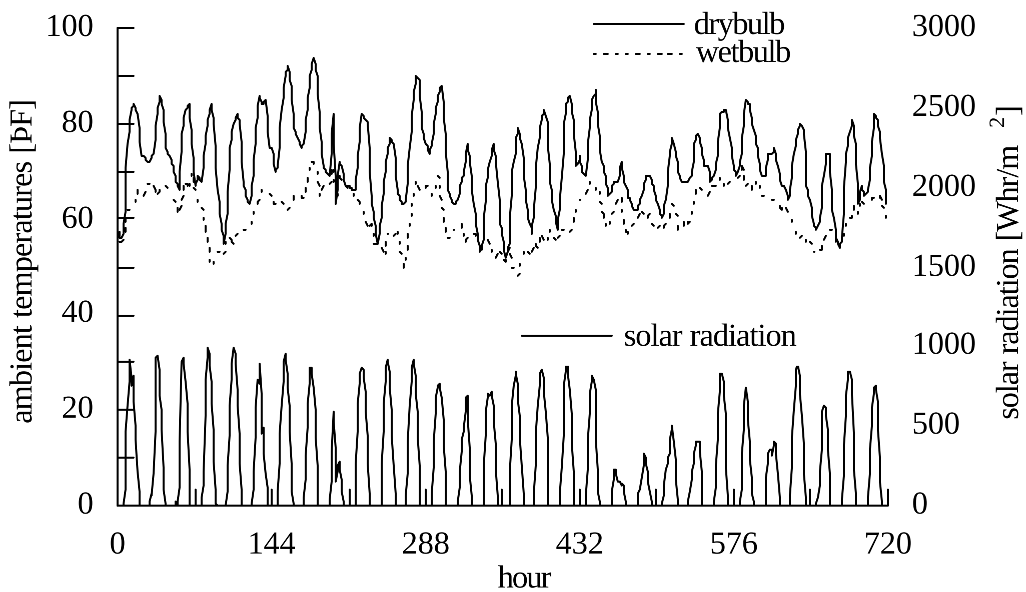

Figure 6.1 July weather data for Madison, from TMY files{ TC "Figure 6.1 July weather data for Madison, from TMY files" \l 5 }

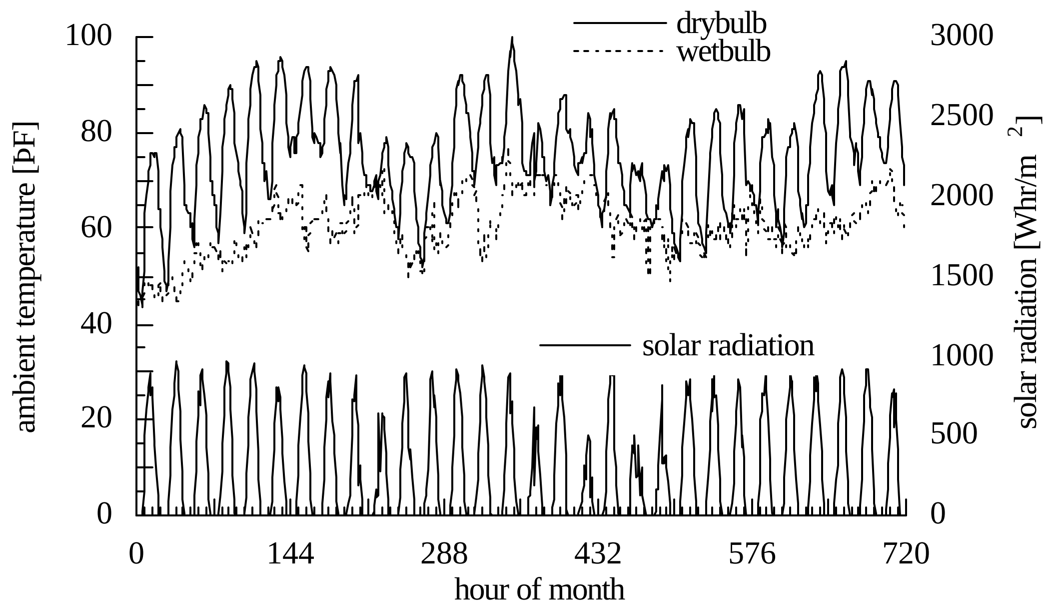

Figure 6.2 July weather data for Madison, actual data for 1988{ TC "Figure 6.2 July weather data for Madison, actual data for 1988" \l 5 }

Table 6.1 shows average values for wetbulb, drybulb and solar radiation. Also the maximum values for wet- and drybulb temperatures and solar radiation are given. By examining the average values of wet- and drybulb temperature in table 6.1 it can be seen that the average drybulb temperature in July 1988 was about 6 F higher than the TMY value. However, the difference in average wetbulb temperature is small. In section 4.1 it was outlined that the wetbulb temperature is the most significant ambient variable with respect to evaporative cooling. Therefore there is not a big difference expected in cooling cycle performance whether one or the other data source is used for simulation. The maximum values for wet- and drybulb temperature were significantly higher in July 1988 than in the TMY data. This may have an impact on short term behavior of the cooling cycle. The solar radiation values are similar in both the TMY data and July 1988. The maximum value for solar radiation is even slightly higher in the TMY data set, while the average is higher in 1988. Considering the weather conditions, not a big difference is expected in the results of the simulation using either TMY or 1988 data.

data source	drybulb average [F]	wetbulb average [F]	solar average [Whr/m^2]	drybulb maximum [F]	wetbulb maximum [F]	solar maximum [Whr/m^2]
TMY	71.7	64.5	249.3	93.9	72	1000
July 1988	77.7	65.1	281.8	100	80.1	992

Table 6.1 Average and maximum temperatures and solar radiation for July data{ TC " Table 6.1 Average and maximum temperatures and solar radiation for July data" \l 4 }

Simulations will be run for both data sets and the impact of different ambient conditions examined. To study the effect of extreme temperatures on system performance other data sets are made up by simply adding or subtracting 10 F to the TMY wet- and drybulb temperatures.

The temperature of the make-up water that is taken from the Wisconsin River is not available from weather data or other sources. The pond model was used to generate the make-up temperature corresponding to weather conditions. This was done by running a pond simulation without an external heat input aside from natural sources such as solar radiation. The calculated water temperature is assumed to be a good approximation of the river water temperature.

The simulations are performed assuming a constant maximum load on the plant of 535 MW for the whole simulation time. This corresponds to the actual load characteristic at the Columbia station during summer months (see section 2.4.1). Although the two power plant units do not perform equally well, in the simulation both units are treated equally with respect to heat rate characteristics. The auxiliary power needed for cooling devices is divided in equal parts to both units.

