A Study to Retrofit Parabolic Trough Collector on Jimah Coal-Fired Power Plant

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Abstract. In Malaysia, coal-fired power plant makes up 40% out of the total installed capacity as of the year 2016. This preference is set to continue despite the global push to reduce carbon emissions. Solar Aided Coal-Fired Power Generation (SACPG) may be a viable option to be considered to help reduce carbon emissions while maintaining the capability to meet the country’s growing electricity demand. This study looks into the possibility and potential of retrofitting Parabolic Trough Collectors (PTC) at Jimah Power Plant (JPP) to substitute the existing steam extraction feedwater heating with solar heating. The main focuses are the potential solar energy that can be harvested and the best feedwater preheating retrofitting scheme. The study found that an area of 59,340.06 m² can be utilised and a maximum solar heating rate of 69,427,870.20 kJ/hr can be harvested. Meanwhile, the lowest feedwater heating was at Feedwater Heater (FWH) A with a heating rate of 153,317,018.40 kJ/hr. Full replacement of any feedwater heater is found to be impossible and the only suitable retrofit scheme is to have 0.45 solar fraction heating at Feedwater Heater A. This retrofit scheme can help to increase 0.59% of JPP efficiency and reduce 8.18 ton/hr of coal consumption.

1. Introduction

The energy consumption per capita in Malaysia has seen a steady increase over the past 25 years starting from only 1101 kWh in 1990 to 4,265 kWh in the year 2015 [1]. This is clear proof of a developing country and a strong indication of an increase in electricity demand. On 6th June 2018, the Peninsular Malaysia’s Grid System Operator (GSO) reported the highest electricity demand of 18,010 MW and this is expected to increase from year to year [2].

To meet this ever-growing demand, the current installed capacity of 22,919 MW as of December 2016, needs to be increased accordingly. In terms of the generation mix, coal accounts of up to 54.05% of the overall fuel mix from January 2017 till November 2017 [3]. Mainly due to its lower price, this preference towards coal is projected to increase until the year 2026 as seen in Error! Reference source not found.

Despite the predominant reliance on coal to meet the energy demand, Malaysia also targets to reduce carbon emissions by as much as 45% by the year 2030 [4]. In this scenario, Solar Aided Coal-Fired Power Generation (SACPG) can be a viable strategy to be adopted. Such hybrid plant would allow the country to meet its electricity demand growth while ensuring sustainable development.

Wide studies, across different focuses, have been done in this particular field. In 1991, Pai studied the integration of solar into coal thermal power plant by adding a solar concentrator field that would
heat up the heat transfer fluid which transfers the heat to the feed water at additional heat exchangers before every existing feedwater heater. Through these modifications, coal consumption decreased up to 24.5% when the period of insolation was achieved [5].

Another study that focused on solar feedwater heating in a conventional coal power plant was done in 2007 by Yinghong et al. They even concluded that the integration would improve the cycle efficiency and that feed water preheating was more economical in larger units [6]. In addition, Hu et al. also proved that feed water preheating using solar would be able to improve energy and exergy efficiencies of the power plant [7]. This paper presents three different scenarios of solar feedwater heating, firstly, a 100% replacement of all the feedwater heaters, secondly, a 10% replacement of all the feedwater heaters, and lastly, a 100% replacement of the IPH2 feedwater heater. The case study was done using THERMOSOLV software and the results showed that the earliest payback period was attained from the third scenario. This is evident that maximum solar energy integration into the coal thermal plant is not necessarily the most viable option of the retrofit scheme. Fuel savings need to be compared against the capital cost of the retrofit scheme in order to ascertain the most viable retrofit scheme.

Qin Ying et al. delves into the concept of Solar Aided Power Generation with direct steam generation (DSG) systems. Their paper proposed that steam generated by solar can be used to replace the steam extraction from the turbine. Maximum efficiency is achieved when steam from DSG is introduced to the highest possible pressure of the feedwater heater. It is also concluded that this is one of the most economical ways to integrate solar energy into a coal-fired power plant as it uses the existing feedwater heaters [8]. Another cost-saving option is to bypass the feedwater heaters with a solar field that will still meet the designed feedwater temperature as what has been studied by Popov [9]. He even describes that “this option needs almost ‘zero’ power plant modification”.

