

## THE PALO VERDE WATER CYCLE MODEL (PVWCM) – DEVELOPMENT OF AN INTEGRATED MULTI-PHYSICS AND ECONOMICS MODEL FOR EFFECTIVE WATER MANAGEMENT

Bobby D. Middleton<sup>1#</sup>, Patrick V. Brady<sup>1</sup>, Jeffrey A. Brown<sup>2</sup>, Serafina T. Lawles<sup>1</sup>

<sup>1</sup>Sandia National Laboratories, Albuquerque, NM

<sup>2</sup>Arizona Public Service, Phoenix, AZ

<sup>#</sup>Corresponding Author

### ABSTRACT

*Water management has become critical for thermoelectric power generation in the US. Increasing demand for scarce water resources for domestic, agricultural, and industrial use affects water availability for power plants. In particular, the population in the Southwestern part of the US is growing and water resources are over-stressed.*

*The engineering and management teams at the Palo Verde Generating Station (PV) in the Sonoran Desert have long understood this problem and began a partnership with Sandia National Laboratories in 2017 to develop a long-term water strategy for PV. As part of this program, Sandia and Palo Verde staff have developed a comprehensive software tool that models all aspects of the PV (plant cooling) water cycle. The software tool – the Palo Verde Water Cycle Model (PVWCM) – tracks water operations from influent to the plant through evaporation in one of the nine cooling towers or one of the eight evaporation ponds.*

*The PVWCM has been developed using a process called System Dynamics. The PVWCM is developed to allow scenario comparison for various plant operating strategies.*

Keywords: Water management, water energy nexus, system dynamics.

mg	Milligrams <sup>1</sup>
Mg	Magnesium
MGD	Million gallons per day
MW	Megawatts
MWh	Megawatt hours
MWth	Megawatts-thermal
NPV	Net present value
OPEX	Operational expenditures
PSS	Powersim studio
PV	Palo Verde Generating Station
PVWCM	Palo Verde Water Cycle Model
PWR	Pressurized water reactor
RO	Reverse osmosis
SD	System dynamics
SG	Steam generator
SNLNCC	Sandia National Labs natural circulation cooler
SSC	Steam surface condenser
SST	Blowdown slipstream treatment
TDS	Total dissolved solids
US	United States of America
$\dot{V}$	Volumetric flow rate
$\dot{V}_0$	Reference volumetric flow rate
WRF	Palo Verde Water Reclamation Facility
WWTP	91 <sup>st</sup> Avenue Waste Water Treatment Plant

### NOMENCLATURE

AF	Acre-feet
APS	Arizona Public Service
Ca	Calcium
CAPEX	Capital expenditures
CO <sub>2</sub>	Carbon dioxide
Cl	Chlorides
GPM	Gallons per minute
GUI	Graphical user interface
l	Liter

<sup>1</sup> Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

*This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.*

## 1. INTRODUCTION

The Palo Verde Generating Station is located approximately 55 miles west of Phoenix, Arizona and is the largest nuclear single site facility in the US, generating on average 32,000,000 megawatt hours (MWh) annually. The site has three Combustion Engineering “System 80” Pressurized Water Reactor (PWR) units - each rated at 3990 megawatts-thermal (MWth). These units provide generation and grid stability for the operating owner Arizona Public Service (APS) and the plant’s six other owners in Arizona, California, New Mexico, and Texas. Figure 1 is a layout of PV.



**FIGURE 1:** Aerial photograph of the Palo Verde Generating Station.

In addition to being the largest domestic nuclear power generating facility, Palo Verde is also the only nuclear facility in the world not located on or near a natural body of water. Preliminary plant design evaluations concluded in the mid-1970s that surface and groundwater resources in the Phoenix area would not be sustainable for the large steam-cycle cooling demands. However, a large supply of municipal effluent was available from Phoenix and the surrounding municipalities. An analysis and treatment testing effort demonstrated the source to be acceptable. Therefore, an agreement was concluded with the City of Phoenix and other municipalities to provide for an assured source of treated wastewater that would be sufficient, after additional treatment, to provide for the steam-cycle cooling water needs for the three Palo Verde units.

The municipal effluent (also just ‘effluent’) is conveyed from the municipal wastewater treatment plant via a concrete pipeline approximately 36 miles west to the Palo Verde Water Reclamation Facility (WRF). The effluent is received at the WRF where it is further treated using a tertiary treatment process. The WRF plant has a maximum capacity of 90 million gallons per day (MGD) and sanitizes and reduces water hardness. The final produced water is stored in large reservoirs that provide continuous makeup to the steam cycle (condenser) cooling systems in each of the three units (i.e., circulating water system). Secondary system waste heat is ultimately rejected from the three individual unit condensers through large mechanical draft evaporative cooling towers (see Figure 2). Combined, the three units evaporate approximately 45,000 gallons per minute (GPM) at full load reactor power conditions. The average water

demand at Palo Verde is approximately 72 thousand acre-feet (AF) per year.



