Desiccant Based Evaporative Air Condition System for Hot and Humid Climate

Muhammad Ehsan Ullah Kayani [1], Syed Shan E Haider Zaidi [1], Tashfeen Ali Ahmed [1], Usama Ishaq [1], Muhammad Ahmad [1], Roha Ashfaq [1], Hafiz M. Abd-ur-Rehman [1,] *

[1] School of Mechanical & Manufacturing Engineering, National University of Sciences & Technology, H-12 Campus, Islamabad, Pakistan.

* Corresponding author: abd-ur-rehman_@hotmail.com

Abstract

Conventional air conditioning system fails to provide comfort conditions in humid areas. Moreover, the refrigerants used in the conventional air conditioning system not only contribute to the ozone layer depletion in stratosphere but also directly lead to global warming when released in the atmosphere. Desiccant based evaporative cooling system has the potential to be an environmentally friendly alternative to conventional air conditioning system. The objective of this work is to design and develop a solid desiccant based evaporative cooling system for hot and humid environment. The system consists of a radial blade solid desiccant wheel for the extraction of the moisture from the air, a combination of direct and indirect evaporative coolers to lower the temperature of air, and solar air heater to provide the regeneration heat for desiccant wheel. Results indicate that human comfort zone can be achieved in hot and humid conditions using the proposed solar regenerated desiccant based evaporative cooling system with 70% less energy as compared to its counter vapor compression air conditioning systems.

Keywords: desiccant wheel, solar air conditioning, silica gel, evaporative cooler

1. Introduction

The rapidly increasing energy consumption along with its adverse effect on the environment is the most threatening concern of present time(Abd-Ur-Rehman and Al-Sulaiman, 2016, 2014). Buildings are major consumer of the primary energy production and most of the energy is utilized for the purpose of cooling and heating (Abd-ur-Rehman et al., 2018; Abd-Ur-Rehman and Shakir, 2016). The widely used method to condition air is the vapor compression refrigeration method. Providing the comfort conditions to the people not only means to control the sensible load capacity (temperature control) but also the latent load capacity (humidity control). In order to control latent load, the conventional vapor compression system uses the process of condensation to condense the water vapors on the coils when the air is cooled below its dew point temperature and then reheated again up to the required supply conditions. Normally the vapor compression cycle is working on 0.75 sensible heat ratio means 75% of the capacity is used in controlling the sensible loading while remaining 25% of the capacity is used in controlling the latent loading. So, it will provide the comfort conditions when the sensible heat ratio is greater than 0.75 (Mujahid Rafique et al., 2015). The sensible heat ratio in hot and humid areas is found to be less than 0.75. In order to condition air in such areas the conventional vapor compression system can be used but it will require a large amount of electrical energy. Moreover, the excess use of vapor compression system has affected the environment in a harmful way. The ozone layer has depleted because of the chlorofluorocarbons used in a vapor compression air conditioning (VAC) system.

An alternative to the VAC systems is required that can use renewable energy. Evaporative cooling, one of the oldest methods, is one technique to meet cooling demand of the building by utilizing evaporative cooling effect, with less power requirements, about one fourth to that of the VAC systems. Evaporative cooling is a simple, cost effective, and environment friendly technique for space cooling. The evaporative coolers are best fit for temperature control when air humidity is low. While for both temperature and humidity control in hot and humid climate, the effectiveness of the evaporative cooler drops remarkably. Therefore, it is used along with some other dehumidification system. One way to achieve comfort conditions for hot and humid climate is through indirect evaporative coolers. However, the efficiency of indirect evaporative cooler is only around 60-70%. A desiccant dehumidifier, whose purpose is to removes the moisture from the process air, can be used in conjunction with a VAC system, to allow the cooling system to function effectively. Such a system is called, hybrid desiccant cooling system. The use of hybrid desiccant cooling system can not only control the latent load but also reduce running costs and power consumption.

