Energy sustainability through integrated solar thermal systems

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Abstract

Renewable energy resources are the pillars for energy sustainability. Topping those resources is solar energy. The problem with solar is the interruption during the night and the cloudy and rainy times. Many techniques have been proposed to enhance solar utilization and minimize the effect of solar interruption. This paper summarizes the author's experience on enhancing the solar thermal systems by means of integration with either other energy resources or integration with thermal energy storages. On solar drying applications, a solar dryer was integrated with a thermal backup unit. The experimental results on hybrid drying showed an enhancement of 64.1% for EFB, and 61.1% for chilli, compared with open solar mode drying. Solar water heating was found to be sufficient to supply hot water during the day and night time by integration with thermal energy storage. The system was able to discharge thermal energy and maintain the heating of water to the next morning. On large scale and industrial application, a modified inclined solar chimney was enhanced via integration with wasted flue gas. By this technique, the system was brought to operate 24 hours a day. At 800 W/m^2 solar intensity, the efficiency was enhanced to over 0.6% in the case of hybrid operation compared to less than 0.3% for solar mode only. Research results demonstrate that integrated solar thermal systems can contribute effectively in sustainability of clean energy resources. The results obtained, so far, from this research program are encouraging; and it is highly recommended to further investigate the solar hybrid and solar integration for energy sustainability from the sun.

Keywords: energy sustainability, hybrid solar dryer, PCM, solar energy, solar chimney, solar water heater, sustainability, TES, waste to energy.

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1 Introduction

Some decades ago, solar energy found its applications moving from domestic to industrial and large scale power generation. Small scale solar application includes hot water systems, solar distillation of sea and brackish water, water pumping, drying of agricultural produce, space heating and cooling, day lighting, solar refrigeration, and building integrated photovoltaic systems. As a sustainable resource of clean energy, solar energy becomes one of the most promising resources for power generation on a large scale. Electric power can be generated by direct conversion of sunlight to electricity by means of photovoltaic or indirect conversion using solar thermal systems. Solar thermal systems for electrical power generation include parabolic trough systems, central receiver systems, dish-stirling engine systems and solar chimney power plant (SCPP). With the fact that solar radiation is not available over 24 hours of the day, it is a major setback for the continuous process of power generation. Adding the fact that it is transient over the day time, and is highly influenced by cloudy and rainy weather, solar thermal systems become questionable for sustainable energy.

This setback encourages researchers to create ideas and technologies to reduce the interruption effect of solar energy on the systems and plants' productivity, whether in small scale or large scale applications. Among the practical techniques used to enhance solar thermal systems are the integration with thermal energy storages (TES), while integration with thermal back up resources are studied mainly in the topic of solar drying. On power generation, some researchers suggested and analysed many ideas to enhance the performance of the SCPP.

This paper presents the enhancing technologies adopted and tested by the research group in Universiti Teknologi PETRONAS. The paper reviews and presents the solutions for the all day operation of solar drying, solar heating, and power generation by SCPP.

2 On hybrid solar drying

Madhlopa and Ngwalo [1] studied an indirect solar dryer with biomass backup heaters. The biomass burner was made of brick and consisted of rock pebbles which acted as a thermal storage. Thanaraj *et al.* [2] came out with a furnace which consists of a heat exchanger using bricks, clay and cement to the rotary dryer. The same material type of burner also has been reported by Prasad and Vijay [3], Prasad *et al.* [4], Tarigan and Tekasakul [5], and Bena and Fuller [6]. Mastekbayeva *et al.* [7] reported on a solar hybrid tunnel dryer incorporated with a biomass stove-heat exchanger, consisting of a cross-flow shell and tube heat exchanger. Serafica and del Mundo [8], and Bhattacharya *et al.* [9] focused on a biomass gasifier stove design as a backup heater to the hybrid solar dryer for fish and fruits and vegetables respectively. The biomass gasifier consists of a shell and fin heat exchanger configuration and the heat delivery and combustion rate could be controlled using a butterfly valve at the primary air inlet. Among the biomass fuel materials that have been reported in biomass burner application are coconut shells (Serafica and del Mundo [8]), woodchips (Bhattacharya, *et al.* [9], and Madhlopa and Ngwalo [1]), charcoal (Prasad *et al.* [4]), paddy husk (Thanaraj *et al.* [2]), fuel wood (Prasad and Vijay [3], Bena and Fuller [6], and Tarigan and Takasakul [5]), and briquetted rice husks (Mastekbayeva *et al.* [10]).

