Recovery and repurposing of low-grade thermal resources in the mining and mineral processing industry

by

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Abstract

A substantial quantity of energy is currently lost as waste heat to the atmosphere in the mining and mineral processing industry. The recovery and application of this waste heat to on-site processes is an opportunity to reduce primary fuel usage, operational cost and environmental impacts. To investigate this, research has been conducted within a nickel smelter's sulphuric acid plant, where operational data was collected on a process water cooling loop that incorporates cooling tower systems. The cooling towers discharge in excess of 50 MW of heat without any recovery. Collected data was then used to develop a model to quantify the potential for low-grade heat recovery and repurposing within the sulphuric acid manufacturing process. Heat pumps were examined as a method to repurpose this waste heat, and use it to replace electric heaters currently used in the mist precipitators and weak acid stripper.

The model allows for an economic and environmental impact comparison between various recovery and application scenarios. Results obtained from the model indicated that the implementation of a heat pump system would provide a reduction in annual operating costs that allows a payback period of 3 years. Furthermore, there would be from less primary energy consumption a reduction in CO_2 emissions of about 42% from heat pump operation compared to electric heaters for the system. To further quantify environmental benefits from implementing the proposed recovery strategy, a comparative life-cycle assessment (LCA) model was also constructed and applied to the sulphuric acid plant. The LCA showed a 20% reduction in emissions in the cooling tower and heating system would be achieved from the impact categories of global warming, acidification, eutrophication, and human toxicity potentials. This includes emissions from cooling tower fans and water pumps, as well as the mist precipitator air heating.

The concepts and models can be applied to a wide range of energy intensive industrial sectors, to help identify and quantify reductions in consumption and improvements in long-term sustainability performance.

Keywords

Low-grade heat recovery, Heat pumps, Environmental sustainability, Mineral processing, Process cooling water, Cooling towers, Sulphuric acid production, Life-cycle assessment

Co-Authorship Statement

Shannon McLean developed both the heat recovery model and the life-cycle assessment model, as well as performed data analysis, investigation, and primary manuscript writing. Jeff Chenier provided information from the smelter site and sulphuric acid plant, as well as feedback on the heat recovery project and life-cycle assessment. Sari Muinonen contributed to funding acquisition and provided additional resources from the smelter site. Corey Laamanen provided manuscript revision and editing, as well as contributed to development of the heat recovery model. John Ashley Scott provided overall direction and supervision, as well as contributed to funding acquisition, manuscript writing, revision and editing.

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Nomenclature

Symbol	Description
α	thermal diffusivity (m^2/s)
A	area of surface (m^2)
A_1	area of interior surface exposed to convection (m^2)
A_2	area of exterior surface exposed to convection (m^2)
A_w	cross-sectional wetted area (m^2)
C	capital costs of heat pumps ($)
C_n	cash flow ($)
C_p	specific heat capacity (J/kgK)
CFM_1	initial air flow through cooling tower (CFM)
CFM_2	reduced air flow through cooling tower (CFM)
D	inner diameter of pipe (m)
E	Efficiency of pump
ε/D	relative pipe roughness
$\boldsymbol{f}$	Darcy friction factor
g	acceleration due to gravity (m/s^2)
h	heat transfer coefficient (W/m^2K)
h_1	heat transfer coefficient inside pipe (W/m^2K)
h_2	heat transfer coefficient outside pipe (W/m^2K)
h_L	head loss (m)
HC	capacity of single heat pump (kW)
Nu	Nusselt number
ρ	density (kg/m^3)
ΔP	change in pressure (Pa)
Pd	dynamic pressure in fluid flow (Pa)
Pr	Prandtl number
NPV	net present value ($)
q	heat transfer (W)
$\dot{q}$	heat transfer rate (W/s)
Q	volumetric flow rate (m^3/s)
$\dot{Q}$	heat flux (W/m^2)
r_1	inner radius of pipe (m)
r_2	outer radius of pipe (m)
r_3	outer radius of insulation (m)
R	thermal resistance (K/W)
Re	Reynolds number
RPM_1	initial fan speed (RPM)
RPM_2	reduced fan speed (RPM)
Δt	time interval (s)
ΔT	temperature change (K)
T_1	temperature of inner surface of pipe (K)
T_2	temperature of outer surface of pipe (K)

HP_1	initial fan power (HP)
HP_2	reduced fan power (HP)
i	hurdle rate
k	thermal conductivity (W/mK)
$k_{insulation}$	thermal conductivity of insulation (W/mK)
k_{pipe}	thermal conductivity of pipe (W/mK)
K_L	minor loss coefficient for pipe components
L	length of pipe (m)
L_e	equivalent length (m)
n	number of years
T_a	ambient air temperature (K)
T_{p1}	temperature of water at initial section of pipe (K)
T_{p2}	temperature of water at final section of pipe (K)
T_s	temperature of surface (K)
$T_{w,in}$	temperature of process water entering heat pump bank (K)
T_{water}	initial process water temperature leaving cooling towers (K)
μ	dynamic viscosity (Ns/m^2)
u	velocity of fluid flow (m/s)
ν	kinematic viscosity (m^2/s)
W_{pump}	pumping work (W)

List of Publications

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Chapter 1

Introduction

1.1 Background

There is a substantial amount of energy lost to the environment from industrial processes in the form of waste heat. Improving energy efficiency through recovery of this heat could be significant in improving both economic and environmental industrial performance. The mineral processing industry is a good example of a sector that presents an opportunity to recover waste heat and apply it to alternative uses, thereby improving the economic and environmental sustainability of the process.

Integrating the recovery and reuse of waste heat can lead to higher process efficiency and a reduction in primary fuel usage and resulting environmental impacts. However, finding a suitable application for any recovered energy depends on the operation, local climate, and significantly on the temperature of the waste heat source.

High-grade waste heat, referring to temperatures greater than 100°C, is regarded as more economically viable to recycle directly within a process as the energy does not usually need to be upgraded (Zhang et al., 2016). High-grade industrial waste heat can be captured and used for power generation by driving heat engine technologies, such as the Rankine or Kalina cycle (van de Bor et al., 2015).

Low-grade waste heat, below 100°C, is often not considered as economically viable to capture due to its low temperature and is consequently commonly rejected to the environment. However, it represents a significant untapped resource for many industries, in particular the heat contained with process cooling streams.

Heat pumps are now recognized as a solution for the recovery of low-grade heat in industry. Industrial heat pumps capture a heat input and use an external power source to upgrade it to a temperature that makes it useful for repurposing in applications, such as space heating. This carries significant potential for the mineral processing industry as substantial amounts of low-grade heat are generated and dissipated to atmosphere from process waters and off-gas streams. Recovery of this waste heat presents a significant opportunity to tackle sustainability issues in industry.

This thesis examines methods for the recovery and subsequent upgrading of thermally low-grade heat. Specifically, it uses as a model system a smelter's sulphuric acid plant, where sulphur dioxide emissions are captured from ore roasting. It is proposed that some of the 50 MW of waste heat currently dissipated to the environment from water cooling towers within the plant can be upgraded with a heat pump circuit to make it useful for repurposing on-site, whilst also reducing the heat load on the towers. The research includes development of a model that is capable of determining if the proposed heat recovery technique is economically viable, as well as a comparative life-cycle assessment (LCA) model that can assess environmental impacts associated with the reduction in net energy consumption in the process.

The research presents significant outcomes for energy intensive industrial sectors, including opportunities for improvement in economic and sustainability performance.

1.2 Thesis Objective

The objective of this thesis is to improve industrial sustainable operation through recovery and reuse of low-grade waste heat in process water streams, a resource commonly overlooked. The aim is to determine a technique that could be applied to recover low-grade industrial heat in an economical and sustainable manner.

The thesis is organized such that Chapter Two identifies and discusses various heat recovery and repurposing methods within the mining and mineral processing industry through a literature review. Chapters Three and Four present a heat recovery system modelled using data from the Sudbury Integrated Nickel Operations (a Glencore Company) smelter site, as well as a comparative life cycle assessment performed on the smelter's sulphuric acid plant. Whilst the research uses a sulphuric acid plant as a basis, the developed approach and models can be adapted to other energy intensive industrial sectors. The concepts can bring awareness to industries of the potential for low carbon emission heating applications through recovery techniques of low-grade waste heat.

Chapter 2

Recovery and Repurposing of Thermal Resources in the Mining and Mineral Processing Industry

2.1 Introduction

Industry as a whole accounts for around one third of the world's total energy consumption and about 36% of CO_2 emissions (Huang et al., 2017). The mining industry is responsible for 4-7% of total energy consumption (Holmberg et al., 2017) and despite an increase in the use of renewable energy, there is still heavy reliance on fossil fuels (Luo et al., 2017). In Canada, for example, CO_2 emissions released from the mining industry grew from about 22.5 Mt in 1990 to 74.5 Mt in 2016 (Natural Resources Canada, 2018). Energy preservation and management can be accomplished by cutting down on high energy consuming equipment and implementing more efficient technologies (Miah et al., 2015). Strides are also being made towards improving energy efficiency through the recovery and reuse of otherwise waste heat.

It has been estimated that of the total amount of energy consumed in industrial processes, up to 70% is lost as waste heat (Kermani et al., 2018), that is thermal energy that is not captured and is rejected into the environment (van de Bor et al., 2015).

Energy usage in mining and mineral processing operations is dominated by a few major processes, including ventilation pumping, comminution and smelting, all of which offer potential for energy recovery. Mine ventilation, for example, can account for up to 40% of a deep underground mine's total electricity consumption (Bluhm, 2008), an essential operation to bring fresh air underground and keep areas cool. While the smelting process is an extractive metallurgy technique, and involves the application of heat to extract metals from their ores (Singh, 2016). Pumping, particularly in large mining sites, uses significant quantities of energy, which is on average 25% to 32% of total motor energy (Norgate and Haque, 2010). Comminution (crushing and grinding) reduces the size of the ore to allow further processing to take place. Comminution contributes to approximately 40% of the total energy used in mineral processing (Department of the Environment and Energy, 2012). Much of the energy consumed by grinding practices is lost as heat to the ore, resulting in an energy efficiency process of only 1% (Norgate and Haque, 2010).

Operations, such as process cooling water and off-gasses, expel considerable amounts of unrecovered energy in the form of waste heat (van de Bor et al., 2015; Luo et al., 2017). Underground mining for example, has several energy intensive stages, including hauling, ventilation, and pumping and dewatering (Norgate and Haque, 2010), with little or none of the generated heat captured. In mineral processing, 20-50% of the primary energy is lost as waste heat (Johnson et al., 2008). It is proposed, therefore, that the industry could benefit significantly from recovery and repurposing of its waste to offset primary energy purchases in order to enhance overall sustainability.

Whilst advancement in technologies and improvement of equipment to reach higher efficiencies can limit the release of waste heat and improve industrial sustainable development, studies have shown that one of the most effective ways to improve energy efficiency without major equipment or facility alterations is through waste heat recovery (O’Rielly and Jeswiet, 2015).

The recycled energy can, for example, be used to power auxiliary equipment, generate steam, or deliver space heating and cooling (O'Rielly and Jeswiet, 2015).

In general, waste heat can be classified as either low or high-grade. High-grade waste heat is at a temperatures greater than 100°C, and is often used to generate steam or recycled directly back into a process (Zhang et al., 2016). High-grade waste heat can be also captured and used for power generation by driving heat engines, such as those that use the Rankine cycle (van de Bor et al., 2015). Low-grade waste heat is, therefore, typically considered to have a temperature below 100°C. Temperatures between 70 and 100°C may be upgraded by adding energy to raise the temperature to allow for beneficial repurposing, such as steam generation (Guo et al., 2015; Bao et al., 2016). However, at temperatures below 70°C, currently little of this low-grade waste heat is recovered in the mining industry.

Error! Reference source not found. summarizes methods to recover various waste heat sources present in mining and mineral processing industry, as well as potential applications for the recovered energy. This review focuses on these various sources of waste heat and the recovery practices and technologies that could be implemented.

Table 1: Summary of waste heat recovery methods and potential applications

Waste Heat Source	**Heat Recovered (MW)**	**Recovery Method**	**Potential Application**	**Stage of Recovery Method**
Mine ventilation exhaust	9-11 (Xiong et al., 2015; Obracaj and Sas, 2018)	Direct spray recovery with heat pump (Xiong et al., 2015)	Ventilation preheating (Holmlund, 2015)	Potential recovery method

		Heat exchangers (Sbarba et al., 2012)	Space heating (Sbarba et al., 2012)	
Mine dewatering	1-5 (Bailey et al., 2016)	Heat pumps (Hall et al., 2011)	Space heating (Hall et al., 2011; Farr et al., 2016)	Implemented in industry
Electric Arc Furnace cooling water	10-60 (G Nardin et al., 2018)	Heat exchangers (Keplinger et al., 2018a) Steam generators (Keplinger et al., 2018a)	Electricity generation (Keplinger et al., 2018b) Steam (Keplinger et al., 2018b)	Potential recovery method
Off-gas	60 (Loken, 2013)	Organic Rankine Cycle (Lecompte et al., 2017) Bubbled-in off-gas (Laamanen et al., 2014)	Electricity generation (Lecompte et al., 2017) Microalgae cultivation (Laamanen et al., 2014)	Implemented in industry
Slag recovery	9-20 (Warhurst and Noronha, 1999; Xie et al., 2007)	Mechanical crushing with heat pump recovery (Zhang et al., 2013) Centrifugal and air blast granulation using fluidized bed recovery (Zhang et al., 2013) Packed-bed heat exchanger (Xie et al., 2007)	Preheating air of ore dryers (Rodd et al., 2010) Reheating boiler feed water (Rodd et al., 2010) Electricity or steam generation (Motz et al., 2015) Combustion air preheating (Motz et al., 2015)	Potential recovery method
Smelter process cooling water	40 (Ross, 2016)	Heat pumps (Ross, 2016)	Space heating (Ross, 2016) Steam production (Institute for	Potential recovery method

Industrial Productivity, 2012a)

2.2 Underground Mining Operations

Mining is classified into surface and underground operations, depending on location, size, depth and grade of the deposit (Norgate and Haque, 2010). Surface mining operations do not utilize heating, ventilation and air conditioning (HVAC), which accounts for over 25% of underground mine energy consumption (Jeswiet and Szekeres, 2016). Underground mining also requires more energy to cope with extended requirements for hauling and dewatering (Norgate and Haque, 2010). As a consequence, the focus here is on heat recovery from underground mines.

Mine Water

The need for dewatering in both operating and closed mines presents a promising opportunity for geothermal energy recovery. Mine dewatering usually consists of pumping water from a series of wells within the mine to the surface. Dewatering is important, as water levels must be continuously managed to ensure stability of mine walls and to prevent flooding. Unwanted water can enter a mine from surface accumulations, aquifers, bed separation cavities, solution cavities and old mine workings (Hall et al., 2011). Extracting heat from deep underground is beneficial due to geothermal gradients and large water-rock interfaces resulting in a transfer of heat to the water (Bailey et al., 2016). The application of geothermal heat pumps can allow for low-grade thermal energy from warm mine water to be used in a variety of space heating and cooling applications (Farr et al., 2016).

Heat pumps use external energy (typically electricity) to upgrade heat to a higher temperature. In a compression heat pump, low temperature heat is absorbed in an evaporator and the vapor is then compressed, resulting in rejection of heat at an elevated temperature in a condenser, illustrated in Fig. 1. Heat is recovered from the condensed fluid, which in turn is expanded and the cycle repeats (Miah et al., 2015). The upgraded temperature can be useful for repurposing in applications.

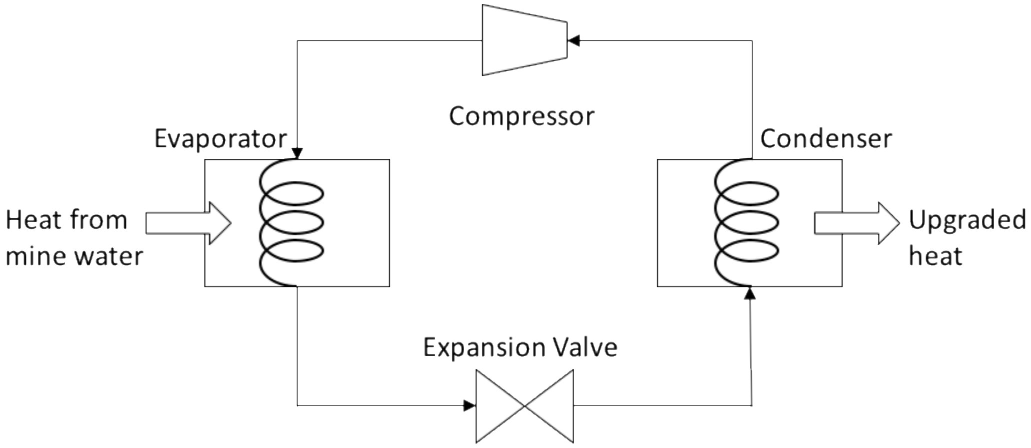

Fig. 1: Heat pump principle in mine dewatering application (adapted from (Ninikas et al., 2014))

Chemical heat pump technologies are emerging for more effective extraction and repurposing of thermal energy. They are driven by reversible chemical reactions and are an environmentally low impact method (Ogura, 2002). The capacity of the system for storage along with the ability to efficiently upgrade thermal energy and deliver it at high temperatures of more than 200°C makes it a beneficial solution for low-grade heat recovery (Wendt et al., 2013).