**FIGURE 2:** Photo of one of the nine Marley Class 700 cooling towers used at the Palo Verde Generating Station.

Evaporation in the cooling towers concentrates salts in the circulating water system. A steady flow of approximately 600 GPM is discharged from the circulating water system of each unit to maintain the water chemistry at or below limits that preclude condenser tube fouling. The discharged water is directed to the on-site 650-acre evaporation ponds. The WRF, reservoirs, circulating water system, cooling towers, and the evaporation ponds make up the physical components of the Palo Verde water cycle. The mass balance between incoming effluent, cooling tower evaporation, and discharge to the evaporation ponds constitutes the water balance. Since Palo Verde is a zero-liquid-discharge facility, if the water balance is not maintained, chemistry limits in the circulation water system and or inventory limits in the evaporation ponds could be exceeded, thereby challenging plant operation.

As the electric power grid evolves in response to variable renewable generation, nuclear power plants are increasingly challenged to operate much more cost effectively. For Palo Verde, the only nuclear plant that produces its cooling water, the cost of the effluent and treatment increase annually and are an operational cost that has been targeted for reduction. To that end, APS has established a long-term water resources initiative to assess and implement options to reduce plant cooling costs through advanced treatment and cooling technologies, and through the use of alternative water sources to replace the increasingly expensive effluent.

The issue of economical plant cooling is also exacerbated by the increasing scarcity of water resources in the US desert southwest. As surface water and groundwater resources continue to be stressed to the point of depletion, municipalities have begun to target other water resources to supply the growing demand. While Palo Verde is assured the necessary water resources to operate through the current licensed life, the demand for effluent will increase and the cost escalates annually, resulting in an increasing fractional cost of generation.

Several independent evaluations were initially completed to assess potentially economically viable options for plant cooling operating cost savings. However, an integrated analysis of two or more options proved to be complex with an almost limitless number of degrees of freedom. As a result, APS sought to develop an evaluation framework that could simultaneously account for changes in water source chemistry, the addition of treatment technology, and the incorporation of cooling technologies to identify the most economically viable alternatives that ensure the long-term water balance for the site.

APS and Sandia National Laboratories have formed a collaborative partnership to advance the development of a simulation tool (model) to integrate power plant operation, the plant cooling water cycle, and a net-present value economic assessment with which to assess plant scenarios proposed to achieve the goal of plant operating cost reduction. The PVWCM provides the flexible analysis capabilities. In addition, the PVWCM provides the ability to forecast the benefits and cost of various plant changes on evaporation pond loading and future high-cost maintenance schedules and provides detailed tertiary chemistry relationships to optimize chemical treatment and reduce cost in the WRF tertiary system.

The model has to date been used to evaluate several options for the use of alternative water supplies that are significantly lower cost than the municipal effluent. Large, sustainable amounts of brackish water are available from a region in the subflow basin approximately 20 miles east of Palo Verde. The use of the brackish water to offset a fraction of the effluent is possible allowing that additional tertiary treatment would be needed to compensate for the added salt load. The additional circulation water system blowdown to the evaporation ponds would be required to compensate for increases in constituent concentrations not treated for in the tertiary system (e.g., chlorides). The simulation has demonstrated that only very small amounts of the brackish water could be used (approximately 3% of the total cooling water flow). The PVWCM demonstrated that increase in cost for tertiary chemistry dosing and the long-term impact on the evaporation pond levels renders the use of the alternate water source non-economic without additional treatment.

In addition, the model has been applied to evaluate on-site supplemental treatment options to assess capacity requirements and the associated economic benefits that would facilitate use of both larger amounts of brackish water, and municipal water treatment concentrate. If sufficiently scaled, the supplemental treatment process integrated with the water cycle would enable Palo Verde to provide reverse osmosis (RO) concentrate management for local municipalities that are currently challenged to produce sufficient water supplies to sustain growth.

It is noted that the integration of a supplemental treatment process with a nuclear power plant for the purposes of large-scale desalination increases the economic viability of this installation when the dispatchable load capability is factored. Dispatchable load or capacity is increasingly more important given that sustained growth of renewable generation in this region has

imposed economic challenges on large, traditionally baseload nuclear plants. Many within the domestic nuclear fleet, have been or will be challenged, if and when these plants are required to operate at less than full capacity when renewable sources provide for demand. An integrated treatment process provides for additional and or dispatchable load (5 - 25 MW) that may avoid some nuclear curtailment during the day while treating concentrate, and later reducing output to facilitate greater power output to the grid. This advanced scenario and others that provide guidance for future cost reduction and operation optimization are within the capabilities of the PVWCM.

