SUSTAINABLE STEAM ON DEMAND FOR THE BAYER PROCESS

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ABSTRACT

In this work, we explore the coupling of Concentrated Solar Thermal to produce the steam required for the Bayer Process used for the conversion of bauxite to aluminium hydroxide. Specifically, we present the use parabolic trough and central receiver tower technologies to produce the required steam for the digestion and electricity demand of a commercial-scale Bayer Process plant. This work explores the integration of different configurations for the production of steam using annual simulations with real direct normal irradiation data. We studied the effect of the solar field size as a critical parameter towards the economic optimisation of the plant. In addition, we analyzed plausible sites based on physical and operational constraints. The results indicated that locations with higher direct normal irradiation deliver lower costs and higher net present value having the potential to incorporate a large amount of CST into the process. From all the sites analyzed, only Learmonth (Western Australia) showed positive NPV and large solar share. For central tower technology with an optimum NPV of M$ 24 and a solar share of 49.4% for a solar multiple 2.2 and 7.3 hours storage. The best scenario was obtained for parabolic trough, a maximum NPV value of M$ 51 and solar share of 35% were obtained for 2 solar multiple and 4 hours storage.

1. INTRODUCTION

Societal pressure is driving novel technologies to be developed for supplying industrial process heat demands via renewable energy sources. Within the industrial processes, Aluminium production industry is one of the largest energy-intensive processes worldwide accounting for about 1% of global greenhouse gas (GHG) emissions (Kermeli et al., 2015). aluminium production is performed in two processes: the Bayer process alumina and the Hall-Heroult electrolytic process (Tabereaux and Peterson, 2014). Steam is necessary for the low temperature stage of the Bayer process (Li et al., 2018) and can be also used for the production of the electricity. The subsequent high temperature stage was coupled with concentrated solar radiation (Davis et al., 2017). However, hybridisation of steam production with renewable energy for the low-temperature step has not been yet attempted in the literature.

One attractive technology that can provide heat and power simultaneously is concentrated solar thermal (CST) (Romero and Steinfeld, 2012). Currently, there are 120 operating solar thermal systems for process heat worldwide (Jebasingh and Herbert, 2016) Parabolic trough concentrators and central tower technology are most widely spread CST systems. These systems can provide steam at temperatures up to 400 and 576 °C.

These two technologies are selected in this work to evaluate the potential of coupling CST to produce process heat and power for the Bayer process. Specifically, the NREL's System Advisor Model (SAM) (Turchi and Heath, 2013) is used as a developing tool to evaluate the steam on demand for Bayer process.

2. METHOD

The SAM was developed to assist solar stakeholders in assessing the performance of renewable technologies for electricity generation (Turchi and Heath, 2013). SAM 2017 9.5 is the version used to provide the optimization of the CST technologies. This software has been previously used in a great number of previous works to evaluate the economic potential of CST technologies including the potential of solar thermal in places like India (Purohit et al., 2013) and Algeria (Boudaoud et al., 2015) in addition to the substitution of natural gas heaters by parabolic trough with thermal energy storage (Poghosyan and Hassan, 2015). The modelling methodology has been performed as follows:

1. Definition of the design and target parameters. The design parameters of the plant are shown In Table 1 for producing a continuous flow of 500 t h^{-1} of steam at 470 °C and 80 bar from liquid water at 25 °C and 1 bar.

Table 1. Design parameters of the plant.

Parameter	*Value*
Locations	Learmonth, Darwin, Gladstone and Mandurah
Boundary Conditions	
Design thermal power (boilers)	447 MW_{th}
Mass Flow Rate Required	500 t h^{-1}
Objective Temperature	470 °C
Pressure	80 bar
Minimum Steam Temperature	25 °C
Minimum Steam Pressure	1 bar
Design Considerations	
Design thermal power (CST plants)	405 MW_{th} (PC) + 51 MW_{th} (BO) 447 MW_{th} (TS)
Storage time	4, 8, 12, 16
Solar Multiple	2 & 3
Boiler efficiency	82%
Economic Parameters	
Natural gas price	\$ 10 GJ^{-1}
Cost of CO_2 emissions	29 in 2020 to \$ 131 t^{-1} in 2065 increasing by 1.052
Emissions of CO_2	51.4 kg J^{-1} of natural gas
Lifetime of the plant	20 years + 3 years of construction
Discount rate	12%
Target Parameters	
Solar input	At least 30%
NPV	At least \$M 20

