Water-saving options for sulphuric acid plants

R.J. Forzatti*, I. Natha[†], L. Roux[†], and D.A. Van den Berg*
**Hatch Associates, Australia*
[†]Hatch Goba (A member of the Hatch Group), South Africa

The production of sulphuric acid from sulphur generates heat. The majority of this heat is recovered as steam and often used to generate electricity. Heat not recovered as steam is rejected to cooling water systems. The design of the turbine condenser and cooling water system impacts the overall plant water, energy, and environmental footprint. This review considers a conceptual 2000 t/d sulphuric acid plant with several alternative cooling water systems. The review utilizes Hatch's 4 Quadrant sustainable design tool to compare options on both an economic and a weighted sustainability scale.

Keywords: Sulphur-burning acid plant, steam, power generation, cooling systems, sustainable design.

Introduction

Sulphuric acid plants require water for their cooling systems. Cooling is required to reject surplus heat not recovered as steam. Reducing water consumption lowers the cost of sourcing reliable supplies of clean water and the cost associated with treating effluent streams. It also helps improve the sustainability of the acid plant operation by reducing the impact on surrounding communities.

This paper focuses on two broad categories of water-saving options:

- Pre-treatment of the make-up water required for evaporative cooling systems
- Replacement of evaporative cooling with dry cooling.

The sustainability aspect of these options is analysed using Hatch's 4 Quadrant design tool.

Process description

A conventional 2000 t/d sulphur-burning sulphuric acid plant is considered in this paper.

Solid sulphur is delivered in bulk bags or containers and is stored and transferred to a melting and filtration circuit. The sulphur melting system uses low and medium-pressure (LP and MP) steam, usually provided from the acid plant steam system. Dirty molten sulphur is filtered to remove ash and other solid impurities. Molten sulphur is also sometimes received instead of solid sulphur if the sulphur source is nearby.

Clean sulphur is transferred to the acid plant where sulphuric acid is produced. It is burned in a furnace at approximately 1200°C in contact with dry air to produce SO_2 gas (approx. 12 vol.%) (King, Davenport, and Moats, 2013). The SO_2 gas is oxidized to SO_3 gas in contact with a vanadium pentoxide type catalyst. The SO_3 is then absorbed and reacts with the water component of strong sulphuric acid to yield H_2SO_4. Circulating and product acid cooling is achieved in heat exchangers supplied with cooling water, typically provided from an evaporative cooling tower.

The acid plant steam system is designed to recover the heat generated by the exothermic reactions within the acid circuit. Heat is recovered from the sulphur burner off-gas via the production of saturated high-pressure (40 bar or 60 bar gauge pressure) steam in a waste heat boiler. Saturated steam from the boiler flows through a superheater to produce superheated steam, which is fed to a steam turbine generator to produce electricity.

Exhaust steam from the acid plant turbine is condensed, re-pressurized, and returned to the acid plant as boiler feed water. The turbine steam condenser ('surface' condenser) uses cooling water from an evaporative cooling tower. The evaporative cooling tower loses water through evaporation, drift (entrainment), and blowdown. A continuous supply of fresh water is required to make up for these losses.

Demineralized water is used as make-up for losses within the steam circuit (e.g., boiler blowdown and de-aerator vent) and for dilution water within the acid plant.

Operating parameters

Typical operating parameters for a 2000 t/d sulphur-burning acid plant are shown in Table I.

Table I. Typical 2000 t/d acid plant operating parameters

Parameter	Units	Value
Acid production (100% H_2SO_4 basis)	t/d	2,000
Sulphur consumption	t/d	660
Steam production (superheated)	t/h	110
Electricity generation (steam turbine)	MW_e	23
Electricity consumption	MW_e	5
Cooling requirements		
Main acid coolers	10^6 kJ/h	144
Product acid cooler	10^6 kJ/h	7
Turbine surface condenser	10^6 kJ/h	234
Other coolers	10^6 kJ/h	11
Nominal Cooling Duty	10^6 kJ/h	396
Design cooling duty*	10^6 kJ/h	468

* Design cooling duty includes an additional 72×10^6 kJ/h installed capacity for when the steam turbine is bypassed

Electricity generation

Steam produced by the acid plant can be:

- Used to generate electricity in a steam turbine generator
- Supplied to other plant consumers (e.g. heating for hydrometallurgical equipment)
- Exported to other customers
- Condensed.

Sulphur-burning acid plants produce more electricity than they consume when all of their steam is sent to a steam turbine generator. This excess electricity can be:

- Used to operate other facilities within the plant
- Sold to the market.

Water balance

The water balance for a conventional 2000 t/d sulphur-burning acid plant, based on evaporative cooling, is given in Table II.

The following can be noted:

- The single largest water loss is due to water evaporation in the cooling tower
- Other losses include drift and blowdown. The blowdown indicated is calculated based on three cycles of concentration, assuming fresh water has a total dissolved solids (TDS) of 300-400 ppm.

Table II. Sulphuric acid plant water balance

Inputs	Flow H_2O In (t/h)	Outputs	Flow H_2O Out (t/h)
Air moisture (to sulphur burner)	4	Steam de-aerator vent	2
Cooling tower make-up water	220	Water in product acid	1
Water to demin plant (for acid dilution)	24	Water converted to H_2SO_4 by reaction	15
		Cooling tower evaporation and drift loss	147
		Cooling tower blowdown	73
		Other effluent (steam system and demin plant)	10
Total inputs	248	**Total outputs**	248

Water saving options

Make-up water pre-treatment

Treatment of make-up water to the cooling tower can be used to change the water chemistry to achieve higher cycles of concentration, thereby reducing blowdown.

Softening

The cooling water make-up can be softened to remove several dissolved salts that cause scale formation such as calcium, magnesium, barium, strontium, and iron. Other scale-forming components, such as silica, are not removed.

A water softener has a vessel filled with cationic resin that exchanges (removes) the dissolved species from the water and replaces these removed species with sodium. Cooling systems fed with high-hardness water will benefit most from having the make-up water softened.