doi:10.18086/eurosun.2020.02.09 Available at http://proceedings.ises.org

The new technology of desiccant based evaporative cooling consists of two components i.e., a desiccant for the moisture removal and an evaporative cooler (Direct or Indirect) for reducing temperature. It significantly reduces the consumption of the electrical energy compared to the conventional vapor compression cycle (Mujahid Rafique et al., 2015). It provides more economical, cleaner and accessible air conditioning. The working mechanism of the system is such that when the hot and humid air enters in the system (ventilated or recirculated), its moisture is extracted by the desiccant. When the moisture is absorbed from this process air, its temperature further rises. The temperature is then lowered by using heat exchangers. For a continuous system, the moisture absorbed by the desiccant should be extracted (regenerated) out from it so that it is able to absorb more moisture from the process air. There is certain temperature needed to regenerate this desiccant that can be done by electric heater, waste heat, or solar energy. The main focus of the experiment is to determine effectiveness of radial desiccant wheel in terms of moisture removal, regeneration requirement and pressure drop but a complete system comprising of fans, coolers and solar air collector is established to evaluate its strength for air conditioning purposes. Table 1 shows the comparison between vapor compression, evaporative cooling, and desiccant based evaporative cooling techniques.

Tab.1: Comparison between vapor compression, evaporative cooling, and desiccant based evaporative cooling techniques.

	Vapor compression system	**Evaporative cooling system**	**Desiccant based evaporative cooling system**
Description	Controls latent load by cooling the air below its dew point. The conditions where latent load is overwhelming, its energy consumption is greatly increased. Leakage of refrigerants are harmful to environment and atmosphere.	Direct Evaporative Coolers with operational efficiency 85% and Indirect with efficiency of 60-70%. Perform well for sensible cooling. Ineffective in controlling latent load in hot and humid environment.	Desiccant controls latent load and evaporative coolers control sensible load. Water and air are used as working medium. Regeneration of desiccant using solar air heater substantially decreases the electricity requirements.
Cost of Operation	High	Low	Low
Investment Cost	High	Low	Medium
Energy Source	High grade energy, e.g., Electricity	Low grade energy, e.g., Solar energy, Waste heat	Low grade energy, e.g., Solar energy, Waste heat
Latent Load Control	Accurate	Low	Accurate
Sensible Load Control	Accurate	Accurate	Accurate
Green House Gas emissions	High	Low	Low
Cooling Medium	Refrigerants	Water	Water

2. Proposed design & Experiment

The proposed design of desiccant based evaporative cooling uses a radial blades desiccant wheel to experience lower pressure drop in comparison to honeycomb structure. Figure 1 shows the radial blade wheel and its comparison with honeycomb structure. (D. O'Connor, J. K. Calautit, and B. R. Hughes, 2016).

	Honeycomb	Radial Blade
Pressure Drop	High	Low
Regeneration Temperature Required	High (90-110°C)	Low (50-60°C)
Performance	Good	Good

Fig. 1: Radial blades desiccant wheel and its comparison with honeycomb matrix desiccant wheel.

The radial blades are coated with silica gel as a solid desiccant material to absorb moisture. The use of solid desiccant material is advantageous in comparison to liquid desiccant as the later has phenomenon of carry over i.e., travelling of the liquid desiccant through the air to the conditioned space which is harmful for the human. Moreover, the regeneration method used in the liquid desiccant system is comparatively complex (Rafique et al., 2016). Table 2 defines the specifications of the radial desiccant wheel.

Tab. 2: Specifications of Desiccant Wheel

Number of blades	30
Blade Length	110 mm
Blade Width	100 mm
Desiccant Wheel Diameter	300 mm
Weight	3 kg

The schematic diagram and 3-D design of the proposed desiccant based evaporative air conditioning system is shown in figure 2 and figure 3 respectively. The actual prototype is exactly similar to figure 3. Prototype is divided into two air passageways. One carries the hot air from solar air collector for regeneration of desiccant wheel while the second is dehumidified through the wheel and cooled through set of coolers. Aluminum V-Corrugated plate solar air collector is used with a surface area of 1m^2. The energy consumption of the system (fans, water pump & motor for rotation of desiccant wheel) is 80 Watts. Humid ambient air at 1 enters the processing side of desiccant wheel that consist of radial blades instead of conventionally used honeycomb structure. After dehumidification, temperature of process air increases due to adsorption. Process air is sensibly cooled between state point 2 and 3 by finned tube heat exchanger. It is further cooled between state point 3 and 4 by evaporative cooler before entering to the room. The water from evaporative cooler is first pumped to the heat exchanger and then passes onto the cooling pads. This is done because water after evaporation is cooler. Ambient air at 5 enters the solar air heater where its temperature is increased by solar radiations. This high temperature air at 6 is them passed from desiccant wheel to remove the moisture and exist at point 7 to atmosphere.