Apart from feedwater heating, there are also numerous papers which discuss the possibility of solar thermal energy integration at different stages of the coal power plant. A work done by Zoschak and Wu in 1975 assessed in detail of seven different retrofit schemes with the intent to identify the best direct thermal input to an 800MW fossil-fuelled power plant. The result shows that combined evaporation and superheating is the best option, and even outperforming feedwater heating which is deemed the second preferred method.

All of the conclusions from the abovementioned works were all drawn without any solar collecting area constraints [10]. This would not be the case for this study as area available for solar collection would be limited and will be main part of the retrofitting study’s consideration.

This paper aims to study the possibility of retrofitting a 2 x 700MW Coal-Fired Power Plant, Jimah Power Plant with parabolic trough collectors to harvest solar heat energy to heat up feedwater heaters. Additionally, this study hopes to prove that parabolic trough collectors are viable to be retrofitted into a commissioned coal-fired power plant and even serves as a reference to other coal-fired power plants in Malaysia.
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Jamel et al. reported in their paper that solar integration replacing the boilers in a coal-fired power plant would allow for a maximum amount of solar contribution. [6] This finding is highly consistent with the study done by Zoschak and Wu as mentioned previously.

2. Methodology

Figure 2. Flow Chart.

The first step was to assess the potential solar energy that can be harvested from the available area within the compound of the power plant. Subsequently, an energy study was done on the feedwater preheating systems to identify different retrofitting options. Using the two findings, a suitable retrofitting scheme
was proposed. The study then discussed the potential benefits of the project if it was to be carried out along the area needed for the best retrofitting option.

2.1. Solar Energy Potential

To calculate the amount of potential solar energy that can be harvested, two main information was needed, which were average daily solar irradiation, \( S \), and the available area for Solar collector installation, \( A \) [11].

\[
\text{Solar Energy potential} = S \times A
\]  

As for average daily solar irradiation, \( S \), one reference year solar irradiation data provided by Sustainable Energy Development Authority (SEDA) was found to be a good reference for the required data. The data was attained by implementing the method from the Sandia National Laboratory. Historical data from 40 ground stations were used to generate a solar irradiation map matrix of Malaysia in [12]. The average daily solar irradiation would then be estimated from this value by dividing with the number of days in a year. This value was then cross-checked with the actual daily solar irradiation reading from Department of Metrology Malaysia’s (MET) Metrology ground station located at Sepang. This location was chosen as it is the closest from the site’s location (17.5 km). Solar irradiation monthly profile from this station will also be used to identify the monthly averaged highest and lowest daily solar energy throughout the year. Additionally, PVsyst© simulation will also be conducted to support the solar irradiation findings.

As for the solar collector installation area, \( A \), Jimah Power Plant as-built layout drawing was used to identify potential areas which are suitable for a solar collector installation. The suitability and practicality of utilising these potential areas were critically assessed using a simple additive decision weighed matrix which took into consideration the distance of the location to the existing feedwater heaters, the overall size of the area and also the complexity involved in installing the solar collector. The size of the location area is given utmost importance as it directly corresponds to the magnitude of solar energy harvest. A score of 1, 3 or 5 was given to each criterion for every location and the highest cumulative score, i.e. Suitability Index, was considered the most suitable location. This method was adapted from a similar work done by Andreas and Dimitrios to identify the optimal site selection for a solar park [13]. The scoring for the suitability index matrix was done based on Table 1.

| Table 1. Score Justification for Suitability Index |
|-----------------------------------------------|
| **Criterion**                  | **Weightage** | **Score Justification** | **1** | **3** | **5** |
|--------------------------------|---------------|-------------------------|-------|-------|-------|
| **Distance from Feedwater Heaters** | 1             | > 200m radius           | > 100m radius | < 100m radius |
| **Size of Area**                | 3             | < 10,000m²              | > 10,000m² | > 20,000m² |
| **Complexity of Installation**  | 2             | more than 2 restriction | 2 restriction | 1 restriction |

Upon identifying the most suitable area for the solar field, the effective aperture area will be determined using a 50% ratio of aperture area over total solar field area. This is the space needed between collector rows to ensure minimal losses due to shading from the adjacent collector [14]. With regards to the solar collector efficiency, a value of 0.65 was taken from a work done by Jianlan Li et. al. in 2016 [15].

