A FEASIBILITY STUDY ON HYBRID SOLAR-GEOTHERMAL POWER GENERATION

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ABSTRACT

A major problem faced by many stand-alone geothermal power plants, particularly in arid regions such as Australia, is the adverse effects of the diurnal temperature change on the operation of air-cooled condensers which typically leads to fluctuations in the power output. These adverse effects could extend from days to seasons, with the worst scenario taking place in summer time during afternoons. The motivation behind the present study is to introduce a direct/indirect solar heating system to moderate the impact of diurnal temperature change and where possible boost the power output. The ultimate goal is to explore the potential benefits from the synergies between the solar and geothermal energy sources. For this purpose two hybrid solar-geothermal power plant concepts based on the Organic Rankine Cycle (ORC) were analysed. Detailed simulations of hourly ambient temperature and hourly solar irradiance were carried out. Two different alignments for solar parabolic trough systems were examined. In addition, the hour-by-hour performances of the hybrid plants under various operating conditions were evaluated. The results showed that by combining the solar heating system, a typical ORC type geothermal plant can achieve a stable and improved performance. Furthermore, up to 29% increase in the net electrical power output and 16.6% increase in the thermal efficiency can be realised by hybridising solar and geothermal energy during the peak demand.

1. INTRODUCTION

The rising energy demand, the limited supply of fossil fuels and their detrimental environmental impacts (e.g. global warming) have intensified the worldwide search for cleaner sources of energy. Of different alternative energy sources, solar, wind, geothermal and biomass have received a particular attention because of their renewable nature and negligible CO_2 footprints. Among renewable energy sources, geothermal energy has a special place largely because of its vast worldwide resources (e.g. based on current electricity demand the Australian geothermal resources can power up the nation for 26,000 years) and its capacity to provide base-load electricity due to non-intermittent nature of geothermal energy. One of the key technologies to harness geothermal energy is Enhanced Geothermal System (EGS), which is also known as the Hot Dry Rock technology. It has been accredited to be the predominant technology in exploring and demonstrating the potential of geothermal energy in Australia. The EGS technology is based on extracting the heat from hot granite formations which are distributed at about 3-5 km deep underground. It involves a drilling process, a hydraulic stimulation process, and a heat extracting process. The hydraulic stimulation process creates a heat exchanger deep underground within the hot granites (as high as 250 °C). Water is then pumped into the injection well, heated by the hot granite, returns with the heat to the ground, and comes out of the production well. On the ground, the electricity is then generated from the heat using a geothermal power plant typically in the form of a binary ORC unit (DiPippo, 2005; Barry and Tony, 2006).

A major impediment in the development/deployment of EGS in Australia is the cooling issue. Most geothermal resources in Australia are located in the centre of the continent (e.g. Great Artesian Basin) which is an arid region with limited supply of water. As a result, air-cooling is the most viable option for satisfying cooling demands in power plants. However, the diurnal temperature change (i.e. variation of ambient temperature between day and night) in these regions is usually quite drastic, particularly in summer, and as such air-cooling becomes ineffective during some parts of the day. This, in turn, leads to a considerable reduction in thermal efficiency and fluctuations in the power output (Imroz Sohel, Sellier et al. 2009). For instance, at Birdsville geothermal power plant which is located in the middle of the Great Artesian Basin in the State of Queensland (Australia), the relationship between the ideal Carnot efficiency of the power plant and the air temperature in two typical summer days is shown in Figure 1. As can be seen, due to diurnal temperature variations the ideal Carnot efficiency drops by as much as 9% for a day with an average diurnal temperature range (DTR) and 14% for a day with an extreme DTR.

Another inherent problem in implementation of EGS is the low overall efficiency of the power plant due to the low enthalpy of typical geothermal resources. A higher energy utilisation rate is possible if higher grade forms of energy (e.g. solar energy) are incorporated into the system in an attempt to increase the average temperature of the working fluid in the ORC and, thereby, uplift the thermal efficiency.