6.2 Evaluation of the operation mode of the cooling towers{ TC "6.2 Evaluation of the operation mode of the cooling towers" \l 2 }

6.2.1 Impact on pond temperatures{ TC "6.2.1 Impact on pond temperatures" \l 3 }

Using TMY data for July the system model is run for no cooling tower operation, for one and two tower pump operation and for a varying or cycling number of tower pumps. In the last operation mode the number of pumps is switched from two to one every time the tower outlet temperature exceeds the pond temperature. When one pump is operated and the tower outlet temperature is more than 10 F lower than the pond temperature, the second tower pump is turned on again. The reason for operating the towers in this way is to avoid heating up the pond water by warmer tower outlet water. Therefore the tower outlet temperature must be about

10 F lower than the pond temperature before the tower water flow is increased again by turning on the second pump. This operation mode describes the way the towers are actually operated, as outlined in section 2.4.2. By varying the water flow to the towers, the water flow rate into the pond is also changed.

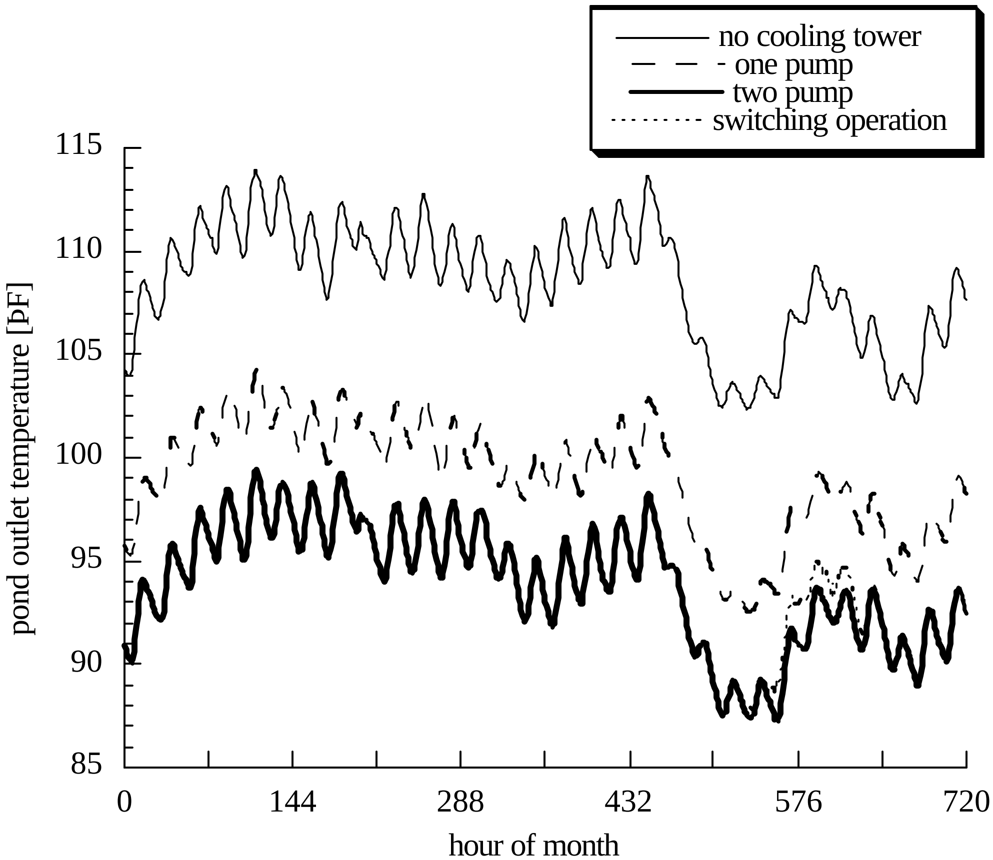

Figure 6.3 Pond outlet temperatures for changing tower operation mode in July{ TC "Figure 6.3 Pond outlet temperatures for changing tower operation mode in July" \l 5 }

Figure 6.3 shows the pond outlet temperatures for various tower operation modes, which means the water flow rates. It can be seen that the pond outlet temperature is the highest for no tower operation. For lower water flow rates in the pond more water is pumped to the towers and the water outlet temperature of the pond decreases. This indicates that although the water temperature begins to oscillate before the water reaches the plant inlet, a longer circulation time in the pond leads to more heat rejection and therefore lower water outlet temperatures for the given set of weather conditions.

From figure 6.3 it can be seen that the water temperature oscillates in a daily cycle. This is caused by solar radiation that heats up the water during the day, while during the night the water cools down again.

The plot shows that there is nearly no difference in pond temperature if the operation mode is switched from two pump operation to a varying number of tower pumps. This is due to the fact that even when two tower pumps are operated the tower outlet temperature seldom exceeds the pond temperature. Therefore further simulations will not be run for a cycling number of pumps.

It was stated previously that only the first part of the pond is effective in cooling the water, while in the second part only a little more cooling is achieved. The differences in temperature for different water flow rates in the pond indicate that this assumption is only partly true. It can be seen that there must be further cooling in the second half of the pond as a lower flow velocity leads to lower pond outlet temperatures of about 5 F. It is important to note that the temperature difference between no tower operation and one pump flow is higher than the difference between one and two pump operation. This behavior indicates that there is a limit on the flow velocity in the pond under which a changing flow rate would have no further effect on the pond outlet temperature. For lower flow velocities in the pond the water temperature closely approaches the equilibrium temperature.

6.2.2 Plant inlet temperature{ TC "6.2.2 Plant inlet temperature" \l 3 }

The plot of pond outlet temperatures gives an idea of how the pond behavior is affected by the tower operation. What is really of interest for the plant operation is the mixed plant intake temperature of pond and towers. Figure 6.4 shows the plant intake temperatures for the same input data that was used for the results shown in figure 6.3, that is weather and load data. It becomes obvious that the plant intake temperature is the highest for no tower operation. There is an average temperature difference between no tower and one tower pump operation of approximately 15 F. The difference between one and two tower pump operation is comparably small, on the order of 3 F to 4 F. If the tower characteristics outlined in section 4.1 are recalled, the tower outlet temperature is lower for one pump operation than for two pump operation. This behavior explains that the mixed plant inlet temperatures for one and two pump operation are close together. The lower pond outlet temperature for two pump operation is partly compensated by a higher tower outlet temperature.