A hybrid solar dryer was designed, fabricated and evaluated to dry chilli as a food representative and EFB as a biomass representative. The hybrid drying apparatus consists of a solar dryer integrated with a biomass burner gas-to gas heat exchanger as the thermal back up unit. The apparatus is shown in fig. 1.

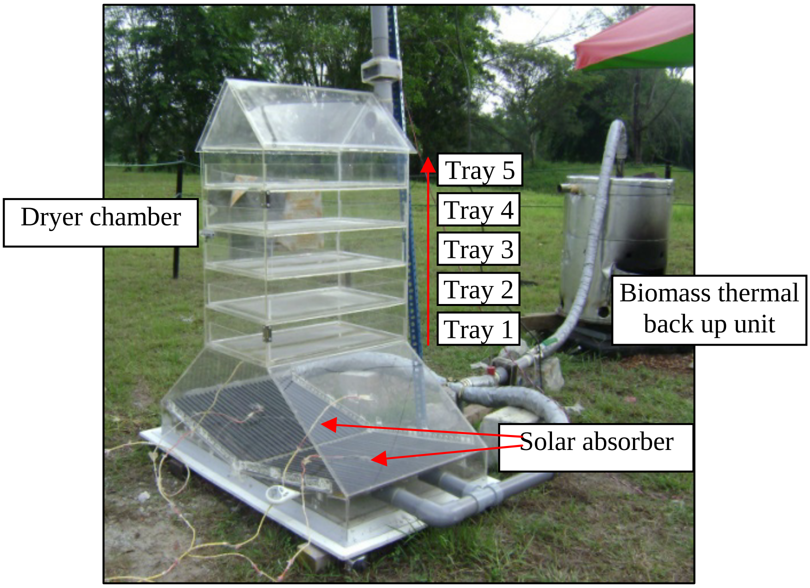

Figure 1: The experimental set up of a solar-thermal back up hybrid dryer.

To demonstrate the effectiveness of the thermal back up, evaluation of the drying process was carried out under open solar drying mode, mixed direct and indirect solar drying mode, thermal back up mode, and hybrid mode. The results of drying efficiency of EFB and chilli under different operational modes are shown in fig. 2. The lowest efficiencies for drying were measured in open sun drying where the drying process took a long time and was interrupted by solar conditions especially during cloudy days and at night. It was observed that the highest efficiencies were obtained in the hybrid drying mode. The EFB drying efficiency was enhanced by 64.1% and the chilli drying was enhanced by 61.1%. Details of the thermal back up unit can be obtained from Yunus *et al.* [11]. Details of the drying of the EFB, including the measurements methodology and evaluation are reported by Yunus and Al-Kayiem [12].

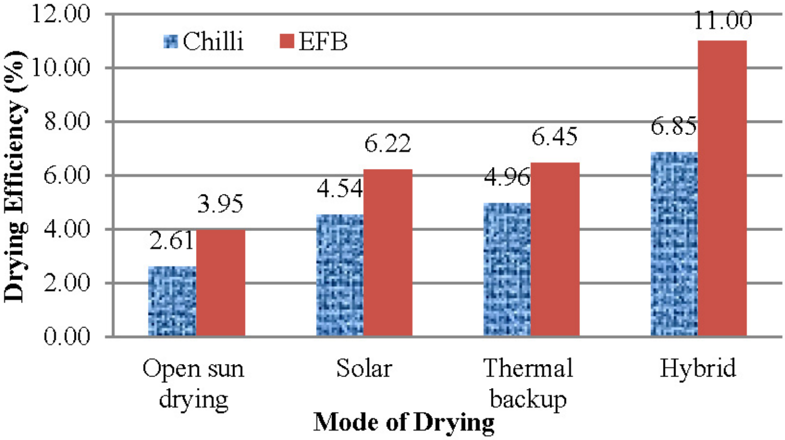

Figure 2: Drying efficiency of chilli and EFB at various solar and hybrid modes.