Additionally, after an underground mine is closed, continuous dewatering practices are usually scaled down or ceased, and water levels may rise until the mine is flooded. As a consequence, abandoned mines can still provide a resource for geothermal energy recovery (Wendt et al., 2013; Loredo et al., 2016). It has been estimated that there are over one million abandoned mines worldwide, with approximately 3000 MW of heat energy remaining untapped in the water within flooded coalfields of Europe alone (Bailey et al., 2016).

Pumping water from abandoned mines may require a significant amount of electricity, and may become too costly, but there are sites where gravity assists in the discharge of water, or pumping is already required for maintenance of abandoned mines (Bailey et al., 2016). In some locations, pumping and treatment facilities are installed to control water levels, as well as treat the water to the extent necessary to make it safe for release to the environment. The treatment technology depends on the characteristics of the mine water, but may include chemical precipitation, membrane applications, and/or biological treatment (Stantec, 2017). As the energy demand of a treatment facility may be very high, particularly due to large pumping requirements, it presents an opportunity for a heat recovery application to off-set costs (Bailey et al., 2016).

Heat pump technology is currently used in many low-grade heat recovery systems for mines. For example, in Great Britain, the escape of contaminated water into the environment from abandoned coal mines is being addressed by the Coal Authority and they have installed 64 treatment systems (Bailey et al., 2016). A study was undertaken that analyzed 21 of these treatment sites, and compared electrical power consumption and thermal power potential (Bailey et al., 2016). The total low-grade thermal energy of all the mine waters considered was 47.5 MW. Many of the mines that required large power consuming treatment facilities also provided the greatest heat resources due to deep mine waters. For example, for a mine in Durham, England with groundwater temperatures around 15°C, it was found that a temperature drop of 4°C could achieve 4.85 MW of recoverable energy. Whilst at another mine in England, a temperature drop of 4°C could achieve 806 kWt of recoverable energy. A gravity fed treatment system with water temperatures around 14°C at Morlais in South Wales was found to offer around 2.90 MW of recoverable thermal energy by reducing the temperature of its water flow by 4°C (Bailey et al., 2016)

It has been proposed that the application of heat pumps would be a feasible option to capture this otherwise waste heat at high efficiencies. In Shettleston, Scotland, a system was installed to recover energy from water in flooded coal mines at a depth of 100 m (Hall et al., 2011). Two heat pumps were used to provide space heating by heating the water to 55°C before storing it in a tank for subsequent distribution to 16 nearby houses. In Heerlen, Netherlands, a geothermal district heating system has been implemented by repurposing thermal energy from several mine shafts in a flooded abandoned coal mine. The system, which provides district heating and cooling to over 350 homes and businesses, was achieved by drilling five wells 700 m deep around the town in order to access underground mine shafts (SKRC, 2008). The wells are able to pump nearly 80 m^3 of water per hour at temperatures between 15°C and 30°C (Hiddes et al., 2014), and a heat pump is used at the surface to extract and generate heat at an average of 28°C (SKRC, 2008).

A heat recovery project in Nova Scotia, Canada was carried out by a plastic packaging manufacturer, which involved the instalment of ground source heat pumps to take advantage of otherwise waste heat in flood water from abandoned coal mines (MacAskill and Power, 2015).

At a water temperature of 18°C, an initial projection found energy savings as high as 70% could be achieved (Jessop et al., 1995). The water was pumped from 140 m below surface, extracting heat and lowering the mine water temperature down to 13°C. Eleven heat pumps were installed to provide hot water heating at the plastics plant, at a rated capacity of 985 kWh/day (Jessop et al., 1995). The capital cost to implement the heat pump system was $110,000, as opposed to $70,000 for the alternative propane heating system (Jessop et al., 1995). However, operating costs of the heat pump system provided annual savings of approximately $45,000 (Koufos, 2011).

A geothermal heat recovery system was implemented in the city of Asturias, Spain, at an abandoned coal mine near the University of Oviedo (Peralta Ramos et al., 2015). The heat from the flooded mine water is recovered using four geothermal heat pumps to provide water heating at a temperature of 46°C to two of the university buildings, as well as to a nearby hospital. At an average water flow of 215 m^3/h, the recovery system reduces the temperature of the mine water from 23°C to 13.9°C, allowing for a total annual energy saving of approximately 73% and an annual CO_2 reduction of 39%.

Other types of mines can be also considered, such as the abandoned Wheal Jane tin mine in Cornwall, England, which after flooding began to leak water into the environment. A treatment system was installed at to control mine water discharges and involved pumping water from the shaft and treating it with lime. When the treatment facility was eventually discontinued in 1992, the mine had released 50,000 m^3 of water with an average metal concentration of 3500 mg/L to the surrounding environment (Hall et al., 2011). It has been proposed that this would have been a prime opportunity to install a heat recovery system and continue long-term monitoring and treatment of the mine water (Hall et al., 2011). A copper, zinc and sulphur mine in Norway that closed in 1941 established a heat recovery system from the water of the abandoned mine (Banks et al., 2004). A heat pump was installed to provide space heating for an underground cavern which is used by the community for various events.

Geothermal heat pumps typically have high initial investment costs due to connections underground, including drilling, piping and excavation (Ghoreishi-Madiseh and Kuyuk, 2017), costs that can largely be avoided if utilizing an abandoned flooded mine. Con mine, an abandoned gold mine in Yellowknife, Canada is a prospective geothermal heat source for the city based on a preliminary study on the potential to recover low-grade heat for space heating (Thompson, 2010). Of the total energy consumed by the community, approximately 70% is for space heating, resulting in about 277,000 tonnes of greenhouse gas emissions annually (Ghomshei, 2007). The study focused on possible technologies to recover heat, as well as approximate costs and payback periods using an example of a 300 kW heat demand (Ghomshei, 2007). Heat pumps were found to be a potential solution for heat recovery from mine water 400 m below surface (Thompson, 2010). The temperature would be upgraded from 35°C to about 45°C, with a total power requirement of 90 kW (Ghomshei, 2007). The net annual savings were projected to be $95,000 for the project, with a payback period of less than 8 years (Ghomshei, 2007). The study demonstrates the economic feasibility of heat pumps over time, as they typically have a higher initial capital cost compared to other heating systems, but lower operating costs.

Mine Ventilation Exhaust

Through heat transfer from the host rock, geothermal heat is a large contributor to the air temperature of deep mines and the necessary air conditioning and ventilation requirements create a high-energy demand. Exhausted mine ventilation air temperature is typically around 30°C, with the relative humidity being about 90% (Xiong et al., 2015), and in many cases this heat is released to the atmosphere at temperatures higher than ambient (Sbarba et al., 2012). A ventilations system's wet airflow carries, therefore, a significant quantity of latent heat that could be available for energy recovery and reuse (Xiong et al., 2015). Waste heat can be extracted from this exhaust air using a medium such as water or glycol, and used for underground ventilation inflow heating or directed to an alternative application, such as space heating of nearby buildings (Sbarba et al., 2012).

For mines located in cold climates, heating the air intake can also contribute significantly to the overall cost of operation. The 700 m deep Kylylahti copper mine in Finland, to prevent shafts and equipment from freezing, requires heating the supply ventilation air to approximately 3°C during months when ambient temperature ranges between 0°C to -15°C (Holmlund, 2015). The heating system is currently achieved with two gas burners, but with the supply airshaft and the return airshaft only 30 m apart, this provides an opportunity to exchange heat between the two airflows.

A laboratory experiment in China analysed the combination of a direct spray recovery unit with a heat pump system for extraction of low-grade energy from air mine exhaust (Xiong et al., 2015). A multi-stage reverse spray heat exchanger was used, where water is sprayed in the opposite direction of the airflow in multiple stages to improve heat transfer efficiency. This allowed the temperature of spray water to increase from 7°C to about 15°C. A heat pump was subsequently used to extract this heat, with the cooled water returned back to the spray tower. The average exhaust ventilation air temperature and humidity at the surface during cold months are parameters that need to be taken into account to calculate heat recovery potential (Sbarba et al., 2012). A heat pump is an efficient option, since the temperature and humidity of the exhaust air remains fairly constant.

In one of the experiments, 3.47 kg/s of cold water recovered heat at 119 kJ/s from 3.52 kg/s of air when the spray coefficient was 0.9. The results showed that the heat exchange efficiency could reach over 85%. This investigation led to the prediction that application to a mine with an air flow rate of about $7.2x10^5$ m^3/h and using 759 m^3/h of cold water could recover about 11 MW.

2.3 Mineral Processing Off-gas

Electric Arc Furnaces

The production of steel is often accomplished with the use of an electric arc furnace (EAF) (Gandt et al., 2016), a technology, which in comparison to a blast furnace, produces less waste and has a lower energy consumption per ton of steel (Kolagar et al., 2016). Electric arc furnaces consume electrical energy and fuels, such as natural gas, to melt and convert solid materials, such as iron scraps, into molten steel, which is then further refined to produce high-grade steel (Institute for Industrial Productivity, 2012b). Nevertheless, the iron and steel industry is one of the largest polluters of the industrial sector (Keplinger et al., 2018a), contributing approximately 4% of total global greenhouse gas emissions (Kolagar et al., 2016).

The amount of energy required by an EAF to melt scrap iron is 350 to 370 kWh/t_{steel} (Institute for Industrial Productivity, 2012b), a process that releases large amounts of waste heat in an off-gas that is typically around 1250°C and with flow rates of up to 150,000 Nm^3/h (Keplinger et al., 2018b). It is estimated that up to 50% of all energy losses and nearly 30% of the energy input is lost in the off-gas from EAFs (Gandt et al., 2016). Heat recovery from EAFs in the steel industry could, therefore, significantly improve process efficiency, and reduce costs and greenhouse gas emissions.

The Organic Rankine Cycle (ORC) is a technology that can be used to recover high-grade heat from an EAF for use in power generation. In 2013, The ORC production company Turboden successfully implemented a heat recovery system from the off-gas of a 133 t/h EAF used in an iron and steel manufacturing in Riesa, Germany (Lecompte et al., 2017). From an off-gas temperature of 1600°C, the ORC unit used in the design allowed for 3 MW of electrical output, resulting in a payback period of approximately five years.

Off-gases from EAFs must be cooled before they can enter the de-dusting (dust collection) stage. Typically, they are cooled inside a water-cooled hot gas duct to reduce temperature to the maximum allowable for the dust collectors, about 600°C, with the removed heat dissipated to the environment (Keplinger et al., 2018a). This has been, therefore, an area of particular interest for heat recovery and application research, as the dissipated low-grade energy could be used by a number of process technologies within the steel production plant. For example, waste heat recovered from an EAF could be used for electric energy generation, steam production, or scrap metal preheating before the melting process (Keplinger et al., 2018b).

Energy can be recovered and repurposed at the gas cooling phase through steam generation for use in processes such as shop and office heating, as well as in mills for jacket heating of pickling tanks and fuel oil lines (Bramfoot et al., 1983). Steam can be also used for electricity generation using steam turbines (Thekdi et al., 2015). In steam generation, an evaporative cooling system can be installed at the de-dusting system of the EAF and steam generated as water evaporates during the cooling process (Gandt et al., 2016).

A study was performed on a 145-ton EAF (Gandt et al., 2016) to determine the effectiveness of an evaporative cooling system integrated in the cooling water circuit of the de-dusting system at various water pressures. It was found that when the pressure of the boiling water was at an optimal 1 MPa, the amount of steam produced from the heat discharged in the gas was 25.3-28.8 tonnes per 145 tonne batch, with a total exergy of 20-23 GJ.

A waste heat recovery model for steam production from a steel plant was developed in order to find optimized operating parameters (Keplinger et al., 2018a). In the model, waste heat was recovered from an EAF used to melt steel scrap and produce molten steel, and the recovery system included heat exchangers, steam generators and a thermocline storage tank. The off-gas was to be cooled to 600°C from a peak temperature of 1200°C using cooling water. The cooling water outlet temperature was around 50°C, but was increased to 200°C in the model to directly recover heat by producing saturated steam in a shell and tube steam generator. An alternative heat recovery option that utilized heat pumps to upgrade this stream temperature was also considered. The mass flow of cooling water inside the cooling system was controlled using a circulation pump to deliver a minimum mass flow of cooling water in the hot gas line and ensure efficient heat transfer. It was determined from this study that stable and continuous operation was achievable with this approach.

Smelters

Industrial waste heat recovery from a smelter can provide the necessary conditions required to grow and maintain microalgae year-round in cold regions (Laamanen et al., 2014), with the lipids they produce a potential biodiesel feedstock (Slade and Bauen, 2013). Due to its relatively clean-burning characteristics, biodiesel can be especially useful in underground mine applications (Cherubini et al., 2009; Ross, 2016).

However, the mass production of microalgae is traditionally not possible in temperatures that drop below 15°C, and, therefore, previously found to be practical only in year-round warm climates (Laamanen et al., 2014; van Esbroeck, 2018). To resolve this issue for cold climates where many mining and mineral processing operations exist, employing waste heat from a nickel smelter site to support algal growth tanks has been investigated (Loken, 2013). The two major sources of waste heat identified were off-gas streams from the fluidized bed roasters and the furnace. The roaster off-gas undergoes on-site gas cooling from 680°C to 50°C to allow capture of SO_2 by production of sulfuric acid. Whilst the off-gas from the furnace is released at a temperature of approximately 350°C (Laamanen et al., 2014). The off-gas streams represent a combined 60 MW of waste heat dissipated into the environment without any recovery (Loken, 2013).

A study modelled the impact on algal pond temperature from direct bubbled-in off-gas from the furnace and heat recovered by a heat exchanger from the roaster off-gas (Laamanen et al., 2014). The results showed that significant microalgae cultivation could be achieved year-round, even when ambient air temperatures fall well below 0°C.

2.4 Slag Waste Heat

The slag from smelter furnaces represents a substantial amount of “stored” energy, which is lost during solidification. It is estimated that over 40% of the energy supplied to a smelter furnace remains in the slag, with 1-2 GJ of thermal energy contained within one ton (Rycroft, 2014; Motz et al., 2015). Slag has potential commercial value after proper cooling and treatment (Das et al., 2007; Chen et al., 2010), and it is during this process that waste heat recovery can be achieved (Zhu et al., 2018). For example, blast-furnace slags can be used as a feedstock in the manufacturing of cement, with slag being approximately 13% of world cement production (Allen, 2018; Zuo et al., 2018).

Traditionally, solidification was achieved through water quenching, with large volumes of water used to rapidly cool molten slags (Zhang et al., 2013; Duan et al., 2018). In this technique, molten slag at a temperature of around 1500°C may be cooled to around 50°C using a high velocity water stream (van Laar et al., 2014; Duan et al., 2018). The water used in this process is recycled and cooled to less than 50°C, typically by using cooling towers (van Laar et al., 2014).

One of the major drawbacks of this technique is difficulty in achieving heat recovery using direct application methods such as heat exchangers, due to the large heat loss through evaporation whilst cooling the slag (Yu et al., 2016; McDonald and Werner, 2017). In addition, low-grade heat is released from the cooling towers to the environment without being recovered (McDonald and Werner, 2017). However, this could provide an opportunity for the application of heat pumps to upgrade this low-grade waste heat, allowing for the implementation of a heat recovery system.

With modern slag solidification methods, heat recovery systems that allow for cooling requirements to be achieved are becoming more common. These include the production of steam or hot water for power generation and other industrial processes, or heating the air of ore dryers (Bisio, 1997; Sun et al., 2015). The recovered energy can be also incorporated back into the furnace process by preheating combustion air (Motz et al., 2015).

A study using both laboratory-scale and pilot-scale experiments evaluated a heat recovery system using a packed bed of hot slag plates (Shigaki et al., 2015). The molten slag was solidified in the shape of a plate using water-cooled rolls, and then used in a packed slag chamber where heat exchange took place with a counter-current gas flow. The slag temperature in the pilot-scale test was around 1100°C, and the maximum gas temperature measured was 716°C (Shigaki et al., 2015). From this it was determined that the heat recovery ratio relative to the total heat of the molten slag was 43% (Shigaki et al., 2015).

