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Modelling and Analysis of a Solar Biomass Hybrid Vapour Absorption Refrigeration System for running a Cold Storage of Potato in India

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Abstract:

India suffers from the wastage of a large amount of agricultural produce due to the lack of proper post-harvest storage system. In this paper, an attempt has been made to propose a novel hybrid solar thermal and biomass driven refrigeration system. The refrigeration cycle used here employs a LiBr-H_2O vapour absorption refrigeration system used for storage of potatoes in cold storage. The objective of the hybrid power system proposed here is to produce a favourable micro-climate inside the cold storage throughout a calendar year irrespective of the seasonal variations in weather. The modelling equations of the proposed system have been developed and solved with the help of Engineering Equation Solver for the location of New Delhi (28°35' N, 77°12' E). The results of the proposed model are validated against a reference model study available in literature and a very good agreement is achieved with a root mean square error of 0.98% in the value of COP. A rudimentary cost analysis has also been included to assess the economic viability of the proposed system. The study thus reinforces the viability of using a solar biomass hybrid system for operation in the rural areas of a developing nation like India.

Keywords: Absorption chiller, Cold storage, Cost analysis, Solar-biomass hybrid cooling, Thermodynamic analysis

1. Introduction:

Food security plays an important role in the development and self-reliability of a nation. The huge population of India gives rise to a large demand for a variety of agricultural products throughout the year irrespective of the seasonal variation in its availability. This creates the need for storing the products in cold storages. Recent studies show that eighteen per cent of India's fruit and vegetable production valued at INR 133 billion is wasted annually [1]. Horticulture alone provides 6.5% of the country's GDP, 14% of employment and accounts for more than 11% of Indian exports with only 9% crop acreage [2]. One of the major parts of fruit and vegetable preservation is post-harvest care. Huge post-harvest losses result in fluctuations in the price of agricultural products and diminished returns for the farmers.

It may be noted that at present most of the conventional cold storages rely upon electricity available from the power grid for their operation. The grid electricity may not be available in rural areas of Indian subcontinent on a sustainable and continuous basis. Also, even if the remote villages are grid-connected, there will be operational issues like large transmission losses, low voltage problems, breakdowns during the storm, etc. So at present, the cold storage units are mostly backed up with diesel generator sets. The combustion of fossil fuels (diesel) causes environmental pollution. Thus, the use of renewable sources of energy in this area can be a viable solution to the given problem. Solar energy and energy from biomass are two such sources of renewable energy that are readily and abundantly available for a developing country like India. Vapour absorption refrigeration systems are capable of utilising the thermal energy available from these renewable sources to produce the desired refrigerating effect. The average intensity of Direct Normal Irradiance (DNI) received in most of the parts of India is 4-5.5kWh/m^2-day [3]. Biomass is considered a renewable source of energy as it can re-grow in a short period of time. Also, combustion of biomass leaves no carbon footprint, as the carbon dioxide released by the burning of biomass is utilised by plants while growing it. Thus, the use of solar energy along with energy from biomass allows the cold storage facility to have desirable inside conditions irrespective of the seasonal and daily variations in the amount of sunshine.

Only a few researchers have exclusively worked on cold storage systems (Lal *et al*. (2015); Etawil *et al*. (2006)). However, many research works have been reported on vapour absorption refrigeration system (VARS) using both LiBr-H_2O pair and Aqua-ammonia pair. It is found that though the aqua-ammonia pair is able to reach very low chiller temperatures it is quite toxic to handle. LiBr-H_2O pair is seen to be more viable for use in the food processing industry for reaching cooling temperatures of above 4^0C. Also, some researchers have worked on the use of solar energy (both thermal and hybrid) to power the vapour absorption cycle (Falahatkar *et al*. (2011); Basu *et al*. (2016); Bellos *et al*. (2016)). Most of these researchers have used the refrigeration cycle for air conditioning purpose. Results obtained by Falahatkar *et al*. (2011) demonstrate that up to 2400 m^3/year Natural Gas energy saving can be reached by use of solar absorption cooling system. Bellos *et al*. (2016), tested four different solar collectors, in a single stage absorption chiller operating with LiBr–H_2O and concluded that the evacuated tube collectors give the exergetically optimum results. Again, only a few research works have been reported using only biomass-based engines or gasifiers for powering the absorption refrigeration system (Rather *et al*. (2018); Mbikan *et al*. (2017)). However, the same has not evolved commercially owing to the low coefficient of performance.