## **2. MATERIALS AND METHODS**

The PVWCM is being developed in a software called Powersim Studio (PSS). PSS is a System Dynamics software (SD). This section describes both SD and PSS.

### **2.1 System Dynamics Overview**

SD is a methodology for modeling nonlinear dynamic processes over time. It uses stocks (quantities with conservation laws), flows (rates of flow among the stocks), feedback loops, and time delays. The basic premise is to connect all equations and treat them as time-dependent ordinary differential equations. Initial values are provided by the user and approximate solutions are obtained via a given difference equation technique. Most SD software tools offer Euler and Runge-Kutta solutions.

### **2.2 Powersim Studio**

The software that is being used for the PVWCM is Powersim Studio 10 (PSS). PSS is provided by a Norwegian company entitled Powersim Software AS. PSS was selected after reviewing several SD software suites. All of the software tools reviewed had the functional requirements for developing the PVWCM. However, it was the opinion of the technical staff involved in PVWCM development that the graphical user interface (GUI) functionality of PSS made it the appropriate software for this project.

## **3. MODEL STRUCTURE**

### **3.1 Heat Generation**

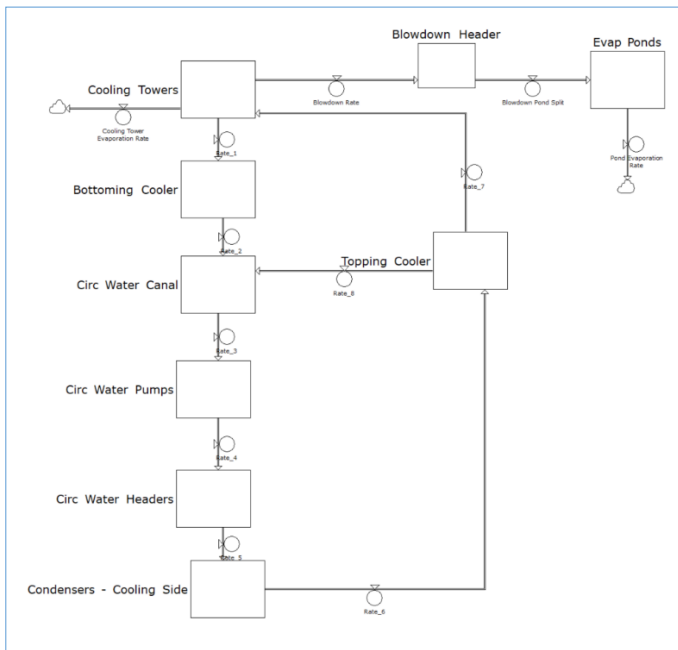
The reactor schedule is simulated in PVWCM as an input drawn from an Excel spreadsheet. Reactor outages are entered into the Excel data sheet and imported into PSS. This allows the analyst to accommodate scheduled outages down to a day. It is possible to recode the model for finer control, but for most purposes, a one-day granularity is adequate.

### **3.2 Power Conversion**

The Power Conversion module simulates conversion of reactor heat into electricity. The excess heat is rejected into the Cooling module via simulation of the shell-and-tube condenser. To faithfully simulate the power conversion process, this module has two loops. The first loop simulates the mass flow of water in the power conversion system; the second loop simulates the flow of energy.

PV utilizes three large shell-and-tube steam surface condensers (SSCs). The shell-side of each condenser is treated as a level in each of the loops in the Power Conversion module. The steam generator (SG) and the steam turbine are also treated as levels in each of the Power Conversion loops.

Figure 3 shows a very simplified version of the diagram of the Power Conversion loop in the PVWCM. This figure illustrates how the various components of a system are connected to one another. The rectangular images are levels (objects which contain conserved quantities). The circular images represent the rates at which the quantities in the levels flow from one level to another. The rates that end in a cloud-like shape are said to flow to an “infinite sink.”



**FIGURE 3:** Schematic of the mass flow of water as modeled in the PVWCM. The boxes are levels. The bars connecting them represent the flow of water from one level to another. The circular variables within these bars are flow rates. All other variables are either auxiliary variables or constants.

Since the goal of this project is to find ways to improve long-term water operations for PV, the power conversion efficiency is calculated as a function of circulating water temperature only. This calculation is part of the Cooling Loop module; the result is fed back into the Power Conversion module.

