Energy and exergy analysis of a solar tri-generation system using TRNSYS

Kamal Kishore Khatri* and Ankush Kumar Singh
*Author for correspondence
Department of Mechanical - Mechatronics Engineering,
The LNM Institute of Information Technology,
Jaipur, 302031,
India,
E-mail: kamalkishorekhatri@gmail.com

Abstract

IC Engine based tri-generation system are readily available in market today. Although such systems are highly efficient, they are mostly based on petroleum and diesel hence, are less environment friendly. This paper presents performance analysis of a small solar tri-generation system to satisfy the needs of an off-grid single family dwelling. Chief functions of this system include electrical power, Domestic Hot Water (DHW) and cooling power production. Key elements of this system include Photo Voltaic Thermal (PVT) collector for electricity and hot-water generation and a hot-water fired LiBr-H_2O absorption chiller for chilled water generation. Energy and exergy analysis have been done to evaluate the efficiency and quality of energy extracted. This paper aims to study the effect of various parameters such as tilt angle and wind speed on energy and exergy efficiency of the overall system. A model was designed and simulated in TRNSYS for the system at different wind speed and tilt angles and optimum working conditions were determined. 2.98 KW electric power and 3.77 KW heating power was produced from 26.25 m^2 of PVT panel. The energy and exergy efficiency were 50.53 % and 35.87 % respectively.

Nomenclature

Q	[Watt]	Energy per unit time
EX	[Watt]	Exergy per unit time
A	[m^2]	Area of PVT panel
I	[W/m^2]	Solar Irradiance
C_p	[J/kg K]	Specific heat capacity
T	[°C]	Temperature
P	[Pa]	Pressure
R	[J/mol K]	Universal gas constant
COP	[-]	Coefficient of performance
Special characters		
η	[-]	Cell efficiency
μ	[-]	Transmittance
ṁ	[kg/s]	Mass flow rate
Subscripts		
I		Incident
hw		Hot water
0		Ambient condition
ref		Refrigeration
chw		Chilled water
c		Panel
gen		Generator of absorption chiller

1. Introduction

With the prospective depletion in conventional energy resources namely coal, petroleum and other fossil fuels, an energy crisis looks certain. World focus is rapidly shifting to sustainable energy resources. Sun being the cheapest source is abundantly available almost anywhere in the world [3]. However most of the solar plants have capacity more than 500 KW which are not accessible for off grid dwellings. Being large in size waste heat recovery systems also are not efficient. Moreover a large part of population in developing countries like India and China live off the grid (mostly hilly and rugged terrain where electricity supply is not economically feasible) In remote locations without any supply of electricity living conditions in such areas can become very deplorable. In such areas micro solar plants with capacity less than 5KW can be installed using Photo Voltaic Thermal (PVT) collectors which are hybrid devices that produce hot water and electricity at the same time. PVT collectors utilise the waste heat which is otherwise lost in conventional solar devices used for cooking and DHW [1]. Such PVT devices are made up of semiconductors. When an electron on n side receives sunlight it diffuses into p side leading to flow of current. These PVT systems can also be integrated with Lithium Bromide (LiBr) based absorption chillers to satisfy the need of cold water and air conditioning in hot summers hence proving as an all-weather solution.

Energy efficiency of a system is the percentage of the input energy that is converted to a useful energy output. Energy analysis is based on first law of thermodynamics and deals with the quantity of energy only. Meanwhile, exergy is a measure of useful work that a system can perform. Exergy analysis is carried out using the second law of thermodynamics and it deals with the qualitative aspect of energy systems [2].

The purpose of this paper is to simulate and optimize a small scale solar tri-generation system in TRNSYS software tool which is widely used in industry and academia today [3]. The performance of the system is predicted through Energy and exergy analysis. This paper also presents the effect of change in parameters such as wind and tilt angle on energy and exergy efficiency of the system. The base line data of simulation results were validated with data available in literature which are presented in section 6.

