Thermodynamic Analysis of a Hybrid Multi-Generation System Using Solar and Wind Power

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Abstract

This paper focuses on the development and thermodynamic analysis of a multi-generation system based on two renewable sources – solar and wind energy. Solar energy enters into the system by installation of parabolic trough collectors whereas wind energy is extracted by wind turbines in a wind farm. The outputs include refrigeration, electrical power and heating of water for domestic purposes. The power output of the system is obtained through two turbines. A thermodynamic assessment of the system is carried out by calculating energy and exergy efficiencies of the system. The relationship of outputs and inputs are also studied by varying various input parameters. The Engineering Equation Solver software is employed in the analytic study by constructing and generating codes on the software.

Keywords: multi-generation system, solar, parabolic trough collectors, wind, exergy, energy.

I. Introduction

Energy is the most important commodity which contributes directly to any country's growth and economy. Pakistan being an underdeveloped nation holds the disadvantage of not having abundance of conventional fuel which greatly halters its progress and development. Pakistan is faced with two great problems which include increased cost of import of fuel (mainly oil) and a constantly increasing demand for energy with the ever-growing population and settlement in major cities. Pakistan needs to improve its energy output considerably if it needs to support a rapidly growing population along with the ability to support new and budding industries that are being developed in the recent years.

The energy crisis cannot be limited to Pakistan only as all of the world is in dire need of new and alternate sources of energy but one fact that cannot be neglected upon is that the energy crisis is mostly severe in Pakistan. Pakistan being a budding nation needs a constant supply of cheap and clean fuel to make sure that their progress is not halted at any stage. The energy crisis not only affects the normal living of people but also hampers the progress in industries due to shortage of fuel in various departments [1]. The extended and extreme summer seasons see drastic increase in the demand of energy throughout the country and eventually leads to shortages and increased rates far too much for the average consumer [2]. Often by international experts, the ever-downhill economy of Pakistan and the 'volatile security situation' is linked to the severe energy crisis prevalent in the country [3]. This demand of energy is constantly not letting the economy grow and in 2008 it was to a point that a total of 4% of Pakistan's Gross Domestic Product was spent on undoing these crisis [4]. As a result, the industries are not flourishing and even closing leading to much more unemployment rates and further unrest in the country [5]. The main point of concern in the energy scenario is that Pakistan produces less amounts of energy from traditional sources (Hydro, Coal, Oil) than its installed capacity and negligible amounts of energy from renewable sources (Solar, Wind, Biomass) [6,7,8]. Renewable energy technologies are gaining worldwide interest due to the immense benefits that they offer in the field of sustainability, availability and modularity [9]. There are two approaches to solve the energy problem. One is to be able to make use of whatever natural resources one has without worrying about the long—term effects it has on the environment and secondly is being able to produce energy sustainably to ensure that the energy produced has a minimum adverse effect on the environment [10,11]. Pakistan has an abundance of coal, with about 185 billion tons of coal. These reserves of coal are mainly found in the interior Sindh or Hardaker region [12,13]. The problem with Pakistan's coal is that when used as a fuel produces comparatively lesser energy as it is not of the finest quality and releases a lot of pollutants including sulphur and ash into the environment [14]. This will eventually lead to pollution and will have harmful effect on all the life on earth. Little has been done to make the energy extraction using a coal an environment friendly project with maximum efficiency. Looking towards the renewable resources is the only solution which is much more viable and in abundance in Pakistan.

One way of putting those natural and renewable resources to good use is to build entire multigeneration systems with them as the primary input. Multigeneration systems are especially useful when the primary source that they are using of the renewable kind as in multigeneration systems the capital cost is comparatively high so the increase in cost is compensated with the abundance and free-occurring natural resource [15]. As it can be implied by the name, the system that is built produces several products from the same energy source to optimise the resource utilisation [16]. The reason why multi-generation systems are valued so highly because previous work and analysis have shown that the production of multiple outputs from one single system enhances the overall efficiency of the system as the losses are minimised when in totality [17-21]. An example of this study can be presented when Ozturk and Dincer analysed a system in which heat, hot water, cooling, hydrogen and power are generated using energy as a source [22]. The resulting overall exergy efficiency of the system was higher than that of the systems with in it. A different approach with the same result was discovered by Yang et al. [23] who combined ground source pump with fuel cell and found out that less energy was consumed by the hybrid system than the ground source system. Numerous other studies and research papers have shown that multigeneration systems are better at overall efficiency than separate single systems.