2.2. Feedwater preheating system energy assessment
A thorough energy balance study was conducted on the feedwater preheating system of JPP. Reference source not found. is the diagram that shows the different stages of feedwater heating and the different stages of extraction steam needed for this preheating process.

![Diagram of JPP Feedwater Preheating System](image)

Figure 3. JPP Feedwater Preheating System

Two important information was needed for this assessment, namely, amount of heat addition at feedwater heaters, \( Q_{fw\,in} \), and the amount of heat extracted from the steam turbine, \( Q_{ext\,stm} \). The amount of heat addition was used to identify the heat energy needed from the solar collector field. While that, the corresponding heat extracted from turbines is to calculate the saving in terms of superheater steam energy which in turn relates to the amount of coal consumption reduction or other forms for savings. The equation is as below.

\[
Q_{fw\,in} = (Enthalpy_{fw\,out} - Enthalpy_{fw\,in}) \times \text{Feedwater Flowrate} \tag{2}
\]

\[
E_{ext\,stm} = Enthalpy_{ext\,stm} \times \text{Ext. Steam Flowrate} \tag{3}
\]

The analysis was conducted on all 6 feedwater heaters and their corresponding steam turbine extraction steam. All data, findings and calculation were tabulated using Excel worksheet.

3. Result

3.1. Solar Potential Assessment

Using the established solar map from SEDA, along with JPP’s coordinate, the annual solar irradiation data was taken to be 1700.29 kWh/m\(^2\) while the daily average was found to be 4.66 kWh/m\(^2\). Using this value as a reference, PVsyst Simulation was done in order to attain the daily solar irradiance profile for the location. From the graph, it can be seen that the maximum solar irradiance for that particular day is 650 W/m\(^2\). However, more importantly, the study also took into consideration a clear sky condition of 1000.00 W/m\(^2\) which is also simulated by PVsyst© as seen in Figure 4 and Figure 5.
The next component is the potential solar collector area. All 20 possible area was identified and was critically assessed whether it was suitable to be retrofitted with solar collectors using the suitability index simple additive decision matrix as defined in Section 2.1 earlier. From the assessment done, the ash pond was found to be the most suitable area for solar collector installation. This is mainly due to the large size of the location with an area that spans 59,340.06 m², the biggest single area within the entire plant. However currently, bottom ash is occupying this piece of land. An off-take contract has been signed for the collection of the bottom ash and is reused to make bricks. JPP’s Management is actively looking at other off-takers to increase the total amount of bottom ash off-take with the intent to maximise returns by selling off this combustion by-product. This arrangement will result in a close to empty ash pond which can be reclaimed. This would be the only prominent challenge of using the ash pond for solar collector area since collector installation would be relatively easy compared to most other possible on-roof location installations.

Using the information gathered, daily solar thermal energy was determined to be 89,838.29 kWh or 323,417,844.99 kJ. The solar collection efficiency was taken as 65% based on a work done by Yawen [16]. This is the average total amount of solar thermal energy that can be harvested from the available
area at JPP. Considering that the site would receive an average of 6 hours of sunlight [17], the average hourly solar energy received is 53,902,974.17 kJ/hour. While for the maximum possible (clear sky condition) daily solar energy harvesting rate is 69,427,870.20 kJ/hr.

3.2. Feedwater Preheating Energy Balance Assessment

Through the energy balance study at the feedwater heaters and the respective extraction steam, the heat addition of every feedwater heater was identified. The increase in thermal efficiency when one of the feedwater heaters was substituted with solar collector was also calculated. Graph of heat addition at every feedwater heater and the thermal efficiency increase is plotted in Figure 6 below while full finding is tabulated in Error! Reference source not found.