BO: Boilers
PC: Parabolic Trough
TS: Tower system

The boiler (BO) design thermal power is 447 MW and it is used when the solar thermal plant is not operative. The parabolic trough (labelled as PC) plant cannot produce 470 °C of steam and it is considered that instead, it produces steam at 360 °C and 80 bar (407 MW required) that is superheated to 470 °C by using additional boilers during the operation of the plant (51 MW). The efficiency of the boilers is considered as 82%. The tower system (TS) is able to produce steam at the required temperature and pressure and, therefore, additional heating is only required when the plant is not operative. It is assumed that the lifetime of the plant is 20 years and the construction period is considered be 3 years. The price of natural gas is assumed to be \$ 10 GJ^{-1} during the lifetime of the plant and the discount rate is considered 12%. Finally, two target parameters are defined to evaluate the potential of the plants under investigation: the solar share which is the amount of solar energy incorporated into the system that has to be at least 30% and the net present value (NPV) which has to be at least M\$ 20.

2. Optimization of the solar multiple and thermal energy storage time to reach at least 30% of solar share. This process is developed by a single year using the typical meteorological year of the location selected and assumed the same performance during the lifetime of the plant.

3. Calculate the amount of amount of energy required by natural gas boilers (Q_{NG}) when the concentrated solar plant is not operating:

$$Q_{NG} = Q_{design} - \int_{t=0}^{365} \dot{Q}_{solar} dt \quad (3)$$

where Q_{design} is the designed thermal capacity required and $\dot{Q}_{solar}$ is the heat flow of solar energy at the time t.

4. Obtain the natural gas savings ($NG_{savings}$) by the following expression:

$$NG_{savings} = \frac{(Q_{NG} - Q_{solar})C_{NG}}{\varepsilon_{boiler}} \quad (4)$$

where C_{NG} is the price of the natural gas in \$ per GJ and ε_{boiler} is the boiler efficiency. Q_{solar} is the annual solar energy incorporated into the system.

5. Obtain the carbon dioxide savings ($CO_{2,savings}$) by the following expression:

$$CO_{2,savings} = \frac{(Q_{NG} - Q_{solar})E_{CO_2}C_{CO_2}}{\varepsilon_{boiler}} \quad (5)$$

where C_{CO_2} is the price of the carbon dioxide emissions in \$ per tonne, E_{CO_2} is the emissions ratio in kg of CO_2 per J of natural gas and ε_{boiler} is the boiler efficiency.

6. Calculate the Net Present Value by using the following equation:

$$\mathrm{NPV}_{plant,N} = \sum_{t=0}^{N} \frac{R_t}{(1+i)^t} \quad (6)$$

where N is the lifetime of the project, R_t is the net cash flow at time t and i is the time of the

cash flow. The economic parameters are shown in Table 2 for the parabolic trough and central tower plants.

Table 2. Economic parameters.

Site improvements	25 \$ m^{-2}
Solar field	150 \$ m^{-2}
HTF system	60 \$ m^{-2}
Storage	65 \$ kWh_t^{-2}
Steam generation	90 \$ kW_t^{-1}
EPM	25%
Central Tower	
Site improvements	16 \$ m^{-2}
Solar field	145 \$ m^{-2}
Tower	3 $M
Tower scaling factor	0.0113
Receiver cost	103 $M
Receiver reference area	1571 m^2
Receiver scaling factor	0.7
Storage	24 \$ kWh_t^{-2}
Steam generation	340 \$ kW_t^{-1}
EPM	25%

3. RESULTS AND DISCUSSION

Figure 1 shows a map of the distribution of bauxite mines and refineries for Alumina and Aluminium production smelters in Australia. There are five bauxite mines located in Northern Territory (Nhulunbuy), Queensland (Weipa) and Western Australia (Waroona, Dwellingup and Boddington). Alumina refineries are located in the same states but in different locations with the exception of Nhulunbuy (NT): Naval Base (WA), Pinjarra (WA), Wagerup (WA), Collie (WA) and Gladstone (QLD). In Weipa, the mine bauxite is transported to Gladstone for processing (Website by Rize Design, 2018). The Aluminium smelters are located all over Australia.