Solar energy is one such evergreen source whose potential has not yet been fully explored. Solar Energy is basically making use of the Sun's radiation and converting it into useful energy for daily use. This can be achieved using various methods which include making using of Solar PV panels but the most basic part is to achieve a higher temperature fluid and then use it to produce steam. The steam drives the turbine to produce energy for our use.
Pakistan being primarily being a country with hot and dry climate have more than 300 sunshine days with 30-34 C average temperature and 1900-2200 kWh/m^3 annual global irradiance [24]. -Many solar PV panels have been installed for the purpose of electricity generation and domestic water heating. Domestic water heating makes almost 10% of the total primary supply [25]. Solar power is increasingly becoming more and more popular in the country due to the shortage of conventional fuels and a lot of effort and investment has been poured in from not only the government but also from the private sector [26]. One such technology used to tap solar energy and convert it into useful energy is of PTC (Parabolic Trough Collector).

PTC consists of a concentric reflector surface and a fluid chamber. The fluid chamber is also termed as the absorber. The principle behind the working of the PTC is that the reflector surface concentrates the incident solar energy onto the absorbed or fluid chamber to raise it to extremely high temperatures. The absorber is enclosed with a transparent glass cover and a vacuum tube to minimise the heat losses. As the fluid is raised to a higher temperature, the fluid then can be used to supply heat to the corresponding subsystems and that fluid in turn becomes a very effective and transportable medium to convey energy to all the underlying components of the multigeneration system. As mentioned above the reflector plate plays a very important role in gathering and focusing energy from the sun, its design parameters and structural features are very significant to the entire multigeneration system as found out by Garcia-Cortes et al [27]. The other component being the absorber tube was studied by Rojas et al. for direct inline steam generation of the absorber tube to make it further compatible with growing applications and appliances [28]. As with any other natural resource or commodity, solar energy does have its downsides as well. Sunlight (a major indication or representation of Solar Energy) due to its inherent shortcoming is not available throughout the day. Even during the daytime its solar irradiances suffer a range of variations limiting the actual time available for the multigeneration system to be running at full throttle. It is imperative for this very reason to include a secondary or support source to supplement the primary source of the multigeneration system and make the overall system more reliable and workable in practical use.

The second source selected for the multigeneration system is Wind power. Wind power is one of the other natural resources which is readily available in Pakistan throughout its longitude without a few exceptions. Pakistan has a great wind potential especially in the plain areas of Sindh and Punjab and the coastal areas of Pakistan where there is prevalent strong uni-directional breeze that can be very fruitful if we tap into this potential [29,30,31]. Wind energy is usually extracted by windmills or wind turbines. Wind turbines run on the basic principle of turning mechanical motion into electrical energy to produce electrical energy. With analysis and studies of previous work it has become more and more cleat that the integrating the two renewable sources (Solar and Wind) can result in a very viable multigeneration system as both of them compliment and balance each other very effectively [32].

II. System Description

The multi-generation system uses two sources of energy; solar energy from parabolic trough collectors (PTC) and wind energy from a wind turbine. The solar collector chosen is a single-axis tracking PTC with a tubular absorber. The single axis tracking feature allows it to absorb more solar radiation by facing it towards the sun throughout the day. Also, it has a concentration ratio of 15 to 85 times more than that of a flat plate collector so it can heat the working fluid to higher temperatures [33] .A total of 10 PTCs are used in series in the system.