2. Solar tri-generation system

This system was based on PVT collectors for production of electrical power and DHW. A part of water after being heated in PVT is fed to absorption chiller specially designed for use in solar energy systems. Ambient temperature used for the model was 35°C and Solar Irradiance was taken as 580 W/m^2. The flow diverter has been set such that 25% of the hot water generated in PVT is sent to hot water inlet of the absorption chiller. An insulated thermal storage tank of capacity 350 Litres is modelled in the system. The thermal storage tank has been incorporated into this system to show the circulation of water in the actual system. However, energy and exergy efficiencies of system have been calculated before the water enters into the tank. This has been done so as to analyse the actual efficiency excluding the storage loss. While calculating exergy and energy efficiencies; auxiliary electrical power needed to run the pump, absorption chiller etc. has been assumed to be negligibly small. The details with parameters of main components used in this model are as follows:

A. Photovoltaic thermal cells

The PVT cells were modelled based on Quadsun CPV CHP 33-500 with parameters as given in Table 1 [4]. A set of 5 PVT panels were modelled together keeping in mind the energy needs of a small family dwelling.

Table 1 Parameters of PVT panel [4]

Parameter	Value
Dimension (Metre)	2.5*2.1*1.8
Cell efficiency	33.85%
Packing factor	0.8
Collector efficiency factor	0.7

B. Absorption chiller

The absorption chiller used in this system was modelled on Rotartica hot water fired Thermal solar line absorption chiller which is specially designed to function as Air Conditioner. The chiller had a 4.3 KW cooling capacity and had a COP of 0.6152 [5].

3. TRNSYS simulation

For simulation purpose TRNSYS (Transient System Simulation) version 17 was used. Layout of the TRNSYS model is as seen in Fig. 1.

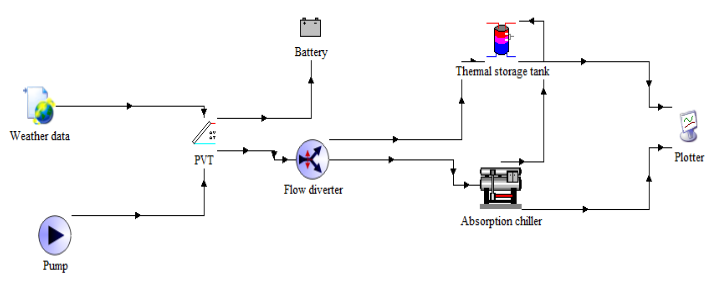

Fig 1. Schematic of TRNSYS simulation

A weather data file is used to define ambient conditions to be used in the model. Water through a pump at room temperature is fed to PVT panel which receives solar irradiation and generates electrical power and heats the water by concentrating solar thermal energy.

The electrical power generated is stored in battery while generated hot water is passed through a flow diverting valve. This valve directs a part of hot water to the absorption chiller while rest of it is sent to insulated thermal storage tank for later use. About 25% of hot water is sent to absorption chiller, which uses its thermal energy to pump the heat and produce air conditioning effect.

4. Energy and exergy analysis

Energy is a measure of quantity while exergy is a measure of quality of energy. Energy efficiency will give the upper limit of part of incident solar radiation that will be converted to useful form of energy. Whereas exergy efficiency will be the measure of potential of that energy to do useful work. In this section, energy and exergy analysis of system developed in TRNSYS under a steady state condition is presented. For analysis ambient temperature has been assumed to be 35°C and atmospheric pressure at 100 KPa while the solar irradiance is assumed to be 580 W/m^2.