Dry solidification of slag is currently being developed as it offers potential for an efficient solidification process whilst also providing the opportunity for heat recovery (Motz et al., 2015). The process involves breaking up liquid slag into droplets that are passed through a dry cooling stage, where heat can be recovered as they solidify into granules (Rycroft, 2014). Using air blast or centrifugal granulation methods in the dry cooling stage, heat is transferred from the droplets to air (Zhang et al., 2013; Duan et al., 2014; Rycroft, 2014). Further heat recovery can be achieved as the solid granules are further air cooled, often with a fluidized bed (Rycroft, 2014; Motz et al., 2015).

Early dry granulation techniques involved mechanical crushing with rotating drums (Zhang et al., 2013) and then transferring the broken slag to a cooling chamber where heat exchange could take place with air (Zhang et al., 2013). However, processing methods such as this typically only allow for low-grade heat to be recovered, wasting a large amount of the thermal content in the slag (Rodd et al., 2010). Heat recovery from mechanical crushing could, therefore, be an opportunity to apply heat pumps to upgrade the thermal energy to a useful temperature.

New technologies are being investigated to allow for recovery at higher temperatures, of which rotating cup granulation is a leading centrifugal method (Zhang et al., 2013; Zhu et al., 2018). This involves liquid slag being poured into a high-speed rotating cup, which forms droplets that cool as they are ejected outwards. The process produces hot air, typically in the range of 200-300°C, which is passed through an exchanger to recover the heat, and can be used for combustion air preheating or to produce steam or electricity (Rycroft, 2014; Motz et al., 2015). In a commercial trial carried out in Britain, it was found that 59% of the slag heat could be recovered when slag particles were cooled to 250°C from an initial slag temperature of around 1500°C (Zhang et al., 2013; Rycroft, 2014).

Another option is an air blast process, where the molten slag comes into contact with gas traveling at high speed and pressure, resulting in the slag breaking up into small particles (Rycroft, 2014). This process again uses a fluidized bed to remove heat from the solid granules. A heat recovery system was adapted to a laterite nickel rotary kiln electric furnace plant in Canada, where slag was granulated using a high velocity air jet inside a waste heat boiler to produce granules (Rodd et al., 2010). The granules were cooled by radiation to water-cooled boiler walls and by convection to the granulation air. Heat application methods were established to integrate the recovered energy into the smelter, including preheating air at the ore dryers, reheating boiler feed water, and electricity generation. From this study, it was determined that the heat recovery system could provide up to 25-30% of the total electrical requirements of the rotary kiln electric furnace, as well as reduce CO_2 emissions by 234,000 tonnes per year (Rodd et al., 2010).

A dry granulation heat recovery technique was developed to recover high-grade heat from molten slag (Xie et al., 2007). Slag droplets were formed in a dry granulator process, which were cooled to produce glassy granules at a temperature of about 900°C. These granules were transferred to a packed-bed heat exchanger to allow for heat recovery from the slag. It was found that the system could allow for approximately 80% of the heat to be recovered to produce hot air or steam at temperatures above 600°C, which could be used in drying and preheating applications.

The challenges associated with employing various slag solidification methods are demonstrated in **Error! Reference source not found.**.

Table 2: Comparison of various slag solidification methods

Slag Solidification Method	Advantages	Disadvantages
Water quenching	Produces a glassy slag suitable for cement industry (Xie et al., 2007) Efficient cooling of high temperature slag (Sun et al., 2014) Reduced greenhouse gas emissions compared to cement production from limestone (Xie et al., 2007) Suitable for large-scale applications (Xie et al., 2007)	Difficult to achieve heat recovery (Yu et al., 2016; McDonald and Werner, 2017) High water consumption (Yu et al., 2016) Air pollution (SO_2 and H_2S emissions) (Sun et al., 2014) High energy consumption with additional drying requirements (Sun et al., 2014)
Mechanical crushing with rotating drums	Opportunity for low grade heat recovery using heat pumps (Rodd et al., 2010) Up to 60% heat recovery can be achieved (Yu et al., 2016) Decreases water consumption and gas emissions for minimal environmental impact (Motz et al., 2015)	Large particle size (Yu et al., 2016) Reduced processing capacity due to slag pieces attaching to drum (Yu et al., 2016) Not suitable for industrial scale operation (Xie et al., 2007)
Rotating cup granulation centrifugal	Minimal environmental impact (Xie et al., 2007) Small slag particle size (Yu et al., 2016) Allows for high grade waste heat recovery (Motz et al., 2015)	Still in development phase (Xie et al., 2007) Not well tested for large-scale applications (Xie et al., 2007) Heat recovery process requires fluidized bed (Motz et al., 2015)

	High glassy phase (Xie et al., 2007) High process capacity (Yu et al., 2016)	
Air blast	Minimal environmental impact (Xie et al., 2007) Allows for high grade waste heat recovery (Rodd et al., 2010) High process capacity (Yu et al., 2016)	Heat recovery process requires fluidized bed (Motz et al., 2015) Large volume of air results in high energy consumption and operating costs (Yu et al., 2016) Low cooling speed (Yu et al., 2016)

2.5 Process Water

During the study of a smelter, a number of process streams in the facility were identified for low-grade heat recovery (Ross, 2016). The smelter processed mainly nickel and copper custom feeds and concentrates, with annual production around 75,000 tonnes of nickel and 23,000 tonnes of copper. With nickel and copper bearing sulphide ores as the primary feedstock, the total waste heat rejected to the environment from the fluidized bed roaster off-gas, the furnace off-gas, the furnace cooling water, the matte granulation cooling water and the acid plant cooling water during operation was calculated to be in excess of 100 MW (Ross, 2016).

The most promising streams were found to be process cooling waters from the calciner, the matte granulation process and the furnace, as these were all in the temperature range suitable for the application of heat pumps (Kahraman and Çelebi, 2009). It was determined that for beneficial application of the recovered energy, the waste heat would first need to be upgraded by heat pumps. They offered the potential to provide space heating and cooling of a nearby office building, and to replace an aging natural gas furnace with an average annual demand of 510 kW, as well as reduce CO_2 emissions by approximately 62% (Ross, 2016).

An iron and steel plant located in the Netherlands was investigated to determine the feasibility of implementing a heat recovery system using cooling water from the rolling process, where rolled steel is cooled by spraying water at a temperature of 80°C (Institute for Industrial Productivity, 2012a). A preliminary study found that waste heat from the cooling water of the hot strip mill can be recovered using an absorption heat pump, which could then be applied to produce low pressure steam at 1.7-3.5 bar and 130°C (Institute for Industrial Productivity, 2012a). It was determined that emission reductions of 1.9 kg $CO_2/t_{\text{rolled steel}}$ could be achieved with the implementation of this technology (Institute for Industrial Productivity, 2012a).

2.6 Conclusion

The mining and mineral processing industry is extremely energy intensive, yet in general exercises relatively little waste heat recovery and repurposing. Many sites are located in very cold climates where recovery and repurposing on-site to supply space heating or pre-heating of gas and liquid process streams could significantly contribute to the sustainability of the operation. Where recovery does exist, the target is generally high-grade waste heat sources in gasses or liquids with temperatures greater than 100°C, most of which is related to smelter furnaces. This high-grade heat in the exhaust gas from electric arc furnaces, for example, can be extracted for direct recovery applications, such as steam generation, electricity production, or process stream preheating. In most cases use of heat exchangers, which are well understood and widely used throughout all industries, are proven the most appropriate recovery route. Although, over 40% of the energy supplied to a smelter furnace remains in the slag, substantial energy that is rarely tapped. High-grade waste heat can be also captured and used for power generation by driving heat engine technologies such as the Rankine cycle.

Significant opportunity also lies in the abundant quantities of low-grade thermal resources which are less than 100°C. Recovered energy, again usually with heat exchangers, from process streams with temperatures between 70 and 100°C may be upgraded by adding energy to raise the temperature to allow for repurposing, such as through steam generation. However, the copious quantities of resources that are below 70°C are usually discounted by the industry as too difficult to capture and repurpose. But it is proposed that an effective way to recover this low-grade waste heat, is upgrading it with heat pumps. This can allow for recovery of waste-heat as an economically viable option as well as reduce overall greenhouse gas emissions. Geothermal heat pumps can be effective for the recovery of waste heat within flooded abandoned mines for use in local space heating, such as in nearby homes or community centers. For operational sites, such as smelters, process cooling streams offer the most potential. The recovered heat becomes more suitable to displace existing process stream heaters or be used to replace fossil fuel fired boilers to supply space heating, thereby reducing both annual operating costs, as well as CO_2 emissions.

Chapter 3

Low-grade Waste Heat Recovery and Repurposing to Reduce the Load on Cooling Towers

3.1 Introduction

Industrial low-grade waste heat within process streams, typically classified as below 100°C, is often overlooked, despite representing a source of significant energy that if recovered could enhance overall operational sustainability (Zhang et al., 2016; Rubio et al., 2020). One such opportunity may lie in cooling towers as for example, a 162 m high wet unit used to remove heat from a 940 MWe generating unit was found to reject approximately 1760 MW of heat while operating at ambient air conditions of 31.7°C (Lee, 1979).

Cooling towers use air to cool process water streams through direct contact which transfers heat to the atmosphere through evaporation. The cooled process water can be then cycled back at a reduced temperature (SPX, 2016; Afshari and Dehghanpour, 2019). There are different types of cooling towers, including cross-flow, where the water flows vertically and the air flows horizontally across water, and counter-flow, where the air flows vertically upward (SPX, 2016). In addition, cooling towers can be induced draft, where fans pull air through the cooling towers, or forced draft, where air is pushed by blowers located at the air inlet (SPX, 2016). Natural draft cooling towers use a stack effect, allowing hot air to rise and create a draft, and thus do not require fans (Hoffschmidt and Hilger, 2012; Enexio, 2020). An enclosure can be used to enhance cooling efficiency, as well as inlet air spray cooling to further improve cooling performance by pre-cooling the air (Afshari and Dehghanpour, 2019).

Many older cooling towers are constructed from wood that requires regular replacement to avoid environmental concerns and allow for increased efficiency (Jordan, 2013; CT/HX, 2014). Cooling towers can also lose 20% of capacity due to defects, such as packing and nozzle blockages (Ning et al., 2015), and older systems are often oversized, and are more expensive to operate than smaller more efficient modern units (Hawkeye, 2015).

Cooling towers present, therefore, a significant opportunity for application of heat recovery systems that would both make reuse of otherwise wasted energy and also reduce the load on them, and hence operational costs (Mazzoni et al., 2017). That is, enhancing rather than replacing aging infrastructure with new technology, such as heat pumps (Hawkeye, 2015), to recover and repurpose low-grade energy in process streams going to a cooling tower.

To investigate this possibility, we looked at a model system, a smelter’s on-site ageing cooling towers linked to a plant used to capture sulphur dioxide (SO_2) emissions from ore roasting and convert them into sulphuric acid. The cooling towers used require energy to operate fans, pump the recirculating water, and replace evaporated water (Gunson, 2013; Rubio-Castro et al., 2013). Enhanced operation of a cooling tower presents an opportunity for substantial energy cost savings (He et al., 2015). Reducing the load on the cooling systems through heat recovery could help significantly to reduce costs associated with energy consumption from fan operation, as well as replacement (Rubio-Castro et al., 2013) and general maintenance (Hawkeye, 2015; Hoffman, 2019).

3.2Cooling Tower Efficiency Limitations

Aging cooling tower infrastructure can result in a loss of heat transfer efficiency due to insufficient water and air flow, as well as corrosion and scaling (Enexio, 2020), and consequently an increase in maintenance costs (Tran et al., 2017). Furthermore as many older cooling towers are constructed from wood, leaching of preservative chemicals into the water is a major environmental concern (Jordan, 2013). Wooden cooling towers have also proven to undergo rapid physical and chemical degradation due to weathering compared to most modern, steel cooling towers (Hoffschmidt and Hilger, 2012; Jordan, 2013).

Reducing the heat load through recovery on any type of cooling tower can improve energy efficiency, as well as increase operational life (Hawkeye, 2015; Hoffman, 2019). Recovered waste heat could be then repurposed to on-site applications such as process streams, building space heating or hot water heating (Ross, 2016; Woolley et al., 2018). Heat load reduction can also achieve decreased fan operation, which reduces wear, energy consumption, and operating costs (Baltimore Aircoil Company).

With an increase in global activities, water consumption by the mining and mineral processing industry continues to grow. As mining resources become depleted, larger volumes of water will be required for mining and mineral processing of lower quality ores, contributing to an increased demand for water (Prosser et al., 2011). Industries account for approximately 20% of the total water consumption and in Western Australia, for example, water consumption within the mining sector is projected to increase from 810 to 940 GL/year by 2027 (Prosser et al., 2011). While a study carried out in 2015 determined that water rates went up nationally in the United States by 41% since 2010 (Hoffman, 2019). As industries look to become more water and energy efficient, cooling towers without the addition of load reduction techniques, may become a less attractive option (He et al., 2015). Implementing strategies to reduce water consumption is key to attaining a sustainable mining industry (Gunson, 2013). Therefore, in addition to improving cooling tower performance, a reduced heat load can also help through decreased water consumption.

3.3 Costs Associated with Cooling Tower Operation

To study the impacts of recovering and repurposing on-site low-grade heat from process water from the cooling towers, we looked at towers in operation at the Sudbury Integrated Nickel Operations (Sudbury INO) smelter site in Canada. The smelter processes nickel and copper custom feeds, as well as smaller amounts of cobalt, gold, silver, platinum, and palladium (Ross, 2016). Three major sources of low-grade waste heat have been identified at the smelter: which are the (1) furnace cooling water, (2) matte granulation cooling water, and (3) acid plant cooling water. In total they represent over 60 MW of low-grade waste heat that is dissipated to the atmosphere (Ross, 2016).

Within the acid plant, sulphur dioxide (SO_2) at a content of 6-7% is recovered from the off-gas of the fluidized bed concentrate roasters and is converted into sulphuric acid at an average product acid flow rate of 40 tonnes/h (Laamanen et al., 2014). The other off-gas that is not directed to the acid plant, undergoes a number of cleaning stages, including an electrostatic precipitator, before it is released to the environment (Ross, 2016). The electrostatic precipitator is the final gas cleaning stage and consists of four operating electric heaters at a capacity of 60 kW each, plus one on standby. The overall process is illustrated in Fig. 2.

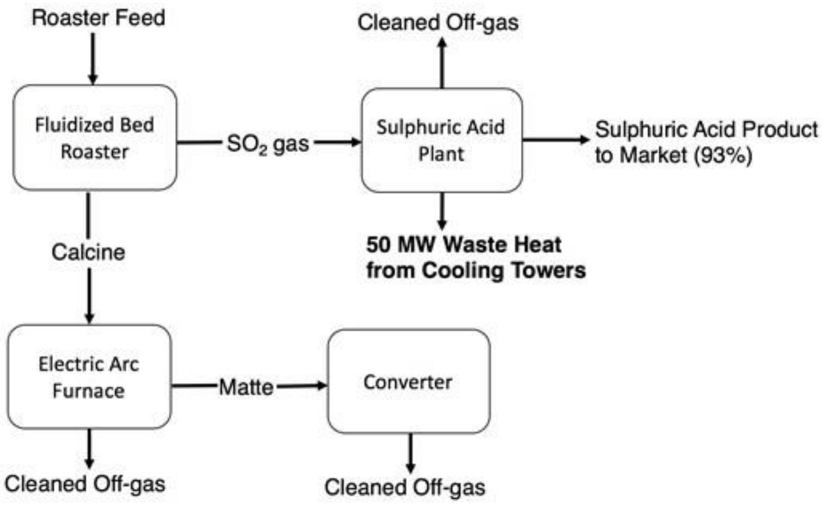

Fig. 2: Sulphuric acid production from smelter off-gas (adapted from (Laamanen et al., 2014))

In the acid plant, a quench-condenser process is used to cool the roaster off-gas, resulting in a weak acid liquid for neutralization and disposal. Cooling tower water removes the heat from the off-gas stream, and the cooled SO_2 gas is brought to the drying tower where water is removed. After this step, the SO_2 gas travels to the converter through a series of gas-gas heat exchangers. After catalytic conversion of the SO_2 to SO_3 the gas is sent to the absorbing tower before it is eventually released through the main stack. The reaction that takes place in the converter is exothermic, and heat from the process is used to preheat the incoming SO_2 gas stream. At the end of the acid plant process, the final acid product reaches its target concentration of about 93% before it is sent to storage and then sold. Cooling tower water is also used to remove heat from the acid in the drying, absorbing, and product transfer stages. The process within the plant is illustrated in Fig. 3.