The availability of direct normal irradiation DNI data made us choose the following locations for the study: Mandurah (WA) which is close to Pinjarra, Collie and Wagerup; Gladstone (QLD); Darwin (NT) close to Nhulunbuy (NT); and Learmonth (WA) that was selected for having a large DNI values and because it has a port next to it (Exmouth, WA). The DNI data at the different locations were obtained from EnergyPlus™ (NREL, 2018) and AREMI (CSIRO's Data 61 and Clean Energy Council, 2017).

3.1 Parabolic Trough

Parabolic troughs are able to provide temperatures up to 400 °C (Fernández-García et al., 2010). A PTC plant consists of a group of reflectors (usually silvered acrylic) that are curved in one dimension in a parabolic shape to focus sunrays onto an absorber tube that is mounted in the focal line of the parabola (Zhang et al., 2013).

Selected days of operation are shown in Figure 2 for Gladstone. The trough system requires the addition of an additional gas fired boiler to keep the thermal power at the design point all the time. The days when the solar radiation is high (April 14th which corresponds with 104 in Figure 2) most of the power is provided by the solar field reaching a maximum solar share contribution of 77% while the boiler provides 23% of the power required. At night, the fire boilers work at 100% providing all the required power. This plant is able to provide 28.8% annual solar share.

The effect of the storage time on the solar share and the NPV values for the four locations under investigation are shown in Figure 3. The solar share values are constant for 8 hours storage and above. From all the locations, Learmonth delivers the largest solar share (CST %) values ranging between 35 to 40% for 4 hours to 14 hours storage. In this location, the values of NPV also reach the maximum of all the study being M$ 50.8 for 4 hours storage (Figure 3 a). The plants in Gladstone reach the target of solar share when operating with solar multiple 2 and at least 5.29 hours of storage and for a solar multiple 3 in all the cases of study (Figure 3 b). However, in this location, the plants are not economically profitable and the NPV values are negative in all the range of study. This is similar to the Mandurah and Darwin locations where either the solar share or NPV values are not achieving the targets. This is due to the fact that in this location the annual DNI is lower as compared to Learmonth. Therefore, a location with high DNI is critical for producing enough solar radiation that allows large savings of natural gas to be profitable. This depends highly on the natural gas price which is considered as \$ 10 GJ^{-1}. Therefore, higher natural gas prices could lead to implementing the solar thermal plants in locations with lower DNI.