A. Energy analysis

Equations for energy analysis of system developed in TRNSYS are given as follows.
Incident radiation on PVT panel:

$$Q_i = AI_{sun} \quad (1)$$

where A is the area of PVT exposed to sunlight, and I_{sun} is solar irradiance.
Useful energy from PVT panel:

$$Q_u = \eta\mu Q_i = \eta\mu A I_{sun} \quad (2)$$

where η is cell efficiency of the inner surface, while μ is transmittance of the outer surface. This gives the useful energy used for producing power and heating of water.
Energy extracted by hot water going to storage tank:

$$Q_{hw} = \dot{m}_{hw} C_p (T_{hw} - T_0) \quad (3)$$

where Q_{hw} is energy received by hot water and $\dot{m}_{hw}$ is mass flow rate of hot water directly to insulated thermal storage tank. C_p is the specific heat of the water, T_{hw} is temperature of hot water and T_0 is ambient temperature.
Energy extracted in the absorption chiller:

$$Q_{ref} = \dot{m}_{chw} C_p (T_0 - T_{chw}) \quad (4)$$

where Q_{ref} is energy extracted during refrigeration. $\dot{m}_{chw}$ is mass flow rate of chilled water produced in the chiller, and T_{chw} is temperature of chilled water.

$$\text{Energy efficiency} = (Q_{electrical} + Q_{hw} + Q_{ref})/Q_i \quad (5)$$

where $Q_{electrical}$ is the electrical energy output.

Table 2. Results of energy analysis

Parameter	Value
Incident power	15225 W
hot water temperature	76.61 °C
Chilled water temperature	15 °C
PVT cell temperature	85.24 °C

Electrical power generated	2984.6 W
Power extracted by hot water	3777.5 W
Power extracted by chilled water	931.11 W
Total energy generated	7693.21 W
Energy efficiency	50.53 %
Absorption chiller COP	0.6152

B. Exergy analysis

High flow rate of water means more pump power is required. Lower flow rates means lesser pumping power required as well as higher work potential due to higher temperatures. However increased entropy leads to lowering of exergy of the system. Hence exergy analysis is an efficient tool to determine optimum flow rates. It should be noted that exergy of electrical power is equal to its value. It has been assumed that the energy and exergy consumed by the pump is negligible.
Exergy incident on the PVT panel is given as follows:

$$EX_i = Q_i(1 - T_0/T_c) \quad (6)$$

where T_c is the temperature of the panel, and T_0 is ambient temperature.
Thermal exergy recovered by hot water is given by:

$$EX_{hw} = \dot{m}_{hw}[C_p(T_{hw} - T_0) - T_0(Cp\int dT/T - R\ln(P_{out}/P_{in})] \quad (7)$$

where $P_{out} = P_{in}$ for the liquid. Hence the resultant equation will be as follows:

$$EX_{hw} = \dot{m}_{hw}C_p[(T_{hw} - T_0) - T_0\ln[(T_{hw} + 273)/(T_0 + 273)]] \quad (8)$$

The exergy recovered during refrigeration is as follows:

$$EX_{ref} = (COP/COP_r)*Q_{gen} \quad (9)$$

where COP_r is maximum possible coefficient of Performance of the chiller. Q_{gen} is Energy supplied to generator of absorption chiller.
The exergy available at the generator of the VAR is as follows:

$$EX_{gen} = \dot{m}_{gen}*C_p*[(T_{gen} - T_0) - T_0\ln(T_{gen}/T_0)] \quad (10)$$

$$\text{Exergy efficiency of the system} = (EX_{electrical} + EX_{hw} + EX_{ref})/EX_i \quad (11)$$

here $EX_{electrical}$ is the amount of exergy in the electrical power generated.

Table 3. Results of exergy efficiency

Parameter	**Value**
Incident exergy	8973.53 W
Electrical exergy generated	2984.6 W
Exergy extracted by hot water	234.3 W
Exergy extracted during refrigeration	0.575 W
Total exergy generated	3219.47 W
Exergy efficiency	35.877 %

5. Results & discussions

Actual data of weather conditions prevalent in Jaipur, India are applied to analyse the effect of ambient conditions on the PVT panel. It was found that although quantity of energy is important, exergy analysis was more efficient method of performance analysis.