Very recently some researchers have started working on hybrid solar and biomass based systems for powering VARS. Among them, only one work (Rather *et al*. (2017)) have been reported at least in the open literature that describes the working of a solar biomass hybrid VARS for cold storage purpose. Both of them have used solar Scheffler discs for solar thermal conversion and the thermal cycle employed for cold storage is based on the water-ammonia absorption system. The maximum COP that was obtained was quite low, about 0.6.

It is thus obvious (from literature) that the vapour absorption refrigeration systems using solar biomass hybrid energy for running cold storages are a viable choice for cooling applications in rural areas. Literature review reveals that different methods of coupling of renewable energies with the refrigeration cycle have been employed by authors. However, no work has been found at least in the open literature that analyses the suitability of using a solar biomass hybrid vapour absorption refrigeration cycle for cold storage of potatoes in the climatic conditions of India around the year. Moreover, a complete work that includes an energy, exergy and economic analysis of a hybrid VAR system based cold storage supported with evacuated tube solar collector and a biomass combustor is not reported in the literature. This is the motivation behind the present work.

In this paper, an attempt has been made to propose a scheme of a single effect LiBr-H_2O vapour absorption refrigeration cycle powered through a combination of evacuated tube solar collector and a biomass combustor. The proposed refrigeration cycle has been designed to run a cold storage that is utilized for storage of potatoes at the location of New Delhi. The proposed system has been validated against a work already present in literature.

Variations in the thermodynamic performance of the system with the variation in generator temperature, monthly solar irradiance, etc. have been studied. After observing the year-round performance of the system a cost analysis has also been done.