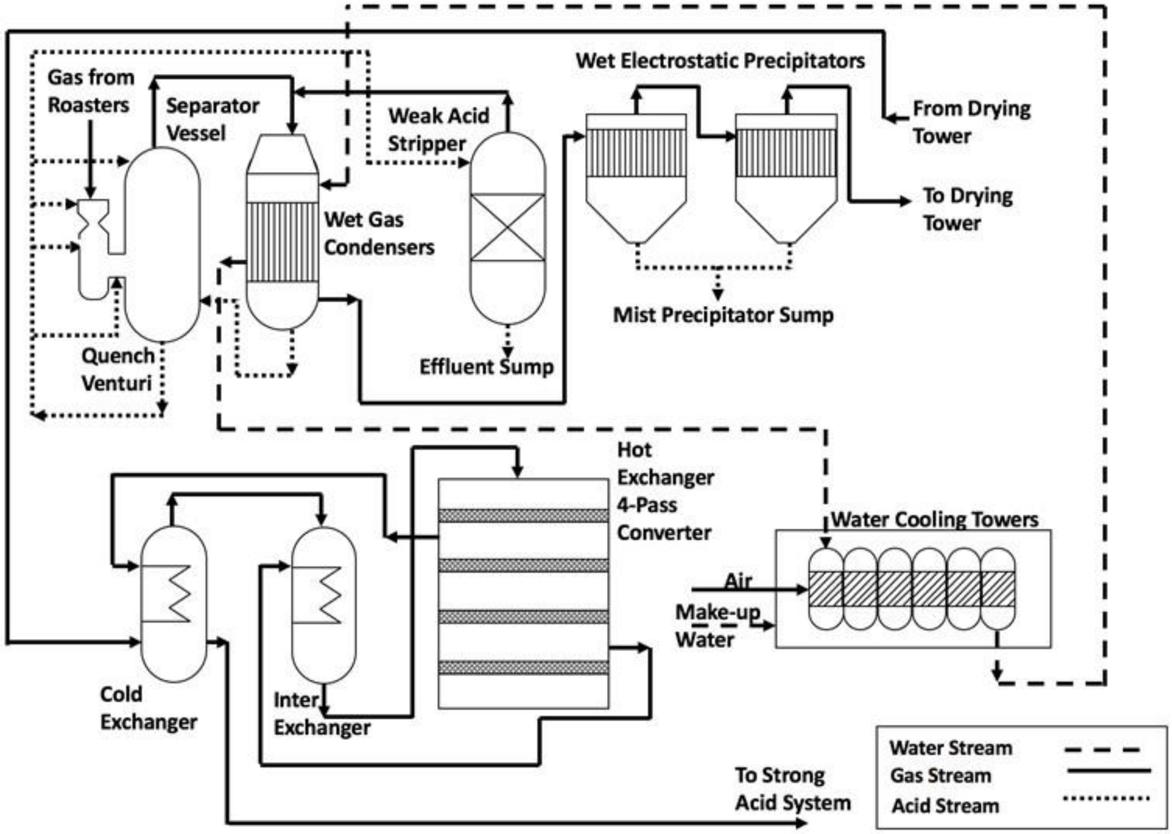

Fig. 3: Acid plant process for weak acid

An investigation was made into heat recovery from the cooling towers for repurposing within sulphuric acid production. Data from the water cooling towers was collected and used to model a number of systems to determine techniques that could be applied to recover and upgrade the low grade industrial heat in an economical manner. The focus was on applying heat pumps as they are generally regarded as one of the better techniques to achieve an appropriate level of heat upgrade from low temperature water streams, compared to heat exchangers and the Organic

Rankine cycle that typically require temperatures greater than 100°C for recovery (Rubio et al., 2020).

The concept is to implement a heat recovery system for the acid plant supply cooling water leaving the tower, which had an average annual temperature of about 18°C (Fig. 4). This includes operating the cooling tower fans at a decreased speed to allow the cooling water supply temperature to increase, thereby creating an opportunity for heat pumps to capture more heat and reduce the temperature back down to the required 18°C. The approach would offer additional benefits from decreasing electricity consumption by the cooling tower fans, and potentially, a reduced number of required cooling towers.

Power consumption by the cooling tower fans contribute substantially to the overall operating costs as typically required is around 0.01 kWh of energy per kWh of cooling energy (Gunson, 2013). As fan power is proportional to the cube of its speed, reducing the speed by 20% should decrease energy consumption by approximately 50%. This has been confirmed as a report described how reducing the speed of a 100 horsepower fan that operates at 1294 RPM for 2000 hours/year by 25%, reduced annual operating costs by more than 50% (Hawkeye, 2015).

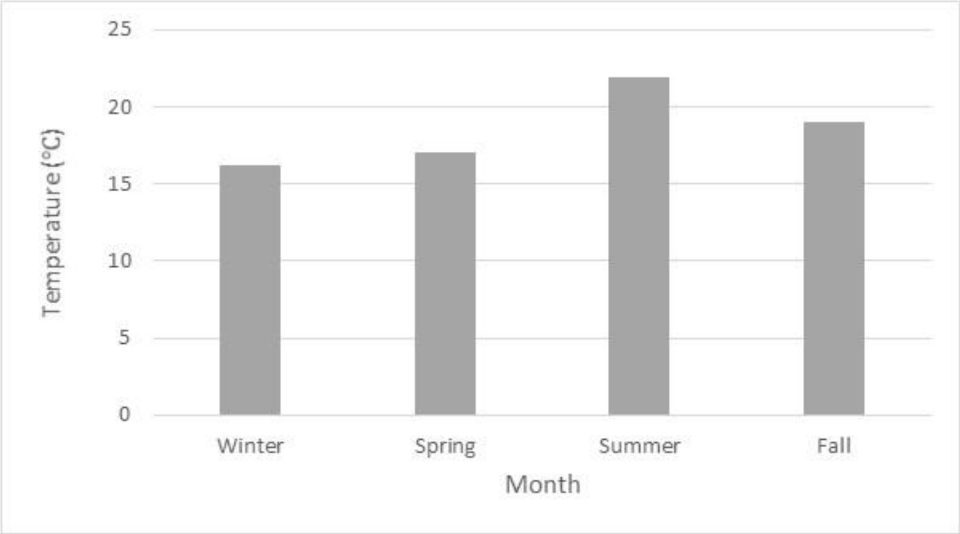

Fig. 4: Average water temperatures from the cooling towers over 2016 and 2017 (Sudbury INO, 2017)

Potential On-site Low-grade Waste Heat Applications

The inlet water from the sulphuric acid plant to the cooling towers is about 33°C, and is distributed equally between six separate cells, each with its own fan. The cells share a common basin where the cooled water is collected and pumped back to the acid plant. The air flow through each cell is about 680,000 m^3/h throughout the year. The average flow rate of cooling water flowing from the cooling tower is about 4000 m^3/h.

The two processes chosen as potential applications for recovered waste heat were the mist precipitators and the weak acid stripper tower, both of which require heating in the colder months (December to April). To prevent the acid from freezing, the weak acid stripper tower employs a thermostat controlled 144 kW electric heater that turns on when the ambient air temperature drops to 5°C. The mist precipitators have four 60 kW electric heaters plus one on standby. The heaters run year-round and raise ambient air temperature to 100°C to provide dry purge air (2,000 m^3/hr) to the electrical insulator compartments. Maintaining the air at this temperature keeps any water in the vapour phase and prevents condensation from damaging the insulators. The annual heating demands of the weak acid (WA) stripper tower and the mist precipitators are illustrated in Fig. 5.

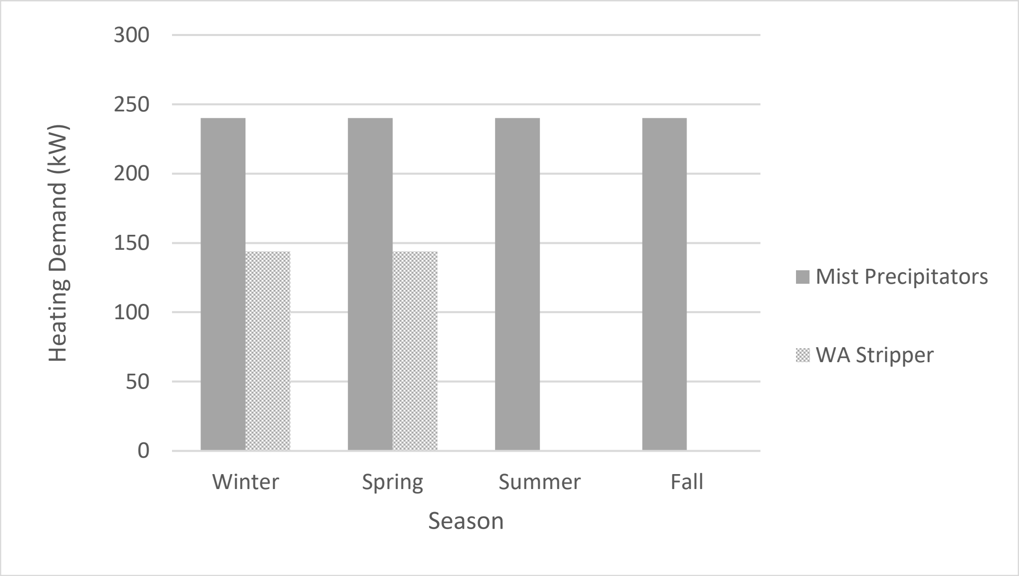

Fig. 5: Heating demands of the weak acid (WA) stripper and mist precipitators (Sudbury INO, 2017)

3.4 Modeled Scenarios

A model was developed to assess two different configuration scenarios of heat pump systems to recover heat from the cooling tower supply water. The aim was to compare purchase and operational costs, energy consumption and overall greenhouse gas (CO_2) emissions. Scenario 1 was aimed at the maximum number of heat pumps that would be required during the colder months when the equipment heating demand is at its peak. The heat pump banks would be installed at each piece of equipment where recovered heat would be used, that is the mist precipitators and the weak acid stripper, and the system would require the cooling water to be split and pumped to the individual heat pump banks.

However, during the summer months when less heat is required, with Scenario 1, some of the heat pumps would remain idle. To avoid this idle capacity, in Scenario 2 a model was constructed that includes only the number of heat pumps required to replace the maximum number possible of year round electric heaters of the mist precipitators, while keeping the existing weak acid stripper heater for the winter months. A process schematic that includes the two heat pump scenarios is given in Fig. 6.

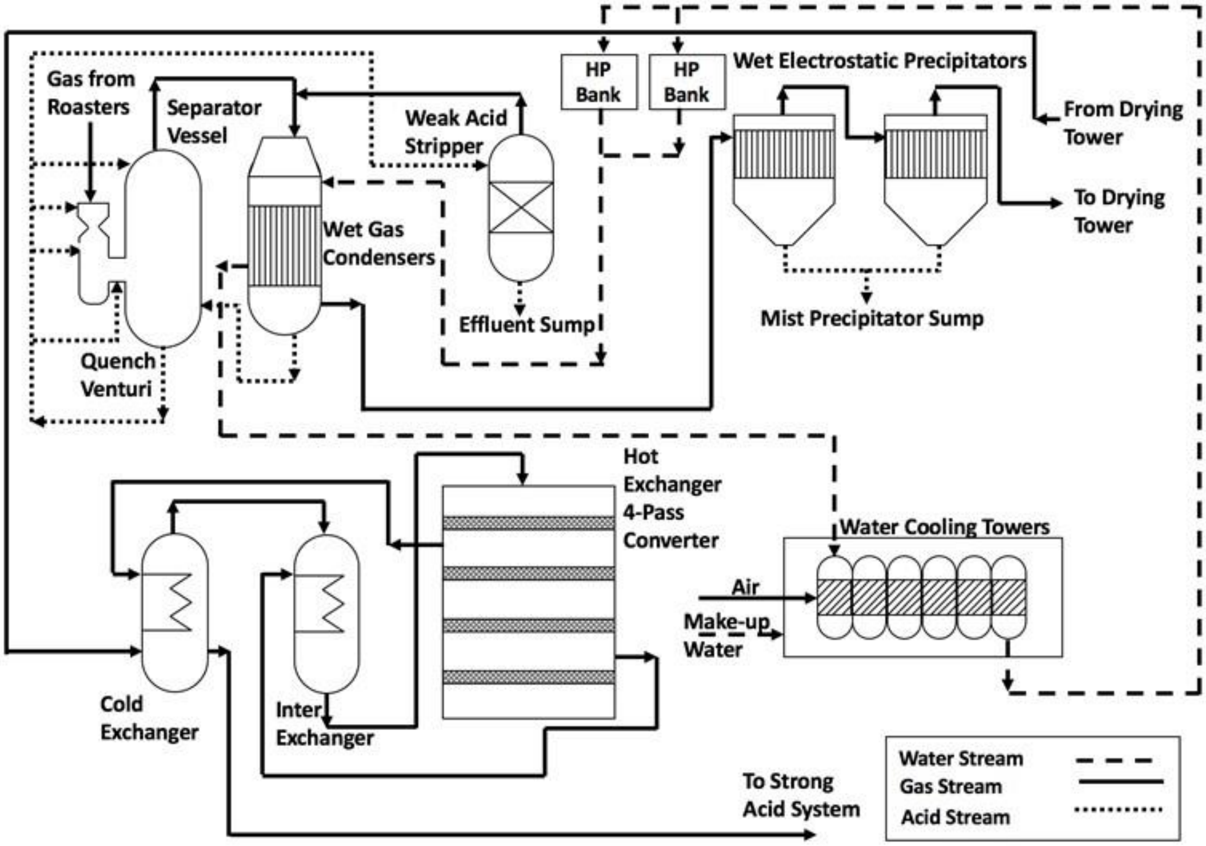

Fig. 6: Heat recovery system (HP = Heat Pump)

The heating scheme for each scenario uses open loop heat pumps in a parallel arrangement to allow for higher recovery efficiency as each unit would be exposed to the process water at its highest temperature (Ross, 2016). Whereas an arrangement in series would result in a lower efficiency of the bank, due to the temperature drop through each individual heat pump. Water-to-air heat pumps were chosen with high capacities and low source temperature applications (Ammar et al., 2012; Ahmad and Prakasha, 2019). These heat pump units are equipped with a blower, and allow for the captured heat to be transferred to the incoming process air through heat exchange between the warm water and a refrigerant within the heat pump coils. The cost of this equipment is factored into the overall cost of heat pumps.

Model construction

Nomenclature

Symbol	Description	Nu	Nusselt number
α	thermal diffusivity (m^2/s)	ρ	density (kg/m^3)
A	area of surface (m^2)	ΔP	change in pressure (Pa)
A_1	area of interior surface exposed to convection (m^2)	Pd	dynamic pressure in fluid flow (Pa)
A_2	area of exterior surface exposed to convection (m^2)	Pr	Prandtl number
A_w	cross-sectional wetted area (m^2)	NPV	net present value ($)
C	capital costs of heat pumps ($)	q	heat transfer (W)
C_n	cash flow ($)	$\dot{q}$	heat transfer rate (W/s)
C_p	specific heat capacity (J/kgK)	Q	volumetric flow rate (m^3/s)
CFM_1	initial air flow through cooling tower (CFM)	$\dot{Q}$	heat flux (W/m^2)
CFM_2	reduced air flow through cooling tower (CFM)	r_1	inner radius of pipe (m)
D	inner diameter of pipe (m)	r_2	outer radius of pipe (m)
E	Efficiency of pump	r_3	outer radius of insulation (m)

ε/D	relative pipe roughness	R	thermal resistance (K/W)
$\boldsymbol{f}$	Darcy friction factor	Re	Reynolds number
g	acceleration due to gravity (m/s^2)	RPM_1	initial fan speed (RPM)
h	heat transfer coefficient (W/m^{2}K)	RPM_2	reduced fan speed (RPM)
h_1	heat transfer coefficient inside pipe (W/m^{2}K)	Δt	time interval (s)
h_2	heat transfer coefficient outside pipe (W/m^{2}K)	ΔT	temperature change (K)
h_L	head loss (m)	T_1	temperature of inner surface of pipe (K)
HC	capacity of single heat pump (kW)	T_2	temperature of outer surface of pipe (K)
HP_1	initial fan power (HP)	T_a	ambient air temperature (K)
HP_2	reduced fan power (HP)	T_{p1}	temperature of water at initial section of pipe (K)
i	hurdle rate	T_{p2}	temperature of water at final section of pipe (K)
k	thermal conductivity (W/mK)	T_s	temperature of surface (K)
$k_{insulation}$	thermal conductivity of insulation (W/mK)	$T_{w,in}$	temperature of process water entering heat pump bank (K)
k_{pipe}	thermal conductivity of pipe (W/mK)	T_{water}	initial process water temperature leaving cooling towers (K)
K_L	minor loss coefficient for pipe components	μ	dynamic viscosity (Ns/m^2)

L	length of pipe (m)	u	velocity of fluid flow (m/s)
L_e	equivalent length (m)	ν	kinematic viscosity (m^2/s)
n	number of years	W_{pump}	pumping work (W)

Pipe flow equations for heat and pressure loss were used in the model to determine the number of heat pumps required to overcome these losses and provide an efficient temperature lift. Annual costs for the heat pump systems could then be calculated from electricity consumption, as well as capital costs. The heat loss (q) that occurs from pumping water across the length of pipe to the heat pump bank during a time interval (Δt) was expressed as follows, where $q^{\cdot}$ is the heat transfer rate:

$$q = \int_0^{\Delta t} q^{\cdot} dt \qquad (1)$$

Heat transfer through the pipe (q), modelled as steady-state, can be determined from the density of the fluid (ρ), as well as the volumetric flow rate (Q), the specific heat capacity of the fluid (c_p) and the temperature change across the section of pipe ($T_{p2} - T_{p1}$):

$$q = \rho Q c_p \left(T_{p2} - T_{p1} \right) \qquad (2)$$

The volumetric flow rate (Q) is determined from the pipe diameter (D) and fluid velocity (u), with the following equation:

$$Q = \frac{\pi}{4} D^2 u \tag{3}$$

The heat flux ($Q^{\cdot}$) is the rate of heat transfer ($q^{\cdot}$) per unit area (A), as represented by:

$$Q^{\cdot} = q^{\cdot}/A \tag{4}$$

Total thermal resistance (R_{total}) is calculated as the sum of the internal resistance to convection ($R_{interior}$), the resistance to conduction through the pipe (R_{pipe}), the resistance through the insulation ($R_{insulation}$), and the resistance to external convection ($R_{exterior}$). The thermal conductivity (k) of a steel pipe, 45 $\text{Wm}^{-1}\ \text{K}^{-1}$, and that of the fiberglass insulation, 0.04 $\text{Wm}^{-1}\ \text{K}^{-1}$, are required to determine resistance through the pipe and resistance through the insulation, respectfully. The Fourier equation was used for steady-state conduction and assuming thermal conductivity is constant, it can be represented as follows:

$$q^{\cdot} = -kA\,(dT/dr) \tag{5}$$

$$A = 2\pi r L$$

Eq.