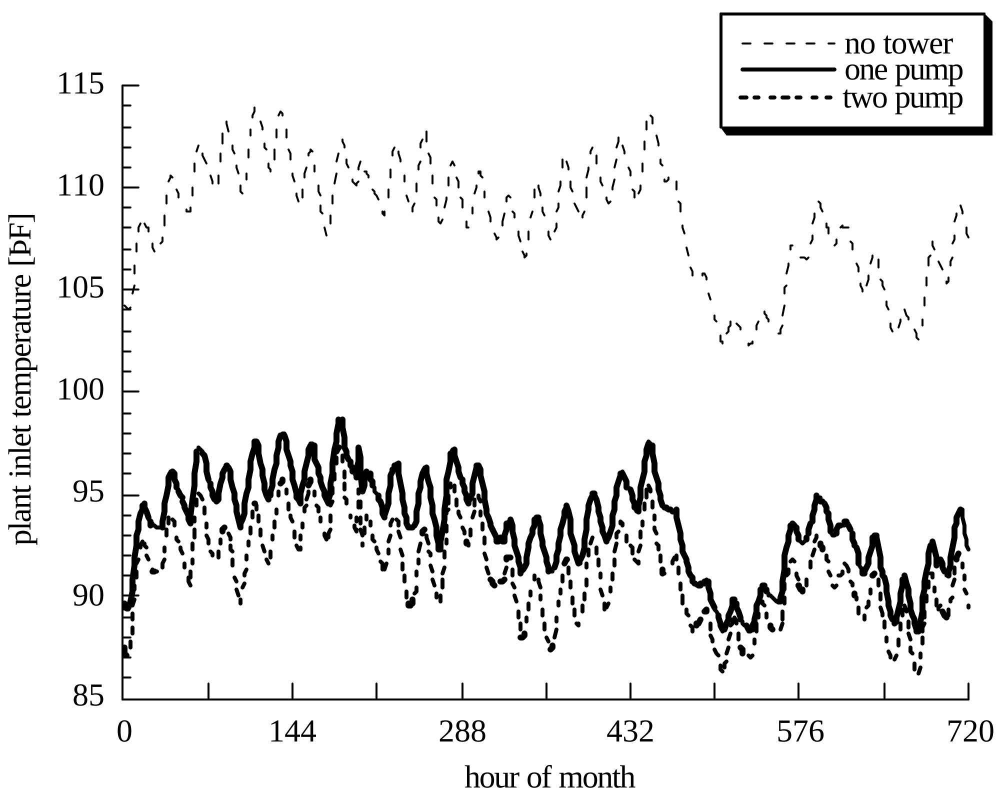

Figure 6.4 Plant inlet temperatures for different tower operation modes in July{ TC "Figure 6.4 Plant inlet temperatures for different tower operation modes in July" \l 5 }

6.2.3 Plant performance{ TC **"6.2.3 Plant performance" \l 3 }**

The water inlet temperature influences the plant performance directly as the circulating water temperature determines the back pressure in the condenser at a given load. There is also a mechanical back pressure limit on the turbine (see section 2.1.3). Therefore it is important to evaluate the back pressure corresponding to the plant intake temperatures shown in figure 6.4. Figure 6.5 shows the back pressure for the same operation conditions and weather data that were used before. The system model has no control mechanism that reduces load if the back pressure limit is exceeded. It is therefore of interest to look at the calculated back pressure for different simulation scenarios. Figure 6.5 shows that for no tower operation the limit of 6"Hg is exceeded during the whole simulation time.

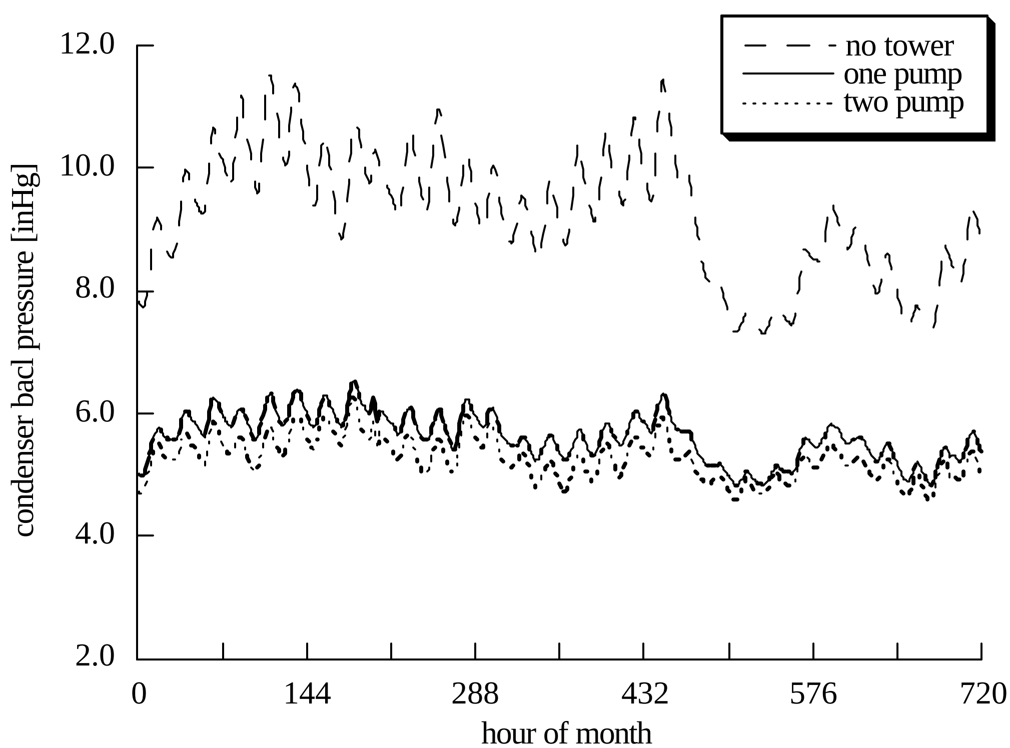

Figure 6.5 Back pressure for various tower operation modes, July weather data{ TC "Figure

6.5 Back pressure for various tower operation modes, July weather data" \l 5 }

That means that the effect of no tower operation is not only a high cooling water temperature but also a loss of capacity as the load has to be reduced when the back pressure reaches its limit. For one pump operation the back pressure limit is exceeded at some times, although for the sequence shown it is less then 20% of the total time.

In chapter 5 the relation between back pressure and plant performance was discussed. The heat rate and operation fuel cost of the plant are the values of primary interest. The fuel costs result directly from the net station heat rate, so that only the fuel costs per MWh output produced are shown in figure 6.6. The costs shown are based on the net station heat rate, which includes the correction for back pressure and auxiliary power. For no tower operation the costs are by far the highest and are 15% higher than with towers on.