As an example, a water source with a feed hardness of approximately 300 mg/ℓ (expressed as $CaCO_3$), pH of approximately 8, and alkalinity of approximately 300 mg/ℓ as $CaCO_3$ might normally be concentrated three times; a cycles of concentration (COC) of 3. The scaling tendency of this water, at a COC of 3, is within the typical range that can be managed with a scale inhibitor. This same make-up water source could be concentrated more than seven times if first softened, representing a reduction in cooling water make-up of approximately 20%.

Filtration

Filtration can be used to remove suspended solids from water, and may be applied to either the entire acid plant fresh water make-up stream or to the cooling tower water recirculation stream. Filtration of the cooling circuit make-up water is generally considered where there is a high level of suspended solids in the feed. These solids, if not removed, can cause fouling within the cooling water circuit, which lowers cooling efficiency and increases the pressure drop through the piping system. The solids can also accelerate corrosion within the water circuit if they are an abrasive material. Unfiltered particles can serve as nucleation sites for biological growth. Filtration is required ahead of cooling water softening systems.

It should be noted that the majority of suspended solids within the cooling circuit are generated within the cooling circuit rather than introduced from the make-up water, as the cooling water is in contact with surrounding air in open-circuit evaporative cooling towers. Internal sources of solids include pipe corrosion products, biological growth material, and dust introduced from the air as it contacts the water in the cooling water tower. For this reason there is often more merit in filtering the cooling water itself rather than make-up water alone.

Demineralised water treatment

Demineralized water is used as make-up for losses within the steam circuit (e.g., boiler blowdown and de-aerator vent) and for dilution water within the acid plant. Typical demineralized water system configurations include:

- Reverse osmosis (RO) only
- Ion exchange (IX) with a decarbonator tower
- RO followed by polishing IX.

Waste generation as a percentage of feed is typically 30%. The selected configuration is dependent on the site raw water quality, and can be optimized to provide water savings. These savings, however, will be small compared to potential savings in the cooling system.

Cooling technologies

The following cooling technologies are discussed:

- Evaporative cooling towers
- Dry cooling technologies
- Hybrid cooling towers.

Evaporative cooling towers

Evaporative cooling tower designers have identified many ways to reduce the overall water losses from these systems. Some of these include:

- Optimizing water chemistry to reduce scaling, corrosion, and biological growth subsequently increasing the cycles of concentration and decreasing blowdown. This includes the use of automated chemical dosing systems
- Better operating procedures and equipment to monitor and control blowdown
- Use of high-efficiency drift eliminators and equipment to recapture drift
- Optimizing the selection and amount of fill inside the tower, which affects the heat transfer efficiency of the tower

- Automatic blowdown based on conductivity, to avoid unnecessary blowdown in cases where the feed water quality is better than initially anticipated
- Minimizing unintentional water losses from leaks or unintentional overflow (i.e. faulty level control resulting in addition of excess makeup water)
- Special tower design considerations to reduce particulates, debris, and cooling water exposure to sunlight.

(AP Tech Group, n.d.)

These advancements in cooling tower design and control have resulted in minor water savings. Fundamentally, the cooling is provided through the evaporation of water, and hence there is an inherent loss of water when adopting this technology.

Dry cooling technologies

Dry cooling technologies work by heat exchange to air and do not rely on the evaporation of water to provide cooling. Applicable technologies for a sulphur-burning acid plant include:

- Air-cooled condenser (ACC) on the steam turbine exhaust
- Fin-fan coolers to supply cooling water to the absorbing acid coolers.

<u>Air-cooled condenser (ACC)</u>

An ACC (Figure 1) comprised of finned tube bundles grouped together into modules and mounted in an A-frame configuration on a concrete or steel support structure. Steam from the turbine exhaust enters the top of the condenser via a steam duct and manifold. Steam flows downward within two or three rows of finned tubes. Condensate is recovered inside bonnet header boxers connected to a hot water tank. The axial-flow forced draft fan is fixed in the module and forces the atmospheric cooling air across the condensate area of the fin tubes.

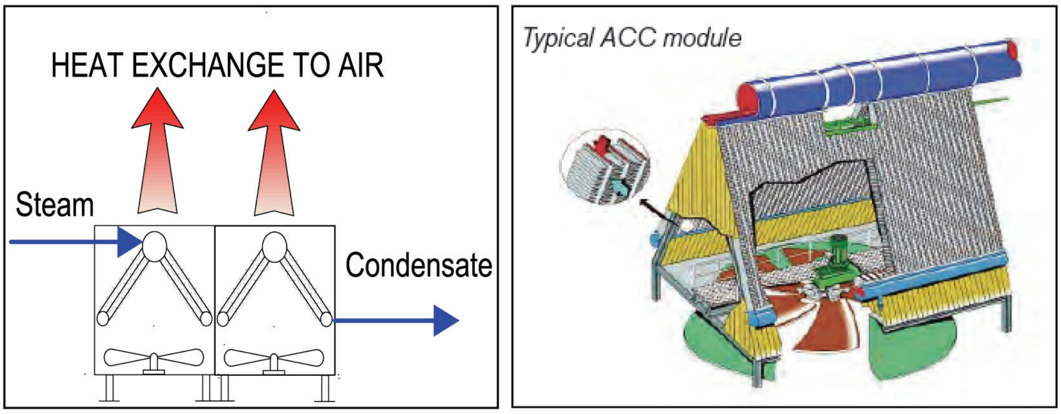

Figure 1. Air-cooled condenser ACC (SPX)

Dry cooling in an ACC requires a significant temperature difference to provide adequate heat exchange to the surrounding air. Typically, the cooling water supply temperature will be 25–30ºC higher than the ambient air temperature. This results in a higher condenser outlet temperature which in turn raises the condenser pressure, causing the steam turbine to operate less efficiently. An ACC can also be impacted by wind direction and speed as well as proximity to large buildings. More recent advancements in ACC technology include (Mortensen, 2011; Maulbetsch, DiFilippo, and Zammit, 2008):

- Wind guide vane technologies to mitigate wind impacts including walls, screens, lips, and louvers. CFD wind flow modelling is also used to optimize the location and arrangement of the ACCs
- Improved finned tube bundle designs for higher heat transfer efficiency and lower pressure drop
- The pre-cooled ACC, which uses the evaporative cooling effect of a fog spray into the upstream side of the ACC fans. The expected water consumption is approximately 75% less than an equivalent evaporative-only cooler. The advantage of this system is that it reduces air temperatures to the fans on very hot days.