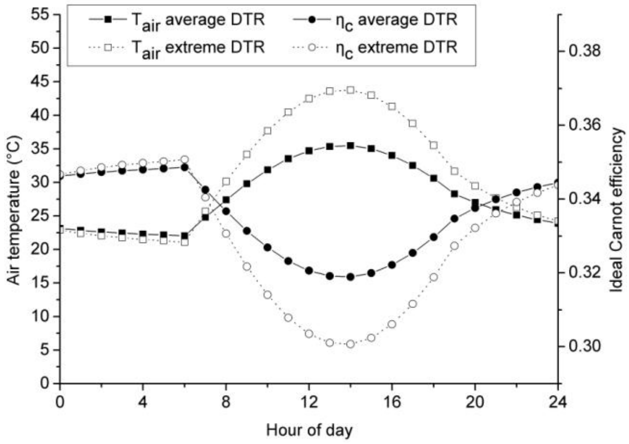

Figure 1: Relationship between the air temperature and the ideal Carnot efficiency in two typical summer days. DTR is the diurnal temperature range. For the heat source, T_{high}=180 °C.

The issues of air-cooling and low enthalpy resource associated with the application of EGS in arid regions can be alleviated if geothermal and solar energies are effectively hybridised in a suitable technology platform. The rational is that given the solar irradiation curve in a typical day is quite similar to that of the ambient air temperature, a hybrid system is expected to cope well with the detrimental effects of the hot weather on the plant and minimise the extent of fluctuations in the power output. Equally important, many existing and potentially suitable geothermal sites for EGS applications are endowed with high quality solar irradiation and, hence, by introducing solar energy into a geothermal power cycle a substantial enhancement of the thermodynamic efficiency and the net electrical output can be achieved.

The concept of hybrid solar-geothermal power generation has been investigated in the past. Mathur (1979) examined a number of potential solar-geothermal hybrid concepts based on a binary cycle arrangement (i.e. when the geothermal heat carried by brine is passed on to a secondary working fluid which runs the power cycle). He demonstrated that solar heating provides the geothermal plant with a higher steam quality which is a thermodynamic advantage over the stand alone system, and also enables the hybrid plant to make a more efficient use of the low-medium grade geothermal resources. However, Mathur's article (Mathur, 1979) did not provide a detailed hourly or daily performance of the relevant hybrid plants. Lentz and Almanza (Lentz and Almanza, 2006a; Lentz and Almanza, 2006b) discussed a hybrid solar-geothermal system which can increase the power generation by introducing a parabolic solar trough system. They concluded that for the Well number '408' at Cerro Prieto IV site in Mexico, an increase of 10% of the steam quality could be achieved by introducing solar energy using a solar concentrator area of 9,250 m^2. Lentz and Almanza,, however, did not consider a binary cycle arrangement for the geothermal component of their proposed solar-geothermal plant despite the fact that such cycles account for nearly 45% of the existing geothermal power plants around the world (Bertani, 2010). Problems associated with not using a binary arrangement can be quite serious within the context of hybrid solar-geothermal power plants. The direct contact between high temperature solar collectors and the brines in the single or double flash non-binary systems can exacerbate corrosion. This not only limits the performance of the hybrid plant, but may also accelerate the corrosion of the solar parabolic trough facilities, preventing it from long-term operation.

Astolfi and co-workers (Astolfi et al., 2011) carried out a techno-economic assessment of a hybrid solar-geothermal concept whereby an ORC based geothermal plant in a binary arrangement was combined with a concentrating solar power system. These authors showed the positive effect of hybridisation and noted that the overall plant performance was affected by the ambient temperature (i.e. cooling), although no discussion or solution on this issue was provided. Imroz-Sohel and co-investigators (Imroz-Sohel et al., 2009) improved the efficiency of geothermal power generation by utilising a water-augmented air-cooled condenser system rather than an air-cooled condenser to generate more power during peak demand periods in hottest days of the year. They found that a maximum power generation increase of about 6.8% on the hottest day can be achieved. However, in areas where water is scarce (e.g. Australia), the above concept would still be difficult to implements and no economic advantage can be gained.

Given the above background, in this paper the results of a comprehensive feasibility study on two ORC based (i.e. binary arrangement) hybrid solar-geothermal power plant concepts are presented. The focus of the study is to assess the effectiveness of these power plant concepts in resolving some of the key challenges associated with geothermal power generation in arid regions, specifically fluctuating power and low thermal efficiencies due to ineffective air-cooling.