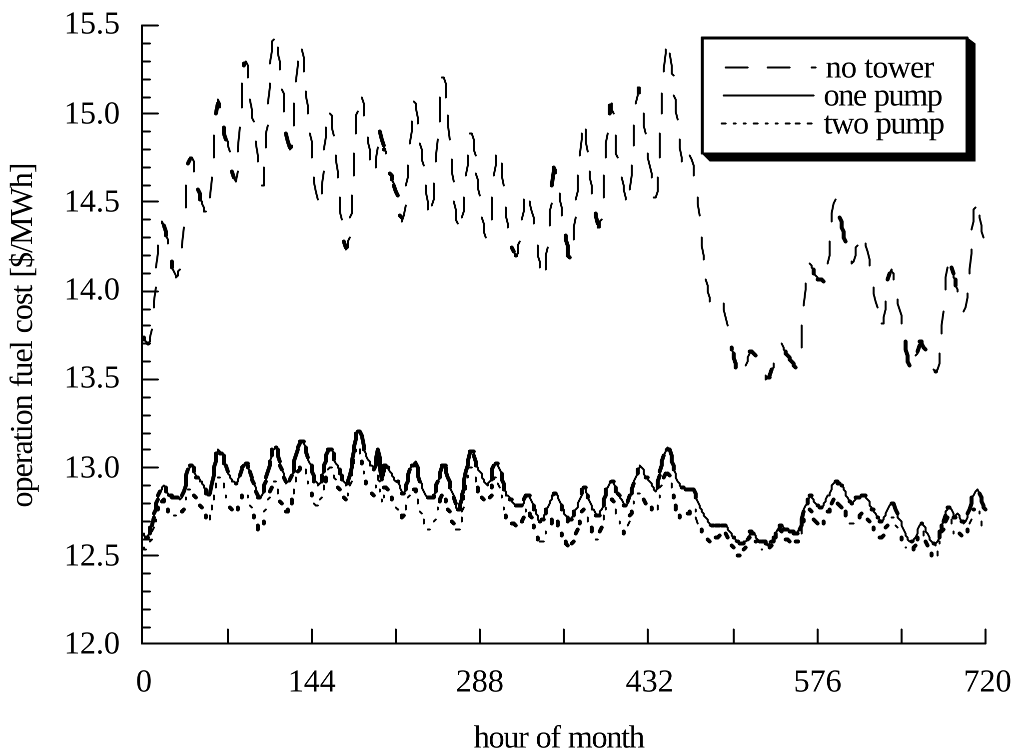

Figure 6.6 Operation fuel costs for different tower operation modes, July weather data{ TC "Figure 6.6 Operation fuel costs for different tower operation modes, July weather data" \l 5 }

The difference in costs for one and two tower operation is comparably small. Operating the cooling towers with two pumps leads to slightly lower costs than operating them with one pump. That means that the decrease in heat rate due to lower water temperatures more than compensates for the higher pumping power needed to achieve this lower temperature. The increment in auxiliary power between one and two pump operation is only due to the second pump that is turned on, as the fans are always operated at maximum power regardless of the water flow. It is interesting to note that between hours 500 and 570, when the water inlet temperatures are low, the cost difference between one and two tower pump operation becomes negligible.

As the load is held constant the system can be evaluated by calculating average values of heat rate and operation costs for the time of the simulation. In table 6.2 the results for the July calculation are summarized. The net heat rate is the ratio of overall energy input to output of the power plant and the correction terms are the incremental energy use due to cooling equipment and increased back pressure, respectively.

tower pumps	fuel cost $/MWh	net plant heat rate Btu/kWh	correction auxiliary cooling Btu/kWh	correction back pressure Btu/kWh
0	14.42	12020	2.2	1842
1	12.85	10710	40.1	679.8
2	12.74	10620	53.9	584.3
variable	12.74	10620	53.4	585.7

Table 6.2 Performance values from TMY data, July calculation, present system set up{ TC "Table 6.2 Performance values from TMY data, July calculation, present system set up" \l 4 }

The results show that the lowest costs can be achieved if two tower pumps are operated, which means the highest possible amount of water is run through the towers. For no tower operation the costs and net heat rate are high. In combination with the high back pressure this would result in a capacity reduction and it is concluded that the cooling towers should never be shut off completely in summer months. In the further analysis the alternative of running the cooling cycle without tower operation is therefore not considered further.

Table 6.2 contains the increment in heat rate associated with auxiliary power. This value reflects the increase in net heat rate that occurs if the auxiliary power of cooling towers and make-up pumps is included in the heat rate calculation. The correction for back pressure given in the table is the difference between actual heat rate and the heat rate that would occur if the back pressure were 1.5 “Hg. There is an auxiliary power correction even if no towers are operated because it is assumed that one make-up pump is always on. The power consumption of the make-up pump is included in the calculation of net heat rate.

It can be seen that for no tower operation the back pressure correction is very large, due to the very high back pressure observed. If the correction values for one and two pump operation are considered, it is observed that the increase in heat rate due to auxiliary power is smaller than the reduction due to a lower back pressure. This explains the lower costs at higher tower flow rate (two pump operation).

There is no difference in net heat rate observed between the operation modes of constant two pump operation and the strategy of varying the number of pumps. However there are small differences in the single correction terms for back pressure and auxiliary power. For the two pump operation the auxiliary power correction is slightly higher while the back pressure correction is a little lower than for the varying number of pumps. The corrections compensate each other so that the net heat rate is the same in both cases.

The reason that the heat rate difference between two pump and varying operation mode diminishes is that in the time period of the simulation the number of tower pumps seldom changed if the varying mode was simulated. The results of the simulation using varying number of pumps are therefore not shown in the plots.

6.2.4 Impact of ambient conditions{ TC "6.2.4 Impact of ambient conditions" \l 3 }

The same simulations that were performed using TMY weather data above were performed using actual observed weather data for July 1988. Only the average performance values are shown, as these values readily determine the system performance. Table 6.3 gives the results of the calculation.

tower pumps	fuel cost $/MWh	net heat rate Btu/kWh	correction auxiliary cooling Btu/kWh	correction back pressure Btu/kWh
0	13.73	11440	2.1	1350
1	12.73	10610	39.7	592.2
2	12.68	10570	53.6	541.3

Table 6.3 Performance data for July 1988 simulation{ TC "Table 6.3 Performance data for July 1988 simulation" \l 4 }

In general the net heat rate and cost values are lower than they were calculated using TMY weather data. This behavior indicates that the ambient conditions given in the TMY files are worse with respect to plant operation than the weather conditions in July 1988. But the table also shows the same general behavior of the whole system. For no tower operation the system performance is by far the worst, while the most efficient operation is achieved when two tower pumps are operated. The absolute difference in cost between one and two tower operation is smaller than for TMY data, being 0.05$/MWh for the 1988 data and 0.11$/MWh for the TMY data.

Another weather data set is made up by adding 10 F to wet- and drybulb temperatures of the TMY values. The result is shown in table 6.4. Again only three operation modes are shown.

tower pumps	fuel cost $/MWh	net heat rate Btu/kWh	correction auxiliary cooling Btu/kWh	correction back pressure Btu/kWh
0	14.90	12420	2.27	2179
1	13.14	10950	41.02	891.4
2	13.00	10830	54.95	773.2

Table 6.4 Performance data for made up weather file, TMY temperatures +10 F{ TC "Table 6.4 Performance data for made up weather file, TMY temperatures +10 F" \l 4 }

The general trend is the same as observed before, two tower pump operation leads to the best system performance. But the absolute increment in cost between one and two pump operation is in the order of 0.14 $/MWh, higher than the increment for the original TMY data.

If another data set is made up by subtracting 10 F from wet- and drybulb temperature of the TMY data, the increment in cost associated with going from one pump to two pump operation is calculated to 0.09$/MWh.