Figure 1 shows the schematic of the multi-generation system. Water at room temperature and atmospheric pressure enters the series of PTCs (17) and receives the solar energy. It then enters the boiler of the Rankine cycle (1). The working fluid of the Rankine cycle is also water which is first pumped to the boiler (3) and receives energy from the water leaving the PTCs. As it absorbs heat, it converts to superheated steam which drives the high pressure turbine (HPT) to produce power (4). The isentropic expansion of steam in the HPT decreases its pressure and the water then reenters the boiler (5) to be reheated. It then isentropically expands in the low pressure turbine (LPT) to produce more power (6). The expansion in the LPT causes the water to become a saturated vapor (7) after which it condenses in the condenser to become a compressed liquid (8). This liquid is again pumped to the boiler to repeat the cycle.

The refrigeration system uses the Vapor Compression Cycle (VCC) with an additional heat exchanger to enhance the refrigeration process. The refrigerant used is the R-134a. The compressor of the VCC utilizes power from the wind turbines and compresses the refrigerant from the heat exchanger to turn it to a superheated form (12). The superheated refrigerant is then condensed to a liquid (13) and it further loses a fixed amount of energy in the heat exchanger (14). It is then expanded by an expansion valve which is an isenthalpic process after which it enters the evaporator (15). It then absorbs heat from the evaporator to produce refrigeration and then enters the heat exchanger (16) again to absorb heat and become a saturated vapor. The saturated vapor is again compressed to repeat the cycle.

The heat lost from the condensers of the Rankine cycle and the VCC is absorbed by the water leaving the boiler which was heated by the PTCs. As the water is heated it enters the Domestic Water Heater (DWH) (10) which is used to heat the water entering at ambient temperature (18) to the desired temperature (19) suitable for domestic purposes. Thus the heat lost from the condensers are utilized.