2. System Description:

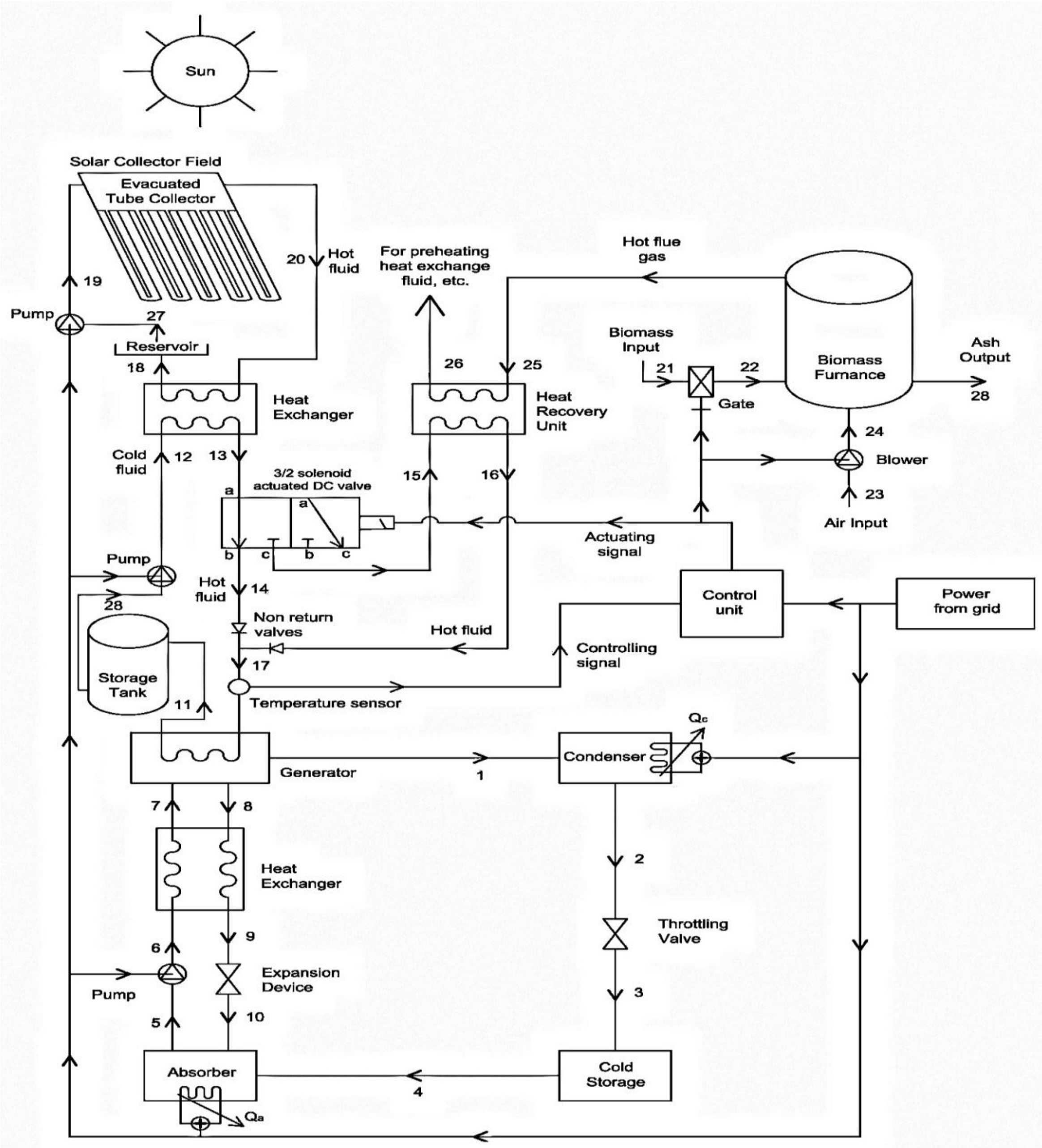

Figure 1: Schematic diagram of the proposed scheme.

Figure 1 shows the schematic diagram of the proposed system. The temperature of the heat exchange fluid is sensed by a temperature sensor before its entry to the generator. This temperature sensor signal is read by the control unit which in turn issues actuating signals to control the amount of gate opening for regulating the entry of biomass and the blower rate. Hence, a closed loop system is formed which is facilitated by a 3/2 DC valve to change the path of flow of heat exchange fluid during different modes of operation:

i. **Sunny day operation:** When enough solar energy is present to heat the heat exchange fluid to the required amount the valve is kept in ab position. Hence the heat exchange fluid bypasses the biomass system.
ii. **Partly sunny operation:** The heat exchange fluid after taking heat from the solar collector heat exchanger goes through the heat recovery unit (HRU) and picks up heat from the flue gas of biomass furnace. This is done by keeping the valve in ac position.
iii. **No sun condition:** The pump feeding the solar collector is kept off, so the heat exchange fluid bypasses the solar heat collection and is heated by utilising biomass.

3. Thermal Modelling:

The thermal model has been developed under the light of the following assumptions:

i. Steady state and steady flow are assumed throughout the cycle.
ii. Change in potential energy and kinetic energy across components is considered negligible.
iii. No frictional losses are considered.
iv. No pressure drop is assumed across the valves.
v. Water is circulated at 5 bar pressure through the solar collector. This is done to avoid phase change up to around 150 ^{0}C.
vi. Water at 5 bar pressure is taken as the heat exchange fluid through the valve and sensor circuit.
vii. Biomass combustor is considered to be adiabatic and at equilibrium condition with a furnace reaction pressure of 1.013bar.
viii. The composition of air is considered as 79% N_2 and 21% O_2 by volume basis.
ix. The heat exchangers are considered to have effectiveness, η of 0.6 which is in good agreement with practically obtained values [8].

3.1. Evacuated Tube Solar Collector:

The available solar energy from the evacuated tube collector may be given by [8]:

$$Q_{solar} = A_c \cdot G_{eff} \quad (1)$$

Where A_c is the collecting area of the collector (200m^2) and G_{eff} is the effective solar radiation in W/m^2. The collector efficiency is assumed to be 65%, which is a very practical assumption. Petela Equation is used to calculate exergy inflow from the sun [8]:

$$Ex_{solar} = \left\{1 - \frac{4}{3}\cdot\left(\frac{T_{am}}{T_{sun}}\right) + \frac{1}{3}\cdot\left(\frac{T_{am}}{T_{sun}}\right)^4\right\} \quad (2)$$

3.2. Biomass Combustor:

Treating furnace as control volume, the energy balance equation can be written as [12]:

$$\bar{h}_{25} = \bar{h}_{CHO,22} + \omega\cdot\bar{h}_{H_2O,22} + \gamma(1+e)\left(\bar{h}_{O_2,24} + (79/21)\cdot\bar{h}_{N_2,24}\right) \quad (3)$$

Here, $\bar{h}$ is the specific enthalpy per kg of biomass burnt; ω is the moisture content factor; γ is the stoichiometric air-fuel ratio and e is the excess air ratio.
Exergy from biomass combustion can be evaluated by multiplying the specific exergy of biomass combustion (16.2MJ/kg [13]) to the mass flow rate of biomass.