The observation that at lower ambient temperatures the difference in operation costs becomes smaller leads to the assumption that the optimum control strategy depends on the season. The results of a simulation for March using TMY data is shown in table 6.5.

tower pumps	fuel cost $/MWh	net heat rate Btu/kWh	correction auxiliary cooling Btu/kWh	correction back pressure Btu/kWh
0	12.88	10230	1.9	291.2
1	12.06	10050	37.6	96.3
2	12.07	10060	51.1	91.8

Table 6.5 Performance data for March, using TMY weather data{ TC "Table 6.5 Performance

data for March, using TMY weather data" \l 4 }

The results from the simulation using March weather data show that indeed the two pump operation leads to higher heat rates than the one pump operation. Running the system without towers still is the worst operation mode, with respect to heat rate and costs. But the increase in net heat rate when no towers are operated over one tower operation is smaller for March than for July data. In March the increase is about 7% while in July it is about 8%.

If the difference between one and two pump operation is examined further, it is observed that the heat rate correction due to back pressure drops for a lower pond flow rate, but only by a small amount. The increase in heat rate due to auxiliary pump power needed to achieve the lower pond flow is higher than the reduction in back pressure correction in the shown case. For hot summer month the effect was the other way round, the back pressure improvement paid for the auxiliary power.

Obviously at lower ambient conditions and lower solar input into the pond, the pond water approaches the equilibrium temperature more closely. Therefore the effect of flow rate on water outlet temperature becomes smaller. Another reason that the pond behavior in March does not influence the plant operation to the same extent as for example in July is due to the turbine characteristics. The sensitivity of the steam cycle to back pressure is higher at higher back pressures, as was discussed in chapter 5. In March the average water temperature is lower and therefore the average back pressure is lower, too. That means that a colder water inlet temperature does not lead to a high enough efficiency improvement to justify the effort of more auxiliary power. This effect is illustrated in the simulation results shown in table 6.5.

6.2.5 Summary{ TC "6.2.5 Summary" \l 3 }

The simulation results show that regardless of the weather condition the towers should always be operated. When no towers are operated the heat rate increases significantly and production capacity can be lost. The efficiency of the system at high ambient temperatures and high solar input into the pond has an optimum when two cooling tower pumps are operated. However the difference in fuel costs between one and two pump operation is rather small. The calculation of steam cycle behavior can only be considered as an approximation. It is therefore possible that the back pressure effect at high water inlet temperatures is either overestimated or underestimated and the cost increment between one and two pump operation is actually smaller or larger than calculated.

For very hot weather conditions the conclusion is drawn that for two cooling tower pump operation the system performs better than for one pump operation. The cost benefit is small. For lower ambient weather conditions the cost increment between one and two pump operation becomes even smaller and at a certain point one pump operation is preferred. All calculated costs account only for fuel costs. Investment, maintenance and wear on the pumps is not included in the economic analysis. The plant operators have to decide whether the fuel savings are sufficient to justify operation of the second pump at any time.

At very cold conditions that occur in winter time the towers are not operated in order to protect the equipment from freezing. But the assumption can be made that for very cold weather conditions the tower operation would not be advantageous at all for plant performance.

As the same trend in performance is observed regardless of the source of weather data used, it seems not to be of major importance to use a certain weather file. For convenience the TMY data will be used in the further analysis.

6.3 Influence of make-up flow{ TC "6.3 Influence of make-up flow" \l 2 }

6.3.1 Simulation of different make-up flow rates{ TC "6.3.1 Simulation of different make-up flow rates" \l 3 }

Based on the results stated in section 6.2 TMY weather data for July is used for the further calculations. To evaluate the effect of make-up water flow rate the simulations are performed for two cooling tower pump operation. If two cooling tower pumps are operated the water flow in the pond is low and the effect of make-up water is higher. Each make-up pump has a flow rate of 10,000 gpm and a rated power of 196 hp. The results of the simulation are shown in table 6.6.

It can be seen that the effect of the make-up flow rate on system performance is very small. Each make-up pump turned on accounts for a decrease of 0.01 $/MWh in production cost, at average.

make-up pumps	fuel cost $/MWh	net heat rate Btu/kWh	correction auxiliary cooling Btu/kWh	correction back pressure Btu/kWh
1	12.74	10620	53.9	584.3
2	12.73	10610	55.7	575.8
3	12.72	10600	57.6	567.4

Table 6.6 Effect of make-up flow rate on plant performance{ TC "Table 6.6 Effect of make-up flow rate on plant performance" \l 4 }

6.3.2 Summary{ TC "6.3.2 Summary" \l 3 }

The effect of make-up flow on system performance is very small compared to the effect of the tower operation mode. This is expected as the available make-up water flow rate is a small fraction of the overall flow rate in the circuit. Although the effect of make-up flow on the cooling system is marginal it can be worthwhile to run the maximum possible amount of make-up flow into the pond, if only fuel costs are considered. But as mentioned in the previous section the equipment costs are not included in the simulation and have to be considered.

The amount of make-up water that may be taken from the river can also be limited by environmental regulations that may prohibit drawing a great amount of water from the river under extremely hot ambient conditions.

6.4 The effect of pond depth{ TC "6.4 The effect of pond depth" \l 2 }

The pond depth can be varied in two different ways. The easiest way is to block the spillway, which would rise the water level in the entire pond. Another alternative is to dredge the pond and make it deeper in certain sections. It is not important for the simulation in which way the depth is altered.

6.4.1 Pond outlet temperature for different depths{ TC "6.4.1 Pond outlet temperature for different depths" \l 3 }

Simulations are performed for the pond depths 6.5 ft, which is the present average depth that was used for the previous calculations, and 10ft and 20 ft. A depth of 10ft is realistic to achieve while a depth of 20 ft is probably not, as a significant effort is necessary to dredge the entire pond to a depth of 20ft. But to make the effect of pond depth visible the value of 20 ft is included as an extreme in the simulation. The limit of rising the water level by blocking the spillway is approximately at 8 ft depth.

The simulations are done for July using TMY data and one and two tower pump operation. The results shown in the plots are calculated for one pump operation.

Figure 6.7 shows the pond outlet temperatures calculated for 6.5 ft, 10 ft and 20 ft pond depth. The temperature level for the depths shown is in the same range. But it can also be seen that at higher pond depths the diurnal temperature fluctuations are smaller. The pond water temperature responds slower to changing ambient conditions at a greater pond depth. This behavior is especially obvious in the first 150 hours of the simulation. The temperature for the

6.5 ft and 10 ft deep pond rises much faster than the temperature for the 20 ft deep one. This is due to the fact that at a higher depth but equal total surface area a greater mass of water is in the pond, which means there is more thermal capacity per unit surface area. The potential for energy transfer, however, remains nearly constant, as the surface area remains the same. Therefore the temperature of the water needs longer to change for higher pond depths.

It can also be seen from the plot that the difference in temperature fluctuations between 6.5 ft and 10 ft is much smaller than the difference between 10 ft and 20 ft depth. A rather large increase in water level is required to achieve a significant effect on the diurnal temperature fluctuations.