### 3.3 Chemical Treatment

The Chemical Treatment module in PVWCM simulates in sequence: mixing of PV source waters; lime softening (sequential addition of lime, soda ash and carbon dioxide (CO<sub>2</sub>), and sulfuric acid and hypochlorite) to remove salts that might otherwise form scale in the cooling towers, evaporation of water in the cooling towers, and discharge to evaporation ponds. The module tracks treatment costs and automatically adjusts lime softening dosing if the PV source water changes. The module

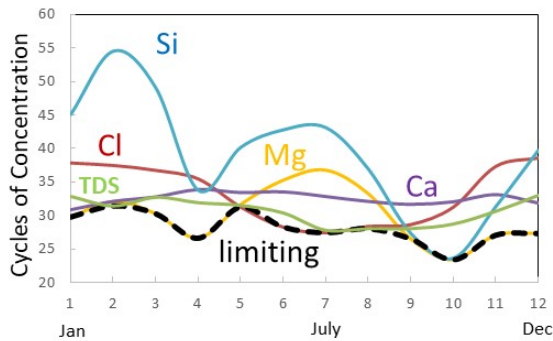
minimizes projected water use by optimizing treatment to achieve maximal cycles of concentration in the cooling tower. It also provides input to calculations elsewhere in PVWCM that project the operational lifetime of evaporation ponds.

Roughly 90% of the water used by Palo Verde is treated effluent from Phoenix’s 91<sup>st</sup> Avenue Wastewater Treatment Plant. Most of the remainder is treated effluent from Phoenix’s Tolleson Wastewater Treatment Plant or from on-site wells. Local brackish groundwater might be used in the future. The Phoenix wastewater effluents have relatively high magnesium (Mg) levels in the winter, and high chlorides (Cl) in the summer. The salinity of the Phoenix wastewater effluent is increasing over time.

The lime-softening treatment sequence at Palo Verde happens in two clarifiers and a gravity filter. Lime is added to the first stage clarifier to raise the pH and remove calcium (Ca) and Mg hardness as respectively calcite and magnesium hydroxide sludge. Dissolved silica is removed by incorporation into the magnesium hydroxide. Effluent from the first stage clarifier is combined with soda ash and CO<sub>2</sub> in the second stage clarifier which produces more calcite sludge. Sulfuric acid and sodium hypochlorite are added at the end to lower the pH and disinfect the effluent, makeup water that ultimately goes to the cooling towers.

Lime-softening at Palo Verde primarily aims to prevent formation of calcite, calcium sulfate, and silica scale in the cooling towers by lowering dissolved Ca, sulfate, and Si in the cooling tower makeup water. Blowdown triggers, maximum salt levels that can be achieved without forming scale, are: Ca 2500 milligrams/liter (mg/l), sulfate 9000 mg/l, Mg 750 mg/l, and Si 155 mg/l. There is also a total dissolved solids (TDS) blowdown trigger of 30,000 mg/L which was set by the EPA to limit dryfall export of salts out of the top of the towers, and a Cl trigger of 12,000 mg/l to limit cooling tower corrosion.

Cooling water is blown down whenever an individual trigger is approached. In winter, blowdown is typically triggered by Mg levels. In summer, chlorides typically trigger blowdown. Figure 4 shows how the limiting blowdown triggers vary seasonally. The achievable cycles of makeup water concentration at Palo Verde is 25 - 30. The cycles of concentration calculated for a particular element is its blowdown trigger level divided by its concentration in the cooling tower makeup water – a high makeup concentration means low cycles of concentration and vice versa.



**FIGURE 4:** Seasonal blowdown triggers. The dashed ‘limiting’ line is the lowest cycles of concentration of the individual scale-forming elements as a function of time.

### 3.4 Plant Cooling

The Cooling Loop module simulates rejection of waste heat via the nine Marley 700 Class cooling towers that PV uses.

The temperature of the water leaving the cooling tower is dependent upon circulating water flow rate, air flow rate, ambient air temperature, relative humidity, and heat rejection rate. Calculation of circulating water temperature is accomplished using an empirical correlation for the plant encoded in an iterative VBScript inside the PSS code. This iterative script runs each time step during simulation. However, if a faster, less accurate approximation is needed for scoping exercises, a non-iterative option is available that has thus far shown to give results for all calculations over a 1-year simulation that are within 2% of the iterative procedure. The non-iterative approximation uses mass and energy balances for all physical procedures, but uses a time delay of one timestep in the heat rejection calculation to facilitate solving the difference equations.

### 3.5 Evaporation Ponds

Palo Verde is designed and licensed for zero-liquid-discharge. All water processed for plant cooling is either evaporated through the cooling towers or discharged as blowdown to the 650-acre evaporation ponds. The impoundment consists of three ponds that are subdivided for a total of eight cells. Subdividing the ponds into the cells provides for inventory management and facilitates repair and scheduled replacement of the PVC liner.