3.3. Vapour Absorption Refrigeration Cycle:

Energy balance across each component gives the COP of the system as [8]:

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$$COP = (h_4 - h_3) \Big/ \Big(h_1 + \big\{ (1-\eta_{HEX}) \cdot h_9 \cdot x_w / (x_{str} - x_w) \big\} - \big\{ \big(x_{str} - (\eta_{HEX} \cdot x_w) \big) \cdot h_5 / (x_{str} - x_w) \big\} \Big) \quad (4)$$

Where, x_w is the weak LiBr solution concentration and x_{str} is the strong LiBr solution concentration.

3.4. Cooling Load of The Cold Storage:

The cold storage dimensions are assumed to be 20 x15 x10 m^3.and the storage conditions are taken as 10^0C, 85% RH [14]. The cooling load can be evaluated from:

$$Q_{load} = Q_{walls,floor} + Q_{fenestration} + Q_{air-change} + Q_{internal} \quad (5)$$

The cooling load for the cold storage being loaded at the rate of 75ton/day has been found out to be 112.5kW and was verified using INTRACON cold room calculator [15]. The ambient outside conditions were taken as 37.9^{o}C (DBT) and 21.4^{o}C (WBT).

3.5. Exergetic Efficiency Analysis:

The chiller exergetic efficiency is evaluated by:

$$\eta_{Ex,chiller} = -Q_E \left(1 - (T_{am}/T_E)\right) \Big/ \left(Q_G \left(1 - (T_{am}/T_G)\right) \right) \quad (6)$$

In Eq. (6), T_E and T_G are evaporator and generator temperatures respectively. While exergy of the system as a whole can be expressed as exergy flow at evaporator divided by total exergy inflow to the system from the sun and biomass combustion:

$$\eta_{Ex,system} = -Q_E \left(1 - (T_{am}/T_E)\right) \Big/ (Ex_{solar} + Ex_{biomass}) \quad (7)$$

3.6. Cost Analysis:

The payback period of the integrated power system (n_p) can be estimated as [16]:

$$n_p = \frac{\ln\left[\dfrac{CF}{CF - (i \times P_{NPV})}\right]}{\ln[1+i]} \quad (8)$$

CF is the annual cash flow generated from the system on account of energy saving. P_{NPV} is the net present value of the integrated heating system and can be expressed as [16]:

$$P_{NPV} = C + R_m \times \left[\frac{(1+i)^n - 1}{i(1+i)^n}\right] + R_p \times \left[\left\{\frac{1}{(1+i)^p}\right\} + \left\{\frac{1}{(1+i)^{2p}}\right\} + --- + \left\{\frac{1}{(1+i)^{n-p}}\right\}\right] - S \times \left[\frac{1}{(1+i)^n}\right] \quad (9)$$

In Eq. (9), 'C' represents the initial cost of the proposed system. 'i' is the rate of interest which is considered to be 8% and 'n' represents the expected life of the system and is assumed to be 25 years. 'R_m' represents the annual maintenance cost which is considered to be 5% of the initial investment cost. 'S' is the salvage value of the heating system which is assumed to be 10% of the initial investment cost. 'R_p' represents the replacement cost of equipment if any and is assumed to be zero for the sake of simplicity.

4. Results and discussions:

The model developed in this paper has been validated against the results obtained by Bellos *et al* [8]. The same data (as used by Bellos *et al.*) has been supplied as input to our model for the purpose of validation. The results thus obtained from the present study have been compared with the results available in literature in terms of COP and exergetic efficiency for generator temperatures ranging from 110^0C to 125^0C. The root mean square deviation of COP has been estimated to be about 0.98% only; whereas for exergetic efficiency it is obtained to be 2.47%. Therefore, the results obtained from our model show a good agreement with the results available in the literature.