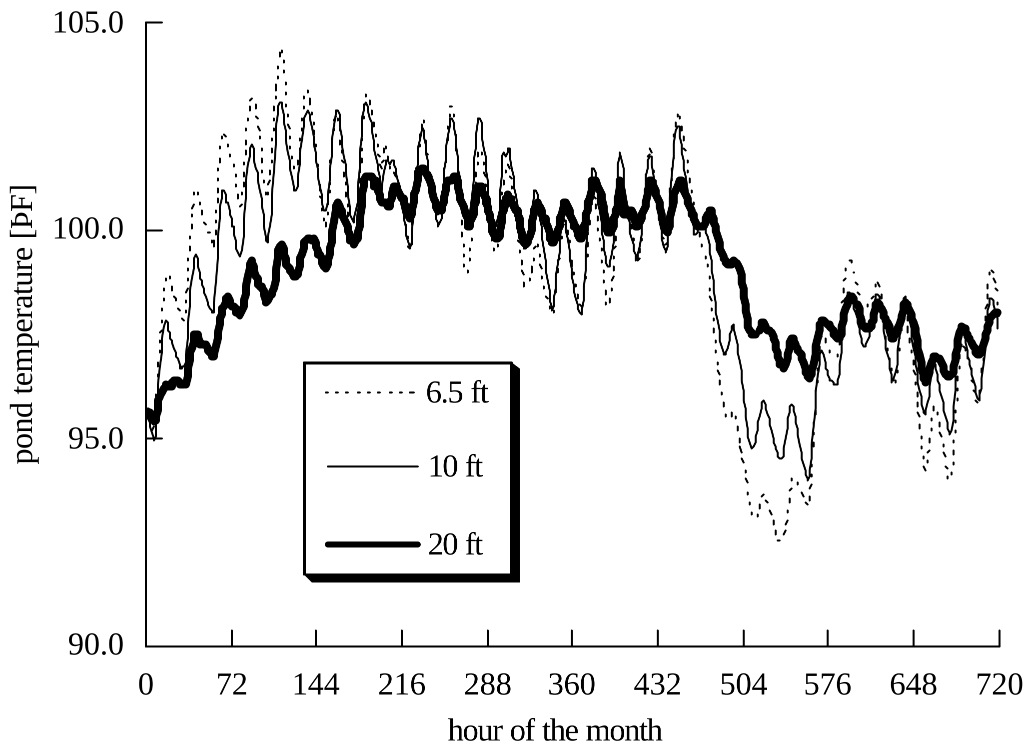

Figure 6.7 Influence of pond depth on pond outlet temperature{ TC "Figure 6.7 Influence of pond depth on pond outlet temperature" \l 5 }

Another effect of a deeper pond is an increase in circulation time, as the crossectional area of the flow channel increases with pond depth. The increase in circulation time compensates for the higher water mass in the pond. On the one hand the water cools down more slowly while on the other hand the water moves more slowly, too, in the case of a deeper pond.

6.4.2 Effect of pond depth on system performance{ TC "6.4.2 Effect of pond depth on system performance" \l 3 }

To evaluate the effect of pond depth average values of net heat rate and fuel costs are taken. Table 6.7 shows the result of the calculation for water levels of 6.5ft, 10ft and 20 ft for one and two pump operation. The last two rows of the table show simulation results for a pond that is 6.5 ft deep in the first 14,000 ft and 20 ft in the last 5000 ft of the pond. A pond with various depth is included in the analysis corresponding to the recommendation for the 'ideal cooling pond', given in section 4.3.1. The idea is to cool the water down quickly in the first part and then store the cold water in the deep reservoir.

tower pumps	pond depth ft	fuel cost $/MWh	net heat rate Btu/kWh
1	6.5	12.85	10710
2	6.5	12.74	10620
1	10	12.85	10710
2	10	12.74	10610
1	20	12.84	10700
2	20	12.73	10610
1	6.5/20	12.85	10710
2	6.5/20	12.73	10610

Table 6.7 Effect of pond depth on system performance{ TC "Table 6.7 Effect of pond

depth on system performance" \l 4 }

The results shown in the table show that deepening the pond has nearly no impact on average plant performance. The heat rate for a depth of 6.5 ft and 10 ft are identical. The same is observed for the pond that is deeper in the second part. This was expected from the considerations outlined in the preceding section, namely that for a constant surface area the average heat flux remains constant. For a pond depth of 20 ft a slightly better performance is observed than for 6.5 ft and 10 ft. Deepening the entire pond to 20 ft is probably not realistic, as was outlined above.

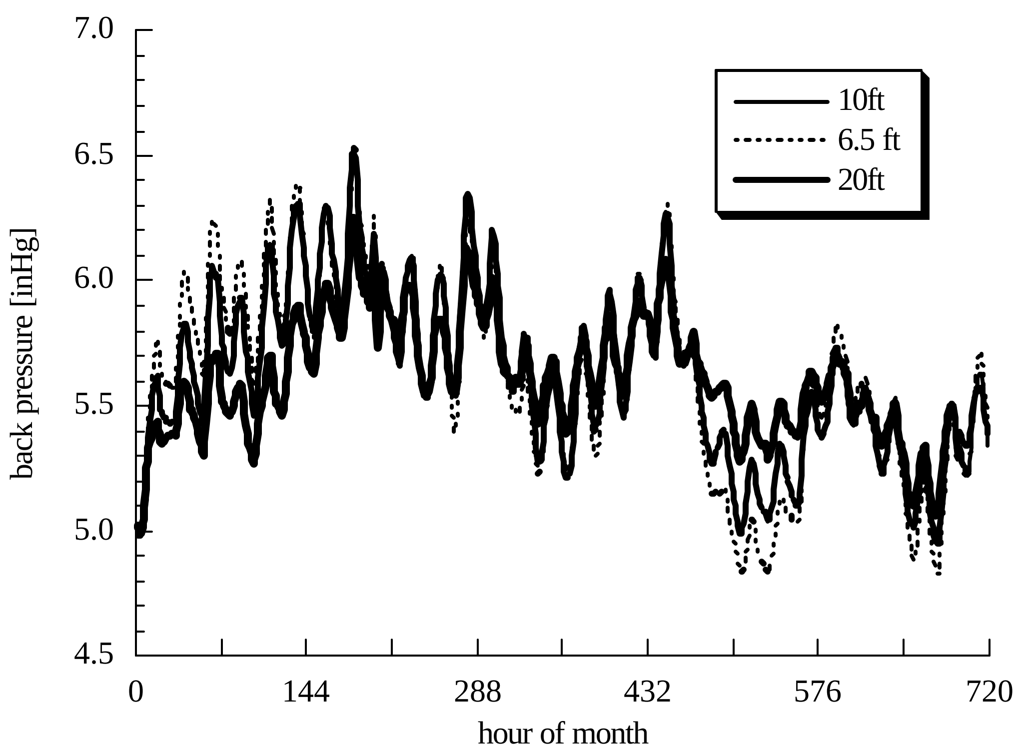

Figure 6.8 Effect of pond depth on back pressure{ TC "Figure 6.8 Effect of pond depth on back pressure" \l 5 }

A useful effect of deepening the pond is the reduction of diurnal temperature fluctuations. If the peaks are eliminated that cause power reduction due to back pressure limits, the effect on plant performance is advantageous. Figure 6.8 shows the back pressure corresponding to the water temperatures shown in figure 6.7. It can be seen that the back pressure peaks caused by water temperatures are much lower in the case of the deeper pond, especially in the first 140 hours of the simulation. The plot shows that for a 20 ft deep pond the back pressure limit is only seldom exceeded, while in the case of the 6.5 ft deep pond the back pressure exceeds the limit quite regularly in the first part of the chart. The same behavior is observed as in figure 6.7, that a rather big increase in depth is necessary to achieve a significant effect on system behavior. The difference between the two curves for 6.5 ft and 10 ft is rather small, while the effect becomes more evident for a depth of 20 ft.