2. METHODOLOGY

In this section a brief description of simulation methodology and its theoretical basis is provided. To facilitate the simulation and analysis, Birdsville (Queensland: 25.9°S, 139.35°E, Elevation: 47 m) the site of Australia's first geothermal plant, was selected as the reference site. All simulations were performed using the process simulation package HYSYS.

2.1 System Configuration

Two hybrid solar-geothermal power plant concepts were considered in this study. The Hybrid Concept (A), see Figure 2, consists of an ORC plant configured in a binary arrangement and a direct solar heating system comprising a solar booster. The geothermal energy is harnessed by the evaporator while the solar booster harnesses the solar energy from the solar trough system. The working fluid within the ORC plant (Isopentane) is pumped to the evaporator first where it collects the geothermal heat while passing through the evaporator. The working fluid then enters the solar booster unit where its temperature is further increased by solar thermal energy. The expansion of the working fluid in the turbine unit allows the combined solar and geothermal heat collected by the working fluid to be converted into mechanical work and ultimately electricity. In the Hybrid Concept (A) the geothermal resource (PW, production well) is specified to have a constant temperature of 180 °C, a constant productivity of 50 kg/s and a constant pressure of 90 bar. Isopentane and air are selected as the working fluid and the cooling agent, respectively within the ORC plant. A pressure drop of 50 kPa is set in both the tube and shell side of the evaporator and the condenser. The adiabatic efficiencies of the pump and turbine are fixed at 80%. The solar booster is simulated using a single heater unit with no pressure drop. The Hybrid Concept (B), see Figure 3, represents a more complex configuration but will provide a better power profile and a greater operational flexibility. The ORC component of the Hybrid Concept (B) is very similar to that described earlier for the Concept (A), but its solar heating unit operates in an indirect fashion. In Concept (B) the solar heating unit consists of a heat exchanger, two thermal storage tanks, and a solar booster. During the day when solar energy is abundant, a certain amount of solar energy is stored in the hot tank (see Figure 3) where the collected heat is regulated for reuse whenever the solar energy becomes weak or unavailable.

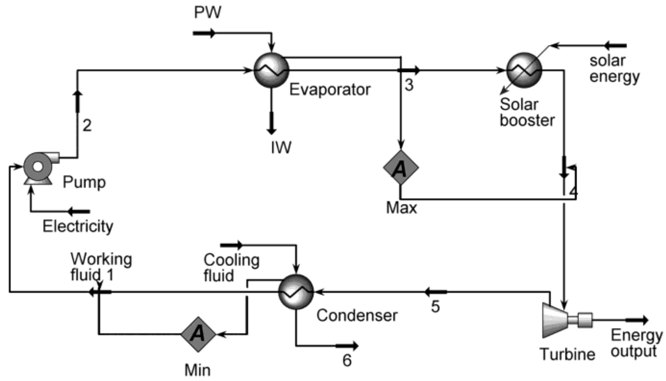

Figure 2: The Hybrid Concept (A): an ORC plant with a direct solar heating system.