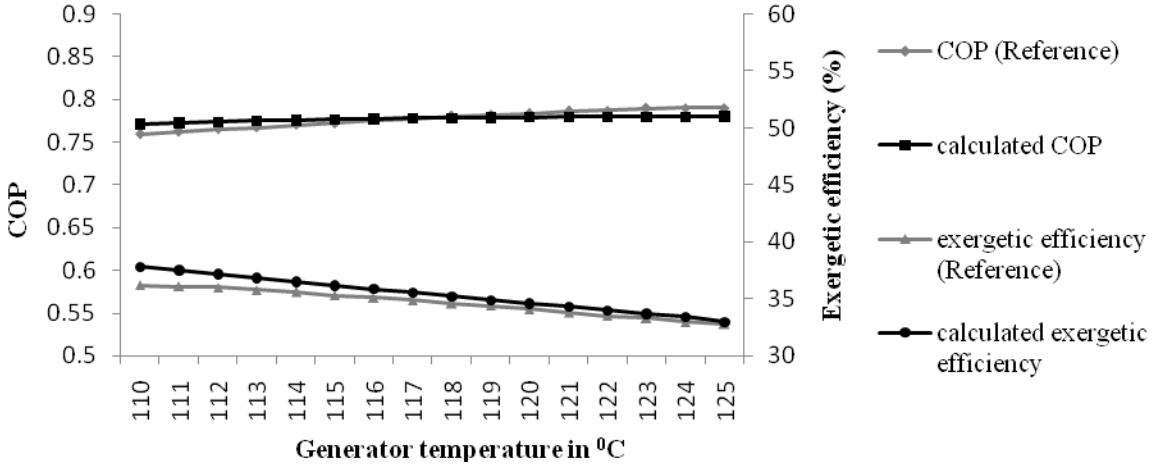

Figure 2: Thermal model validation.

Taking optimum chiller temperature for storage of potatoes (10^0C) and generator temperature as 115^0C the chiller performance has been evaluated for a representative day of every calendar month at the location of New Delhi, taking into account the monthly average ambient temperature and solar radiation variation. The data hence obtained is shown in fig. 3. It is observed that when the cycle achieves an energetically maximum performance at that month the exergetic performance is low and vice versa. The system gives the highest COP for the month of January but has very low exergetic efficiency; on the other hand, it reaches maxima of exergetic efficiency for the months of May and June when the COP is quite low. The overall system exergetic efficiency throughout the year is also recorded and depicted.

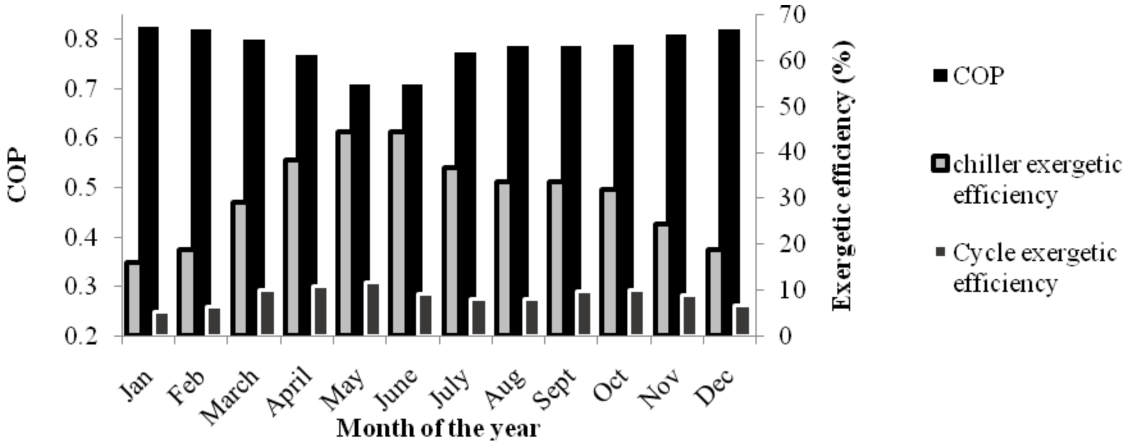

Figure 3: Year-round thermodynamic performance of the system.

Cost Analysis: The initial investment for the proposed refrigeration cycle has been estimated to be INR 2000000 and the net present value is found to be INR 3038277 over a lifetime of 25 years. Based on the cost of the energy saved by the hybrid system using the standard tariff available in the market [17] the annual cash flow has been estimated to be INR 1376113. Although, it can be seen that the initial investment for the hybrid system appears to be significantly high; however, a decent cash flow gives a payback period of about 2.6 years. This payback has been estimated considering no subsidy on the rate of interest, however, usually in developing nations like India some subsidy is offered by the government under different solar schemes for promoting the application of solar energy. This subsidy may reduce the payback period further. Finally, the cooling cost is obtained to be almost as much as INR 0.1 per kg, which is a very affordable price. Thus the economic viability of the hybrid system is justified.