The application of an ACC for cooling of turbine exhaust is widely adopted on many steam turbine systems. Eskom, the South African power utility, has adopted the largest ACCs currently in operation in the world for the Matimba, Kendal, and Majuba power stations (Eskom, 2010).

Fin-fan coolers

Fin-fan coolers (as depicted in Figure 2) include one or more bundles of finned tubes connected by headers with an air-moving device such as an axial fan located above (induced draught) or below (forced draught) the tube bundle. Cooling water flows within the tubes and heat is exchanged to ambient air. The fin-fan circuit uses demineralized-quality water and is closed-loop (not open to the atmosphere), eliminating the need for a continuous water supply.

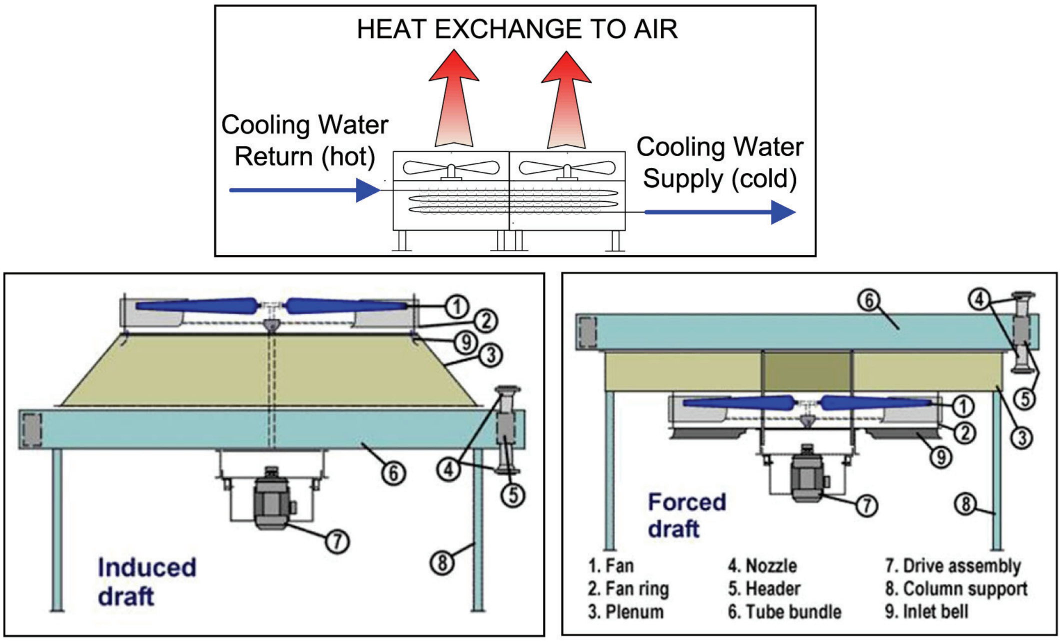

Figure 2. Fin-fan cooler (Wilson, 2011)

Fin-fan coolers require a significant temperature difference to provide adequate heat exchange to the surrounding air. Typically, the cooling water supply temperature will be 15ºC higher than the ambient air temperature. A fin-fan cooler can be used to provide cooling for the drying and absorption sections of an acid plant because the absorbing acid heat exchangers target approximately 70ºC. The product acid heat exchangers target 35–40°C, which cannot be consistently achieved using fin-fan coolers in most locations.

Hybrid cooling towers

Hybrid cooling towers have an air-to-air (dry cooling) section and evaporative cooling section operating in series. As shown in Figure 3, heated cooling water first passes through the dry section, where part of the heat load is removed by an air current, typically induced via fans. After passing the dry section, water is further cooled in the wet section of the tower, which can be cooled in a conventional open evaporative circuit or closed circuit (tubes are cooled with water on the outside).

The resulting heat transfer performance is similar to a wet cooling tower, with the advantage provided by a dry cooler of protecting the working fluid from environmental exposure and contamination. Depending on the hybrid tower configuration, the water consumption lies between those of the wet and dry circuit options reported in this evaluation.

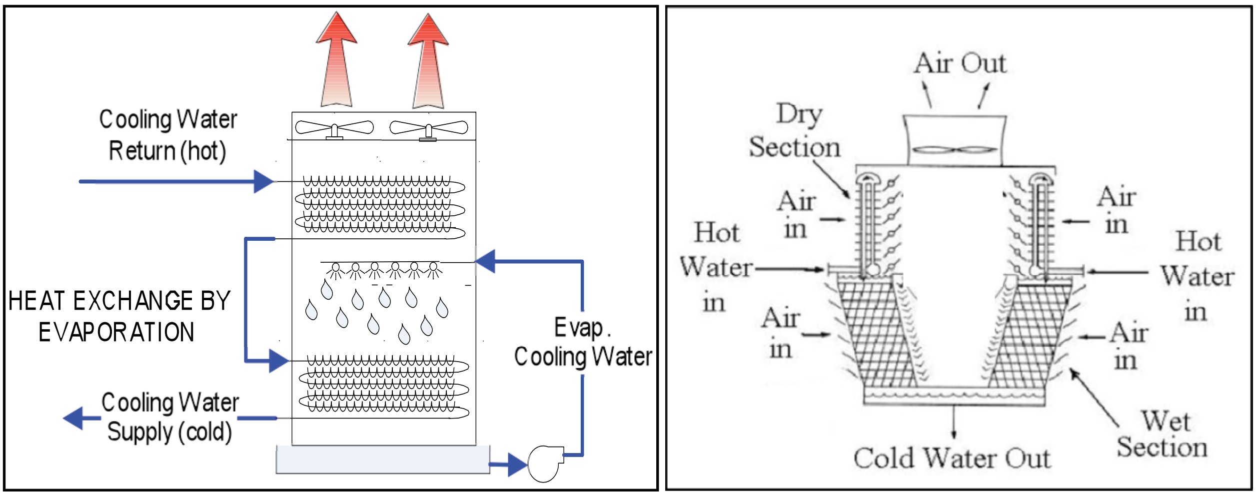

Figure 3. Hybrid cooler examples (adapted from EPRI, 2002)

Cooling technology and steam turbine electricity generation

The turbine exhaust cooling system performance directly affects the output of the steam turbine generator. The lower the condenser outlet temperature, the lower the condenser outlet pressure and turbine exhaust back-pressure. A lower turbine exhaust back-pressure increases turbine power output.

