2.1. Introduction

An extensive review of the literature has been done on energy and exergy analyses of different renewable energy systems in the present chapter. The literature review on the exergoeconomics has also been done as one of the objectives of the thesis is to evaluate the renewable energy systems on the basis of available literature on exergoeconomic. The main idea was to get thrust and scant area of exergy analysis of Renewable energy systems and have possible future direction of research. The literature review has been classified as under:

a) Solar heating systems - It has been classified in two different categories as below:
   i. Solar air heater
   ii. Solar water heater
b) Solar photovoltaic (SPV) systems
c) Renewable energy cooking devices - It has also been classified in two different categories as below:
   i. Solar cookers
   ii. Biomass cook stoves
d) Exergoeconomics

2.2. Solar Heating Systems

This section deals with the literature survey on solar heating systems viz. solar air heater and solar water heater for useful applications.
2.2.1. Solar Air Heater

For commercial applications, ability of the drier to process continuously is very important to dry the end products for their safe storage to maintain the quality and nutrient values of the product. Normally thermal storage systems are employed to store thermal energy, which includes sensible heat storage, chemical energy storage and latent heat storage. The solar drier is an energy efficient option in the drying processes [1]. Use of forced convection solar driers seems to be an advantage compared to traditional methods and improves the quality of the product considerably [2-4]. The common sensible heat storage materials used to store sensible heat are water, gravel bed, sand, clay, concrete, etc. for different applications [3-6].

In recent years, few authors [7-13] have studied different feature of solar collector systems using various approaches. For example, Kurtbas and Durmus [7] have studied the solar air heater for different heating purposes whereas, Luminosua and Farab [8] and Torres-Reyes et al, [9] have studied the optimal thermal energy conversion and design of a flat plate solar collector using exergy analysis. On the other hand, Bakos et al [10], Kaushik et al. [11], and Tyagi et al [12] have studied the optimum design of a parabolic trough collector (PTC) and gave some fruitful results, especially, the mass flow rate of the moving fluid and the concentration ratio of PTC collector.

Ozturk and Demirel [13] experimentally investigated the thermal performance of a solar air heater having its flow channel packed with Raschig rings based on the energy and exergy analyses. Average daily net energy and exergy efficiencies were found to be 17.51 and 0.91%, respectively. Also, the energy and exergy efficiencies
of the packed-bed solar air heater increased as the outlet temperature of heat
transfer fluid increased. Potdukhe and Thombre [14] designed, fabricated, simulated
and also tested a solar dryer fitted with a novel design of absorber having inbuilt
thermal storage capabilities. The length of operation of the solar air heater and the
efficiency of the dryer were increased, and better quality of agricultural products in
terms of colour value was obtained compared with open sun drying. MacPhee and
Dincer [15] worked on thermodynamic analyses of the process of charging of an
encapsulated ice thermal energy storage device (ITES) through heat transfer. The
energy efficiencies are found to be more than 99%, whereas the thermal exergy
efficiencies are found to vary between 40% and 93% for viable charging times. The
results confirm the fact that energy analyses, and even thermal exergy analyses,
may lead to some unrealistic efficiency values.

Enibe [16] worked on the design, fabrication and performance evaluation of a
passive solar powered air heating system based on exergy analysis. The system
consists of a single-glazed flat plate solar collector integrated with a phase change
material (PCM) heat storage system. The PCM is prepared in modules, with the
modules equispaced across the absorber plate. The spaces between the module
pairs serve as the air heating channels, the channels being connected to common air
inlet and discharge headers. The experiments were carried out under the climatic
conditions of Nsukka (Nigeria) in the daytime with no-load conditions where the
ambient temperature varied in the range of 19–41 °C, and a daily global irradiation
varied in the range of 4.9–19.9 MJ/m². Peak cumulative useful efficiency was found
to be about 50% while peak temperature rise of the heated air was about 15 °C. The
system has been found suitable for the use as a solar cabinet crop dryer for aromatic
herbs, medicinal plants and other crops, which do not require direct exposure to sunlight.

Kurtbas and Durmus [17] designed a new solar air heater and evaluated it on the basis of exergy analysis. In their study they used five solar collectors with dimensions of 0.9x0.4 m and the flow line increased where it had narrowed and expanded geometrically in shape. These collectors were set to four different cases with dimensions of 1x2 m. Therefore, heating fluids exit the solar collector after at least 4.5 m displacement. According to the collector geometry, turbulence occurs in fluid flow and in this way heat transfer is increased. In this study they found that the efficiency of the collector enhances with the increase of mass flow rates due to an enhanced heat transfer to the air flow and also increase in efficiency depends on the surface geometry of the collector and extension of the air flow line. Collector efficiency, temperature difference of the air and pressure loss is the more important parameters in order to decrease the exergy loss.

Ajam et al. [18] worked on the optimization of the solar air heater based on the exergetic analysis. For this purpose, an integrated mathematical model of thermal and optical performance of the solar heater has been derived. The overall thermal loss coefficient and other heat transfer coefficients of the heater were assumed to be variable while deriving an equation for the exergy efficiency. Using the MATLAB toolbox the exergy efficiency equation has been maximized. After maximizing the exergy efficiency equation it has been compared with the thermal efficiency of the heater, which ultimately results in an extraordinary increase of the exergy efficiency according to the optimized parameters. They also concluded that the exergy analysis was a better method for design, development and optimization of solar air heaters due to the fact that exergy efficiency is a proportion to common quantities in solar
engineering such as thermal efficiency, temperature, pressure drop, mass flow rate of fluid and others etc.