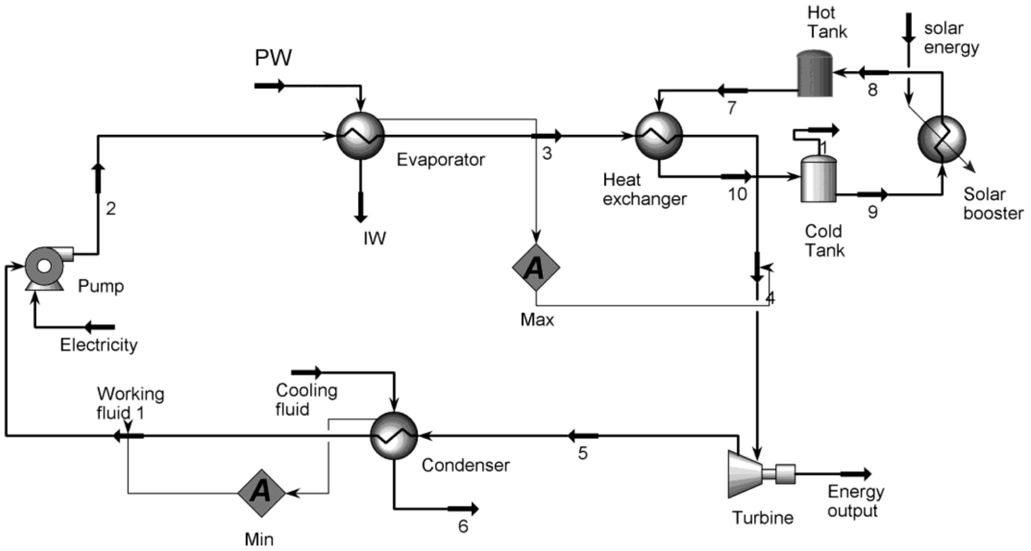

Figure 3: The Hybrid Concepts (B): an ORC plant with an indirect solar heating system.

In the ORC plants, a certain heat sink (the air) and a certain heat source (the geothermal resources plus the solar energy input) will give a maximum available work obtainable by optimizing the operating parameters of the working fluid; wherefore, three methods were applied in the HYSYS models to ensure that the maximum performances of the hybrid plant were achieved for every hour of operation: i. the working fluid entering the turbine and leaving the condenser was set always saturated; ii. two adjusters were used to maintain a 5 °C minimum temperature approach in both the evaporator and the condenser; iii. the flow rate of the working fluid was analysed and its optimum value was specified.

2.2 Performance Indicators

Three attributes of hybrid plants were selected as performance indicators for comparison and analysis. These were the ideal Carnot efficiency, the thermal efficiency, and the maximum net electrical output. Since the net power gain is the final product, the maximum net electrical output is regarded as a more important attribute.

The ideal Carnot efficiency can be obtained from Eq (1), where T_{high} is the temperature of the geothermal heat source in Birdsville (defined as 180 °C) and T_{low} is the temperature of the heat sink, i.e. the ambient temperature at Birdsville. Both units are in degree Celsius. The maximum thermal efficiency of the hybrid plant is obtained from Eq (2), where the thermal power input by solar system, Q_{solar}, is calculated using Eq (3). The expression for calculating the maximum net electrical output is represented by Eq (4). Note that by setting Q_{solar} to zero, Eq (2) reduces to the standard expression for calculating the thermal efficiency of a power plant. All the coefficients in Eq (4) are ratios of the electrical work to the shaft/mechanical work. For instance, W_T is the work generated from the turbine with a 80% adiabatic efficiency, while only 93% of the work can be converted into electricity due to the loss in the conversion processes.

$$\eta_C = 1 - \frac{T_{low} + 273.15}{T_{high} + 273.15} \quad (1)$$

$$\eta_{max} = 1 - \frac{Q_C}{Q_E + Q_{solar}} \quad (2)$$

$$Q_{solar} = sG\eta_{solar} \quad (3)$$

$$W_{net}^{max} = 0.93W_T - \frac{W_P}{0.93} - 0.022W_C \quad (4)$$

2.3 Hourly Air Temperature Simulation

The TEMP air temperature model defined by Parton and Logan (Parton and Logan, 1981) is adopted here for predicting the hourly air temperature in two typical cases during summer, namely: (i) the hourly air temperature in a day with an average diurnal temperature range (DTR) and (ii) the hourly air temperature in a day with an extreme DTR. The parameters used in the model are specified according to the annual daily air temperature data in Birdsville (see Figure 4, adopted from Meteorology, 2009), namely, for the day with average DTR: T_{min} = 21.7 °C, T_{max} = 35.5 °C. ΔT = 13.8 °C; and for the day with extreme DTR: T_{min} = 20.5 °C, T_{max} = 43.8 °C. ΔT = 23.3 °C. It should be noted, though, that the TEMP model can give a good estimation in clear days but might have errors in cloudy days (Reicosky et al., 1989).