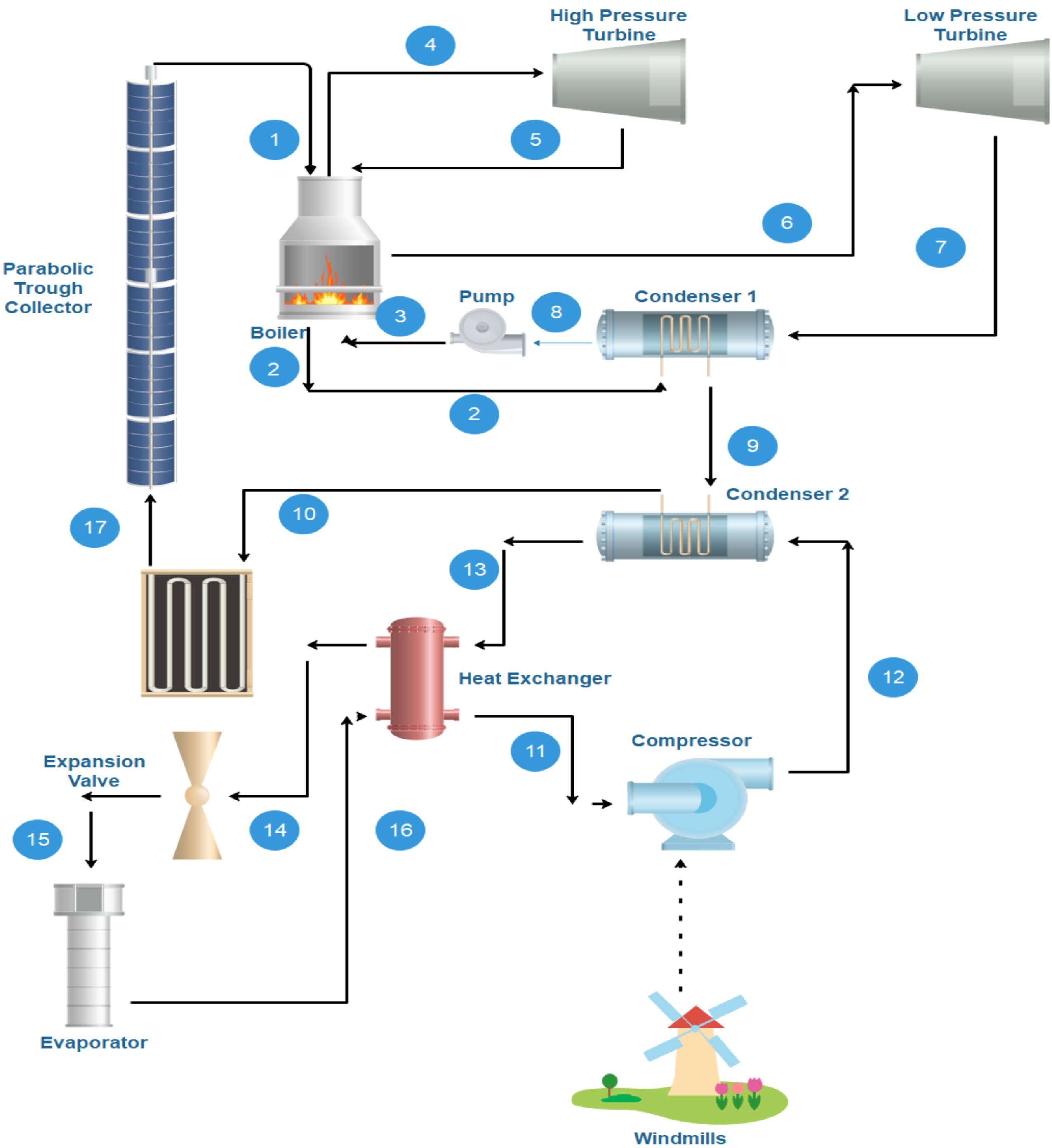

Fig. 1: Schematic of the multi-generation system

III. Analysis

Thermodynamic assessment of individual components of the multi-generation system
The thermodynamic analysis of each major component of the multi generation system is given below.

- **Parabolic Trough Collector**

Assuming there are no changes in the velocity and density of the working fluid in the PTCs and since the area of the tubes of all the PTCs are constant throughout, mass flow rate at the inlet of the first PTC is equal to the mass flow rate at the exit of the last PTC.

$$\dot{m}_{17} = \dot{m}_1. \quad (1)$$

The useful energy gained, Q_u, from a PTC is given as follows: [34]

$$Q_u = F_R(SA_a - A_r U_l(T_i - T_a)) \quad (2)$$

where S is the amount of solar radiation absorbed by the PTC, A_a is the aperture area, A_r is the receiver area, T_i and T_a are temperature of the inlet and ambient temperature respectively. U_L is the overall heat transfer coefficient given by :

$$U_L = \left(\frac{A_r}{(h_w + h_{r,c-a})A_g} + \frac{1}{h_{r,r-c}}\right)^{-1} \quad (3)$$

where $h_{r,c-a}$ and $h_{r,r-c}$ are radiation heat transfer coefficients from collector to atmosphere and receiver to collector respectively. h_w is convective heat transfer coefficient from collector to atmosphere and A_g is the area of the glass cover. F_R is the heat removal factor which is given by:

$$F_R = \frac{\dot{m}c_p}{A_r U_L}\left(1 - e^{\left(\frac{-FA_r U_L}{\dot{m}c_p}\right)}\right) \quad (4)$$

where $\dot{m}$ is the mass flow rate of the fluid through the PTC and c_p is specific heat capacity of fluid at constant pressure. F is the collector efficiency factor which can be expressed as:

$$F = \frac{\frac{1}{U_L}}{\frac{1}{U_L} + \frac{D_0}{D_i h_{fi}} + \left(\frac{D_0}{2k} ln \frac{D_0}{D_i}\right)} \quad (5)$$

where D_0 and D_i are the outside and inside diameters of pipe receiver respectively, k is the tube thermal conductivity and h_{fi} is the heat transfer coefficient inside the pipe.

The table below shows the values of different parameters of the PTCs.

No. of solar collector	*10*	**Glass cover diameter**	*90 mm*
Length of each collector	*30 m*	**Tube thermal conductivity, k**	*15 W/mK*
Aperture width	*5 m*	**Mass flow rate**	*0.1 kg/s*
Outside diameter of pipe receiver	*50 mm*	**Ambient temperature**	*25 °C*
Inside diameter of pipe receiver	*40 mm*	**Atmospheric pressure**	*101325 Pa*
Receiver emissivity	*0.92*	**Wind velocity**	*5 m/s*
Glass cover emissivity	*0.87*	**Receiver temperature**	*64.5 °C*

The heated fluid leaving the PTC enters the boiler of the Rankine cycle.