The impact of increasing ambient temperature (dry bulb temperature) on the turbine power output is shown in Figure 4, similar to the loss of electricity generation reported by others (US Department of Energy, 2008). It compares the base case (turbine surface condenser on evaporative cooling) to the turbine ACC option. For both options, the equipment is sized to remove the full heat load over the full ambient temperature range. As can be seen, with an ACC, the power generation is lower because an ACC runs at a higher temperature than a surface condenser.

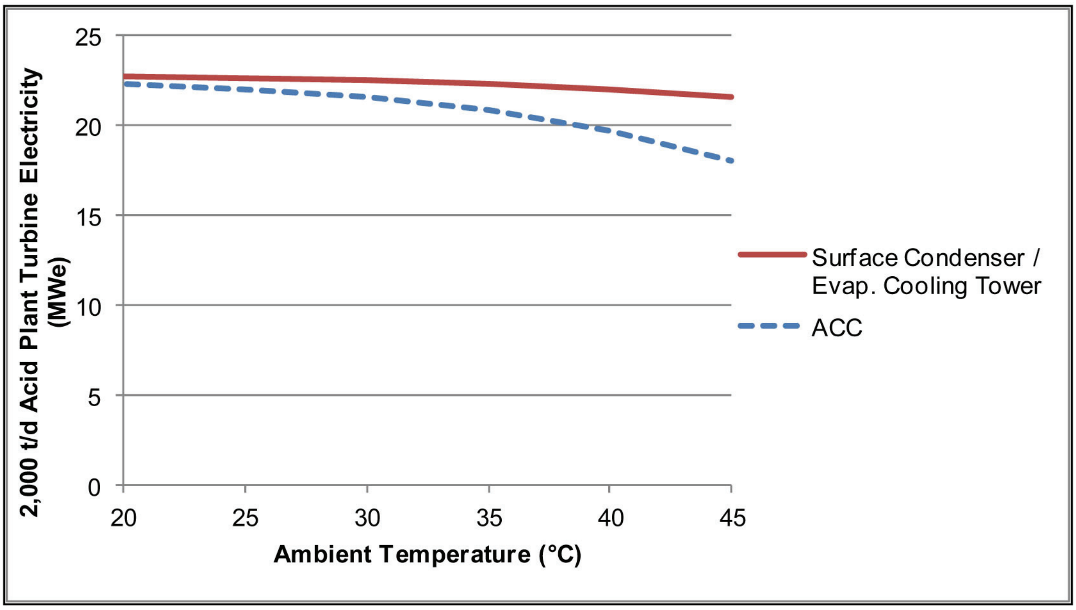

Figure 4. Impact of ambient temperature on turbine power output

Summary

The following cooling-circuit water-saving options were compared in this paper:

- Base case – evaporative cooling (no pre-treatment)
- Evaporative cooling (with pre-treatment)
- Dry cooling (no pre-treatment) with the following variants:
    - ACC on turbine exhaust

- ACC on turbine exhaust, and fin-fans on absorbing acid circuit.

These options are shown in the schematic in Figure 5.

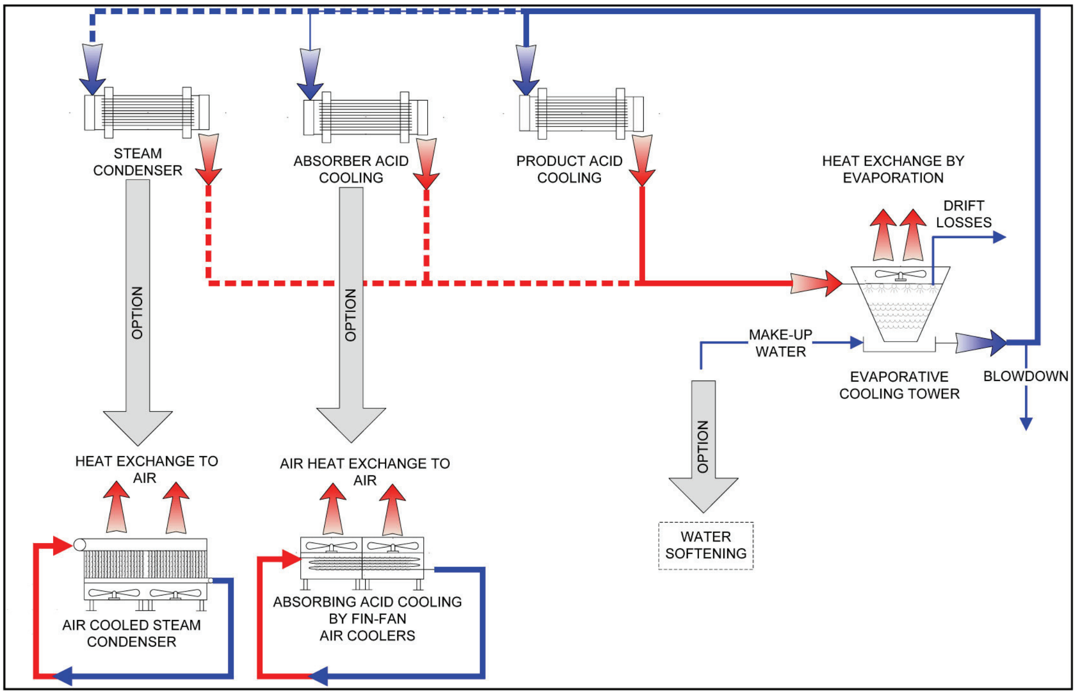

Figure 5. Water-saving options schematic

All options assume that steam is generated in the sulphur burner waste heat boiler and electricity is generated in a steam turbine generator. Where dry cooling options are considered, the balance of cooling is provided by evaporative cooling.