5. Conclusions:

From the analysis of the proposed scheme the following conclusions can be drawn:

i. The year-round performance shows that the highest COP is obtained in the month of January.
ii. The exergetic efficiency reaches a maximum during the months of May and June for the chosen location.
iii. The proposed system is economically viable with an annual cash flow of INR 1376113 and a payback period of about 2.6 years.
iv. The study thus underlines the necessity of the solar biomass hybrid cold storages and gives an idea of its economic viability for operation in the rural areas of a developing nation like India.

References:

1. Report of The Energy and Resources Institute: Solar-Biomass Hybrid Cold Storage-cum-Power Generation system for Rural Applications, *Energetica India*, 15 Apr 2012, Available from: http://www.teriin.org/opinion/solar-biomass-hybrid-cold-storage-cum-power-generation-system-rural-applications [Accessed 15 Jan 2019].
2. Report of The Directorate of Economics and statics, Ministry of Agriculture and Farmers Welfare, Government of India: State of Indian Agriculture, 2016, Available from: http://eands.dacnet.nic.in/PDF/State_of_Indian_Agriculture.2015-16.pdf [Accessed 15 Jan 2019].
3. A. P. Tyagi, *Solar Radiation Energy over India*, Indian Meteorological Department and Ministry of New and Renewable Energy, Govt. of India, 2009.
4. Shiv Lal, “Design of Cold Storage for potato in India”, *Cooling India*, 2015, 11, pp. 38-42.
5. Mohamed A. Eltawil, D. V. K. Samuel, O. P. Singhal, “Potato Storage Technology and Store Design Aspects", *Agricultural Engineering International: the CIGR Ejournal*, 2006, Invited Overview No. 11. Vol. VIII, pp. 1-18.
6. A. Falhatkar, M. K. Assadi, “Analysis of solar lithium bromide-water absorption cooling system with heat pipe solar collector”. In Proceedings of the *World Renewable Energy Congress, Sweden*, 8-13 May 2011, pp. 3889-3896.
7. Dipankar N. Basu, A. Ganguly, “Solar thermal–photovoltaic powered potato cold storage–conceptual design and performance analyses”, *Applied Energy*, 2016, 165, pp. 308-317.
8. Evangelos Bellos, Christos Tzivanidis, Kimon A. Antonopoulos, “Exergetic, energetic and financial evaluation of a solar driven absorption cooling system with various collector types”, *Applied Thermal Engineering*, 2016, 102, pp.749-759.

9. Nasir U. R. Rather, Arun Tripathi, “Design of Biomass Gasifiers for Power generation, cold storage and Heating for Jammu and Kashmir state”, *International Journal of Advances in Scientific Research and Engineering*, (2018), 4(1), pp.85-94.
10. Munyeowaji Mbikan, Tarik Al-Shemmeri, “Computational model of biomass driven absorption refrigeration system”, *Energies*, 2017, 10 (234) pp. 1-15.
11. Nasir U. R. Rather, Sheen Moses, Umakanta Sahoo, Arun Tripathi, “Performance Evaluation of Hybrid Cold Storage using Solar & Exhaust heat of Biomass Gasifier for Rural Development”, *International Journal on Recent and Innovation Trends in Computing and Communication*, 2017, 5(7), pp. 563-569.
12. A. Mondal and A. Ganguly, “Modelling and performance analysis of a biomass combustion based power generation and grain drying system”. In Proceedings of the *1st International Conference on Mechanical, Materials and Renewable Energy, Sikkim,* 2017, pp. 58.
13. A. Wang, X. Zhang and M. Huang, Exergy analysis of biomass gasification process. In Proceedings of the *International Conference on Materials for Renewable Energy and Environment (ICMREE), Chengdu*, 2013, pp. 211-214.
14. A. Ganguly and R. K. De, Conceptual design and performance analysis of a parabolic trough collector supported multi-commodity cold storage. In Proceedings of the *2nd International Conference on Advances in Mechanical Engineering (ICAME), Chennai,* 22-24 March 2018, pp. 393-403.
15. Intracon, Refrigeration calculator. [Online] Available from: http://www.intarcon.com/calculadora/calc_en.html [Accessed 15 Jan 2019].
16. Pradyuman Barnwal, G. N. Tiwari, “Life cycle cost analysis of a hybrid photovoltaic/thermal greenhouse dryer”, *Open Environmental Sciences*, 2008, 2, pp. 39-46.
17. CESC, Electricity tariff 2018. [Online] Available from: https://www.cesc.co.in/wp-content/uploads/tariff/TARIFF%20AND%20ASSOCIATED%20CONDITIONS.pdf [Accessed 15 Jan 2019].