System as shown in Figure 1 was simulated in TRNSYS and results of energy analysis are shown in Table 2. For this analysis wind speed was assumed to be 15 Km/h, and tilt angle of PVT panel was kept 0°. Total flow rate of hot water from PVT was set at 104 kg/h. Out of this 78 kg/h went directly to insulated storage tank, whereas rest was sent to absorption chiller. Chilled water temperature was set at 15°C. The hot water coming out from chiller was almost at ambient temperature hence it was recirculated to PVT panel. Total thermal energy efficiency achieved was 50.53 %. A large part of this energy was extracted in form of hot water equal to 3777.5 W. Electrical power generated was 2984.6 W which is sufficient for a small single family dwelling. The COP of absorption chiller was found to be 0.6152.

Table 3 shows results for exergy analysis. Incident exergy was lower than incident energy because solar power has lesser potential to do work than say electrical power. This low exergy is due to the irreversibility of the photo voltaic conversion process. There is also a significant waste of solar exergy incident on the module. The PV conversion process with conventionally available silicon modules, despite their advantage and widespread availability, implies an enormous loss of exergy.
Here electrical exergy was assumed to be equal to its energy as almost of electrical energy has potential to do useful work. Also chilled water has very less exergy. Hence total exergy output was lesser than energy output and the exergy efficiency stood at 36.88 %.
The variation in energy efficiency with respect to wind speed is shown in Figure 2.

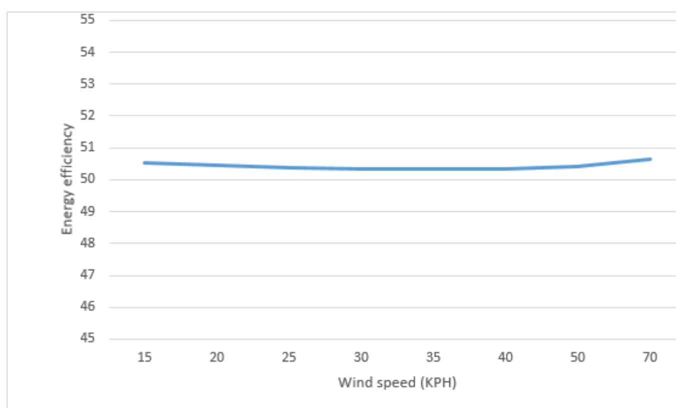

Fig 2. Change in energy efficiency with wind speed

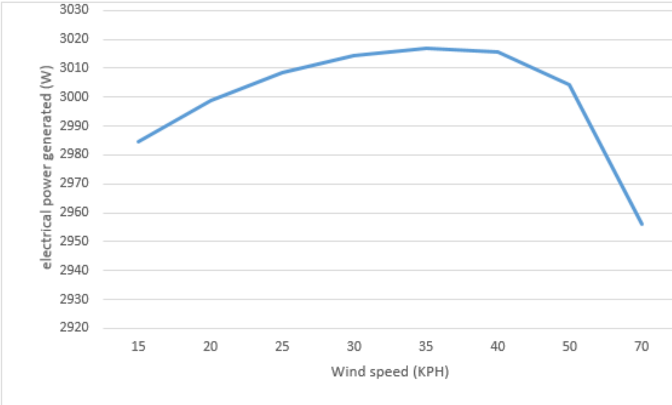

Fig 3. Change in electrical power generated with wind speed

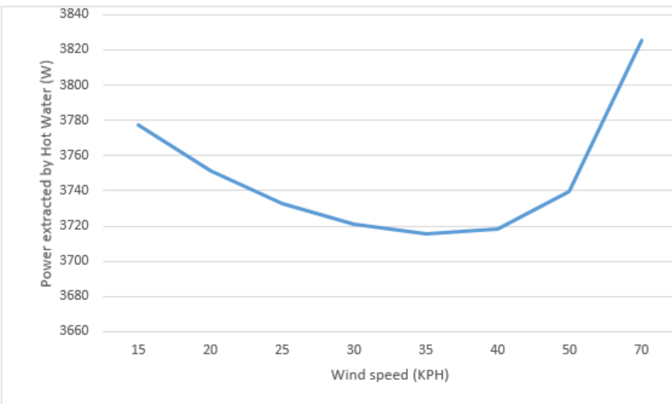

Fig 4. Change in energy extracted by hot water with wind speed

There is only a very slight variation in energy efficiency with the change in wind speed. Energy extracted from the hot water decreased initially due to drop in cell temperature as shown in Figure 4. However further drop in cell temperature causes a significant increase in cell efficiency resulting in increase in energy extracted by the hot water. This initial increase in cell efficiency also causes higher electrical power generation. However at extremely high wind speeds panel orientation may be disrupted leading to significant decrease in electrical power generation as shown in Figure 3.