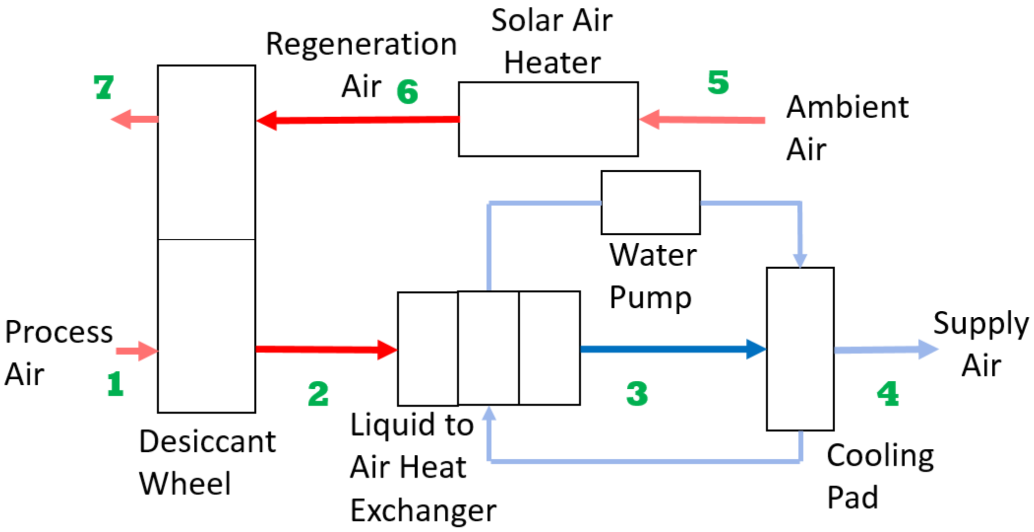

Fig. 2: Schematic diagram of the proposed desiccant based evaporative cooling system.

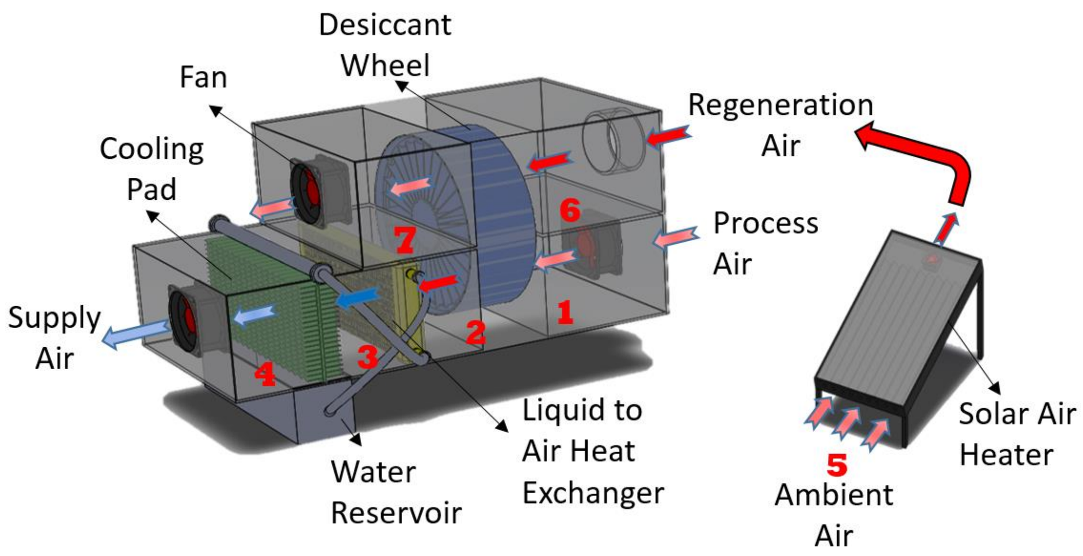

Fig. 3: 3-D diagram of the developed prototype of desiccant based evaporative cooling system.