The PVWCM has included the evaporation pond cell subdivision and has accounted for the respective cell basement elevation and the slope of the respective cell impoundment walls to correlate volume and water elevation. Flow to the individual evaporation pond cells is determined by Palo Verde Operations and is managed to optimize evaporation and minimize inventory. The PVWCM, however, adjusts flow to the individual cells to maximize surface area for evaporation unless the user defines a specific flow scheme and shuts off flow to individual cells.

The Penman-Monteith evapotranspiration correlation has been used to determine evaporation rates [1]. Weekly plant

elevation readings for the pond cell levels have been recorded which provides for calibration and refinement of the evaporation pan factor.

Baseline cell relining schedules have been included and also allow for the user to adjust outage dates and duration to optimize the schedules should material inspection demonstrate extended life of the liner materials. This represents a significant economic benefit since the relining activities are high OPEX costs.

### 3.6 Economics

Costs associated with water operations are accounted for in six separate categories: water supply, chemicals, labor, electricity, options, and residuals.

The majority of water supply costs are due to the purchase of reclaimed water that is delivered from the 91<sup>st</sup> Avenue Waste Water Treatment Plant (WWTP). These costs increase each year through 2025. From 2026 through 2050, a tiered cost structure is implemented. There are four tiers, in 2000 AF increments, based on water usage per month. At the beginning of each month, the accounting for water will restart. Throughout the lifetime of the contract, there is also a non-usage fee for any amount less than 80,000 AF per year. The non-usage fee is 20% of the cost of water through 2025. Beginning in 2026, the fee is 30% of the average cost of water during the year. PV does not have a contract for water from the WWTP after 2050.

PV also purchases water from other municipalities in the area and they have wells, both on and off the PV site. The model provides user inputs for the costs associated with these water sources.

Chemical costs are modeled for lime, ash, carbon dioxide, and hypochlorite. There are user inputs for baseline cost (for each chemical), baseline year, and chemical cost inflation rate.

Labor costs are modeled the same way chemical costs are modeled. There are user inputs for baseline labor cost, baseline year, and labor cost inflation rate.

Electrical costs are dependent upon the location of the asset requiring power. The Hassayampa Pumping Station is located off the PV site. This station provides energy to move cooling water to the site from the WWTP. All electricity required to drive these pumps is charged at a rate negotiated by PV. There are user inputs for baseline cost per MWh, baseline year, and inflation rate. Pumps that are onsite (TB and FC pumps) draw electricity from the plant itself and therefore there is no bill to be paid. However, the power use decreases the amount of electricity that PV delivers to the grid. Thus, there is a decrease in revenue that is dependent upon hub price of electricity.

Options costs refer to the capital expenditures (CAPEX) and operational expenditures (OPEX) for technologies that are not currently in use at PV, but which are being given consideration. The options are discussed in Subsection 3.7. User inputs are provided for CAPEX and OPEX for each option.

Residual costs are any expenses that are not related to any of the aforementioned cost categories. They could also be called miscellaneous costs. To model these, user inputs are available for residual baseline costs, residual baseline year, and residual inflation rate.

### 3.7 Options

Options are technologies and methodologies that may be useful in a long-term water management strategy at PV, but are not currently in use. There are currently five options that are allowed in the PVWCM. These options may be used separately, in parallel, or not at all. They are: topping coolers, bottoming coolers, blowdown slipstream treatment, manual chemical dosing, and lime leveling.

#### 3.7.1 Topping Cooler

As defined for the PVWCM, a topping cooler is any cooling technology that precools the circulating water after it leaves the SSC before it reaches one of the cooling towers in operation at PV. The prototypical topping cooler is a dry cooler that is installed with a defined maximum water flow rate and maximum air flow rate. Estimates for the amount of electricity required to drive fans are based on cubic power laws for fan power, as shown in Equation 3.7.1.

$$P = P_0 \left( \frac{\dot{V}}{\dot{V}_0} \right)^3 \quad (1)$$

The PVWCM incorporates code for two types of topping coolers. One is based on the Johnson Controls Bluestream Cooler [2] and one is based on Sandia's patented Sandia National Labs Natural Circulation Cooler (SNLNC) [3].

User inputs for flow rates and minimum approach temperatures are provided.

#### 3.7.2 Bottoming Cooler

A bottoming cooler is defined to be any cooling technology that postcools the circulating water after it leaves the cooling tower and before it reaches the SSC. Although such a device could be a dry cooler, this is highly unlikely since a dry cooler should operate more efficiently and during a greater portion of the year if installed as a topping cooler. Another option for a bottoming cooler would be a chiller. However, chillers require large amounts of electricity to operate. This option was included in case advances in cooling technology in the future makes it feasible to test such an idea.