Variation in exergy efficiency is shown in Figure 5. Graph of exergy efficiency shows a close resemblance to that of electrical power generation as electrical exergy makes about 92% of total exergy. Hence the optimum wind speed is 35 KM/H.

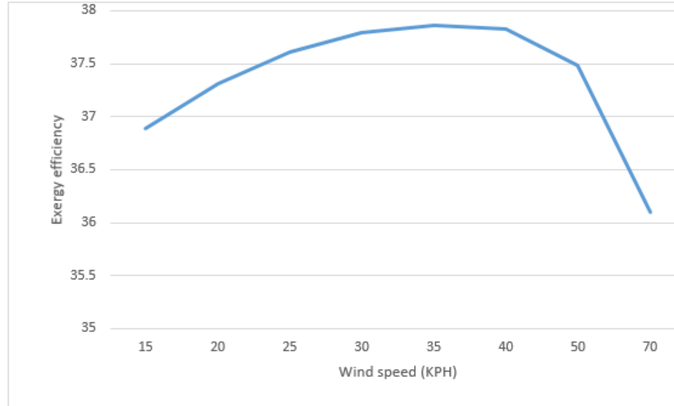

Fig 5. Change in exergy efficiency with wind speed

Figure 6 shows change in energy and exergy efficiencies with change in tilt angle. There is only slight change in efficiencies until the tilt angle is 45° as direct solar radiation falls on the panel. However after 45°, a part of solar radiation gets blocked as now panel starts to move to the other side of sun. This affects amount of electrical power generation hence the efficiencies are lower.

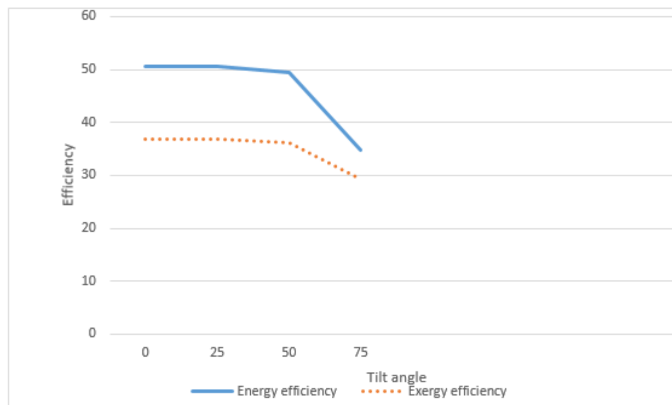

Fig 6. Change in energy and exergy efficiency with tilt angle

6. Related work and Validation

The initial base line validation is done by matching the performance of the system through modelling results with data of Quadsun [4] and Rotartica [5]. In addition to it, the simulation results have been compared and validated from the literature available as per the following details:

Zhai, H., et al. studied a solar tri-generation system using parabolic trough solar collector. Although energy efficiency achieved in this case was 58% as compared to 50.53%, exergy efficiency achieved was only 15.2% as compared to 35.87% [6]. Higher exergy is due to higher electrical power generation capacity and module efficiency used in the system presented in this paper.

Ranjan K., et al. presented energy and exergy analysis of a solar power based water distillation system. Energy and exergy efficiency achieved was 30.42% and 4.93% due to large energy and exergy destruction in basin liner, water body and glass cover used to create the system [7].

Koca, A., et al. performed 1st and 2nd law analysis of a latent heat storage system based on a solar collector made up of phase changing material. Although energy efficiency achieved was 45%, exergy efficiency was limited to 2.2% [8].