- **Rankine cycle**

The fluid exiting the PTCs deliver their entire energy to the boiler since they are assumed to leave the boiler at room temperature and atmospheric pressure. The heat gained by the boiler, $\dot{Q}_{boiler}$, is received by the fluid of the Rankine cycle twice. The energy balance for the boiler is:

$$\dot{m}_3(h_4 - h_3) + \dot{m}_3(h_6 - h_5) = \dot{m}_1(h_1 - h_2) \quad (6)$$

The power produced by the high pressure turbine, $\dot{W}_{HPT}$, and the low pressure turbine, $\dot{W}_{LPT}$ are expressed as:

$$\dot{W}_{HPT} = \dot{m}_3(h_4 - h_5) \quad (7)$$
$$\dot{W}_{LPT} = \dot{m}_3(h_6 - h_7) \quad (8)$$

The heat given off by condenser 1, $\dot{Q}_{cond,RC}$, and the power required by the pump, $\dot{W}_{pump,RC}$, are given by:

$$\dot{Q}_{cond,RC} = \dot{m}_3(h_7 - h_8) \quad (9)$$

$$\dot{W}_{pump,RC} = \dot{m}_3(h_3 - h_8) \quad (10)$$

The table below shows the values of different parameters of the Rankine Cycle.

Pressure at pump inlet	*100 kPa*
Pressure at pump outlet	*1000 kPa*
Mass flow rate of fluid	*0.1 kg/s*
Temperature of fluid leaving the boiler	*500 °C*
Pressure at HPT outlet	*400 kPa*

- **Vapor Compression Cycle**

The compressor of the VCC utilizes power ($\dot{W}_{comp,VCC}$) from the wind turbines and the energy balance equation for the compressor is given by:

$$\dot{W}_{comp,VCC} = \dot{m}_{11}(h_{12} - h_{11}) \quad (11)$$

The heat given out by the condenser and the heat absorbed by the evaporator are given by:

$$\dot{Q}_{cond,VCC} = \dot{m}_{11}(h_{12} - h_{13}) \quad (12)$$
$$\dot{Q}_{evap} = \dot{m}_{11}(h_{15} - h_{16}) \quad (13)$$

The additional heat exchanger is designed in such a way to give out a certain amount of heat. The compressed refrigerant from the compressor loses heat to the refrigerant leaving the evaporator. The energy balance equation for the heat exchanger is:

$$\dot{m}_{11}(h_{13} - h_{14}) = \dot{m}_{11}(h_{11} - h_{16}) \quad (14)$$

The table below shows the values of different parameters of the Vapor Compression Cycle.

Refrigerant	*R-134a*
Mass flow rate	*0.05 kg/s*
Pressure of fluid entering the compressor	*800 kPa*
Pressure of fluid leaving the compressor	*140 kPa*
Heat transferred by the heat exchanger	*250 J*

- **Domestic Water Heater**

The Domestic Water Heater is used to heat the water entering at ambient temperature to the desired temperature suitable for domestic purposes. In order to attain hotter water, mass flow rate of water can be decreased. The energy balance for the DWH is:

$$\dot{m}_1(h_{10} - h_{17}) = \dot{m}_{18}(h_{19} - h_{18}) \quad (15)$$

- **Energetic and Exergetic efficiencies**

The overall efficiency of the system, $\eta_{overall}$, is the ratio of all the inputs and outputs of the system. It is given by:

$$\eta_{overall} = \frac{\dot{W}_{HPT,RC} + \dot{W}_{LPT,RC} + \dot{Q}_{evap} + \dot{m}_{18}(h_{19} - h_{18}) - \dot{W}_{pump,RC}}{\dot{m}_1(h_1 - h_{17}) + \dot{W}_{comp,VCC}} \quad (16)$$

And the overall exergetic efficiency of the system can be defined as:

$$\psi_{overall} = \frac{\dot{W}_{HPT,RC} + \dot{W}_{LPT,RC} + \dot{Q}_{evap}\left(1 - \frac{T_0}{T_{15}}\right) + \dot{m}_{18}(ex_{19} - ex_{18}) - \dot{W}_{pump,RC}}{\dot{m}_1(ex_1 - ex_{17}) + \dot{W}_{comp,VCC}} \quad (17)$$

ex_1, ex_2, ex_{18} and ex_{19} are exergies at different states.