(7) results from integrating the Fourier equation, where the temperature difference across the layer is represented by $T_1 - T_2$. After integration, the thermal resistance against heat conduction of the pipe layer is determined in Eq.

(9), where r_2 and r_1 are the outer and inner radius of the pipe, respectively.

$$\int_{r_1}^{r_2} (q^{\cdot}/A)\, dr = -\int_{T_1}^{T_2} k dT \tag{6}$$

$$q^{\cdot} = 2\pi kL \frac{T_1 - T_2}{\ln{(r_2/r_1)}} \tag{7}$$

$$q^{\cdot} = \frac{T_1 - T_2}{R} \tag{8}$$

$$R = \frac{\ln{(r_2/r_1)}}{2\pi kL} \tag{9}$$

The heat transfer across the fluid/solid interface comes from Newton's law of cooling, where *h* is the heat transfer coefficient, T_s is the temperature of the surface, and T_a is the temperature of ambient air. This is used to determine the thermal resistance of the surface against heat convection (R_{conv}) written as Eq.

(11).

$$q^{\cdot} = hA(T_s - T_a) \tag{10}$$

$$R_{conv} = \frac{1}{hA} \tag{11}$$

In a pipe, interior and exterior resistance due to convection are represented below with Eq. (12) and Eq. (13), respectively. Thermal resistance against heat conduction through the pipe, Eq. (14), and thermal resistance through insulation, Eq. (15), are shown. In Eq. (15), the outer pipe radius (r_2) and the outer insulation radius (r_3) are used to determine the thermal resistance through insulation.

$$R_{interior} = \frac{1}{h_1 A_1} \tag{12}$$

$$R_{exterior} = \frac{1}{h_2 A_2} \tag{13}$$

$$R_{pipe} = \frac{\ln{(r_2/r_1)}}{2\pi k_{pipe} L} \tag{14}$$

$$R_{insulation} = \frac{\ln{(r_3/r_2)}}{2\pi k_{insulation} L} \tag{15}$$

The total resistance is calculated as the sum of the resistance equations:

$$R_{total} = R_{interior} + R_{pipe} + R_{insulation} + R_{exterior} \tag{16}$$

With values for total thermal resistance, ambient air temperature and process water temperature (T_{water}), the overall heat loss to ambient air from the process water travelling through a length of pipe (q) can be determined:

$$q = \frac{T_a - T_{water}}{R_{interior} + R_{pipe} + R_{insulation} + R_{exterior}} \tag{17}$$

$$q = \frac{T_a - T_{water}}{\frac{1}{Nu\,(k/D)\,\pi DL} + \frac{\ln{(r_2/r_1)}}{2\pi k_{pipe} L} + \frac{\ln{(r_3/r_2)}}{2\pi k_{insulation} L}} \tag{18}$$

$$h = \frac{Nuk}{D} \tag{19}$$

To solve for the convection heat transfer coefficient (h), Eq. (19), the Nusselt number (Nu) must be first calculated. The Nusselt number represents the convection heat transfer that occurs at the surface, and is a ratio of thermal energy convected to thermal energy conducted within the fluid. For fully developed turbulent flow in a pipe, the Nusselt number may be obtained from the

Dittus-Boelter expression, Eq. (21), where *Re* is the Reynolds number and *Pr* is the Prandtl number:

$$Nu = f(Re, \mathrm{Pr}) \tag{20}$$

$$Nu = \frac{q_{conv}}{q_{cond}} = \frac{h\Delta T}{k(\Delta T/L)} = \frac{hL}{k} \tag{21}$$

$$Nu = 0.023Re^{0.8}Pr^{0.4} \tag{22}$$

Application of Eq. (22) is valid under the following conditions:

$$0.6 \leq Pr \leq 160$$

$$Re > 10\ 000$$

$$L/D > 10$$

The Prandtl number represents the ratio of momentum diffusivity to thermal diffusivity, and is approximated by Eq. (23), where ν is the kinematic viscosity of the fluid, α is the thermal diffusivity, and μ is the fluid viscosity.

$$\mathrm{Pr} = \nu/\alpha = \frac{(\mu/\rho)}{(\frac{k}{C_p/\rho})} = \frac{\mu C_p}{k} \tag{23}$$

To determine the additional power requirements needed to pump the cooling water to the heat pump bank (W_{pump}), the pressure drop across the length of the pipe can be calculated from volumetric flow rate, pressure loss (ΔP) and efficiency (E):

$$W_{pump} = \frac{Q\Delta P}{E} \tag{24}$$

The Darcy-Weisbach equation (Eq. (25)) was used to determine head loss or pressure loss for a length of pipe due to friction, from the average velocity of the fluid flow (u). The pressure drop across the length of the pipe can be calculated as the sum of the major losses (ΔP_{major}) in pipe flow due to friction, with a friction factor f, and minor losses (ΔP_{minor}) due to tees and elbows along the piping route, written as Eq. (25) and Eq. (26), respectively. The minor loss coefficient for pipe components (K_L) can be used to determine the pressure drop due to minor losses, Eq. (26).

$$\Delta P_{major} = f\,\frac{L}{D}\frac{\rho u^2}{2} \tag{25}$$

$$\Delta P_{minor} = K_L P_d = K_L\,\frac{\rho u^2}{2} \tag{26}$$

$$K_L = f(L/D) \tag{27}$$

The following denotes the total pressure drop as the sum of major and minor losses:

$$\Delta P_{Total} = f\frac{L}{D}\frac{\rho u^2}{2} + \sum K_L \frac{\rho u^2}{2} \tag{28}$$

The major and minor losses can also be expressed as equivalent pipe length (Le) to solve for head loss (h_L):

$$h_L = f(L/D + \sum (Le/D))\frac{u^2}{2g} \tag{29}$$

$$h_L = (f\,(L/D) + \sum K_L)\frac{u^2}{2g} \tag{30}$$

The Darcy-Weisbach equation can be used to solve for head loss in terms of volumetric flow rate in a pipe, Eq. (33), by substituting the following:

$$u^2 = Q^2/A_w^2 \tag{31}$$

$$A_w^2 = (\frac{\pi D^2}{4})^2 \tag{32}$$

$$h_L = \frac{8fLQ^2}{g\pi^2 D^5} \tag{33}$$

The Swamee-Jain equation is an approximation that is widely used to solve the Darcy friction factor for turbulent flow in smooth and rough pipes, where $\frac{\varepsilon}{D}$ represents the relative pipe roughness:

$$f \ = \frac{0.25}{(log_{10}(\frac{\varepsilon/D}{3.7} + (5.74/Re^{0.9})))^2} \tag{34}$$

The Reynolds number (*Re*), which represents the ratio of inertial forces to viscous forces, is used to predict if a flow will be laminar or turbulent. Eq. (34) is valid for a Reynolds number between 2300 and 4000, $\sim 2300 < Re <\sim 4000$.

$$Re = \frac{\rho u D}{\mu} = \frac{uD}{\upsilon} \tag{35}$$

Substituting the Reynolds number, expressed as Eq. (35), into Eq. (34) yields the pressure loss along a given length of pipe in terms of the Darcy friction factor:

$$\Delta P = \frac{0.25}{(log_{10}(\frac{\varepsilon/D}{3.7} + \frac{5.74}{\left(\frac{uD}{\upsilon}\right)^{0.9}}))^2} \frac{L}{D} \frac{\rho u^2}{2} \tag{36}$$

The temperature of the process water entering the heat pump bank ($T_{w,in}$) was determined from the water temperature drop across the length of pipe:

$$T_{w,in} = T_{water} - \frac{q}{QC_p\rho} \tag{37}$$

As fan horsepower (*HP*) will vary by the cube of the ratio of fan speed, to determine the power savings by reducing the speed of the cooling tower fans (*RPM*), the following relation was used:

$$(\, RPM_1/RPM_2\,)^3 = HP_1/HP_2 \tag{38}$$

The speed of the fan and the airflow are proportional and, therefore, decreasing the speed of the cooling tower fans will result in a reduced air flow through the cooling tower cells. The revised speed of fans (RPM_2) can be determined by relating the original air flow (CFM_1), the new desired air flow (CFM_2) and the original speed of the fans (RPM_1):

$$RPM_1/RPM_2 = CFM_1/CFM_2 \tag{39}$$

Water temperatures and flow rate data were collected for each day of the year, along with ambient air temperature and heating requirements for each month. MATLAB (*MATLAB*, 2014) was then used to create a model to determine the overall annual operating costs of the two heat pump scenarios, as well as the number of heat pumps required in each bank for each system. The developed model used efficiency, power and capacity data from various heat pumps, as well as cooling water temperature and flow rate data as inputs.

In addition to the heat and pressure losses through the piping, the number of heat pumps required was calculated based on the capacity of each individual heat pump, and the required heating of the mist precipitators and the weak acid stripper. A commonly used performance indicator for a heat pump cycle is the coefficient of performance (COP) (Ataei, Abtin et al., 2016; Yang and Lee, 2020). For heating applications, the COP is the ratio of heat delivered from the heat pump to the work input required from all external sources, such as electricity to run the compressors (Gudjonsdottir et al., 2017). Therefore, a higher COP indicates a better efficiency (Antwan and Maree, 2010).

In Scenario 1, the number of heat pumps required to supply heat to both the weak acid stripper and the mist precipitators throughout the winter months was determined. Operating costs for both scenarios included electricity to run the heat pumps, as well as the power to pump water to the heat pump banks and back to the process cooling lines. In addition, for Scenario 2 were the costs associated with using electric heaters for the weak acid stripper during the winter months.

Capital costs of the heat pump systems (C) were determined in order to calculate a payback period. The capital cost of an individual heat pump as a function of capacity (HC) can be approximated by (Ross, 2016):

$$C = 1.64HC(200 + (4750/HC^{1.25})) \tag{40}$$

Along with the cost of purchasing the heat pumps, the capital costs must also include those for [illegible] the heat pump life (n), assumed to be 20 years (Staffell et al., 2012), to [illegible] value (NPV) using Eq

(). In this equation, i represents the hurdle rate, C_n is the cash flow, and t is the number of periods.

$$NPV = \sum_{t=1}^{n} \frac{C_n}{(1+i)^t} \tag{41}$$

3.5 Results and Discussion

(1) Scenario 1

The simulations for Scenario 1 showed potential as an economically feasible system to replace the current electric heaters. The temperature dependent COP of each heat pump was calculated within the model using the varying temperature values of the cooling water entering the heat pump bank. With the heat pump efficiencies consisting of a COP of about 5.4, and accounting for heat losses across the pipe network to the equipment, replacing the electric heaters of both units of equipment would allow for a heat load reduction of the cooling towers by 7% in the winter, and 5% in the summer.

The temperature of heated air supplied by the heat pumps must be appropriate for the potential applications chosen. For the mist precipitators, the heat pump bank selected could raise the ambient air temperature to 85°C, with a 10 kW electric heater then employed on the combined outflows to produce a final air temperature of 100°C.

To determine an efficient heat pump brand and model for this application, two different heat pump brands were chosen, each comparing three different commercially available heat pumps. The heat pump displaying the best results for reduced operating costs in Scenario 1 was selected for further investigation, including comparing operating costs and CO_2 emissions of both scenarios. The temperature change of the process water leaving the heat pump bank, along with the temperature dependent COP for the heat pumps from various suppliers were determined and used in the model. Operating costs (shown in Canadian dollars) were obtained using cost of electricity in Ontario ($0.0685/kWh) where the smelter is located (Hydro One, 2019).

The heat pump units investigated were compared against the current electric heater system. The capacity and power input of each heat pump chosen are presented in Table 3.

Table 3: The types of heat pumps used in modeling Scenario 1

Heat Pump Unit	Capacity (kW)	Power Input (kW)
Heat Pump #1	86.75	12.77
Heat Pump #2	58.12	10.51
Heat Pump #3	86.98	16.46

The number of heat pumps required in a bank for each system was determined and is presented in Table 4. The water temperature change provided by the heat pump systems was about 5°C. The operating costs calculated for each heat pump system include those associated with pumping water to and from the heat pump bank, as well as those to power the required number of heat pump units and remaining electric heater of the mist precipitators. In Fig. *7*, the annual operating costs for each heat pump systems chosen are compared against the existing electric heater system (EH). Additional costs of running the single electric heater for the mist precipitators are added onto the total annual costs of the heat pump system.

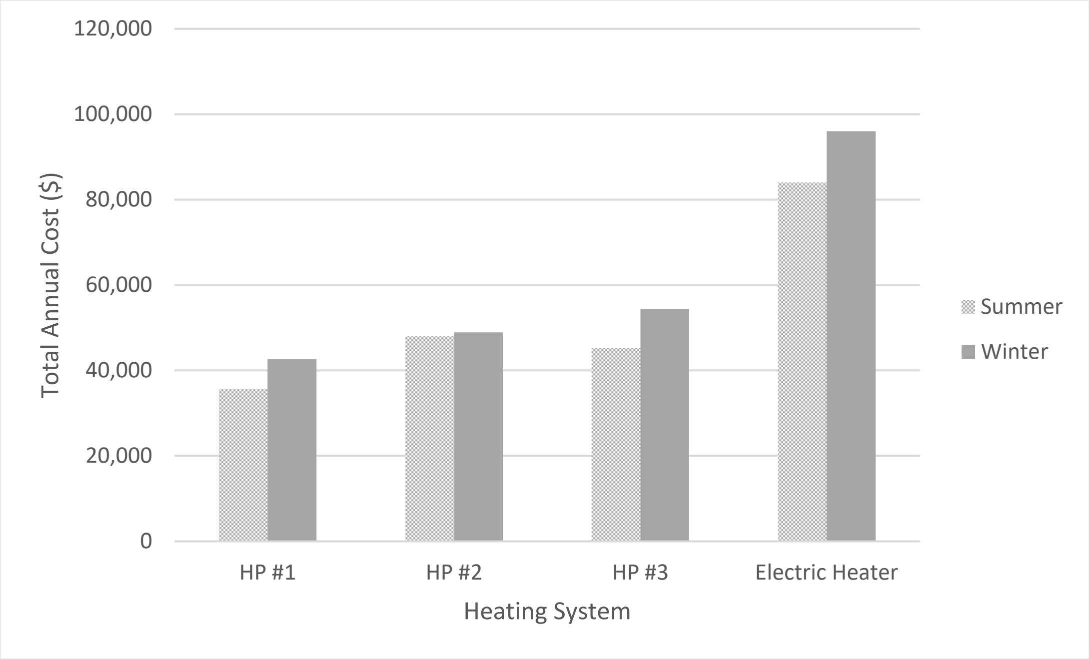

Fig. 7: Total annual operating costs of selected heating systems for Scenario 1

The results of the model, illustrated in Table 4, indicate that for this scenario the most efficient heat pump system results from using Heat Pump #1. Therefore, Heat Pump #1 is used for further investigation in comparing annual operating costs and CO_2 emissions from Scenario 1 against Scenario 2. Capital costs for this system were calculated to be $334,000 while total annual operating costs were reduced by 57% from the current heating system in place. The capital costs of the heat pump systems were calculated based on the capacity of the individual heat pump units used. The approximation is shown as Eq. (40). These costs vary for each heat pump system modelled, since the heat pump brands investigated each have different capacities for varying water temperatures. The capital costs also included costs of additional piping.