#### 3.7.3 Blowdown Slipstream Treatment

Blowdown slipstream treatment (SST) is a generic term encompassing any action that diverts a portion of the blowdown, performs some chemical treatment, returns the permeate to the circulating water system, and sends the concentrate to the evaporation ponds.

The option was included for two reasons. The recycled permeate can potentially decrease the amount of water that PV is required to buy. However, this benefit is necessarily small since blowdown only accounts for 4-5% of the makeup water; the other 95-96% is evaporated. However, it is possible that the level of water in the evaporation ponds could increase to the point that a new pond would need to be built. The cost for

building new evaporation ponds is significant. Reducing blowdown via SST could potentially eliminate this cost, thereby making the option economically attractive.

The PVWCM provides user input options for CAPEX, OPEX, power requirements, flow recovery fraction, and chemical recovery fraction.

#### 3.7.4 Manual Chemical Dosing

For current operations, targets for makeup water chemical concentrations and pH are defined by plant personnel. Given influent concentrations, optimal lime and ash dose rates are then calculated to achieve the targets. However, it is possible that someone will want to deviate from these dose rates. The manual chemical dosing option was added for this purpose. Correlations for how the makeup water chemical concentrations would change with deviations from the optimal dose rates have been developed and incorporated into the PVWCM. These calculations are expected to be reliable with up to a 10% deviation from the optimal dose rates.

User inputs are provided for Delta Lime and Delta Ash for the seven clarifier trains. Any number of trains may be selected for manual dosing.

#### 3.7.5 Lime Leveling

Increasing the intensity of lime-softening in the winter might decrease water usage and needed evaporation pond area by increasing the cycles of concentration in the cooling tower; decreasing lime-softening in the summer would decrease chemical costs but not change cycles of concentration (see below).

Varying the intensity of lime-softening is here termed "lime-leveling". For example, winter-time lime-leveling could reduce makeup Mg and Ca levels sufficiently that Cl became the blowdown trigger and cycles of concentration of 38 – 41 could be achieved, but only if the TDS blowdown trigger were raised above 30,000 mg/l. There should be ample room for raising the TDS limit because it was very conservatively calculated in the original permit. The added cost of treatment in lime-leveling up must be compared against the decrease in water used and evaporation pond footprint.

Lime leveling down in the summer when Cl is the blowdown limiter would save chemical costs but would not affect Cl levels since lime-softening does not remove Cl.

## 4. OUTPUT

The PVWCM allows the user to save as many reference runs as desired in Excel format. The results for selected variables are written to Excel. These results can be imported when a new simulation is run. The results of up to five previously saved simulations can be compared with the current simulation. Figure 5 shows an example comparison of Evaporation Pond levels for three different simulations. Figure 6 shows the Actual Cost results and Figure 7 shows the net present value (NPV) results for the same three simulations. These results are not intended to show actual output, but are only representative values for illustration.

Figure 5 has two graphs. The top graph shows traces of three different simulations as well as the total pond capacity for a single pond at PV (Pond 2A).

- The total pond capacity is the straight maroon line at the top. Note that the capacity drops to zero just before January 2030. This is due to a scheduled pond relining at that time.
- The baseline simulation is the green line.
- The purple line (middle pond water volume) is a simulation that assumes topping coolers that can reject up to 600 MWth from each reactor. This heat rejection is limited by ambient temperature and the operating characteristics of a currently available dry cooler. In theory, this would be very beneficial to the plant as it saves about 6000 AF per year in water use. However, in this simulation, CAPEX and OPEX (not including electricity required to drive fans) were assumed to be zero. The reason for running a simulation in this manner is that one can then look at the NPV savings and determine a ballpark figure for the total amount that could be paid and still break even for a given discount rate.
- The red line (lowest pond water volume) shows the pond level when running a hypothetical topping cooler that could save the plant about 10,700 AF per year. As can be seen from Figure 5, not only is the water use greatly decreased, but the pond water volume also greatly decreases. In this scenario, there is almost no chance that pond capacity would ever be strained, even given large uncertainties and a catastrophic failure of the largest pond.

The second graph in Figure 5 shows the same information as the first graph, but this time it is for all eight evaporation ponds. The total pond capacity (top trace) is the sum of the capacities for the individual ponds. The total capacity changes as one pond or another is taken out of service for relining or returns to service after relining.