IV. Results and discussions

The outputs of the cycle are the power generated by the two turbines, $\dot{W}_{HPT}$ and $\dot{W}_{LPT}$, the amount of hot water from the DWH, $\dot{m}_{19}$, and the amount of heat absorbed by the evaporator to produce refrigeration, $\dot{Q}_{evap}$.

The input variables which are varied are solar irradiance absorbed by the PTCs, the amound of wind power available at the compressor of the VCC, $\dot{W}_{comp,VCC}$, and the ambient temperature.

- **Effect of Solar Irradiance**

The table below shows the relationship of the output variables and the solar irradiance on the PTCs. It can be seen that an increase in solar irradiance increases the power output of the LPT. The mass flow rate of the hot water leaving the DWH also increases since more heat is given out by the condenser 1 so the more heat is transferred to the DWH. However, the increase in solar irradiance decreases the energetic and exergetic efficiencies since the increase in input is more than the increase in outputs of the system. This can be seen by an increase in enthalpy at state 1 which determines the input of the PTC. The energetic and exergetic efficiencies are greater than 1 because $\dot{Q}_{evap}$ is taken as an output since one of the aims of the system is to provide refrigeration despite the fact that it adds energy to the system.

Solar Irradiance (W/m^2)	Power Output of LPT (W)	Power Output of HPT (W)	Mass flow rate of water at DWH (kg/s)	Enthalpy at state 1 (J/kg)	Energetic Efficiency	Exergertic Efficiency
150	*90682*	*27209*	*1.092*	*3.46E+06*	*1.533*	*1.044*
170	*98005*	*27209*	*1.121*	*3.60E+06*	*1.481*	*1.042*
190	*105709*	*27209*	*1.148*	*3.73E+06*	*1.434*	*1.041*
210	*113509*	*27209*	*1.177*	*3.87E+06*	*1.389*	*1.039*
230	*121395*	*27209*	*1.207*	*4.01E+06*	*1.347*	*1.038*
250	*129358*	*27209*	*1.237*	*4.15E+06*	*1.307*	*1.037*
270	*137392*	*27209*	*1.268*	*4.30E+06*	*1.269*	*1.035*
290	*145493*	*27209*	*1.301*	*4.45E+06*	*1.234*	*1.034*
310	*153653*	*27209*	*1.334*	*4.60E+06*	*1.202*	*1.033*
330	*161866*	*27209*	*1.368*	*4.75E+06*	*1.171*	*1.032*

- **Effect of Wind Power**

The table below shows the relationship of the output variables with the wind power. It can be seen that an increase in wind power increases the mass flow rate of hot water from the DWH since more heat is given out by the condenser 2 so the more heat is transferred to the DWH. The power output of the turbines remain constant as they are not a part of VCC and are not affected by any change in the VCC. The energetic and exergetic efficiencies decrease because the increase in input power is more than the increase in output.

Wind Power (W)	Power Output of HPT (W)	Power Output of LPT (W)	Mass flow rate of water at DWH (kg/s)	Enthalpy at state 1 (J/kg)	Energetic Efficiency	Exergertic Efficiency
1000	*27209*	*116221*	*1.182*	*3.917E+06*	*1.039*	*1.385*
1500	*27209*	*116221*	*1.185*	*3.917E+06*	*1.039*	*1.38*
2000	*27209*	*116221*	*1.187*	*3.917E+06*	*1.039*	*1.374*
2500	*27209*	*116221*	*1.19*	*3.917E+06*	*1.039*	*1.369*

3000	27209	116221	1.192	3.917E+06	1.039	1.363
3500	27209	116221	1.194	3.917E+06	1.039	1.358
4000	27209	116221	1.197	3.917E+06	1.039	1.352
4500	27209	116221	1.199	3.917E+06	1.039	1.347
5000	27209	116221	1.202	3.917E+06	1.038	1.342
5500	27209	116221	1.204	3.917E+06	1.038	1.336

- **Effect of Ambient Temperature**

The table below shows the relationship of the output variables with the ambient temperature.The ambient temperature varies throughout the year due to different seasons. It can be seen that an increase in ambient temperature increases the power output of the LPT since the initial temperature of the water entering the PTCs increased and as a result the enthalpy at state 1 also increased. The energetic efficiency remains the same but the exeregetic effieciency increases because exergy is a function of the ambient temperature.