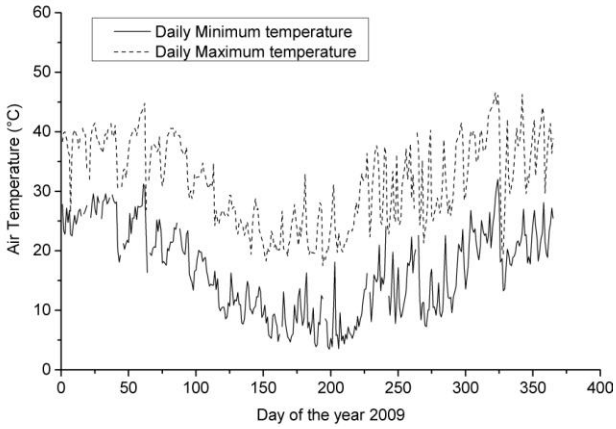

Figure 4: Annual daily maximum and minimum air temperature at Birdsville in 2009.

2.4 Estimation of Solar Irradiance

The estimation of local solar irradiance is performed according to the method proposed by John and co-workers (John and William, 1991). The standard LS-3 Solar trough assembly, which is specified with a concentration ratio of 85 and a fixed solar-thermal efficiency of 0.7, was used in our simulations for both hybrid plant concepts. Initially two alignments were considered for parabolic collectors in an attempt to achieve a higher overall usage of the solar irradiance. These were the North-South alignment (N-S) and the East-West alignment (E-W). The calculation of effective solar irradiance on the collectors was implemented according to the methodology introduced by Lentz and Almanza (Lentz and Almanza, 2006b). While a typical day is not necessarily clear and as such the solar irradiance might be affected by local weather conditions, it is of practical importance to take the impact of weather conditions on solar radiation into consideration. A study that takes account of atmospheric transmittance coefficient and difussive component of the global irradiation in various weather conditions has been done; however, due to space limitation, these results will be subjected to future journal publication.

3. RESULTS AND DISCUSSION

The modelling results of the hourly air temperature in days with average DTR and extreme DTR are presented in (Figure 5). These two curves are then utilized to analyse the effect of air temperature on the performance of the hybrid plants. The modelling result of hourly solar irradiance in Birdsville is also shown in Figure 5 for a particular day (Dec.27th, 2009), where the air temperature generally follows a similar variation to that exhibited by the solar irradiance but with a two-hour delay.

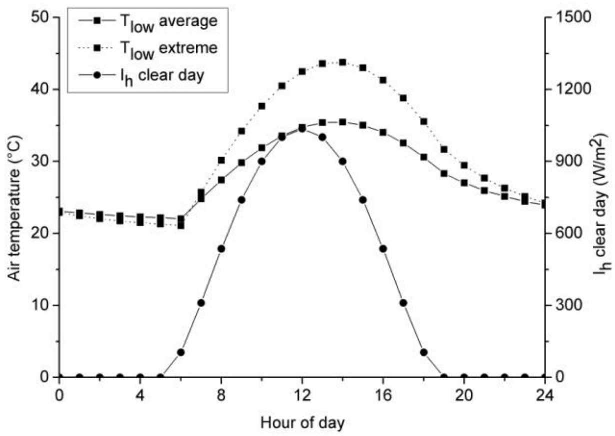

Figure 5: Hourly solar irradiance in a clear day combined with hourly air temperature in typical days with both an average DTR and an extreme DTR.

The result of alignment effect on the performance of solar heating system was not presented here in details due to space limitation; nonetheless, it shows that during summer the North-South alignment has generally a higher daily solar irradiation than that of the East-West alignment; while during winter the East-West alignment shows a larger daily solar irradiation. Given the above background and noting that summer is the time when problems become more severe for geothermal power plants, only the North-South alignment was chosen for detailed simulation and analysis of