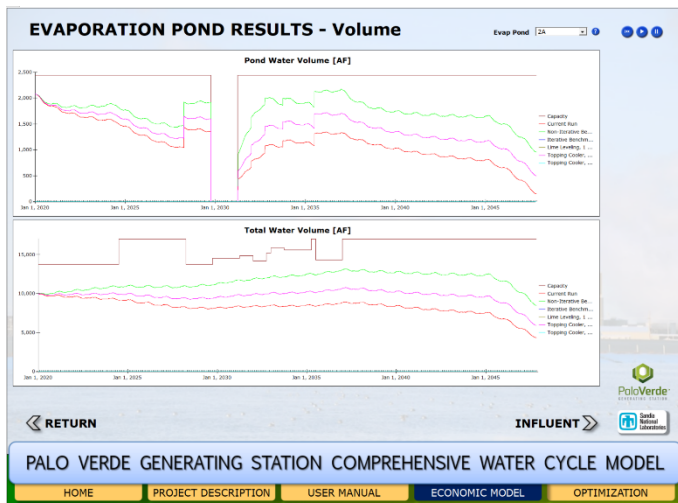


FIGURE 5: Comparison of Evaporation Pond levels for two different simulations. See Section 4 for an explanation of the various traces.

Figure 6 shows the dollar cost value of water operations for the same three simulations that are represented in Figure 5. The baseline simulation shows a total cost for water operations from January 2020 to end of currently licensed life to be about \$1.519 Billion. Use of the topping cooler (purple line in this graph) brings the cost down to about \$1.439 Billion, for a total savings of about \$80.8 Million. Remembering that this does not include CAPEX and OPEX, it is obvious that installation of dry cooling capacity at this level would not be feasible in this scenario. The red line shows total estimated savings (again without CAPEX or OPEX) of about \$142.4 Million. This is a much more attractive number, but does not tell the whole story. A better estimate of the value of dry cooling in this scenario is the NPV. This is shown in Figure 7.

Figure 7 shows the NPV cost for operating the water plant under the three scenarios previously described. The important value in this figure is the NPV savings between the baseline simulation and the other simulations. This value is about \$48.8 Million for the first topping cooler (~ 6,000 AF per year savings in water) and about \$85.9 Million for the second (hypothetical) topping cooler (~10,700 AF per year savings in water), assuming a 5.0% discount rate. Thus, if a company could provide dry cooling that could be automated and provide the cooling capacity required in this simulation for ~\$86 Million one-time cost, it might be feasible for PV ownership to investigate this possibility. As of the submission date of this article, no technology with these characteristics is known.

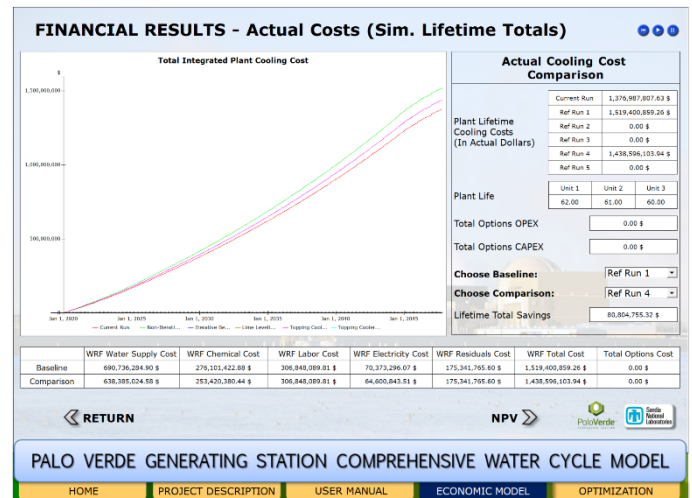


FIGURE 6: Comparison of Actual Costs for two different simulations. See Section 4 for an explanation of the various traces.

The PVWCM has too many features to list them all in this paper. However, some of the outputs that are available but not described above are:

- Power Generation – This output presents Gross Power generation, Net Power generation, and Water Plant Parasitic Load for both the entire plant and for the individual reactor units. These outputs can be compared

for different scenarios just as those outputs in Figures 5-7 can be compared for different scenarios.

- **Water Use** – This feature allows comparison of cooling tower evaporation, blowdown, makeup use, and rate of influent from various water sources. As in other outputs, all values can be compared for different operating scenarios.
  - **Topping Cooler Economic Analysis Estimates** – This feature is for advanced users and allows one to estimate the effects of optimizing topping cooler performance as a function of electricity hub price and instantaneous water cost. There are three modes:
    - Limited by physics only – In this mode, the topping cooler is limited only by environmental conditions.
    - Maximum water savings – In this mode, the topping cooler rejects as much heat as possible without decreasing plant net revenue.
    - Maximum net revenue – In this mode, the topping cooler rejects the amount of heat which maximizes net revenue.
- It should be noted that this feature is only an estimate.