3. Results and Discussion

The readings for this experiment were taken half an hour after the system was turned on so constant values can be obtained without any fluctuations. Rotation speed for desiccant wheel was kept at 35 Revolutions per hour. The pressure drop in radial desiccant wheel lies in the range of 2 – 10 Pascal depending on number and geometry of blades in the wheel (D. O'Connor, J. K. Calautit, and B. R. Hughes, 2016). The moisture removal in the radial blade desiccant wheel was 11 g/kg of dry air at 35 ˚C dry bulb temp and 65 % relative humidity of inlet process air. The states in table 3 are same as mentioned in figure 3.

Tab. 3: Experimental results of temperature and humidity

State	Temperature (°C)	Relative Humidity (%)	Specific Humidity (g/kg)
Process Air (mass flow rate = 0.035 kg/s)			
1	35	65	23.5
2	45	20	12
3	35	35	12
4	26	75	16
Regenerative Air (mass flow rate = 0.04 kg/s)			
5	35	65	23.5
6	55	23	23.5
7	42	66	35

The point 1 on the psychometric chart figure (4) indicate the ambient air conditions (35 C temperature with 65 % relative humidity) at the inlet of the desiccant based evaporative cooling system. As the ambient air pass through the radial blade desiccant wheel, its moisture is reduced to 20 % but its temperature is increased to 45 ˚C due to dehumidification as shown by point 2 on the psychometric chart. The dehumidified air is then passed through the indirect air-water heat exchanger that reduce its temperature to 35 ˚C without adding moisture in it as shown by point 3 on the psychometric chart. The air is further cooled using cooling pads that acts as an evaporative cooler to reduce the temperature of air and the moisture content increase due to the direct contact of air with water. The point 4 on psychometric chart represents the supply air temperature of 26 ˚C with 75 % relative humidity that is very close to the human comfort zone in summer region defined by ISO standards (ISO/EN 7730) and shown in figure 4 and 6.

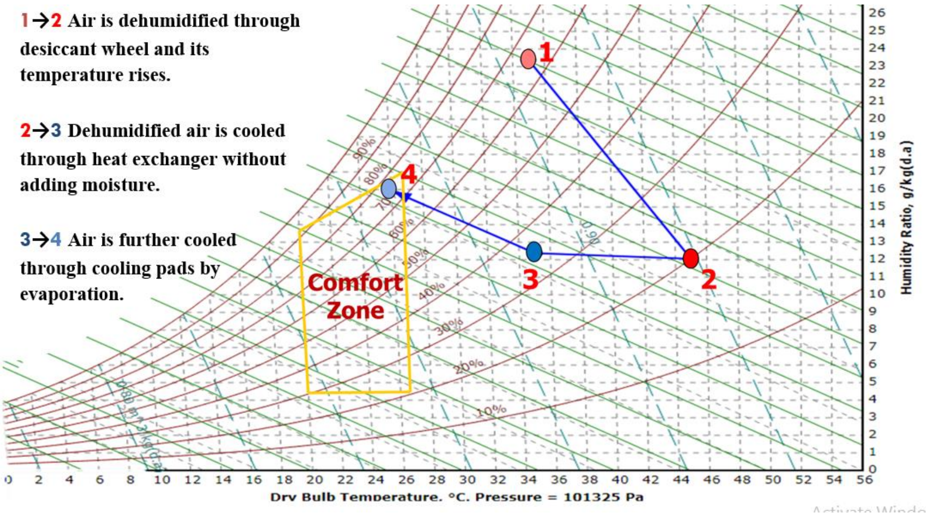

Fig. 4: Psychometric chart showing the temperature and humidity at different locations of the desiccant based evaporative air conditioning system.

The enthalpy difference between state 1 and 4 is 29 kJ/kg. Using mass flow rate, the cooling load comes out to be approximately 1kW. Energy Efficiency Ratio = (Cooling output in BTU/h)/Energy Consumption in Watts

$$\text{Energy Efficiency Ratio} = 3412/80$$

$$\text{Energy Efficiency Ratio} = 42$$

Energy efficiency ratio of Vapor Compression Air Conditioners is in the range of 10 – 12 which proves that Desiccant based evaporative coolers can save up to 70 % energy.