6.4.3 Summary{ TC "6.4.3 Summary" \l 3 }

The influence of pond depth on the overall plant performance seems negligible when only average performance values are calculated. This indicates that the overall heat transfer is only dependent on the water surface area and not on pond depth.

Equation 4.95 shows that the cooling range of the pond under constant ambient conditions and constant flow rates depends only on the pond surface area. Although equation 4.95 is only an approximation as outlined in section 4.2.5, it can be used to explain that the pond depth has no major influence on the level of the pond outlet temperature. When the surface area remains constant the range of the pond does not change under otherwise constant conditions. If a longer time period is considered average values for ambient conditions and heat load can be assumed.

However, if a short term analysis of the pond is performed, it becomes obvious that the pond depth influences the diurnal temperature fluctuations. The temperature peaks that occur in the present pond in the early afternoon become smaller if the pond depth is increased. This behavior is due to a higher thermal storage capacity of the pond at a greater depth. The results shown in the plot were calculated by assuming a pond depth of 20 ft. As was mentioned before, a considerable effort would be necessary to increase the pond depth entirely to 20 ft; therefore such a large depth is not realistic. Realistic values are to increase the pond depth by 1 or 2 ft, which would have almost no effect on pond behavior, as could be seen for the 10 ft deep pond in comparison to the present 6.5 ft.

Another alternative would be to leave the pond the same in the first part and to build a deep reservoir before the plant intake section. Such a pond shape can decrease the pond sensitivity to diurnal temperature fluctuations without altering the water level in the entire pond.

6.5 Effect of increasing the tower capacity{ TC "6.5 Effect of increasing the tower capacity" \l 2 }

The total tower capacity can be increased in two different ways. One possibility is to add cooling tower cells but leave the pump capacity constant. In this way each single tower cell has a lower heat load, as the total water flow rate is distributed to a greater number of cells. Another possibility to increase the tower capacity is to add tower cells and increase the tower flow rate in the same ratio, so that each single cell receives the same water flow rate as in the present arrangement.

6.5.1 Adding tower cells while not increasing the pump capacity{ TC "6.5.1 Adding tower cells while not increasing the pump capacity" \l 3 }

If the pump capacity is not increased, addition of tower cells does not affect the cooling pond behavior. The impact on the cooling cycle occurs only through a changing tower outlet temperature that mixes with the pond water before the plant intake.

Table 6.8 shows the impact of the addition of tower cells on power plant performance. The simulations were run for the case of four and eight additional cooling tower cells. For the calculation the same tower coefficients that were found for the existing tower are applied to the added cells. The calculation is set up so that two or four cells are added to each existing tower. The flow distribution, that is the ratio of water flow of one to two pump operation and the amount of water that each tower receives, are held at the same values that were used in the previous calculations. The pond depth corresponds to the present value of 6.5 ft at average.

tower cells added	tower pumps	fuel cost $/MWh	net heat rate Btu/kWh	correction auxiliary cooling Btu/kWh	correction back pressure Btu/kWh
0	1	12.85	10710	40.1	679.8
0	2	12.74	10620	53.9	584.3
4	1	12.79	10660	44.7	630.2
4	2	12.62	10510	60.0	488.8
8	1	12.76	10630	53.3	600.7
8	2	12.55	10460	66.3	430.3

Table 6.8 Effect of the addition of tower cells on plant performance, for a water **{** TC "Table 6.8 Effect of the addition of tower cells on plant performance, for a water " \l 4 **}**

flow rate equal to the present value

For comparison table 6.8 contains performance values for the present number of tower cells, too. The trend observed is that if the number of tower pumps is increased the net heat rate and production costs decrease. In any case the operation of two tower pumps is of advantage with respect to plant performance for weather such as July. It can be seen that the value for the auxiliary power correction term increases with a rising number of tower cells. This is due to a higher fan power requirement, as each cell needs a single fan. But as the correction value for back pressure shows, the increase in heat rate due to more required fan power is compensated by a lower heat rate correction due to back pressure. The lowest cost is achieved for eight added tower cells.

6.5.2 Adding cooling tower cells in addition to an increase in water { TC "6.5.2 Adding cooling tower cells in addition to an increase in water " \l 3 } flow rate

Another possible way to increase the capacity of the cooling towers is to add cells and simultaneously increase the water flow rate. The amount of water pumped is increased so that the water flow rate for each cell is maintained at the present level. For example, if four cells are added to the existing 14, the flow rate is increased by a factor of 18/14. The pump power is adjusted in the same way.

tower cells added	tower pumps	fuel cost $/MWh	net heat rate Btu/kWh	correction auxiliary cooling Btu/kWh	correction back pressure Btu/kWh
0	1	12.85	10710	40.1	679.8
0	2	12.74	10620	53.9	584.3
4	1	12.70	10580	50.4	556.2
4	2	12.52	10530	68.1	499
8	1	12.64	10540	54.1	513.3
8	2	12.77	10640	76.8	587.3

Table 6.9 Effect of the addition of tower cells on plant performance, for an { TC "Table 6.9 Effect of the addition of tower cells on plant performance, for an " \l 4 } increased water flow rate

Table 6.9 shows the results of the simulation. For comparison the present tower size is given, too. As the tower flow rate per cell is maintained constant, the tower outlet temperature does not change with a increased number of cells, as was the case in the simulations outlined in section 6.5.1. The effect on the plant performance is therefore due to the amount of tower water as a fraction of the overall amount of water in the cycle. This amount influences the circulation time in the pond and the pond outlet temperature. Also the ratio of pond water to tower water in the inflow section of the pond, where pond and tower water mix, is altered. For higher tower flow the impact of the towers on cooling cycle behavior becomes more dominant.

The table shows that if a total of four tower cells is added the performance of the plant can be increased. The value of 12.52 $/kWh is the lowest cost that can be achieved when four cells are added and the water flow corresponds to two pump operation. Although the auxiliary power consumption increases significantly due to more pump and fan power, the benefit in back pressure reduction is large enough to compensate for that loss.