![Figure 6. Heat Addition and Increase in Efficiency](image)

From the graph plotted, it can be seen that the highest amount of heat addition process occurs at Feedwater Heater D with a heat addition rate of 418,658,409 kJ/hr. To add this amount of heat energy into the feedwater heater, the amount of energy needed from the extraction steam D was 457,876,480.80 kJ/hr. However, substituting this extraction steam feedwater heating at Feedwater Heater D did not result in the highest amount of increase in thermal efficiency with only a 3.76% increase in thermal efficiency. The highest increase in efficiency can be attained by doing the retrofit project on Feedwater Heater F with an increase in efficiency of 4.37%. However, this required 340,811,577.00 kJ/hr of heat energy rate to substitute the feedwater heater, which was still very high to be attained by a solar collector field. The lowest heat addition was at Feedwater Heater A with the rate of heat energy of 153,317,018.40 kJ/hr. This value was much closer to the solar thermal energy potential as calculated in section 3.1 earlier. This retrofit option would result in a 1.32% increase in thermal efficiency but this was if only the total of 153,317,018.40 kJ/hr can be harvested from the solar collector. This was proven earlier to be impossible as the maximum amount rate of thermal energy that can be harvested from the solar collector with the proposed area of the retrofit was only 127,106,408.52 m². Therefore, only partial substitution can be done to Feedwater Heater A which will be discussed further in the next section.

4. Discussion

4.1. Proposed Retrofit Scheme

As identified in the previous section, the rate of heat energy that can be derived from the usable size of the area is not sufficient to fully substitute the heat addition achieved from feedwater heater 1 even
during clear sky condition. Solar fractions of 0.45 and 0.35 are identified for the clear sky and average condition respectively. This means that the retrofit scheme will on average, during the period of insolation, increase the cycle efficiency by 0.46% while the maximum possible increase in efficiency is 0.59% which is during a clear sky condition.

4.2. **Size of area needed**

In order to reach the energy output to fully replace the Feedwater Heater A, an area of 168,781.80m$^2$ is needed. This is highly impossible as this study has considered every possible location within the existing power plant. This suggests that in order for such retrofit project to be done, consideration has to be placed much earlier in the designing phase of the plant. This will ensure proper allocation and planning to make available sufficient area to achieve full replacement of feedwater heater. Additionally, the study also found that to attain the biggest increase in efficiency, ie. substituting Feedwater Heating F, the area needed is 375,188.56m$^2$. This finding is consistent with a work done by Hongbin who has reported a similar amount of size of solar collector area [18]. This proves that for such retrofitting project to take place, a sizable amount of area is needed.

4.3. **Potential benefits**

This section looks at the potential saving of the retrofit project if it is carried out. The benefits are mainly attained from the increase in efficiency of the overall steam cycle. Using the calculated improvement in heat rate in the earlier section, the amount reduction in coal used is calculated to be 8.18 ton/hr for the best-case condition and on average 6.37 ton/hr. This is determined using the design coal calorific value attained from power plant design data. Furthermore, the CO$_2$ reduction associated with the reduction in coal consumption is calculated to be 13.49 ton/hr and 10.50 ton/hr, respectively. Using the coal price of 10.85 RM/GJ, the potential savings are estimated to be RM 2,152.93 and RM 1,676.00 respectively. It is important to note that these savings are during the period of insolation as the proposed design does not include thermal storage and that the values are highly dependent on the coal price.

5. **Conclusion**

In conclusion, the study looks at every possible location within the JPP compound and found that with proper bottom ash management in place, an area of 59,340.06m$^2$ at the ash pond can be used for solar collector installation. With the size of solar collector area available, it is also found that the most suitable retrofit scheme is to introduce the solar collector feedwater heating at Feedwater Heater A. Even so, the potential solar heat harvested from the PTC can only add a maximum of 69,427,870.20 kJ/hr and an average of 53,902,974.17 kJ/hr of heat power into the 1st stage of feedwater heating which is 45% and 29% solar fractions respectively during the of insolation.