The point 5 on the psychometric chart (figure 5) indicate the ambient air conditions (35 ˚C temperature with 65 % relative humidity) at the inlet of the solar air collector. As air passes through solar air heater, its temperature rises but specific humidity remains constant as shown by point 6 on psychometric chart. Finally, this heated air passes through desiccant wheel to regenerate it, lowering its temperature and increasing the humidity content as evident from point 7 on chart.

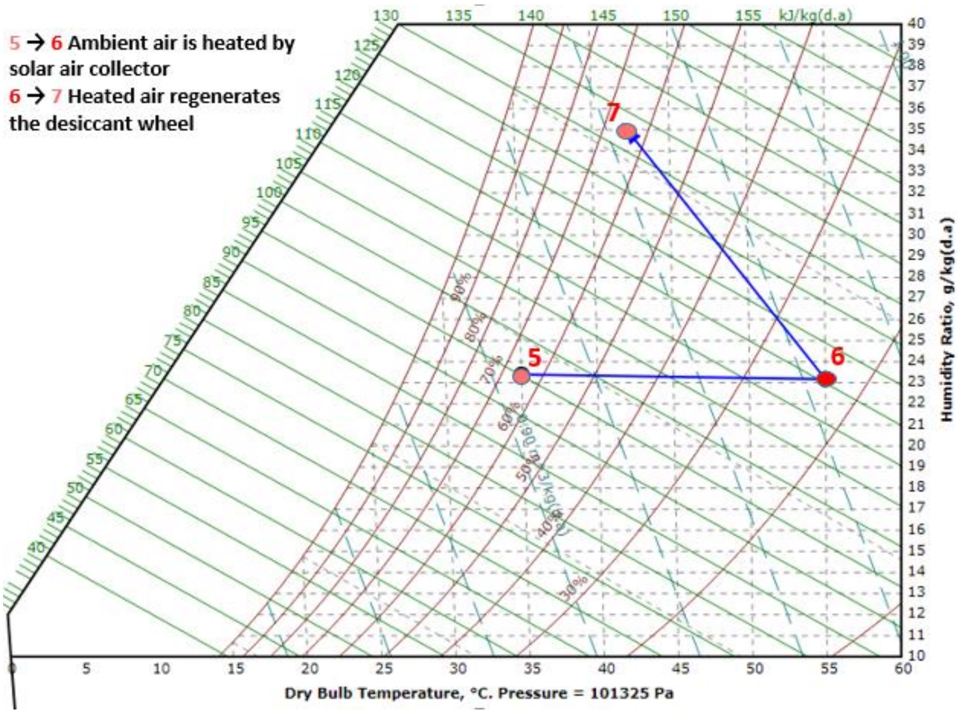

Fig. 5: Psychometric chart showing the temperature and humidity of regenerative air.

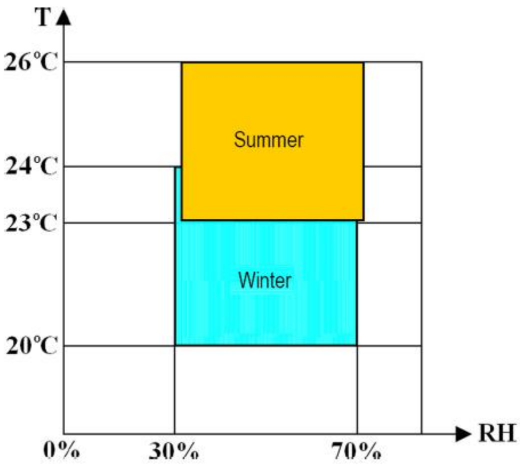

Fig. 6: ISO/EN 7730 chart depicting human thermal comfort conditions (ISO, 2005).

These experimental results needed comparison with industrially manufactured honeycomb desiccant wheel so NOVEL Aire Simulator was used. This software produces practical results corresponding to various inlet conditions across honeycomb desiccant wheels. (Model: WSG 250 x 200) was selected because it was in closest resemblance to the prototype radial desiccant wheel. These desiccant wheels have a lower limit on regeneration temperature so temperature lower than 66 ˚C could not be used for regeneration. Rest of the inlet conditions are mentioned in figure 7.