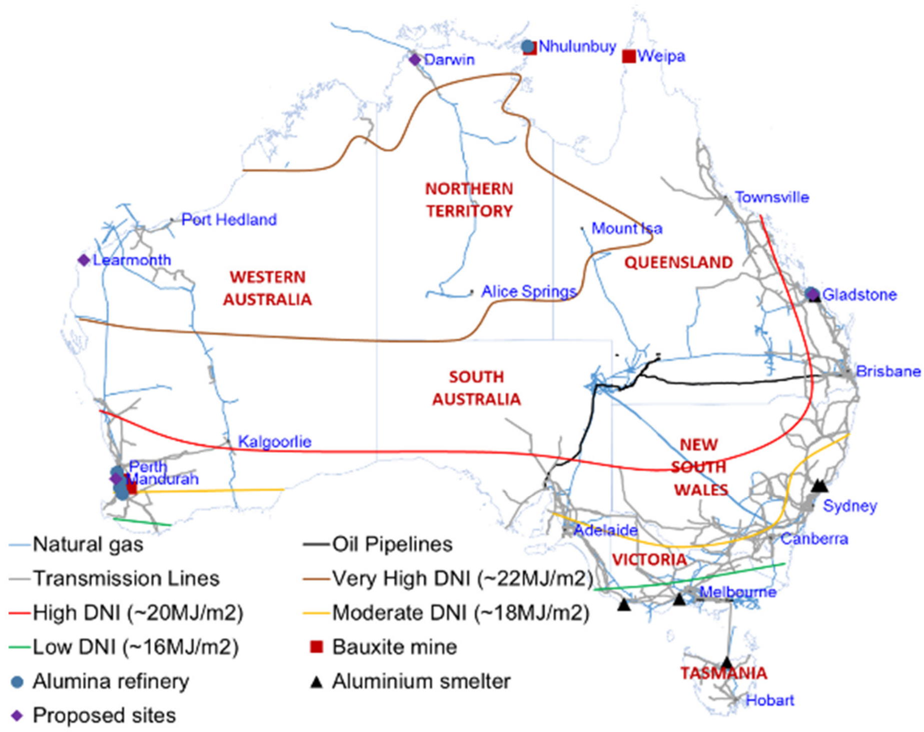

Figure 1. Australian map of Bauxite mines, Alumina refineries and Aluminium smelting sites. The proposed sites under investigation are also presented in the map (Beath, 2012)**.**

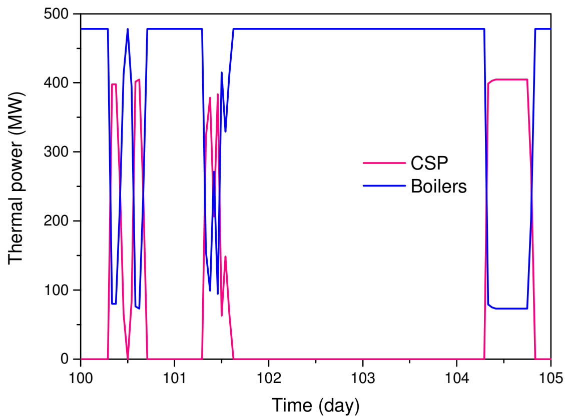

Figure 2. Distribution of energy loads from CST parabolic trough plant (solar multiple 2 and 4 hours storage) located in Gladstone and boilers over selected days of a year.

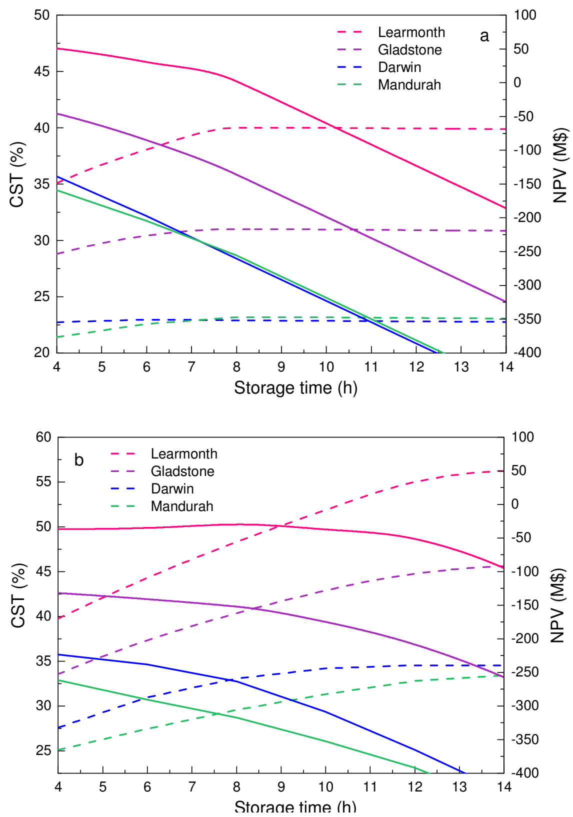

Figure 3. CST % (dashed lines) and NPV (solid lines) values in million $ for parabolic trough CST plant in three locations with several storage times and solar multiples of a) 2 and b) 3.

The plant in Learmonth with 4 hours storage has been further investigated. An analysis of all the solar multiple values from 2 to 3 was performed in order to find the best possible solar multiple for that storage time. Figure 4 shows these results. The solar share values increase with the solar multiple while the NPV values decrease. There is not a maximum value that achieves the best NPV and therefore the maximum is achieved by solar multiple 2. This can be explained by the fact that the increase in the investment is not counteracted by larger natural gas and CO_2 emissions savings. However, it can be chosen to obtain larger solar share by sacrificing benefit with the expectancy of having larger benefit in future years when the natural gas price increases. A maximum NPV value of M$ 51 is achieved for a solar multiple 2 and solar share of 35%.