The study also concludes that to attain the most significant efficiency increase, the retrofit has to be done at the Feedwater Heater F. This would require a solar field area of 375,188.56m$^2$ which is impossible for JPP and therefore suggests that for such retrofit project to take place in a commissioned coal-fired power plant, land and area planning has to be done much earlier in the designing phase of the project. This should allow for sufficient area allocation for the solar field.

Looking at the existing thermal plant in Malaysia, this retrofitting study should be done on a smaller capacity thermal plant where the feedwater heating requirement is much lower and therefore might be more suitable for the retrofit project. Future studies should look at the technical design of the solar collector field and the commercial feasibility of the retrofitting project.

**References**

[1] Energy Commission, "Malaysia Energy Statistics Hanbook 2017," Putrajaya, 2018.
[2] Grid System Operator. (2018, August) Home: Grid System Operator. [Online].
   https://www.gso.org.my/LandingPage.aspx
[3] Energy Commission, "Transitioning Towards Sustainable Energy Security," in *Energy Malaysia Volume 14|2018*. Putrajaya: The IBR Asia Group Sdn. Bhd., 2018, pp. 40 - 43.

[4] Energy Commission, "A Pledge Towards Sustainability," in *Energy Malaysia Volume 14|2018*. Putrajaya: The IBR Asia Group Sdn. Bhd., 2018, pp. 26 - 28.

[5] B R Pai, 1991, "Augmentation of thermal power stations with solar energy," *Sadhana*, 16-1, 59.

[6] Jamel M S, A Abd Rahman, and A.H. Shamsudin, 2013, "Advances in the integration of solar thermal energy with conventional and non-conventional power plants," *Renewable and Sustainable Energy Reviews*, 20, 71.

[7] Hu E, Yang Y P, Nishimura A, Yilmaz F, and Kauzani A, 2010, "Solar Thermal Aided Power Generation ," *Applied Energy*, 87, 2881.

[8] Yan Q, Yang Y, Nishimura A, Kauzani A, and Hu E, 2010, "Multi-point and Multi-level Solar Integration into a Conventional Coal Fired Power Plant," *Energy Fuels*, 24, 3733.

[9] Popov D, 2011, "An option for solar thermal repowering of fossil fuel fired power plants," *Solar Energy*, 85, 344,

[10] Zoschak R. J. and Wu S. F, 1975, "Studies of the direct input of solar energy to a fossil-fueled central station steam power plant," *Solar Energy*, 17, 297.

[11] O’Hegarty R, Kinnane O, and McCormack S, 2014,"A Simplified Procedure for Sizing Solar Thermal Systems: Based on National Assessment Methods in the UK and Ireland," in 6th Intl. Conf. on Sust. in Energy and Bldgs, Ireland, 647 .

[12] Sustainable Energy Development Authority, *Solar Irradiation Data For Malaysia*, Sustainable Energy Development Authority, Ed. Putrajaya: Sustainable Energy Development Authority, 2016.

[13] Georgiou A and Skarlatos D, 2016, "Optimal site selection for siting a solar park using multi-criteria decision analysis and geographical information systems," *Geoscientific Instrumentation Methods and Data Systems*, 5, 321.

[14] Odeh S D,Behnia M, and Morrison G L, 2003, "Performance evaluation of solar thermal electric generation systems," *Energy Conversion and Management*, 44, 2425.

[15] Li J, Yu X, Wang J, and Huang S, 2016, "Coupling performance analysis of a solar aided coal-fired power plant," *Applied Thermal Engineering*, 106, 613.

[16] Zhao Y, Hong H, and Jin H, 2017, "Optimization of the solar field size for the solar-coal hybrid system," *Applied Energy*, 185, 1162.

[17] Kotorkoshi I M, Zulkifli Z, and Dasuki K A, 2015, "Challenges and Prospect for the Development of Parabolic Trough Solar Collectors (PTC’s) in Malaysian Environment," *International Journal of Scientific and Research Publications*, 5-8, 1 .

[18] Zhao H and Bai Y, 2014, "Thermodynamic performance analysis of the coal-fired power plant with solar thermal utilizations," *International Journal of Energy Research*, 38, 1446.