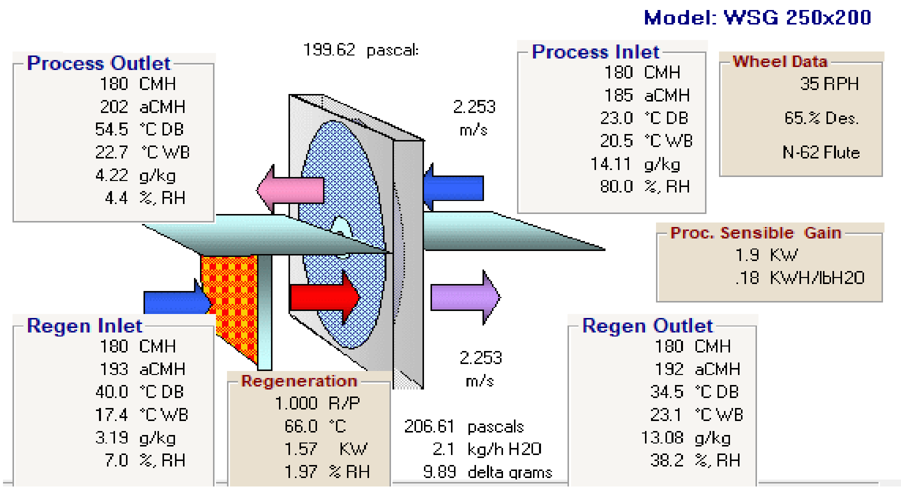

Fig. 7: The NOVEL Aire Technology simulator interface along with inlet and outlet parameters.

It is to be noted that moisture removal rate is almost 10 g/kg of dry air which is less as compared to radial desiccant wheel even with higher regeneration temperature. Secondly the massive pressure drop across the wheel will increase the overall energy consumption of the system.

4. Conclusion and Future Work

A prototype of solar regenerated desiccant based evaporative cooling system is design and tested for hot and humid environment. The radial blades desiccant wheel requires lower regeneration temperatures, experience lower pressure drop in comparison to honeycomb structure matrix and the tested system consumes around 70 % less energy as compared to vapor compression air conditioning systems. However, the system needs further improvement to fully satisfy the human comfort zone. One of the major issues that reduces the efficiency of the cooling process in the system is the carryover of the warm regenerative air when the blades move from the regeneration side to the process side. This warm air is mixed with the process air and increases its temperature. Consequently, the overall cooling effect of the system is reduced. Therefore, the design needs further improvement to avoid the mixing of regeneration and process air.

5. Acknowledgments

The authors acknowledge the anonymous reviewers for providing valuable suggestions.

6. References

Abd-Ur-Rehman, H.M., Al-Sulaiman, F.A., 2016. Optimum selection of solar water heating (SWH) systems based on their comparative techno-economic feasibility study for the domestic sector of Saudi Arabia. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2016.04.047

Abd-Ur-Rehman, H.M., Al-Sulaiman, F.A., 2014. Techno-economic evaluation of different types of solar collectors for water heating application in domestic sector of Saudi Arabia, in: IREC 2014 - 5th International Renewable Energy Congress. IEEE Computer Society. https://doi.org/10.1109/IREC.2014.6826977

Abd-ur-Rehman, H.M., Al-Sulaiman, F.A., Mehmood, A., Shakir, S., Umer, M., 2018. The potential of energy savings and the prospects of cleaner energy production by solar energy integration in the residential buildings of Saudi Arabia. J. Clean. Prod. 183, 1122–1130. https://doi.org/10.1016/j.jclepro.2018.02.187

Abd-Ur-Rehman, H.M., Shakir, S., 2016. ENERGY CONSERVATION OPPERTUNITIES AND SOLAR ENERGY INTEGRATION PROSPECTS IN THE RESIDENTIAL SECTOR OF KSA. pp. 11–14. https://doi.org/10.18086/eurosun.2016.11.01

ISO, 2005. ISO 7730: Ergonomics of the thermal environment Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria. Management 3, 605–615. https://doi.org/10.1016/j.soildyn.2004.11.005

Mujahid Rafique, M., Gandhidasan, P., Rehman, S., Al-Hadhrami, L.M., 2015. A review on desiccant based evaporative cooling systems. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2015.01.051

Rafique, M.M., Gandhidasan, P., Bahaidarah, H.M.S., 2016. Liquid desiccant materials and dehumidifiers - A review [WWW Document]. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2015.11.061