3 On the hybrid solar heater

For a continuous supply of hot working fluid in the solar dryer, the common practice is the use of an electrical heater at night and on cloudy/rainy days. The working fluid may be air, water, or oil. However, the new trend in compensation for the interruption of the solar energy is the integration of the solar absorber with thermal energy storage. Although the basic idea on solar energy storage has not changed, many innovative solar collectors have been proposed and tested. As an example, Reis *et al.* [13] used water-filled barrels as a solar collector. Reddy *et al.* [14] came out with a sand mix concrete absorber solar collector buried in the ground. Hamdan [15] designed a metallic box solar collector. De Beijier [16] developed a system that incorporates two cylindrical tubes, an outer absorbing tube coated with a selective surface and an inner storage tube. Goetzberger and Rommel [17] investigated the performance characteristics of a solar transparent honeycomb-insulated passive hot water system using both water and the ground as collector.

Solar integrated collector storage for water heating systems is simply a combination of collection and storage in a single unit. Its shape is not very complex; and the elimination of a separate storage tank and the collector from the conventional solar heater make it cost effective. However, it may have a relatively low efficiency, as mentioned by Shimdt *et al.* [18].

A solar collector integrated with a PCM-TES was designed, fabricated and evaluated at various operational modes, as shown in fig. 3.

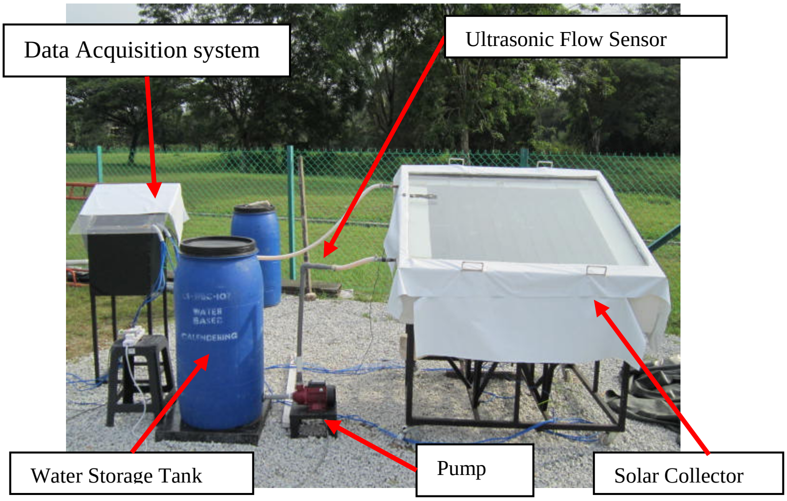

Figure 3: Experimental set up of integrated solar-PCM TES water heater.

The results of measurements at various operational modes are presented in fig. 4. The PCM starts to store the energy at 9.00 am and solidify at 6.00pm as shown in fig. 4. PCM starts to solidify before water is changed at 7.00pm. All the temperatures will reach the equilibrium at 12 midnight. Five hours of extension period of water heated by PCM from 7.00 pm to 12 midnight was achieved and the water temperature obtained for domestic use is around 40°C.

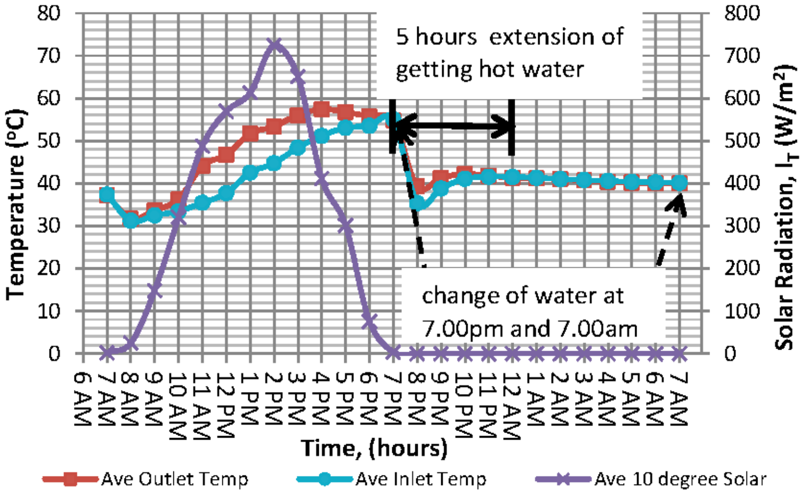

Figure 4: Experimental results of integrated solar-TES using paraffin wax as PCM.