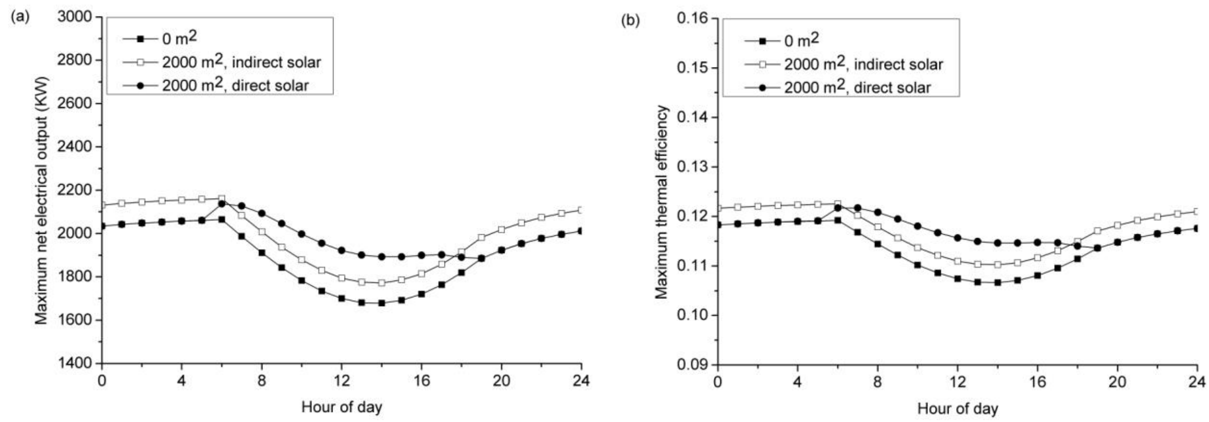

Figure 6: Performances of the hybrid power plants in a clear day with an average DTR, the collector surface area is 2000 m^2, (a) the maximum net electrical output, and (b) the maximum thermal efficiency.

the hybrid power plant.

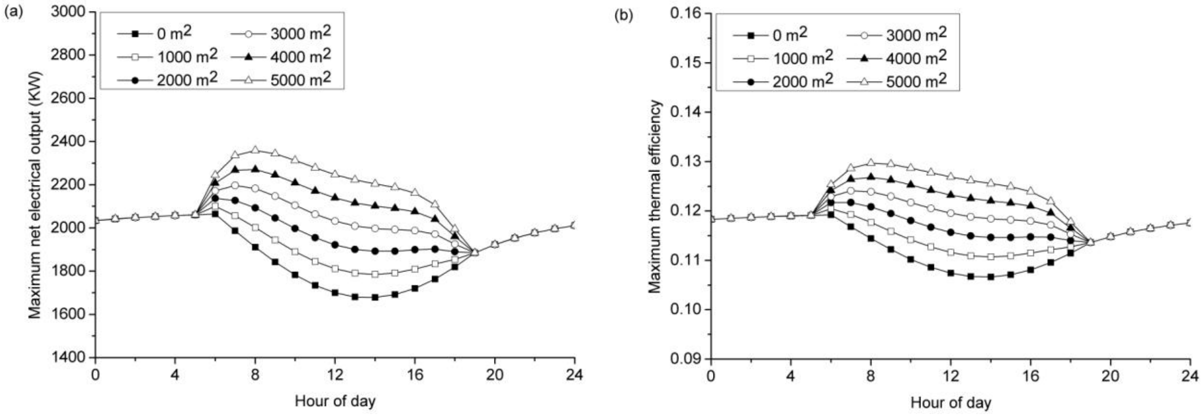

Figure 7: Performances of the hybrid direct solar-geothermal plant in relation to the collector surface area, operated in a clear day with an average DTR, (a) the maximum net electrical output, and (b) the maximum thermal efficiency.