However, the data and projections that are imported into the model from Excel spreadsheets are assumed to begin January 1<sup>st</sup>, 2013 and end December 31<sup>st</sup>, 2067.

The Main Interface page of the GUI allows the user to set simulation parameters, including: Start Date, End Date, and Timestep for the numerical solver. It also allows the user to input a ‘Pause’ date that can be used for diagnostic analysis. This page also includes links to the other pages of the GUI. Figure 8 is a screenshot of the Main Interface page.

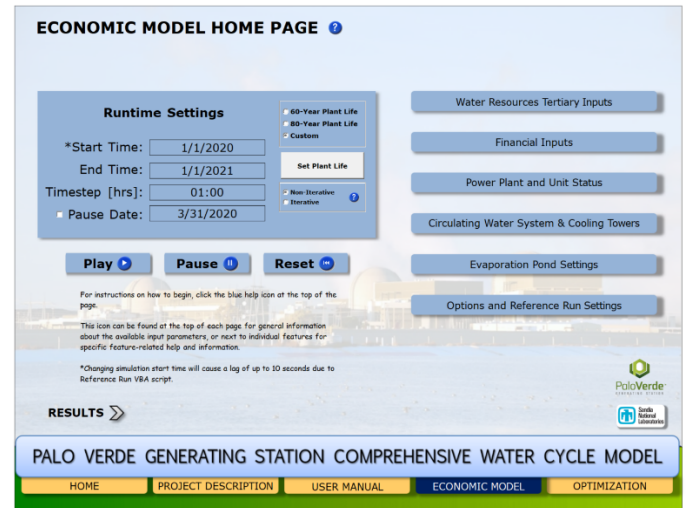


FIGURE 8: PVWCM Main Interface page.

The links on the right side of the Main Interface allow the user to navigate to other input screens. Inputs for the following parameters can be found as listed below.

- **Water Resources Tertiary Inputs** – Flow rates and chemical concentrations for all water sources.
- **Financial Inputs** – Base year unit costs for water, chemicals, labor, electricity, and residuals. Inflation rates and assumed discount rate for NPV calculations.
- **Power Plant and Unit Status** – Reactor unit power level as fraction of total power. This is variable by month for any month of the simulation.
- **Circulating Water System and Cooling Towers** – Circulating water pump operational status for all circulating water pumps, circulating water TDS limit, cooling tower outage periods, fractional fan power for any fan on any cooling tower.
- **Evaporation Pond Settings** – Outage and reline schedule for evaporation ponds, pond capacities (e.g., in case pond liner has a leak somewhere above the floor but below top of pond), and manual input for initial pond water volumes.
- **Options and Reference Run Settings** – Which options will be used (if any), CAPEX and OPEX for options, start date for options, capacity for options. Reference settings allow the user to determine whether current run is to be saved for use later as a reference. It also allows the user to choose which previously saved

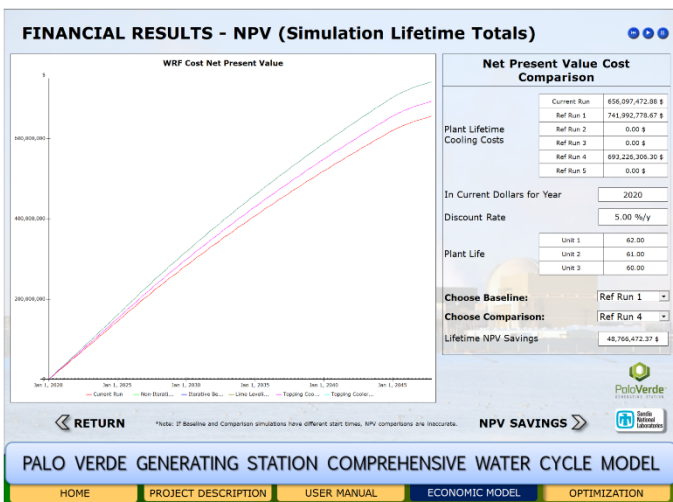


FIGURE 7: Comparison of NPV for two different simulations. See Section 4 for an explanation of the various traces.

## 5. USER INTERFACE

The GUI for the PVWCM allows users to choose among several scenarios and run the simulation for any length of time.

reference runs are to be imported for comparison with current run.

## 6. CONCLUSION

PV and Sandia personnel have developed a dynamic multi-physics and economics software tool that reasonably simulates water operations at PV. The tool (PVWCM) allows the user to perform scenario analysis for a multitude of operational strategies throughout the remaining lifetime of the plant. The PVWCM has already been used to assess the economic feasibility of various water-purchase options and will be used for other options in the future. The tool can be modified for various types of water operations strategies and for different types of power plants.

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