4 On the hybrid solar-flue chimney power plant

In 1981, the German structural engineering company, Schlaich Bergermann and Partners (SBP) proposed, designed, built, and tested a SCPP in Manzanares, Spain. The plant has a collector diameter of 240 m and a chimney of 196 m high with 10 m diameter. It is the largest constructed SCPP to date designed to produce 50 kW electricity (Fluri [19]). Considering the experimental results from the SCPP in Manzanares and different research models developed so far, SCPP total efficiency is still below 0.2% and depends largely on the chimney height and the collector area (Gruenstein [20]). Many approaches have been suggested to enhance the system performance.

In 1997, Kreetz [21] introduced the concept of water-filled tubes under the collector roof for thermal energy storage. Bernardes [22] investigated the possibility of using water-filled tubes on the collector floor as a heat storage device and finds that its implementation smoothes out the daily fluctuation of power output and, hence, increases the power output after sunset.

Hussain [23] proposed a Hybrid Geothermal/Solar Chimney Power Plant and Hybrid Geothermal/PV/Solar Chimney Power Plant for prospective SCPP in the south region of Libya. Akbarzadeh *et al.* [24] examine the potential benefit of combining a chimney with a salinity gradient solar pond for production of power in salt affected areas (a case study of northern parts of the state of Victoria in Australia). A review on the enhancement technologies of SCPP is reported by Chikere *et al.* [25].

Elementary experimental measurement on an inclined solar chimney model integrated with flue gas was reported by Al-Kayiem *et al.* [26], and a simulation result which was validated through comparison with the measurements was reported by Al-Kayiem *et al.* [27].

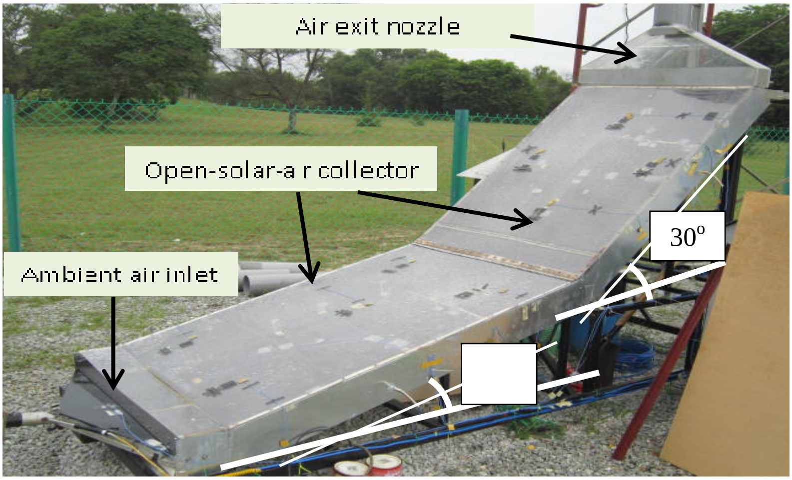

Figure 5: The open-solar-air collector component of the hybrid S-FGCPP.

Further work on modified double inclined SCPP, suggested by Chikere *et al.* [25], was designed, fabricated, and tested experimentally (as shown in fig. 5).

The measurement results show considerable enhancement in the system after integration with flue gas. By recovering the wasted thermal from flue to air in the chimney; it is found that the system can operate all day with a more stable power output. Comparison of the efficiency results of the solar and hybrid modes is shown in fig. 6.