The influence of direct or indirect hybrid concepts (i.e. Concepts A and B) on the performance of a hybrid solar-geothermal plant was analysed following the procedures outlined in Section 2. The comparison between Hybrid Concepts (A) and (B) for a fixed collector surface area of 2000 m^2 operating in a clear day with an average DTR has been summarised in Figure 6. From the results shown in Figure 6, it is evident that both hybrid concepts yielded uplifted overall performances of the hybrid power plants but in a quite different way. The improved performances included an increased overall net electrical output (see Figure 6.a) and a higher overall thermal efficiency (see Figure 6.b). The Hybrid Concept (B) improved the overall performance evenly during the day by storing parts of the peak solar energy when the solar irradiance was abundant, and distributing it evenly for reuse when the solar irradiance was scarce, while the Hybrid Concept (A) yielded much better performances during the daytime from 7am to 5pm by incorporating the solar energy directly, and showed no improvements after 9pm and before 5am when the solar energy was unavailable. Even though the total solar energy input during the day was the same for the two hybrid concepts, customers have two choices according to their types of energy demands. The Hybrid Concept (A) is recommended when the customers are looking for a lower cost technology which specifically increases the peak time performances of a geothermal power plant. One example can be found in big cities where peak energy demands are prominent and the market price of the peak time energy is much higher than that of the off-peak time, the Hybrid Concept (A) can, thereby, yield a greater profit in this case as more power is generated during the peak time. Another example is in arid regions where the performances of a geothermal power plant plunge during afternoon due to the detrimental effects of a hot climate. By applying the Hybrid Concept (A), such phenomenon can be effectively avoided. Accordingly, the Hybrid Concept (B) is chosen if the customers simply require an overall even improvement of the performances of a geothermal power plant. Overall, the Hybrid Concept (A) shows the abilities to not only substantially boost the peak time power output, but also ease the fluctuating performances of a geothermal power plant in arid regions due to the hot climate, while Hybrid Concept (B) simply provided an overall improvement in the performances of a geothermal power plant. Given the above comparisons, the Hybrid Concept (A) appears to be more favorable.

The power generating intensity of the solar heating systems, mainly determined by the collector surface area, has a direct impact on the overall performances of a hybrid solar-geothermal power plant. Based on the Hybrid Concept (A), the performances of the hybrid power plant operated in a clear day with either an average or an extreme DTR were plotted against the collector surface area, which have been summarized in Figure 7 and Figure 8. As shown in both figures, the overall performances of the hybrid power plant were directly proportional to the collector surface area; however, in periods when the solar energy was less available or unavailable, the collector surface area has weaker impacts or even no effects on the performances of the hybrid power plant. Furthermore, by having the same collector surface area, a greater uplift was observed in the daytime with an

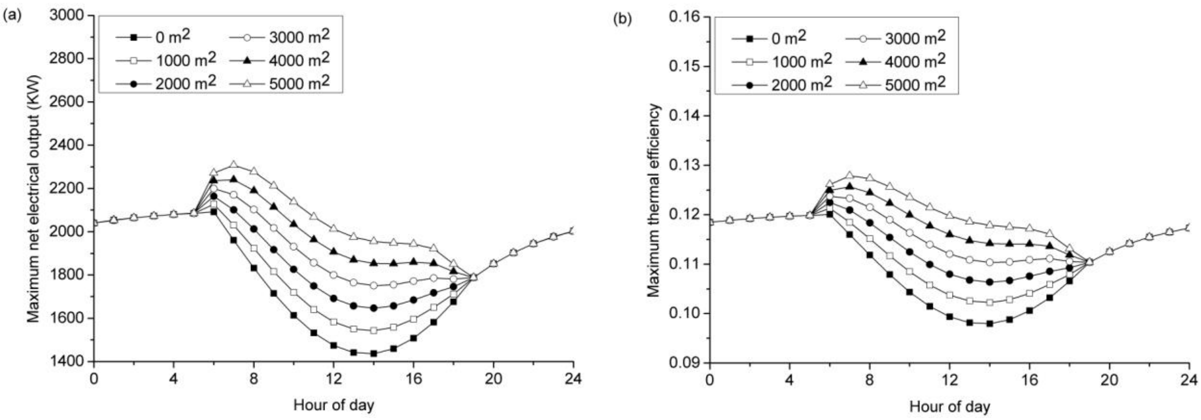

Figure 8: Performances of the hybrid direct solar-geothermal plant in relation to the collector surface area, operated in a clear day with an extreme DTR, (a) the maximum net electrical output, and (b) the maximum thermal efficiency.

extreme DTR (see Figure 8) than with an average DTR (see Figure 7) for both the net electrical output and the thermal efficiency. Since higher performance simply requires more collector surface area, which inevitably involves higher cost, a direct solar heating system with a collector surface area of 2000 m^2 and 4000 m^2, respectively operated in a clear day with an average DTR and extreme DTR, were estimated as a cost effective configuration, by which a relatively stable and improved performances of the hybrid power plant can be achieved. It is calculated that the former configuration (2000 m^2), in turns, increased the performance of the hybrid power plant by 12.7% in the net electrical output and 7.5% in the thermal efficiency in maximum, while the latter one (4000 m^2) yielded a 29.0% increase in the net electrical output and a 16.6% increase in the thermal efficiency in maximum.