Table 4: Number of heat pumps and total annual operating costs of selected heating systems for Scenario 1

Heading System	Number of pumps in bank	Number of Operating Pumps During Summer	Annual Cost ($)
Electric Heaters	N/A	N/A	180,000
Heat Pump #1	5	3	77,000
Heat Pump #2	7	5	96,000
Heat Pump #3	5	3	99,000

As CO_2 is released during the combustion of fossil fuels to produce electricity (US EPA, 2018), electricity use is, therefore, related to greenhouse gas emissions. The annual emissions calculated for each system was based on 0.04 kg CO_2/kWh of electricity consumption where the smelter is located (Williams et al., 2017). The CO_2 emissions associated with each modeled heat pump system were calculated based on overall electricity consumption by Scenario 1 and compared against the emissions released by the current electric heaters (Fig. 8).

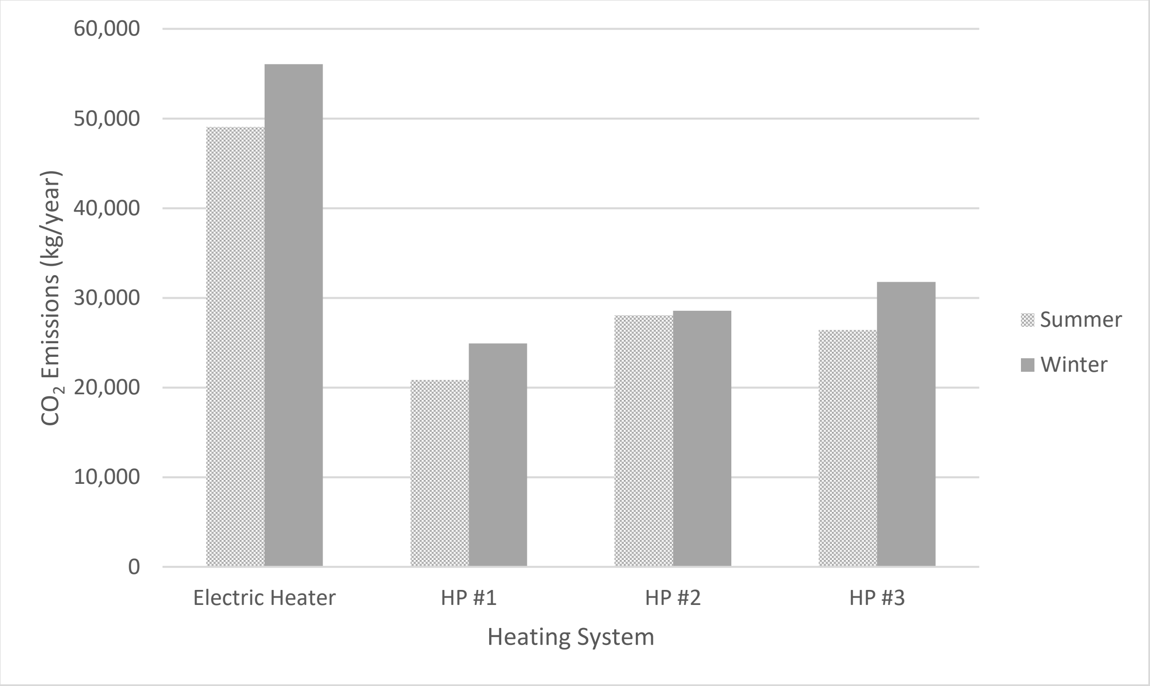

Fig. 8: Annual CO_2 emissions from Ontario electricity supply associated with the heating systems selected for Scenario 1

(2) Scenario 2

In Scenario 2, the three heat pumps needed are linked to the year-round heat demand of only the mist precipitators. That is, the electric heaters already in place for the weak acid stripper would remain in place for operation when required over the winter months. Scenario 2 allows, therefore, for elimination of idle heat pumps during the warmer summer months, when no heat is required by the weak acid stripper.

Implementing Scenario 2 would allow for a year-round 5% reduction in the heat load of the cooling towers. The number of heat pumps required in a bank for the heat recovery system in both scenarios is illustrated in Table 5. In Scenario 2, as the existing weak acid stripper electric heater is in operation during the winter months, less heat pumps will be in operation when compared to Scenario 1.

A comparison of both scenarios using Heat Pump #1, as well as the current electric heater system in place, is illustrated in Fig. 9. Additional costs of running this electric heater in the winter are added onto the total annual costs of the heat pump system in Scenario 2.

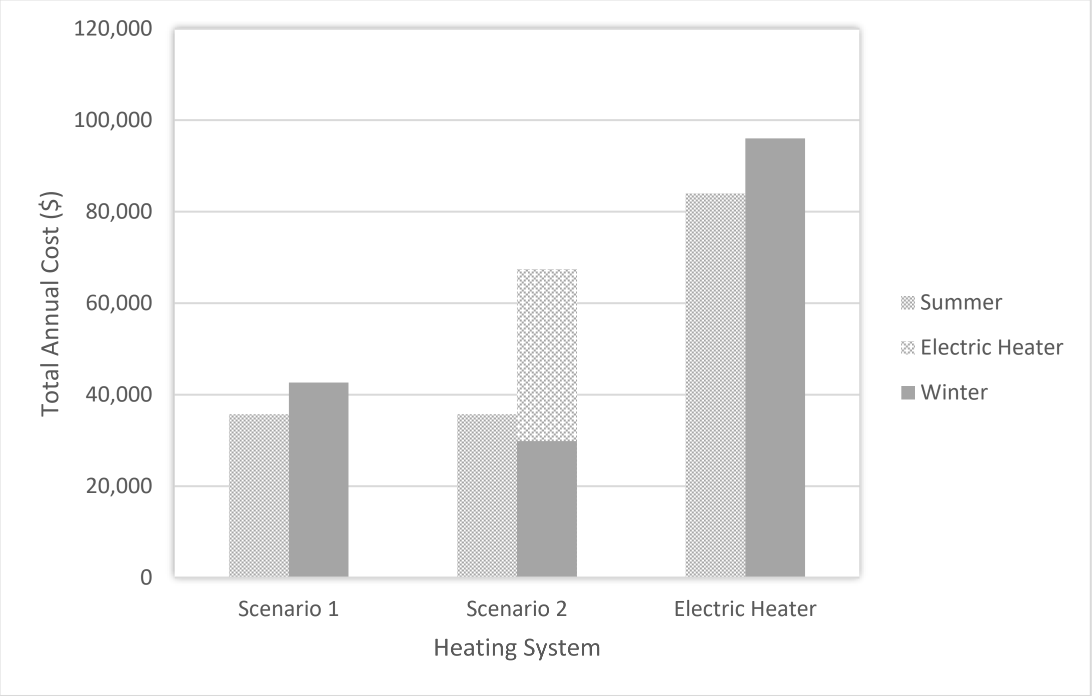

Fig. 9: Total annual operating costs of selected heating systems using Heat Pump #1

Table 5: Number of heat pumps and total annual operating costs of selected heating systems

Heading System	# Pumps in bank	# Operating Pumps During Summer Months	Annual Cost ($)
Electric Heaters	N/A	N/A	180,000
Scenario 1	5	3	77,000
Scenario 2	3	3	105,000

As a greater number of heat pumps are required for Scenario 1 then capital costs are higher than those of Scenario 2. That is, keeping the electric heater in place for the weak acid stripper (Scenario 2) will result in a reduction in capital costs. The results of the model indicated that the most efficient scenario and heat pump system would be Scenario 2 when using Heat Pump #1 units. Capital costs for Scenario 2 were calculated to be $184,000 and with total annual operating costs at $105,000 for both the heat pump system and the existing electric heater. This would require three heat pumps to be operated at full capacity throughout the year, resulting in a 42% reduction in operating costs from the current heating system in place. Pumping water directly to the heat pump bank of the mist precipitators, while using the electric heater already in place for the weak acid stripper in the winter, would result in the lowest payback period of approximately three years. Therefore, Scenario 2 was selected as the most economically viable solution.

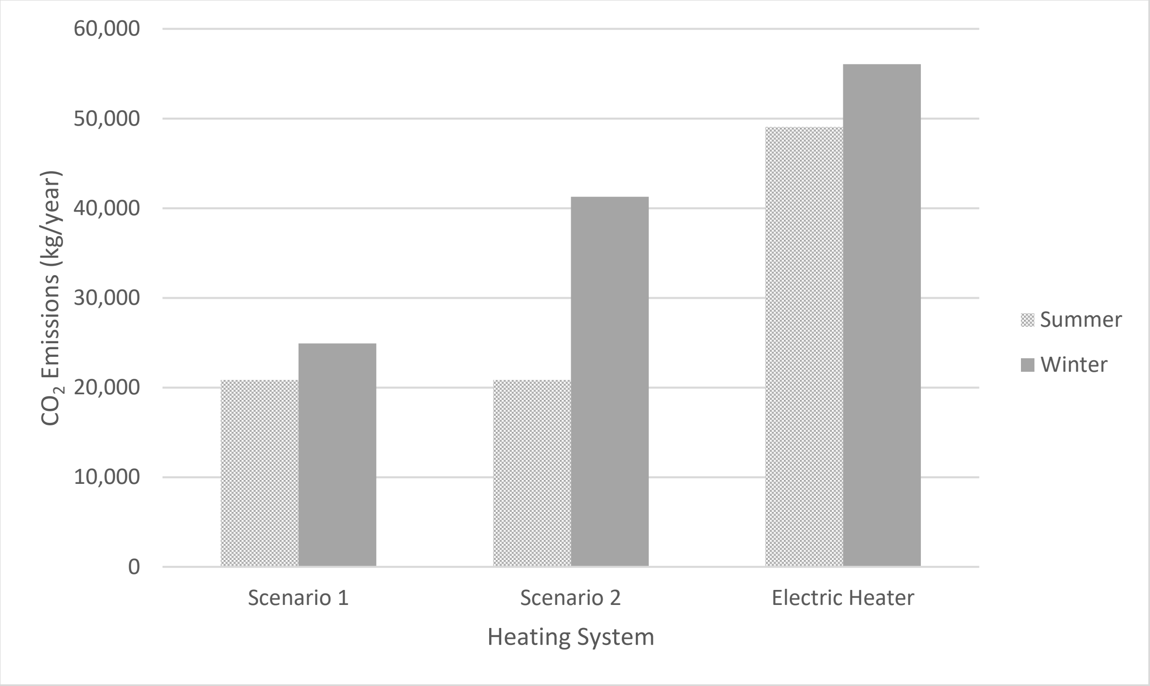

Fig. 10: Annual CO_2 emissions from Ontario electricity supply associated with the heating systems selected using Heat Pump #1

In both Scenarios 1 and 2, the heat pump systems investigated resulted in an overall reduction in electricity consumption. Not only does this offer a potential economically viable solution for waste heat application, but it also allows for a more environmentally sustainable operation with a reduction in CO_2 emissions due to electricity generation. Annual CO_2 emissions released with the heating systems of Scenario 2, illustrated in Fig. 10, resulted in a 42% reduction from the original heating system. It was established that the system with the least CO_2 emissions would be Heat Pump #1 used in Scenario 1, releasing approximately 45,000 kg/year, and thus was selected as the most environmentally sustainable design. This would result in a CO_2 reduction of about 60,000 kg annually. However, the implementation of this system would result in a payback period of approximately 4 years, and thus is not the most economically feasible option.

One of the major benefits of reducing the heat load of the cooling towers is the opportunity to reduce the number of cooling towers required within the acid plant. This would be beneficial for smelter sites with aging cooling towers scheduled to be replaced, or new sites in the start-up phase, looking to install fewer cooling towers with an integrated heat recovery system. Minimizing cooling tower units will also reduce costs associated with energy consumption and general maintenance costs (Rubio-Castro et al., 2013). For example, according to one study's projections, eliminating the need for three cooling tower units scheduled to be replaced could result in savings of $1,085,000 in capital (Young, 2018). In addition to reducing construction costs associated with replacing aging infrastructure, reducing the number of cooling towers required can also aid in minimizing fan operational costs.

In this case study, a reduced heat load could allow for an improvement in energy efficiency, as well as an increase in the life of the existing towers. Reduced fan operation can be achieved, minimizing wear and operating costs. Reducing the fan speed of all 6 cooling tower fans by 5% results in a new airflow of approximately 3,870,000 m^3/h through the 6 cells of the cooling tower. The power of the fans decreases from 180 kW to about 155 kW, which allows for a savings in fan operating costs of about $15,000 per year.

3.6 Conclusion

There is potential in industry for reducing emissions related to heating applications through recovery of low-grade waste heat. This has been demonstrated by a novel use of heat pumps to recover waste heat from cooling tower water streams and repurpose to replace on-site process stream heaters. The model developed allows for various heat pump and on-site repurposing scenarios, comparative predictions in energy savings, operating costs and reduced CO_2 emissions.

It was determined that the payback period was approximately three years. Furthermore, reducing the heat load on the cooling towers would allow for a further improvement in energy efficiency from lowering fan power consumption, as well as overall operating and maintenance costs. A reduction in the number of cooling towers required can be also achieved due to a reduced heat load, an approach of significant benefit to sites with aging cooling towers requiring major refurbishment or replacement. The concepts are, therefore, significant as they introduce new ways for the mining and other energy intensive industrial sectors to make much better use of resources and improve their long-term sustainable performance.

Chapter 4

A comparative life-cycle assessment of the sulphuric acid plant

4.1 Introduction

Opportunities exist throughout industry to reduce emissions related to process heating applications through the recovery and repurposing of otherwise waste heat. The energy intensive mineral processing industry is an excellent example, as 20-50% of energy consumed is lost as waste heat, primarily from cooling waters and off-gasses (Johnson et al., 2008; van de Bor et al., 2015). Recovery and repurposing of this energy is an opportunity to reduce operating costs and improve sustainability (Luo et al., 2017; Rubio et al., 2020).

Waste heat is typically categorized as either low-grade (temperatures below 100°C), or high-grade heat (temperatures above 100°C) (Zhang et al., 2016). High-grade heat is often captured and repurposed through direct contact heat exchangers or for power generation, using technologies such as the Rankine cycle (van de Bor et al., 2015). However, industry in general is lacking in recovery systems for low-grade waste heat (Zhang et al., 2016).

Low-grade heat recovery from industrial cooling towers could be an especially beneficial target, as they dissipate substantial amounts of energy to the atmosphere (Mazzoni et al., 2017). For example, a smelter site in Northern Ontario was found to emit over 50 megawatts (MW) of low-grade waste heat to the environment from its cooling towers (Ross, 2016). Extracting low-grade energy from this system would allow for improved economic and sustainability performance from a reduction of heat load on the cooling towers and, therefore reduced fan power requirements and maintenance costs (Mazzoni et al., 2017).

When deciding the merit of a recovery and repurposing scheme, it is not only economic improvements that should be looked for, but also improved environmental impacts. For the latter, life cycle assessment (LCA) is a well established and useful tool (Tokimatsu et al., 2020). LCAs can be used to analyze the environmental impact contribution of each process stage, with the goal of identifying areas for improvement and/or to compare different products or processes (Adeniran et al., 2017; Muralikrishna and Manickam, 2017). However, despite their significant environmental impact footprint and strides to improve it, mineral processing operations, such as smelters, have not generally considered incorporation of LCA in their decision-making processes. This provides, therefore, an opportunity to explore a new application and its effectiveness for this type of assessment.

Although very limited LCA studies have been carried out on sulphuric acid plants, an investigation was conducted in Nigeria on Drury Industries (Adeniran et al., 2017), which uses elemental sulphur from petroleum refining and natural gas operation for on-site production of sulphuric acid. Through a life-cycle assessment, the study found that on-site and off-site energy consumption is a significant area for environmental improvement, demonstrating the potential value for such tools in similar operations.

As such, a novel LCA application was carried out on a smelter's sulphuric acid plant with no existing low-grade heat recovery. The overall electricity consumption of the plant is about 1.2

MW, with the major energy losses, in excess of 50 MW, being from the plant's towers. The aim of the LCA was to demonstrate to the industry how it can be used to provide a comparison between the environmental impacts of a current process operation and any changes brought about by introducing a process modification. The example used was heat recovery from the cooling tower system and repurposing it to supply process heating to replace four 60 kW electric heaters. These heaters run year-round to prevent condensation in electrical insulator compartments. The LCA model developed, whilst using the sulphuric acid plant as a basis, can be easily adapted as a research tool for other sites utilizing cooling towers or equivalent non-beneficial heat dispersion systems.

Comparative LCAs involving heat recovery applications for sulphuric acid production is a new concept in the mineral processing industry. However, the results of this research demonstrate the usefulness of the technique as a tool to quantify environmental impacts as a result of instigating process changes.