Ambient Temperature (K)	Power Output of HPT (W)	Power Output of LPT (W)	Mass flow rate of water at DWH (kg/s)	Enthalpy at state 1 (J/kg)	Energetic Efficiency	Exergertic Efficiency
290	27209	117085	1.026	3.899E+06	1.039	1.343
292	27209	116869	1.062	3.904E+06	1.039	1.35
294	27209	116653	1.101	3.908E+06	1.039	1.358
296	27209	116437	1.142	3.913E+06	1.039	1.366
298	27209	116221	1.187	3.917E+06	1.039	1.374
300	27209	116005	1.236	3.922E+06	1.039	1.382
302	27209	115789	1.289	3.926E+06	1.039	1.391
304	27209	115573	1.346	3.931E+06	1.039	1.4
306	27209	115358	1.409	3.935E+06	1.039	1.409
308	27209	115142	1.479	3.940E+06	1.039	1.418
290	27209	117085	1.026	3.899E+06	1.039	1.343

V. Conclusions

A multigeneration system is designed to produce power outputrs from a turbine, refrigeration through the Vapour Compression Cycle and some hot water for domestic purposes. Various input parameters are changed to visualize the effect on output parameters.The results show that increasing the input parameters of this multigeneration system does increase the outputs of the system. However, increasing the input parameters decrease the overall energetic and exergetic efficiencies of the system because the change in input parameters are more than that of the output parameters.

Nomenclature

A : Area (m^2)
c : Specific heat capacity (J/K.kg)
D : Diameter (m)
$\dot{Ex}$: Rate of exergy (W/kg)
ex : Exergy per unit mass (J/kg)
F : Collector efficiency factor
F_R : Heat removal factor
g : Gravitational field strength (m/s^2)
h : Enthalpy per unit mass (J/kg), heat transfer coefficient (W/m^2.K)
h_w : Convective heat transfer coefficient from collector to atmosphere (W/m^2.K)
k : Tube thermal conductivity (W/m.K)
m : Mass (kg)
$\dot{m}$: Mass flow rate (kg/s)
Q : Heat energy (kJ/kg)
$\dot{Q}$: Rate of heat energy (W)
S : Absorbed solar radiation (W/m^2)
s : Entropy per unit mass (J/kg.K)
T : Temperature (°C or K)
U_L : Overall heat transfer coefficient (W/m^2.K)
V : Velocity (m/s)
W : Work (J)
$\dot{W}$: Rate of Work (W)
z : Elevation (m)

Greek letters

η	: Energetic efficiency
ψ	: Exergetic efficiency

Superscripts

°	: degree Centigrade

Subscripts

$1,2,\ldots$	: state numbers
a	: ambient, aperture
air	: air
$boiler$	: boiler
$comp$	: compressor
$cond$	: condenser
DWH	: Domestic Water Heater
$evap$	: evaporator
HPT	: High Pressure Turbine
HX	: Heat Exchanger
in	: inside, inlet
LPT	: Low Pressure Turbine
out	: outside, outlet
$overall$	: overall
p	: at constant pressure
$pump$	: pump
Q	: heat
r	: receiver
RC	: Rankine cycle
$system$	: system
u	: useful
VCC	: Vapor Compression Cycle
W	: work
$water$	: water
$c-a$	: glass cover to atmosphere
fi	: inside the pipe
$r-c$	: receiver to glass cover

Acronyms

COP	: Coefficient of performance
DWH	: Domestic water heater
EES	: Engineering Equation Solver
PTC	: Parabolic Trough Collector
VCC	: Vapor Compression Cycle

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