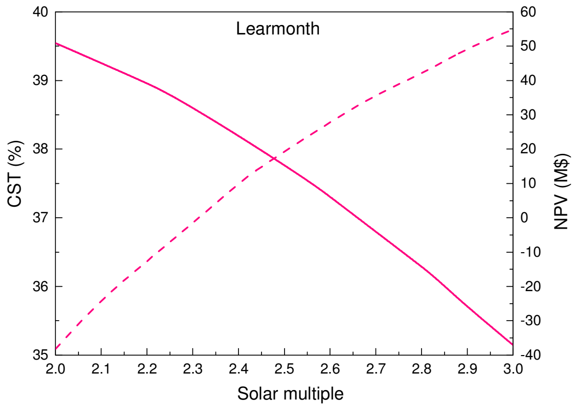

Figure 4. Effect of solar multiple in the CST % (dashed line) and NPV (solid line) values in million $ for a parabolic trough plant located in Learmonth with 4 hours storage time.

3.2 Central Tower

In this technology, a field of sun-tracking reflectors, called heliostats, that reflect and concentrate the sun rays onto a central receiver placed in the top of a fixed tower (Zhang et al., 2013). This technology is able to provide a wide range of temperatures up to 576 °C when a mix of molten salts is used as a heat transfer fluid (Fernandes et al., 2012).

The central tower CST plant results are shown in Figures 5, 6 and 7. Figure 5 shows the thermal power distribution over the days 10th to 15th of April in Gladstone, analogously to Figure 2 for parabolic trough plant. In this case, the central tower system is able to provide 100% of the thermal power required to produce the steam at 470 °C and 80 MPa. This is because the central tower technology is able to provide larger concentration ratios as compared with parabolic troughs (Zhang et al., 2013). In fact, this CST technology is able to produce steam at temperatures around 560 °C in which the limitation is the heat transfer fluid working temperature, in this case, the solar salt $NaNO_3/KNO_3$ (Sabharwall et al., 2010). This plant configuration achieves a maximum solar share of 42.26% for solar multiple 2 and 62.7% for solar multiple 3, both at 14 hours storage.

Figure 6 shows the solar share and NPV values achieved at every location under investigation and for solar multiple 2 and 3 across storage times from 4 to 14 hours. A solar share larger than 30% is achieved in most of the cases of study, except for storage times below 6 hours in Mandurah (Figure 6 a). Learmonth achieves positive NPV for solar multiple 2 and 3 between 6 and 8 hours of storage and at 14 hours storage respectively. This can be caused by the fact that the investment in central towers is first, larger as compared with parabolic trough systems and second it cannot counteract the savings in natural gas similarly with many of the cases of the parabolic trough. The maximum NPV achieved with this technology is M$ 17.4 which lays slightly behind the targeted value. The maximum %CST incorporated in the process is achieved by using a solar multiple 3 and 14 hours storage with a 78% of the total power.

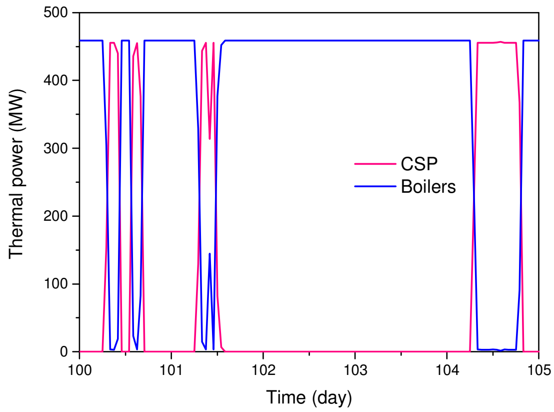

Figure 5. Distribution of energy loads from CST central tower plant (solar multiple 2 and 4 hours storage) located in Gladstone and boilers over selected days of a year.