4.2 LCA of a Smelter's Sulphuric Acid Manufacturing Facility

Over 260 million tonnes of sulphuric acid (H_2SO_4) are produced globally each year, making it amongst the most manufactured chemicals (Bloomberg, 2019). It is a strong acid that has a wide range of applications, including in manufacturing dyes, detergents, batteries, petroleum refining, and metallurgical processes (Adeniran et al., 2017; Encyclopaedia Britannica, 2019). It is also required to produce phosphoric acid used in fertilizers, which accounts for about 65% of the acid produced globally (Kiss et al., 2006; Adeniran et al., 2017). Sulphur for the acid can be extracted from a number of sources, including off-gas from smelting processes containing sulphur dioxide

(SO_2) (Desmet Ballestra; Shang et al., 2011). The SO_2 is generated by roasting and/or smelting sulphide metal ores and it can be captured and converted into sulphuric acid (Shang and Scott, 2011; ECI, 2016) in plants that are integral in meeting emission regulations (Shang et al., 2012; Aas et al., 2019), and protecting the public. Exposure to only 0.1 ppm of SO_2 can begin to cause negative health-related problems (Public Health Sudbury, 2019) as it can be an irritant to the respiratory tract and eyes, causing exaggerated symptoms associated with asthma (Queensland Government, 2017). In addition, H_2SO_4 forms when SO_2 mixes with water and air to create acid rain (Queensland Government, 2017).

At the sulphuric acid plant studied in this work, SO_2 from nickel ore roasting and oxygen (O_2) are combined to form sulphur trioxide (SO_3) using the contact process (Encyclopaedia Britannica, 2019). It involves passing SO_2 and O_2 over a vanadium pentoxide catalyst to produce SO_3, and subsequently H_2SO_4 at a target concentration of 93% (Fig. 11). The off-gas from the smelter's roasters enters the sulphuric acid plant (Fig. 12) at an average flow rate of 204,500 m^3/h and composition of 5% SO2, 7% O2, 58% N2, and 30% H_2O. It first enters a quench-condenser where it is cooled to its adiabatic saturation temperature, below 38°C, to produce a weak acid liquid that is neutralized before disposal (DKL Engineering, Inc., 2003). The mist precipitators collect acid mists consisting of fine particulates and employ electric heaters to maintain the temperature of purge air to the electrical insulator compartments. The gas is brought to the drying tower to remove water vapour and then sent to the converter inlet at a new dry gas flow rate of 101,700 m^3/h. SO_2 is converted to SO_3 using a catalyst, at a 99% conversion. Smelter linked H_2SO_4 plants are typically 98.5 to 99.7% efficient in their SO_2 capture

(Schlesinger et al., 2011) from nickel, copper and zinc sulphide ore roasting, and worldwide account for approximately 35% of the sulphur used in sulphuric acid production (ECI, 2016).

After conversion, the gas travels to the absorbing acid tower from the tail gas reheater where the SO_3 is absorbed by the acid such that the gas (90,000 m^3/h) leaving the absorbing acid tower consists of N_2, O_2, and only trace amounts of SO_2, and is released to the atmosphere through the main stack. The absorbing acid pump tank circulates sulphuric acid from the absorbing acid tower, as well as the crossflow stripper, and pumps it to the absorbing acid cooler. From here, a portion travels back to the absorbing acid tower, while the remaining acid travels to the drying acid pump tank. The drying acid system allows for water vapor to be removed from the gas after the cleaning stages, and helps prevent corrosion (DKL Engineering, Inc., 2020). Hydrogen peroxide at 50% concentration and dilution water are added to the sulphuric acid at the absorbing acid pump tank to maintain acid quality specifications. Ambient air is drawn into the process through the weak acid stripper, as well as the crossflow stripper, at 6,000 m^3/h and 10,000 m^3/h, respectively.

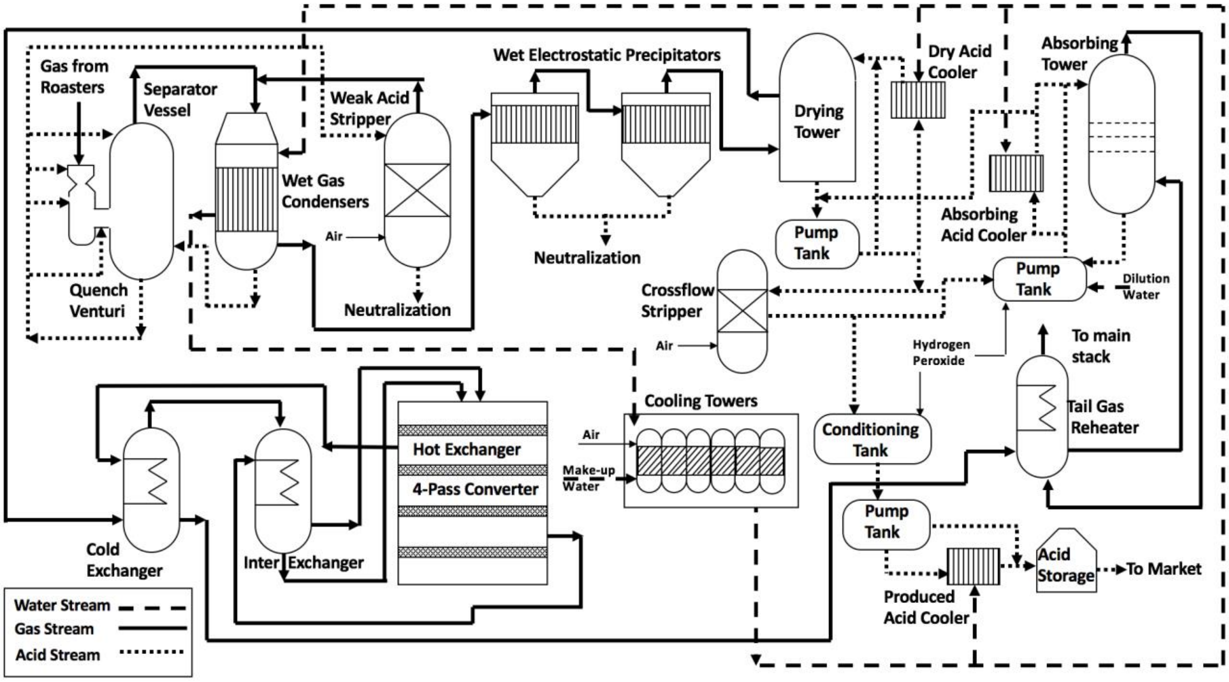

Fig. 11: The sulphuric acid plant process

The final acid is produced at an average flow rate of about 40 tonnes/h. Cooling tower water is used to remove heat from the gas stream leaving the quench-condenser, with the remaining water traveling to the drying, absorbing and product transfer stages to remove heat from the acid (Table 6). It is repurposing of low-grade waste heat from the cooling towers to provide a replacement of electric pre-heaters within the manufacturing process that is the focus of this study.

Table 6: Cooling water flows to equipment

Equipment	Cooling water flow rate (m^3/h)
Wet gas condenser	1,976
Drying acid cooler	2,129
Absorbing acid cooler	1,065
Product acid cooler	1,065

The aim of this study was a systematic LCA comparison between the current process and any impacts that arise from implementing revisions to incorporate a heat recovery and repurposing system from the cooling towers. This novel application of an LCA in mineral processing was first performed within a boundary that encompassed the entire H_2SO_4 plant (Fig. 12). This was followed by a comparative one to demonstrate if a proposed heat recovery system is an appropriate solution to aid improvements in not just long-term economic, but also environmental sustainability.

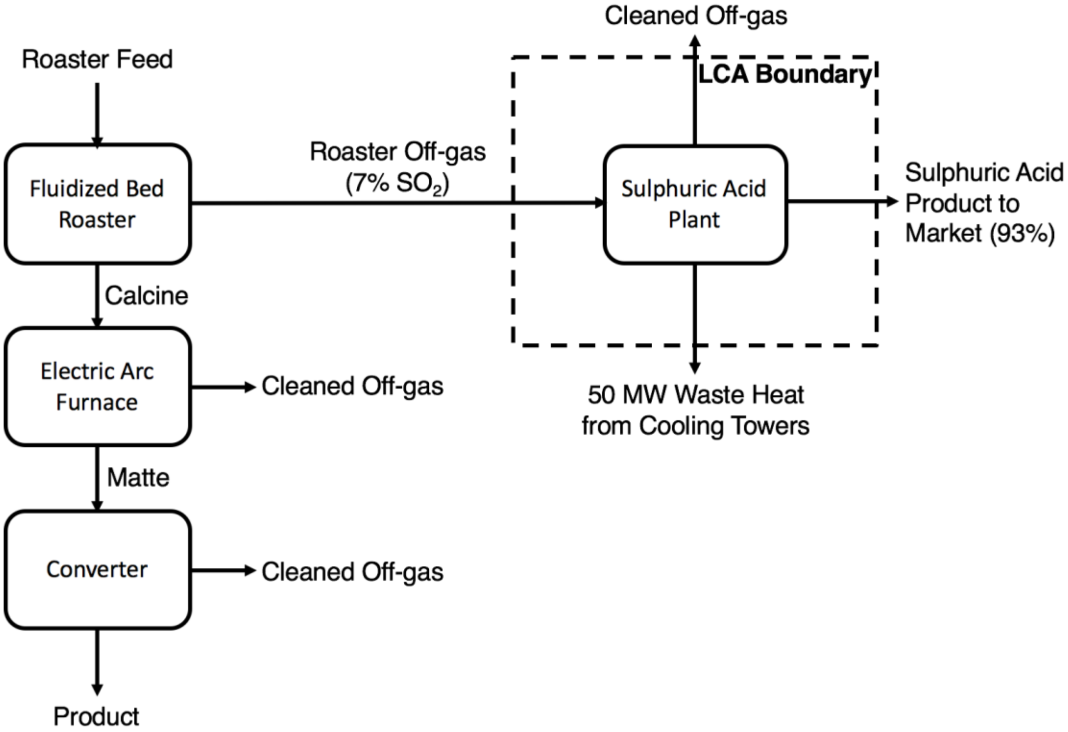

Fig. 12: Boundary for the LCA study of the sulphuric acid plant within the smelter operation

4.3 LCA Methodology and Software

The optimization of the H_2SO_4 plant to reduce primary energy consumption and, reduce associated emissions, was investigated using Thinkstep's GaBi Solutions LCA software (Thinkstep, 2015). The associated databases available consist of over 12,700 datasets, along with over 15,000 plans and processes based on data collected from companies globally (sphera). The databases in GaBi are available for a large variety of industries, including metals and mining, and chemicals.

Operational data used in the software for this LCA was collected from the smelter's sulphuric acid plant. The manufacturing process was modeled in the software to compare the environmental impacts associated with the current system against a new process that incorporates a heat recovery technique within the plant's cooling water system.

An environmental analysis was accomplished using an Impact Assessment methodology called TRACI (Tool for the Reduction and Assessment of Chemical and other environmental Impacts), developed by the U.S. Environmental Protection Agency (sphera). The impact categories assessed by the TRACI methodology were global warming potential, acidification potential, eutrophication potential, and human toxicity potential.

4.4 Data Collection for the LCA

As a basis for comparison between alternative process strategies, the defined functional unit used was 1 kilotonne of 93% H_2SO_4, which is approximately the quantity produced per day by the plant. Table 7 lists the flow rates used in the model of substances entering and leaving the LCA boundary.

Table 7: LCA boundary input and output flows

Equipment	Flow type	Flow rate (m^3/h)
Input to LCA boundary		
Quench Venturi separator	Smelter off-gas	2.05×10^5
Weak acid stripper	Ambient air	6.00×10^3
Crossflow stripper	Ambient air	1.00×10^4
Conditioning tank	Hydrogen peroxide (50%)	9.60×10^{-4}
Absorbing acid pump tank	Hydrogen peroxide (50%)	3.36×10^{-3}
Absorbing acid pump tank	Dilution water	3.54
Output from LCA boundary		
Tail gas reheater	Gas to stack (93% N_2, 7% O_2)	8.95×10^4
Weak acid stripper/mist precipitators	Weak acid to neutralization	100
Product acid pump tank/cooler	Product acid (93%)	22

4.5 The Proposed Heat Recovery System for the comparative LCA

The average inlet cooling water temperature to the tower is 33°C, with a flow rate of about 4,100 m^3/h. In the proposed modifications, heat from the supply cooling water leaving the tower, at an average annual temperature of 18°C, would be recovered using heat pumps. This is to allow for a suitable temperature range of the cooling water necessary for heat pump application, as the tower's inlet cooling water is above the temperature range for the application of typical commercial water-to-air heat pumps.

Heat pumps unlike direct use technologies, such as heat exchangers, use external energy to absorb heat and upgrade it to a useful temperature. The goal for this work was to use heat pumps to allow the cooling tower fans to operate at a decreased speed, thereby reducing their energy consumption. The cooling towers contribute significantly to the overall consumption of electricity of the acid plant, with the four pumps operating at a total average of 305 kW and the six fans at about 180 kW.

The target of the recovered heat is to repurpose it at the mist precipitators in the H_2SO_4 plant in order to replace four existing 60 kW electric heaters (Fig. 13). These heaters ensure that the temperature of purge air provided to the electrical insulator compartments of the mist precipitators is maintained at a minimum of 100°C to prevent condensation. The heat recovery system was modelled using MATLAB (*MATLAB*, 2014) to determine an effective design that would allow for the appropriate amount of energy to be provided by the system, ensuring the purge air temperature is maintained. From the model, it was found that a heat pump bank could be installed near the mist precipitators. The bank would consist of three heat pumps in a parallel arrangement, to raise the ambient air temperature to 85°C, with a 10kW electric heater then employed on the combined outflows to produce a final aitemperature of 100°C. The open-loop, water-to-air units investigated have a capacity of 87 kW and consist of a blower and heat exchanger coils containing a refrigerant to transfer the captured heat from the process water to air. These heat pump units were chosen due to their high capacities for low source temperature applications. The temperature dependent coefficient of performance (COP) of the heat pump units was calculated to be about 5.4, with a power input of about 13 kW. The heat pump specifications are displayed in Table 8.

Table 8: Specifications of heat pump used in recovery system

Heat Pump	Capacity (kW)	Power Input (kW)
Water-to-air	86.75	12.77

Cooling water from the cooling towers would be pumped directly to the mist precipitators heat pump bank from the cooling towers, before continuing to the smelter and acid plant processes. A schematic of the heat recovery system with the boundary used in this LCA study is illustrated in Fig. 13, with the aim of an overall reduction in electricity consumption of the H_2SO_4 plant.

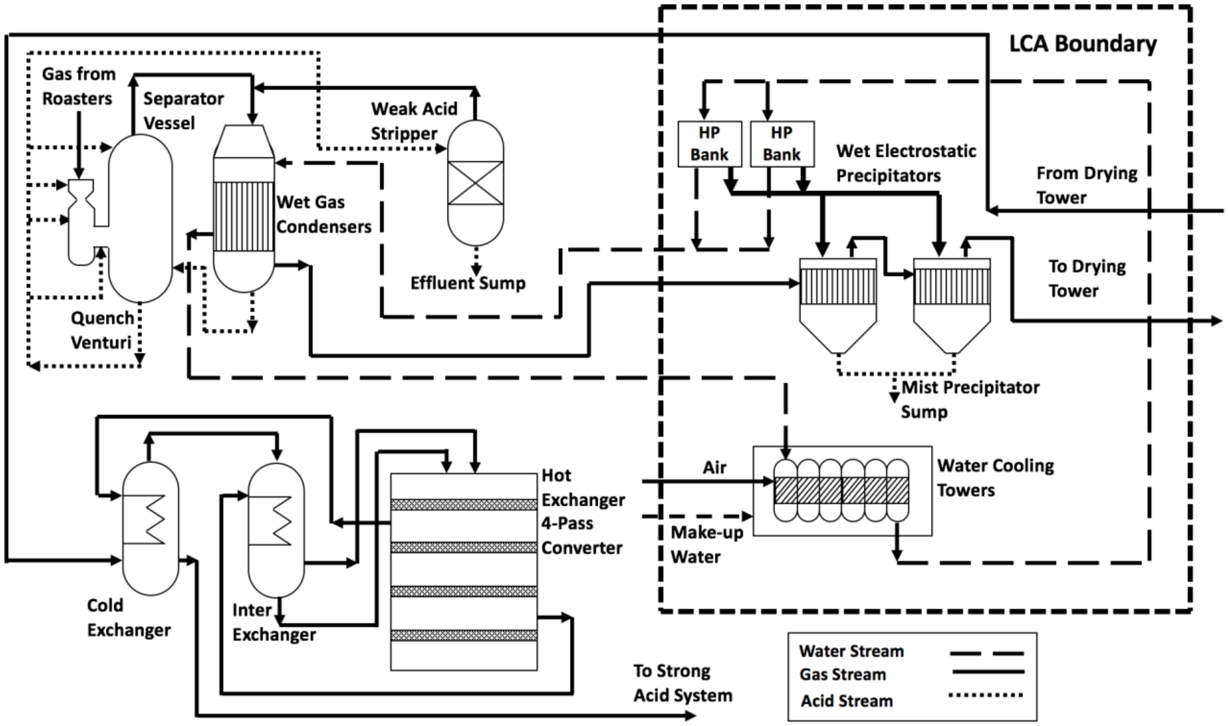

Fig. 13: Heat recovery system on weak acid side with LCA boundary (HP = Heat Pump)

The LCA model used a value of 0.04 kg CO_2/kWh of electricity consumption, relating the quantity of carbon dioxide emissions associated with electricity generation in Ontario, Canada where the plant is located (Government of Canada, 2019). Electricity generation within Ontario is typically low-carbon emitting due to extensive use of hydroelectric, nuclear, wind and solar power generation (Government of Canada, 2019).