Sudhakar, K., et al. conducted first and second law analysis of an experimental PVT setup. The energy efficiency ranged between 6 – 9 % while the exergy efficiency ranged between 8 – 10 %. Comparitively lower efficiencies are attributed to higher ambient temperature because of summer. Apart from this the PVT cell efficiency used in this experiment was also slightly lower [9].

Khaldi, F., et al. performed thermodynamic analysis of a solar – gas hybrid power plant in Algeria. Out of 160 MW of total energy, 22 MW is being produced by solar trough collectors. These collectors not only generate electricity but also produce steam to run turbines. Energy and exergy efficiency of this plant was 35 % and 34 % respectively. By using the steam incident exergy lost was minimised [10].

7. Conclusions

In this study a Combined Cooling Heating and Power (CCHP) system based on PVT collector has been done. The system has been designed keeping in mind the need for electrical power and DHW of a small family dwelling leaving off grid. Energy and exergy analysis was presented as well as variation in energy and exergy efficiencies with respect to change in parameters such as wind speed and tilt angle of the module were studied. From the present study interesting results were found and can be summarised as follows:

- This solar CCHP system is able to produce 2984.6 W of electrical power, 3777.5 W of heating power as well as 931.11 W of cooling power with incident solar radiation of 580 W/m^2, and collector area of 26.25m^2 sufficient to satisfy the needs of a small family dwelling.
- Comparing energy and exergy efficiencies shows that only energy efficiency cannot be standalone measure to choose a desired system. Exergy is more relevant parameter to determine suitability of a system for it is a true measure of work potential.
- Although exergy efficiency is lower due to exergy destruction in hot water generation and refrigeration, it is still higher than conventional solar collectors being used for cooking or single generation which means quality of energy has been improved.
- Changing wind speed and tilt angle can affect energy and exergy efficiencies. Tilt angle must be less than 45° to ensure maximum solar energy is available to PVT panel.

References

1) Fraisse, G., Ménézo, C., & Johannes, K. (2007). Energy performance of water hybrid PV/T collectors applied to combisystems of Direct Solar Floor type. *Solar Energy*, *81*(11), 1426-1438.
2) Çengel, Y. A., & Boles, M. A. (2015). *Thermodynamics: an engineering approach*. M. Kanoğlu (Ed.). McGraw-Hill Education.
3) Chen, J. F., Dai, Y. J., & Wang, R. Z. (2016). Experimental and theoretical study on a solar assisted CO 2 heat pump for space heating. *Renewable Energy*, *89*, 295-304.
4) Quadsun CPV CHP 33-500 Manual, available at http://www.quadsunsolar.com/wp-content/uploads/2015/10/QUADSUN-CPV-CHP-33-500.pdf : Last accessed on February 15, 2016.
5) Rotartica Absorption chiller manual, available at http://andyschroder.com/static/pdf/Rotartica/Rotartica_Product_Description.pdf : Last accessed on February 22, 2016.
6) Zhai, H., Dai, Y. J., Wu, J. Y., & Wang, R. Z. (2009). Energy and exergy analyses on a novel hybrid solar heating, cooling and power generation system for remote areas. *Applied Energy*, *86*(9), 1395-1404.
7) Ranjan, K. R., Kaushik, S. C., & Panwar, N. L. (2013). Energy and exergy analysis of passive solar distillation systems. *International Journal of Low-Carbon Technologies*, ctt069.
8) Koca, A., Oztop, H. F., Koyun, T., & Varol, Y. (2008). Energy and exergy analysis of a latent heat storage system with phase change material for a solar collector. *Renewable Energy*, *33*(4), 567-574.
9) Sudhakar, K., & Srivastava, T. (2014). Energy and exergy analysis of 36 W solar photovoltaic module. *International journal of ambient energy*, *35*(1), 51-57.
10) Khaldi, F. (2012). Energy and exergy analysis of the first hybrid solar-gas power plant in Algeria. *ECOS*, 26-29.