Table III summarizes the make-up water consumption and heat removal duties of the cooling circuit options.

Table III. Summary of cooling circuit options

Parameters	Units	Evaporative cooling		Dry cooling (no pre-treatment)	
		No pre-treatment	Pre-treatment included	ACC	ACC + fin-fan
Make-up water consumption					
Make-up water	t/h	220	172	86	7
Heat removal duty (nominal)					
Evaporative cooling tower	10^6 kJ/h	396	396	162	18
ACC	10^6 kJ/h	0	0	234	234
Fin-fan	10^6 kJ/h	0	0	0	144
Total (nominal)	10^6 kJ/h	**396**	**396**	**396**	**396**
Total (design)*	10^6 kJ/h	**468**	**468**	**468**	**468**

* Design cooling duty includes an additional 72×10^6 kJ/h capacity for when the steam turbine is bypassed

Evaluation of options

The Hatch 4QA approach compares the economic and sustainability impacts of alternative project options.

Economic impact

Order–of-magnitude capital and operating cost estimates were developed for each cooling system option and compared to the base case (evaporative cooling with no pre-treatment). A summary of the comparison is given in Table IV.

Table IV. Cooling system capital and operating cost comparison

	Base case		ACC	ACC + fin-fan
Cost parameters	No pre-treatment	With pre-treatment	No pre-treatment	No pre-treatment
CAPEX (relative to base case)	1.00	1.21	1.33	1.43
OPEX (relative to base case)	1.00	1.18	0.99	0.87

Sustainability impacts

Sulphur-burning acid plant emissions include:

- Gaseous emissions: sulphur dioxide, nitrogen oxides,, and acid mist in tail gas
- Liquid effluents: waste heat boiler and cooling circuit blowdown, demineralized water treatment plant waste, plant washings, spillages and leakages
- Solid effluent: sulphur filter cake residues and spent converter catalyst
- Noise pollution: main blower and turbine.

Commitments by major corporations as well as government regulatory requirements have resulted in the development of several new and cost-effective technologies to effectively reduce gaseous emissions from an acid plant. Noise pollution has been addressed with suitable sound reduction measures such as acoustic insulation, enclosures, and silencers.

The treatment and disposal of liquid and solid effluents is facing more stringent controls through public awareness and government regulations. Reduction in water consumption is potentially the greatest beneficial impact on the local communities and environment. Furthermore, a reduction in the cooling water blowdown will reduce the plant effluent and ultimately reduce the impact on the overall plant effluent catchment area.

Water, footprint, power, and waste

Four sustainability criteria were identified to quantitatively compare the different water-saving options, namely: water intensity, power intensity, waste intensity, and footprint. A comparison of these criteria is given in Table V.

Water and waste intensity are calculated from the mass balance; power and footprint values are estimated from recent project experience. The values shown are for the cooling system only and exclude the criteria associated with the remainder of the acid plant.

Table V. Sustainability criteria values for cooling system options

Sustainability criteria values		Base case		ACC	ACC + fin-fan
		No pre-treatment	With pre-treatment	No pre-treatment	No pre-treatment
Water intensity	m^3/t acid	2.6	2.3	1.0	0.1
Power intensity	kWh/t acid	36	38	44	48
Footprint intensity	m^2/t acid	10	12	18	23
Waste intensity	m^3/t acid	0.9	0.5	0.3	0.03

The following is noted with respect to each of the intensity factors:

- Water intensity:
  - Pre-treatment provides water savings when applied to the base case
  - Dry cooling options provide the lowest overall water consumption.
- Power intensity:
  - Evaporative cooling includes power to operate the cooling tower fans and the cooling water supply pumps
  - Base case with pre-treatment has a slightly higher power usage due to more pumping required between upfront unit operations
  - Dry cooling includes power to operate the fans only. Although electricity consumption is lower for dry cooling options, the power intensity shown in Table V is higher because it has been calculated taking into account a reduction of 1.5 MW_e in turbine power output.
- Footprint intensity:
  - The footprint of the base case with pre-treatment is comparable with the base case
  - Dry cooling options require a larger footprint for the same cooling duty.
- Waste intensity:
  - Evaporative cooling options generate more blowdown and therefore increased waste for effluent treatment
  - There is a large reduction in waste generated when pre-treatment is included ahead of the evaporative cooling tower.

Four Quadrant analysis

Hatch developed the Four Quadrant analysis (4QA) approach to compare project options using the economic and sustainability impacts. The 4QA tool plots each option compared to a base case:

- The x-axis is a cost ratio, with a lower cost ratio representing a lower cost option relative to the base case,
- The y-axis is a sustainability ratio, which compares the intensity of the option to the base case. A lower sustainability ratio is preferred, which indicates a lower impact on the environment.

The cost ratio (CR) is calculated for each option, relative to the base case (BC), using the following equation:

$$CR = \left(OPEX + \frac{[Annual\ Interest\ Rate\ (10\%) \times CAPEX]}{\left[1 - \left(1 + \frac{Annual\ Interest\ Rate\ (10\%)}{12}\right)^{-60}\right]} \right) \div BC \quad [1]$$

The CR is the sum of the annual operating cost and the annual capital cost repayments, based on a nominal 5 year repayment (compounded monthly). Any credits received for selling electricity to market have not been included into the evaluation.