4. CONCLUSIONS

In this paper, a feasibility study on hybrid solar-geothermal power plant was carried out. The problem of air cooling in arid regions for a geothermal power plant has been technically solved by incorporating solar energy. Four main steps have been carried out: firstly, the definition and analysis of hybrid direct and indirect solar-geothermal system; secondly, the simulations of the ambient air temperature; thirdly, the calculation of effective solar irradiance onto the collectors and the analysis of two alignments of the solar collectors; finally, the evaluation of the overall performances of the hybrid plants.

From all the analyses results, we found that: (i) the North-South alignment of the solar collector system generally bring higher solar irradiation during summer than that of the East-West alignment; (ii) the Hybrid Concept (B) has an evenly increased performance in both peak time and off-peak time, while the Hybrid Concept (A) has a much better performance over the peak time; (iii) although the solar heating system with higher collector surface area yielded more power and higher thermal efficiency, the higher cost of the facility limited further application; (iv) note that the improved performances of the hybrid power plant, achieved by the increased capacity of the solar system, will be limited by the supercritical properties of the working fluid as well as the high cost of solar heating systems. Thus, in order to get a relatively stable performance of the geothermal power plant, a solar heating unit with a surface area of 2000 m^2 is recommended for the days with an average DTR and 4000 m^2 for the days with an extreme DTR. The former configuration, in turns, increased the performance of the hybrid power plant by 12.7% in the net electrical output and 7.5% in the thermal efficiency in maximum, while the latter one yielded a 29.0% increase in the net electrical output and a 16.6% increase in the thermal efficiency in maximum.

The hybrid solar-geothermal power plant has shown its merits and large potentials, compared with a stand-alone solar power plant or a geothermal power plant. It includes a relatively lower cost compared to a high cost stand-alone solar power plant, the ability to capture more diverse economic incentives and to improve the power profile, the buffering effect on the depletion rate of geothermal resources and also the higher utilization rate of the local renewable energy sources and facilities. In addition, the hybrid power plant provides much less land-use per megawatt compared to stand-alone solar power plant due to the integration of a compact geothermal power plant. The hybrid concept can also effectively alleviate the detrimental effects of the hot climate on a geothermal power plant. However, a practical solar-geothermal hybrid plant will still greatly depend on its economic factors. Further research work should be done on a comprehensive techno-economic feasibility study.

ACKNOWLEDGEMENTS

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NOMENCLATURE

Variables

I_h = terrestrial global irradiance on a horizontal plane
I_{oh} = extraterrestrial irradiance on a horizontal plane
G = effective solar beam irradiance of the collectors (W/m^2)
$K(12)$ = atmospheric transmittance coefficient at 12:00
$K(t)$ = atmospheric transmittance coefficient at certain hour, t
$K_c(12)$ = atmospheric transmittance coefficient at 12:00 in a clear day
$K_c(t)$ = atmospheric transmittance coefficient at certain hour, t, in a clear day
K_t = atmospheric transmittance coefficient
Q_C, Q_E, Q_{solar} = heat rejected by condenser, heat input of expander, solar energy input (kJ/h)
s = collector surface area of the solar heating system (m^2)
ΔT = air temperature difference between the maximum and minimum during a day (°C)
T_{max}, T_{min} = maximum, minimum air temperature during a day (°C)
T_{high} = temperature of the geothermal resources at Birdsville (°C)
T_{low} = air temperature (°C)
W_T, W_P, W_C, W_{net}^{Max} = work of turbine, work of pump, work of air cooler, the maximum net electrical output (kW)

Greek Symbols

η_c, η_{max} = ideal Carnot efficiency and maximum thermal efficiency of an Organic Rankine Cycle
η_{solar} = thermal efficiency of a solar heating system

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