When eight tower cells are added an interesting effect occurs. The net heat rate rises above the value that was calculated for the addition of four cells. If two pumps are operated at a respective higher water flow for eight additional cells, the plant performance is worse than for one pump operation at the same tower size. This is the first occurrence that the operation of two pumps is actually worse than the operation of one pump when July weather data is used.

If the heat rate corrections are considered it can be seen that between row five and six in table 6.9 the heat rate correction due to auxiliary power rises, as is expected if the second pump is turned on. But, different from the observations made before, the heat rate correction due to back pressure also rises. This can only be the case if the plant inlet temperature increases, as the load is held constant. For higher water flow rates through the tower the water outlet temperature rises. In the former simulations this temperature rise was compensated by a lower pond outlet temperature in the case of a lower pond flow rate when more water is pumped to the towers. When eight tower cells are added and the tower flow is increased in the same ratio, obviously the point is reached at which the pond water flow rate no longer affects the pond outlet temperature. The pond water reaches the equilibrium temperature before the plant intake point is reached. If the pond water temperature is not affected by tower flow rate any more, an increase in tower flow rate must lead to higher plant intake temperatures, as the tower outlet water gets warmer. Besides more auxiliary power is needed. Higher water temperature and a higher auxiliary power requirement lead to an increased heat rate. The above effect is observed if the simulation is run with eight additional tower cells and a respectively higher water flow rate, as shown in table 6.9.

6.5.3 Summary{ TC "6.5.3 Summary" \l 3 }

The addition of tower cells has a significant effect on the plant performance. Values for operation costs that were calculated for the present size of the tower are in the range of 12.60 $/MWh to 12.80 $/MWh for July, if the best control strategy is used. However, the addition of tower cells can reduce the cost to 12.52 $/MWh, as was calculated for four additional tower cells and a respective higher water flow rate through the tower (see table 6.9). If only cells are added and the flow rate remains at the present value, the best value was calculated to 12.55 $/MWh, which occurs when eight cells are added (see table 6.8). The absolute values of these production costs are certainly dependent on weather conditions, but the tendency is considered reliable. If components are to be added to the cooling cycle, the alternative of adding cooling tower cells and simultaneously increasing the flow rate is to prefer, not because of the marginal cost benefit, but because this seems to be the less capital intensive alternative as less cooling tower cells have to be added. As was mentioned before, the plant operators have to decide whether the benefit in operation costs justifies the effort for constructing additional cooling tower cells and maintaining them.

6.6 Conclusion for optimum plant performance{ TC "6.6 Conclusion for optimum plant performance" \l 2 }

6.6.1 Reliability of results{ TC "6.6.1 Reliability of results" \l 3 }

The difference in performance and cost that is observed in the simulation when the tower operation mode is switched from one to two pump operation is rather small and depends on ambient conditions. The maximum cost benefit that occurred in the simulation was calculated to 0.14 $/MWh. This value was determined for an extremely hot weather. The ratio of improvement in costs is on the order of 1% for summer months, which is a big benefit economically if absolute numbers are considered. Assuming a constant load of 1000 MW, a 0.10 $/MWh savings amounts to $2,400 per day in absolute savings.

On the other hand a difference of 1% appears small from the engineering point of view, considering the error in the calculation associated with the component models. The simulation program calculates the increment in performance values due to back pressure and auxiliary power. That means 1% error in the calculation does not mean an error of 1% in the overall heat rate. If the heat rate correction is on the order of 500 Btu/kWh a 10% error in the calculation would lead to an uncertainty of ±50 Btu/kWh. Assuming a base heat rate of 10500 Btu/kWh, a 10% error in the calculation would amount for a relative error of the overall heat rate of ±0.5%. As a 10% error in the calculation may be reasonable, the possible error in absolute performance values must be considered when the simulation results are applied.

6.6.2 Recommendation for plant operation{ TC "6.6.2 Recommendation for plant operation" \l 3 }

The results of the simulation can be summarized to give recommendations for the best plant operation strategy. Also the best alternative of increasing the cooling system capacity is shown.

It has to be noted that there is no general strategy that would yield the best performance at any given ambient and load condition. The main recommendations are:

- The primary interest of the plant operators is to achieve the best possible plant performance with the present available equipment. The results of the simulation show that plant performance can be influenced by the tower operation mode. The most significant result is that the system should never be run without cooling towers for high and moderate ambient temperatures. Without cooling tower operation the plant inlet temperatures become high and capacity reductions can occur. This effect was observed in all simulation runs.

- The difference between one and two pump operation with respect to heat rate and cost is rather small. For high ambient temperatures and high solar input into the pond the operation of two pumps yields lower heat rates than one pump operation. If the ambient temperatures are moderate, as was shown for March weather data, one pump operation is beneficial. Considering the uncertainties in the calculation and including maintenance and capital costs, the conclusion can be drawn that one pump should be operated most of the time except for extremely hot weather conditions.

- At the present time, the cooling towers are operated at a varying number of pumps. For the simulations performed using TMY data the heat rate and costs for the varying water flow mode were in between the values for constant one or two pump operation. That means that at certain weather conditions the varying operation mode can be advantageous. That may occur when the weather is too warm to switch to one pump and too cold to go to two pumps.

- The tower operation mode that yields the best performance is dependent on weather conditions and it is hard to predict exactly at which times the operation mode should be switched. To predict the plant performance in advance a reliable weather forecast for three days that is the approximate circulation time in the pond is needed. A reliable forecast for such a long time is not available. The recommendation for the plant operation is therefore to run only one pump most of the time. Only in severe weather conditions the second pump should be turned on.

- If environmental restrictions allow, the make-up pumps should be run at full capacity to take advantage even from the small effect that the make up flow has on system performance.

- Dredging the pond is not considered an useful alternative for performance improvement. As shown in section 6.4 the pond would have to be dredged to a considerable depth to achieve an impact on plant performance. More important is that the pond depth has no effect on the average performance of the power plant, only on the short term behavior. But even to lower the diurnal temperature fluctuations in the pond by only a small amount the water level would have to be raised considerably. The increase in pond depth that could be reached by blocking the spillway is limited to approximately 2 ft. An increase in depth of such magnitude has almost no noticeable effect on the pond behavior and on plant performance.

- The alternative of adding devices to the cooling system is not considered at the present time to keep capital costs low. If a cooling device is to be added in the future, a cooling tower is a better alternative than a cooling spray (see section 4.3).

- The calculations showed that in summer months the addition of cooling tower capacity can result in performance improvement. The best alternative found is to increase the number of tower cells and simultaneously increase the water flow through the towers. There exists an optimum number of cells at an optimum water flow rate for a given set of weather conditions. The results shown in section 6.5 show the general influence that the increase of tower capacity has on the cooling cycle.

- An attempt to find the optimum cooling tower capacity is not performed in this work. This is left to the plant operators. The TRNSED program can be used for this task when the actual design of a capacity increase has to be performed. The capital costs will have to be included in such a calculation, too.