The sustainability ratio (SR.) is calculated for each option, relative to the BC, using the following equation:

$$SR = \sum 40\% \left[\frac{Water}{BC}\right] + 15\% \left[\frac{Power}{BC}\right] + 20\% \left[\frac{Footprint}{BC}\right] + 25\% \left[\frac{Waste}{BC}\right] \quad [2]$$

The weightings can be adapted based on the general importance of each criterion. The weightings used in this evaluation (Table VI) have placed a high importance on water intensity, as many plants strive to reduce water consumption. The relative weightings will be site-specific; for example, in arid locations water impacts may be considered more important and footprint less important.

Table VI. Weightings of sustainability criteria

Sustainability criterion	Weighting
Water intensity	40%
Power intensity	15%
Footprint intensity	20%
Waste intensity	25%

The relative CR and SR of the water-saving options are shown in Table VII, and the 4QA plot in Figure 6.

Table VII. Sustainability and cost ratio Summary

	Base case		ACC	ACC + fin-fan
Ratio	No pre-treatment	With pre-treatment	No pre-treatment	No pre-treatment
Cost ratio	1.00	1.19	1.10	1.04
Sustainability ratio	1.00	0.87	0.77	0.67

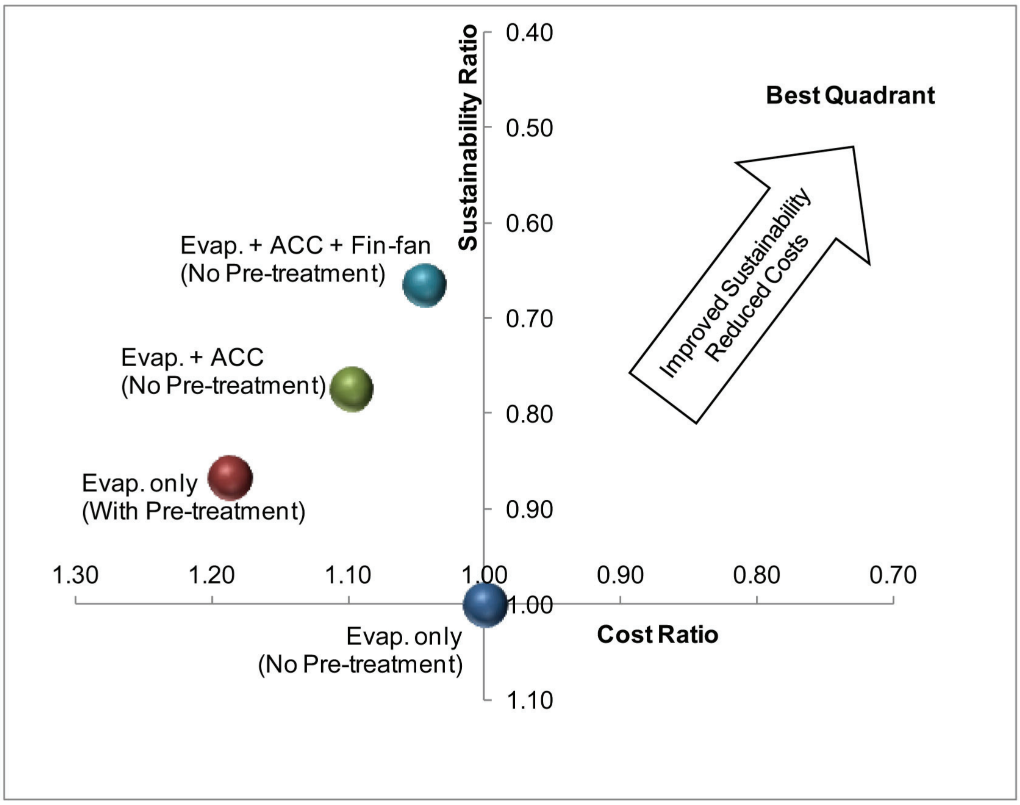

Figure 6. Hatch 4Q analyses (average fresh water and power cost)

The 4QA shows that for typical site locations:

- Base case with pre-treatment has a better sustainability ratio than the base case alone; however, the cost ratio will increase by 19%. This is due mainly to the high operating cost associated with reagent consumption for cationic resin regeneration. Alternative pre-treatment options with lower reagent usage and allowing increased cycles of concentration in the cooling tower can be investigated
- Dry cooling offers considerable improvements to the sustainability ratio, but the cost ratio will increase by 10% for ACC and 4% for ACC and fin-fan.

Sensitivity analysis

The cost and sustainability ratios can be affected by several factors, some of which are briefly considered in the following sensitivity analyses.

Water costs

Fresh water supply costs are location-dependant. The relative water supply costs used for this sensitivity are based on:

- Low water cost (US\$0.2 per m^3): typical for locally available water source of good quality (e.g. dam located close to plant) with no additional extraction charges
- Average water cost (US\$1.0 per m^3): typical for water sources located a reasonable distance from the plant, requiring minor infrastructure to be built and some minor water treatment on site (e.g. sand filtration)
- High water cost (US\$3.0 per m^3): typical for water sources located at a considerable distance or water of poor quality requiring significant treatment (e.g. reverse osmosis). High water cost could also apply to water that is local and of good quality, but with a high extraction charge.

Table VIII summarizes the cost ratios for the water cost sensitivity analyses. The sustainability ratios remain unchanged.

Table VIII. Cost ratios for water cost sensitivity

Cost sensitivity		Base case		ACC	ACC + fin-fan
		No pre-treatment	With pre-treatment	No pre-treatment	No pre-treatment
Low fresh water cost ratio	US\$0.2 per m^3	1.00	1.24	1.22	1.22
Average fresh water cost ratio	US\$1 per m^3	1.00	1.19	1.10	1.04
High fresh water cost ratio	US\$3 per m^3	1.00	1.10	0.91	0.77

The sensitivity analysis shows that:

- Reduced water costs (US\$0.2 per m^3) increase the cost ratio of dry cooling options, making them unfavourable compared to the base case
- Increased water costs (US\$3 per m^3) reduce the cost ratio of dry cooling options to less than the base case (by as much as 23%)
- This supports the general observation that as water extraction costs increase, dry cooling options are preferred
- The base case with pre-treatment has the highest overall cost ratio, which is in agreement with the data in with Table VII. At reduced water costs (US\$0.2 per m^3) the base case with pre-treatment compares well with the dry cooling options, but becomes the least favourable overall at increased water costs (US\$3 per m^3).