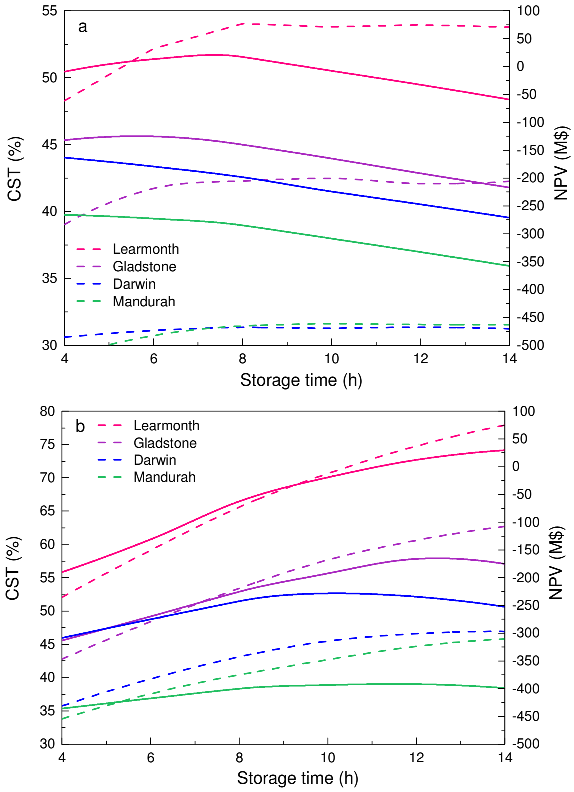

Figure 6. CST % (dashed lines) and NPV (solid lines) values in million $ for central tower CST plant in three locations with several storage times and solar multiples of: a) 2 and b) 3.

An optimization of the NPV in Learmonth for solar multiple 2 and 8 hours storage is shown in Figure 7. It can be observed that a maximum NPV value of M$ 20 is achieved for a solar multiple 2.15. Under these design conditions, the maximum annual solar shared achieved is 49.7% which is 14.7% larger than parabolic trough case for solar multiple 2 and 4 hours storage shown in Figure 4. Additionally, the central tower plant achieves nearly 60% lower NPV. This is mainly driven by the largest investment required in the concentrated solar collection in central tower plants. Finally, the optimum case in storage time was obtained by a solar multiple 2.2 and 7.3 hours thermal storage in a separated case. In this case, the maximum achievable NPV was M$ 24 and 49.4% solar share. This NPV is also 63% lower compared with the best case scenario of the parabolic trough. This could be explained by the fact that the combined heliostat field, tower and receiver costs is larger for central tower technology as compared with parabolic trough plant. However, parabolic trough plant has to work in combination with a natural gas heater during the whole year of operation which capital investment was not considered in this work as it can be taken from the actually installed boilers in the alumina processing plants.

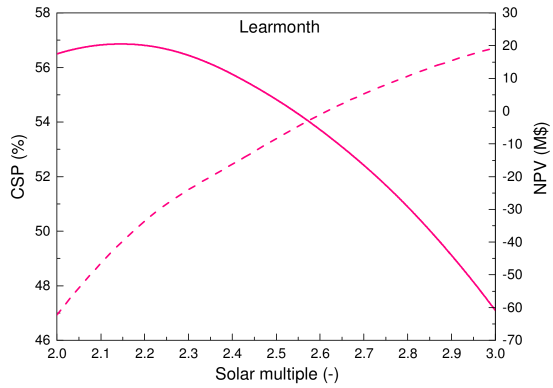

Figure 7. Effect of solar multiple in the CST % (dashed line) and NPV (solid line) values in million $ for a central tower plant located in Learmonth with 8 hours storage time.

4. CONCLUSIONS

A techno-economic analysis of the potential to incorporate CST into the alumina refinery process was investigated for four key locations in Australia. The results indicated that locations with higher direct normal irradiation deliver lower costs and higher net present value having the potential to incorporate a large amount of CST into the process. The best scenario shows a maximum NPV value of M$ 51 and solar share of 35% for parabolic trough technology using a solar multiple 2 and 4 hours of thermal storage. For central tower technology, the optimum NPV was M$ 24 and the %CST was 49.4% for a solar multiple 2.2 and 7.3 hours thermal storage. Both plants were located in Learmonth (WA) showing the best target values in both configurations. This work demonstrated the need of having large values of DNI to make steam production with CST economically interesting. However, having a large solar resource will require the installation of the alumina refinery far from the bauxite mines and transporting the bauxite to that locations. Further investigation has to be performed accounting for the transportation cost of the bauxite to key locations in Australia where the solar resource is high.

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