The consequence of installing heat pumps would be a 5% year-round heat load reduction for the cooling towers. The electric heaters of the mist precipitators consume 240 kW on average, while the heat pumps used to replace the electric heaters of the mist precipitators, as well as the single electric heater required, use on average 120 kW. This results in about a 50% reduction in electricity consumption from the mist precipitators (Table 9). In addition, as cooling tower fan power is related to the cube of its speed (Baltimore Aircoil Company), a reduction of 5% in fan speed could result in a 14% fall in their energy consumption. The implementation of the proposed recovery system could, therefore, provide economic benefits, whilst reducing waste heat and improving emissions associated with primary electricity generation.

Table 9: Comparison of electricity requirements from implementing heat recovery system

Equipment	Electricity demand for process in place (kW)	Electricity demand for process with heat recovery (kW)	Reduction in electricity demand (%)
Mist precipitators	240	120	50
Cooling tower fans	180	154	14

4.6 Results and Discussion

LCA of the H_2SO_4 Plant

With the LCA scope covering all of the processes shown in Fig. 11, a breakdown of the emissions contributing to the four impact categories investigated was completed (Table 10). Global warming potential was considered for each process within the sulphuric acid manufacturing process through carbon dioxide equivalent (CO_{2eq}) emissions determined on a basis of one kilotonne of acid produced. The consumption of electricity (Table 11) creates CO_{2eq} emissions through the combustion of fossil fuels, which contributes to the environmental impact of the smelter (US EPA, 2020).

Table 10: A breakdown of equipment with emissions contributing to impact categories

Equipment	Global Warming Potential (kg CO_{2eq}/kt)	Acidification Potential (kg SO_{2eq}/kt)	Eutrophication Potential (kg N_{eq}/kt)	Human Toxicity Potential (CTUh/kt)
Cooling towers	6.01×10^{2}	13.8	7.03×10^{-1}	9.58×10^{-5}
Mist precipitators	2.97×10^{2}	6.82	3.47×10^{-1}	4.73×10^{-5}
SO_2 blower	2.28×10^{2}	5.23	2.66×10^{-1}	3.62×10^{-5}
Quench Venturi separator	1.26×10^{2}	2.89	1.47×10^{-1}	2.01×10^{-5}
Drying acid pump tank	1.02×10^{2}	2.34	1.19×10^{-1}	1.62×10^{-5}
Absorbing acid pump tank	1.01×10^{2}	2.32	1.19×10^{-1}	1.61×10^{-5}
Product acid pump tank	7.67	1.76×10^{-1}	8.97×10^{-3}	1.22×10^{-6}
Total	1.46×10^{3}	33.6	1.71	2.33×10^{-4}

Table 11: Electricity requirements of various acid plant equipment

Equipment	Electricity demand (kW)
Quench Venturi separator	102
Absorbing acid pump tank	81.8

Drying acid pump tank	82.3
SO_2 blower	184
Product acid pump tank	6.19
Cooling tower fans	180
Cooling tower pumps	306
Mist Precipitators	240
Total	1.18×10^3

Acidification of soils and water results from elevated sulphur and nitrogen content in the environment, typically leaching from soils to surface waters (Cardoso et al., 2009; Singh et al., 2018) and can create a toxic environment that many aquatic organisms cannot survive (Cardoso et al., 2009). A drop in pH will affect freshwater ecosystems by reducing biological activity, while a decrease in soil pH can result in a nutrient deficiency in plants (Trick et al., 2018; USDA, 2020). The model was, therefore, also used to calculate SO_2 equivalent emissions per kilotonne of acid from the product system. The largest contributors to acidification include the cooling towers, at about 13.8 kg SO_{2eq}/kt, as well as the mist precipitators at 6.8 kg SO_{2eq}/kt. The SO_2 blower, separator, and the drying, absorbing and product acid pump tanks were also contributors to acidification potential, due to electricity consumption.

The eutrophication potential from H_2SO_4 manufacturing was analyzed in terms of kilogram of nitrogen equivalent per kilotonne of acid produced. Eutrophication (the “ageing” of ecosystems) naturally occurs within the environment, but is accelerated by anthropogenic emissions, in particular nutrients such as nitrogen and phosphorus that encourage excessive growth of plants and algae (Chislock et al., 2014). The cooling towers and the mist precipitators were the largest contributors to eutrophication, at 0.7 kg N_{eq}/kt and 0.35 kg N_{eq}/kt, respectively, due to high energy consumption. The SO_2 blower, separator, and the drying, absorbing and product acid pump tanks were also contributors to this impact category.

The final assessed impact category was human toxicity potential, which represents potential harm on human health of a unit of chemical emitted to the environment, with emissions categorized as cancerous or non-cancerous (McKone and Hertwich, 2001). Human toxicity potential is measured in Comparative Toxic Units (CTUh), representing the estimated increase in disease cases in the population per unit mass of the substance released (European Commission, 2011; Eckelman, 2016). Human toxicity potential emissions include heavy metals such as mercury, lead, and cadmium, as well as volatile organic compounds, chlorinated organic compounds and particulate matter. Examples of emissions contributing to human toxicity from electricity generation include nitrous oxides, and SO_2 (Chen et al., 2017).

The highest contributors to human toxicity emissions are the cooling towers, at about $9.6x10^{-5}$ CTUh/kt, as well as the mist precipitators, at $4.7x10^{-5}$ CTUh/kt. Other contributors include the SO_2 blower, separator, and the drying, absorbing and product acid pump tanks. A breakdown of the processes from the manufacturing plant contributing to the examined impact categories is presented Table 11.

Comparative LCA of Heat Recovery System

The proposed heat recovery system is aimed at achieving reductions in electricity consumption associated with electricity consumed by both the mist precipitators and the cooling towers. Fig. 14 illustrates calculated emissions contributing to global warming potential by both the existing arrangement, and with heat recovery and repurposing in place. The total electricity consumption of the mist precipitators and cooling towers was reduced by about 20%. CO_{2eq} emission reductions were achieved with the proposed heat recovery system, with a 5% reduction from the cooling towers and a 50% reduction from the mist precipitators.

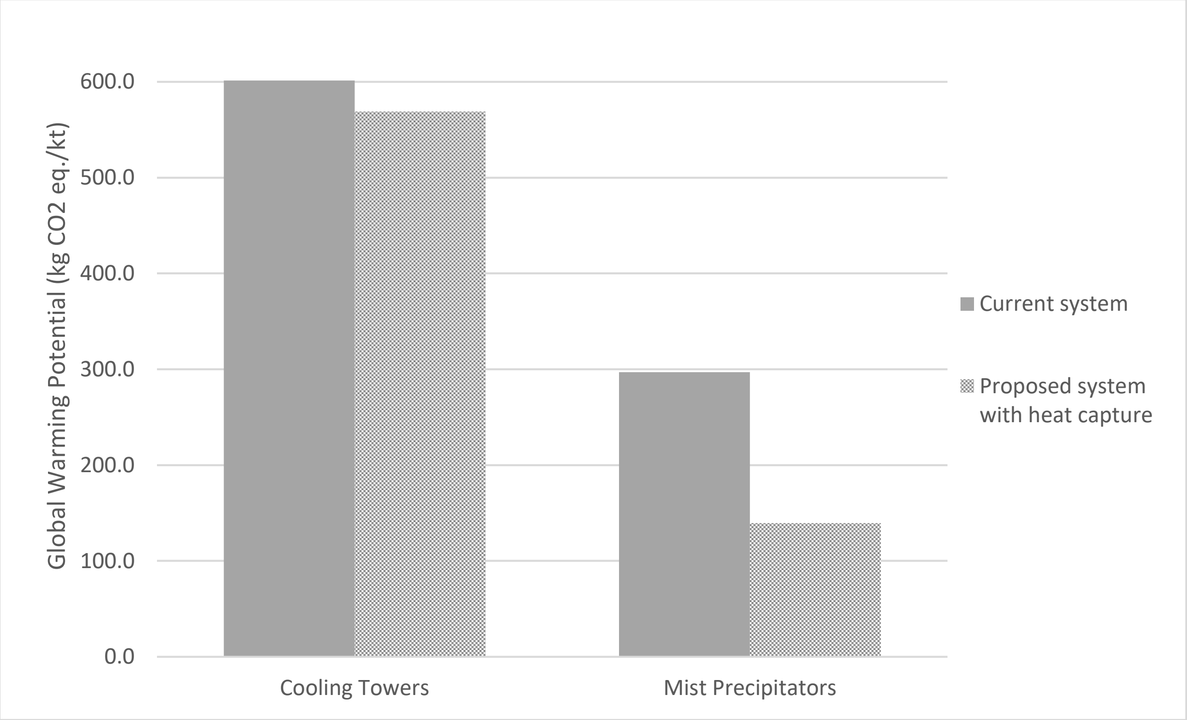

Fig. 14: Global warming potential of processes affected by heat capture per kilotonne of 93% sulphuric acid

The emissions relating to the cooling towers and mist precipitators for a kilotonne of acid produced with the current electric heaters in place, compared against emissions from the implemented heat recovery system, can be seen in Table 12 for the remaining impact categories. Reductions in sulphur dioxide equivalent emissions, as well as emissions contributing to both eutrophication potential and human toxicity potential, were achieved from the cooling towers and mist precipitators.

Table 12: Comparison of impact categories for equipment affected by implementing heat recovery system

Equipment	Acidification potential (kg SO_{2eq}/kt)	Eutrophication potential (kg N_{eq}/kt)	Human toxicity potential (CTUh/kt)
Process in place			
Mist precipitators	6.82	3.47×10^{-1}	4.73×10^{-5}
Cooling towers	13.8	7.03×10^{-1}	9.58×10^{-5}
Process with heat recovery			
Mist precipitators	3.21	1.63×10^{-1}	2.22×10^{-5}
Cooling towers	13.1	6.66×10^{-1}	9.06×10^{-5}

The implementation of a heat recovery system using heat pumps to replace the electric heaters of the mist precipitators allowed for a reduction in emissions from all impact categories analyzed. The total emissions from all processes within the plant, expanding the LCA scope to all of the processes shown in Fig. 13, for each impact category, per one kilotonne of sulphuric acid produced is compared in Table 13.

Table 13: Comparison of total impact category emissions for one kilotonne sulphuric acid produced

Manufacturing scenario	Global warming potential (kg CO_{2eq}/kt)	Acidification potential (kg SO_{2eq}/kt)	Eutrophication potential (kg N_{eq}/kt)	Human toxicity potential (CTUh/kt)
Process in place	1.46×10^{3}	33.6	1.71	2.33×10^{-4}
Process with heat recovery	1.27×10^{3}	29.2	1.49	2.03×10^{-4}

The annual emissions from each impact category was determined by scaling up the model to annual production, and are compared in Table 14. Replacing the electric heaters of the mist precipitators in the recovery system would allow for an annual reduction in emissions from the investigated impact categories by 50% for this equipment. The results from the LCA model therefore highlight the potential to reduce emissions associated with the sulphuric acid manufacturing process through recovery and repurposing of low-grade heat.

Table 14: Comparison of impact category total annual emissions from implementing heat recovery system

Manufacturing scenario	Global warming potential (kg CO_{2eq}/year)	Acidification potential (kg SO_{2eq}/year)	Eutrophication potential (kg N_{eq}/year)	Human toxicity potential (CTUh/year)
Process in place	$5.125x10^5$	$1.177x10^4$	$5.994x10^2$	$8.160x10^{-2}$
Process with heat recovery	$4.460x10^5$	$1.024x10^4$	$5.217x10^2$	$7.100x10^{-2}$

4.7 Conclusion

The developed LCA model for a sulphuric acid plant highlighted the highest contributors to the environmental impact categories analyzed (global warming, acidification, eutrophication, and human toxicity) are the cooling towers and the mist precipitators. LCA is also shown to be a practical tool for predictions in environmental impacts from implementing proposed process modifications relating to heat recovery and repurposing.

Implementing heat pumps to repurpose low-grade waste heat from cooling towers can improve environmental performance by replacing electric process heaters. The comparative LCA quantified a 13% reduction in overall electricity consumption, as well as a 5% reduction in heat load on the cooling towers. This led to a 20% reduction in carbon dioxide equivalent emissions from the mist precipitators and cooling towers, as well as acidification, eutrophication, and human toxicity potentials.

Chapter 5

Conclusions

5.1 Conclusion

The energy intensive mineral processing industry carries out little recovery and repurposing of low-grade waste heat. Many sites, including those of smelters, are located in cold climates, where costly space heating and gas preheating practices are required. Repurposing process waste process heat within these systems can be economically beneficial, but also improve sustainability performance.

Existing recovery systems for industry in general target high-grade waste heat sources with temperatures greater than 100°C, and often use heat exchangers to recycle the heat within the process. In the mining processing industry, heat from smelter furnace off-gas may be also extracted for use in electricity generation, steam production, or process steam preheating.

Whereas, significant low-grade waste heat (<100°C) also exists in industry, for example in process streams, such as cooling water. The recovery of this waste heat may be suitable for use in space heating applications to displace fossil fuel fired boilers, as well as replacing existing process stream pre-heaters. Heat pumps are an effective method to recover and upgrade low-grade waste heat to allow for economically viable application in industry, while reducing a range of environmental impacts.

Industrial cooling towers linked to process cooling circuits expel considerable amounts of low-grade waste heat, making them a suitable option for heat recovery. Recovery and repurposing of this heat with heat pump systems has been demonstrated by incorporation of a novel concept. This was achieved by developing a model using operational data on cooling towers linked to a smelter's sulphuric acid plant. The model allowed for a comparison of economic and environmental impacts between various heat recovery and repurposing scenarios.

The recovery systems proposed incorporated circuits consisting of 3 to 5 heat pumps in parallel to allow for repurposed waste heat to replace on-site process pre-heaters for the weak acid stripper and the mist precipitators. The results show that annual operating costs could be significantly reduced after implementation and the payback period was only 3 years. A reduction in CO_2 emissions by 42% for the associated equipment could also be achieved.

Further improvement in energy efficiency and operating costs would be achieved by a reduced heat load of 5% on the cooling towers due to lower fan power consumption. A reduced heat load can also allow for a reduction in the number of towers required, an approach of significant benefit to sites with aging towers that are scheduled to be replaced.

The comparative life-cycle assessment (LCA) performed on the sulphuric acid manufacturing plant, allowed for environmental impact comparison between the current process and the proposed heat recovery system. A 20% reduction in emissions from the mist precipitators and the cooling tower was achieved in all impact categories investigated, including global warming, acidification, eutrophication, and human toxicity potentials. The emission reductions from the impact categories investigated in the LCA are due to the reduction in electricity consumption with the implementation of the heat pump system. Therefore, the method for electricity generation in the region being investigated has a significant effect on these emissions.

The combined results highlight an opportunity to improve energy efficiency and sustainability in a smelter's sulphuric acid plant. The developed model and LCA whilst used on a sulphuric acid plant, can be applied to other energy intensive sites utilizing cooling towers as heat dispersion systems. The outcomes of the research are significant as they show the potential of, and bring awareness to, the opportunities for low carbon emission heating applications in industry, through recovery techniques of low-grade waste heat.

5.2 Future Work

The heat recovery and repurposing project can be continued in a number of areas, with opportunities for future work including:

- Investigating the implementation of direct use heating schemes to recover waste heat from cooling towers. In industries that use cooling water with an increased temperature compared to the investigated site, heat pumps become a less attractive option for heat recovery. Direct use heating schemes may be a more suitable alternative for the recovery and repurposing of this higher grade energy. For example, systems involving the use of heat exchangers can be modelled, with repurposing to applications with higher heating demands. One particular application of interest could be hot water heating on-site.

- Modelling cooling water temperatures and flow rates from various industrial sites. This will allow for heat recovery methods to be compared for a range of cooling water temperatures and repurposing applications, and for annual cost savings and reductions in CO_2 emissions to be determined. In addition, an LCA could be performed on sites in various regions to illustrate the effects that the method of electricity generation has on emissions from the investigated impact categories. For example, areas that produce electricity from zero-carbon emitting sources, such as hydroelectricity, would have lower emissions than those that use coal as a primary method. This would affect the results of the heat recovery system, with varying emission reductions depending on the region of application.

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