The 4QA was updated with the low and high water costs in Figure 7.

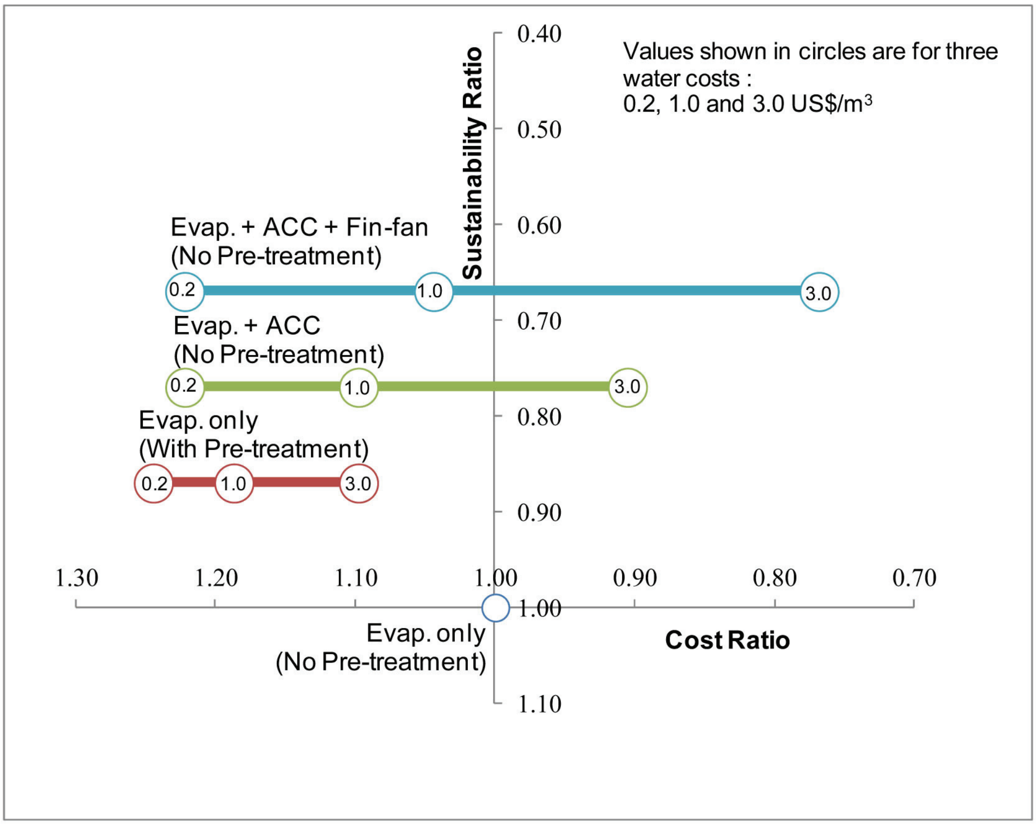

Figure 7. Hatch 4Q analyses for water cost sensitivity

Electricity costs

Electricity supply costs are also location-dependant. The relative electricity supply costs used for this sensitivity are based on:

- Low electricity cost (US$0.05 per kWh): for locations with abundant low cost electricity, e.g. hydroelectricity
- Average electricity cost (US$0.1 per kWh): for locations with a typical mixed electricity supply, e.g. a mix of coal, renewable, and gas-fired power stations
- High electricity cost (US$0.3 per kWh): for locations where electricity is generated on site, e.g. local diesel or gas-fired generators.

Table IX summarizes the cost ratios for the electricity cost sensitivity analyses.

Table IX. Cost ratios for electricity cost sensitivity

Cost sensitivity		Base case		ACC	ACC + fin-fan
		No pre-treatment	With pre-treatment	No pre-treatment	No pre-treatment
Low electricity cost ratio	US$0.05 per kWh	1.00	1.21	1.08	1.00
Average electricity cost ratio	US$0.1 per kWh	1.00	1.19	1.10	1.04
High electricity cost ratio	US$0.3 per kWh	1.00	1.13	1.13	1.14

The sensitivity analysis shows that:

- Lower electricity costs have a minor impact on the 4QA plot

- At increased electricity cost, the advantage of evaporative cooling is clear due to the increased turbine electricity output
- The base case with pre-treatment compares well with the dry cooling options at increased electricity costs; however, it becomes the least favourable at the lower electricity costs.

The 4QA was updated with the low and high electricity costs in Figure 8.