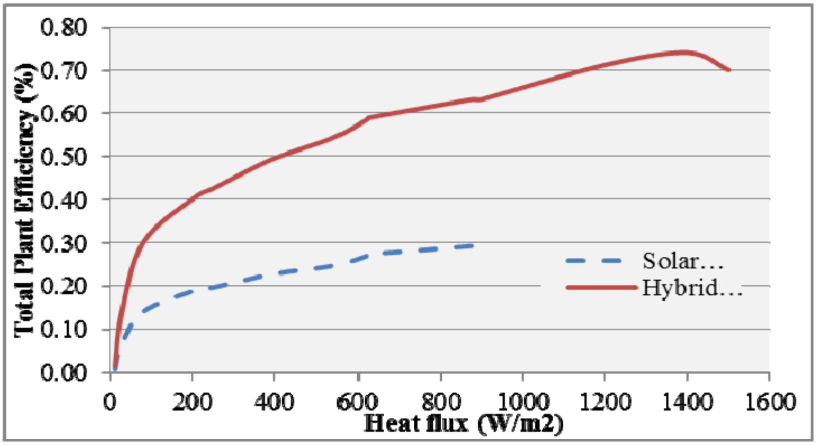

Figure 6: Total plant efficiency of solar mode and hybrid mode.

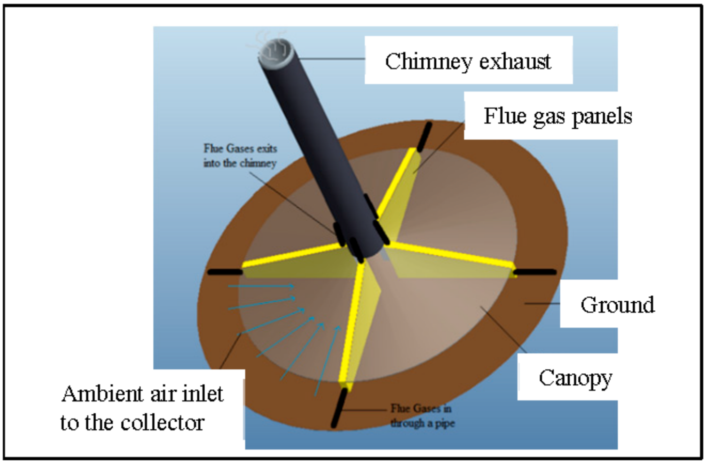

Figure 7: Simulated hybrid SCPP integrated with flue gases.

Along the same lines of the SCPP enhancement, simulation has been carried out considering the same design and operating conditions of Manzanares SCPP. Two simulations were carried out using ANSYS software. One was to simulate the system under solar mode, while the second was in hybrid mode. The hybrid mode is representing solar plus waste to energy of flue gas exhausted from a thermal power plant.

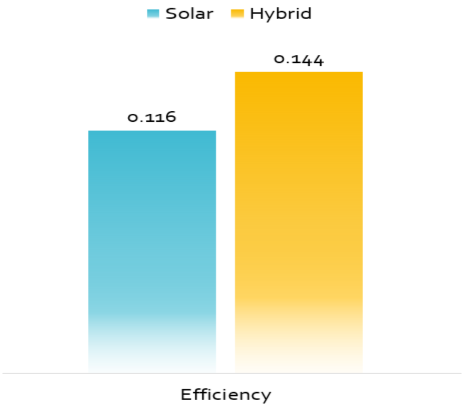

Figure 8: Overall thermal efficiency of the SCPP system.

The simulation results proved that the plant is capable of delivering power during the night. Also, daytime power generation is increased because both solar and flue are contributing in adding heat to the collector air. This also enables the overall efficiency of the plant to increase. When assuming 1000 W/m^2 solar intensity, the simulation results of the two operation modes are presented in fig. 8. For more details on influencing the temperature, velocity, and power, readers can refer to Azeemuddin *et al*. [28].

5 Conclusion

This study represents analysis of newly proposed and investigated approaches for enabling the continuous day and night operation of solar thermal systems. The investigation involved applications on drying, water heating, and power generation. The partial presence of the solar energy in the day, and the transient nature of solar energy are compensated by integration with other clean resources. So far, the performance of the solar thermal systems is enhanced by bringing the systems to operate continuously 24/7 with higher efficiency.

The conclusion which could be drawn is:

- Solar drying can be improved by integration with a thermal back up which is a biomass burner gas-to-gas heat exchanger.
- Domestic solar water heating could be improved and enabling overnight hot water production to be achieved via integrating the sola absorber with PCM TES.
- In the power production by solar chimney power plant, the performance can be improved by integrating the CGPP with waste to energy of flue

gases. Results show higher stability in the power production, higher efficiency, and continuous 24/7 operation.

The results are encouraging and it is recommended to investigate more integration and back up technologies to enhance the performance of solar thermal systems.

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