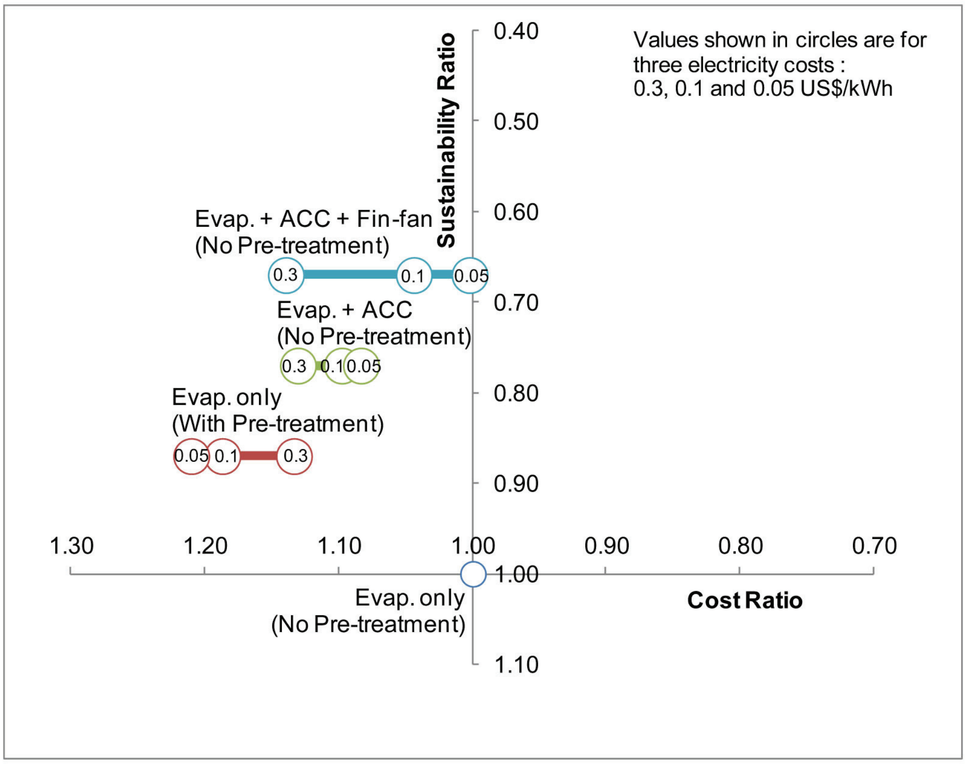

Figure 8. Hatch 4Q analyses for electricity cost sensitivity

<u>Sustainability criteria weightings</u>

The sustainability criteria weightings can be adjusted to suit the plant location and requirement for generating electricity, thereby impacting the sustainability ratio. As an example, the weightings can be adjusted as water or power becomes more or less important to the local community. Furthermore, additional sustainability criteria can be included, such as:

- Specific reagent consumption (e.g. high RO membrane costs)
- Downstream impact and stewardship (qualitative)
- Operability and maintainability (qualitative)
- Social, for example using local labour(qualitative)
- Government and externals (qualitative)
- Emissions (qualitative).

The 4QA approach is flexible and can be customized and adapted to meet specific project criteria.

Conclusions

The Hatch 4QA approach compares the economic and sustainability impacts of alternative project options. It can be used for technology and site selection from concept through to feasibility studies and beyond. The 4QA additionally serves as a risk management tool to quantify the impacts of varying sustainability criteria and input costs.

For the water savings options considered in this paper, it is the acid plant location that largely determines the sustainability and cost ratios. Key findings include:

- The cost ratio of evaporative cooling is generally lower, provided there is good quality and low- to medium-cost water available. The sustainability ratio is generally higher due to the high water consumption, which can make evaporative cooling unfavourable even at sites with low water costs (Maulbetsch, DiFilippo, and Zammit, 2008).

- The cost ratio of the base case with pre-treatment is the highest overall due to the high reagent usage. Optimizing the make-up water chemistry by adjusting the pH and adding scale inhibitors might be a more efficient way of increasing the cycles of concentration, but needs to be investigated on a case-by-case basis
- Reverse osmosis (RO) can also offer water savings, but this could be offset by the RO waste generation
- The sustainability ratio of the base case with pre-treatment is lower than without pre-treatment due to the decreased water usage
- Dry cooling options have a higher capital outlay, but can have lower operating costs in locations where water extraction costs are high. The sustainability ratio is generally lower for dry cooling, due to lower water consumption. and the power consumption is similar to evaporative cooling
- The acid plant electricity generating capacity is lower with dry cooling options and is decreased with higher ambient temperatures. For large acid plants generating electricity that is sold to market, this will adversely impact plant revenue.

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The Authors

Ross James Forzatti, *Senior Process Engineer*, Hatch Associates

11 years' experience in the non-ferrous industry across a range of pyrometallurgical and other processing facilities. Various roles held from lead process engineer to testwork lead, site engineer, and study manager. Site-based roles at Queensland Nickel, Kalgoorlie Nickel Smelter, and KCGM Gidji Roaster.

Process design for various hot and wet gas cleaning systems at all project levels from concept to detailed design:

- Sulphuric acid plant process design and infrastructure requirements.
- Debottlenecking studies for kiln, fluid bed, and furnace off-gas systems.
- Furnace, calciner, dryer, and roaster process design.
- Secondary off-gas system sampling and process design.

Ishani Natha, *Process Engineer*, Hatch Goba

Over 7 years' experience in the hydrometallurgical and minerals processing industries. Project assignments include numerous conceptual studies, feasibility studies, and EPCM assignments for such clients as Barrick, Anglo Platinum, Impala Platinum, Lonmin Platinum, Kumba Resources, Anglo American, and TFM among others.

Experience is in the engineering design and commissioning environment for the extraction of non-ferrous metals such as nickel, cobalt, copper, gold, and zinc, with exposure to project set-up, control, and management activities.

Lisa Roux, *Specialist Engineer*, Hatch Goba

Lisa is a process engineer with more than 10 years' experience in the production, commissioning, design, and test work environment of various hydrometallurgical and mineral processing projects. She recently completed her role as process lead for the Tenke Fungurume Mining (TFM) Phase II expansion execution phase, and she is currently wrapping up her role as process lead for TFM's new acid plant prefeasibility study.

Other relevant experience includes extensive exposure to copper and cobalt processing facilities. As plant metallurgist at Anglo Platinum's PMR refinery, she was part of the Capacity Increase Project commissioning team and assisted with commissioning of the new AuSX and RhDETA precipitation circuits.

Dylan Adrian van den Berg, *Process Engineer*, Hatch Associates

Dylan is a Chemical Engineer with more than 6 years experience in the design and engineering of various pyrometallurgical and hydrometallurgical facilities. He has developed specialist technical expertise in areas that include METSIM and IDEAS process modeling and mass and energy balance calculations, dynamic modeling, utilities and reagents design. As a process engineer he was involved on two significant base metal hydrometallurgical execution projects in Africa, namely the Kamoto Redevelopment Project in the D.R.C. and the TATI Activox Project in Botswana.

Following these projects, he was involved in several studies with unique effluent treatment plant designs, including acid plant blowdown treatment, for the KCGM Gidji site (including testwork supervision and coordination) and Anglo American Mortimer and Polokwane sites.