Kurtbas and Turgut [19] investigated the solar air heater with free and fixed fins using exergy analysis. In this study each of the fins with rectangular shape was having two different surface areas and located on the absorber surface in free and fixed manners. In the first type, the fins were located on the absorber surface in a way that the fins are able to move freely, while in the second type model fins were fixed to the absorber surface. The absorber surface area was 1.64 m$^2$ while the fixed and free fins with 8 and 32 items were having surface areas 0.048 and 0.012 m$^2$ respectively. Therefore the total fin area in the absorber surface was equal to 0.384m$^2$. They found that the fins located in flow area increases the heat transfer coefficient and output temperature of air due to which collector efficiency increases too. Also they found that there exists a reverse relationship between exergy loss ratio and collector efficiency as well as temperature difference of the fluid. Thus if there is increase in the pressure drop, both heat transfer and exergy loss were also found to be enhanced, while it has been observed that the exergy loss ratio was affected less because heater has very little pressure drop.

Ucar and Inallı [20] worked on the solar air collectors with passive augmentation techniques using exergetic analysis. In order to provide better heat transfer surfaces suitable for the passive heat transfer augmentation techniques different shape and arrangement of absorber surfaces of the collectors were reorganised. The performance of such solar air collectors with staggered absorber sheets and attached fins on absorber surface were analysed and tested. It has been found that the efficiency of solar collector has been increased approximately 10% to 30% as compared with the conventional solar collector using the passive techniques.
In conventional solar air heater, only a little part of solar energy absorbed by the collector can be used therefore the performance of the conventional solar air heater was found to be least.

Koca et al. [21] investigated the flat-plate solar collector with phase change material (PCM) using energy and exergy analyses, CaCl$_2$•6H$_2$O has been used as PCM in thermal energy storage (TES) system. Solar energy collection and storage has been combined in single designed collector unit. Phase Change Material was stored in a storage tank, which was located under the collector. For transferring heat from collector to PCM a special heat transfer fluid was used. The experiments were carried out for 3 different days in the month of October. From the measured data calculations were made and they found that stored and instantaneous solar radiation show bell-shaped variation during all experimental days. Also a significant difference between energy and exergy efficiencies had been reported and the energetic efficiency was always higher than that of exergetic efficiency. From the obtained experimental data and calculations it has been found that the exergy efficiencies of latent heat storage systems with PCM are very low.

Esen [22] worked on the energy and exergy analysis of a novel flat plate solar air heater (SAH) with and without obstacles. The experiments were carried out at different values of mass flow rate of air and different levels of absorbing plates in flow channel duct. The measured parameters were solar radiation and temperatures at different state of points such as inlet, outlet, at the absorbing plate and the ambient. After the analysis of the results it had been found that, the optimal value of efficiency was in the middle level of absorbing plate in flow channel duct for all the operating conditions and it was also found that the double-flow collector supplied
with obstacles (60.97%, for 0.025 kg/s and State II) were better than that of without obstacles (25.65%, for 0.015 kg/s and State I).

Gupta and Kaushik [23] presented a comparative study of various types of artificial roughness geometries in the absorber plate of solar air heater duct and their characteristics based on energy, effective and exergy efficiencies. The performance evaluation for some selected artificial roughness geometries in the absorber plate of solar air heater duct in terms of energy efficiency, effective energy efficiency and exergy efficiency has been carried out at various values of Reynolds number \( (Re) \). In this study the correlations for heat transfer and coefficient of friction developed by respective investigators have been used to calculate efficiencies. From the study it has been found that the artificial roughness on absorber surface is the better option in the enhancement of the efficiencies in comparison to smooth surface. The energy efficiency was found to be increased in the following manner: smooth surface, circular ribs, V shaped ribs, wedge shaped rib, expanded metal mesh, rib-grooved, and chamfered rib–groove. The effective efficiency also found to be following the same trend of variation among various considered geometries however trend was reversed at very high Reynolds number. The exergy efficiency based criteria also follows the same pattern; but the trend was reversed at relatively lower value of Reynolds number and for higher range of Reynolds number the exergy efficiency approaches zero or may be negative.

Ozgen et al. [24] had worked on a device for inserting an absorbing plate made of aluminium cans into the double-pass channel in a flat-plate solar air heater. In this experimental study, three different absorber plates had been designed and tested. In the first type (Type I), cans had been staggered as zigzag on absorber plate, and in Type II they were arranged in order, while in Type III a flat plate was
without cans. Experiments were performed at air mass flow rates of 0.03 kg/s and 0.05 kg/s. From the experiments it has been found that the double-flow type of the solar air heater with aluminium cans has been introduced for increasing the heat-transfer area has the improved thermal efficiency. Because of the double heat-transfer area in double-flow systems, the performance of double-flow type solar air heater, in which air was flowing simultaneously over and under absorbing plate, is found to be more efficient than that of the devices with one flow channel over or under the absorbing plate.

Farahat et al. [25] worked on the exergetic optimization of flat plate solar collector, in this study a simulation program has been developed for the thermal and exergetic calculations. A detailed energy and exergy analysis was carried out for evaluating the thermal and optical performance, exergy flows and losses as well as exergetic efficiency for a typical flat plate solar collector under given operating conditions. The optical efficiency has a great effect on the exergy efficiency. By using the flat plate solar collectors with optical concentrators, the optical efficiency increases. It was found that the energy efficiency increases without extremum points with operating parameters. The absence of such maximum points has created difficulties in the design of flat plate solar collectors. However, the exergy efficiency presents points of local maxima and a point of global maximum. The exergy efficiency was found to be decreasing rapidly with increasing nature of ambient temperature and the wind speed.

Akbulut and Durmuş [26] had worked on energy and exergy analyses of the thin layer drying process of mulberry via forced solar dryer. The drying experiments were carried out at five different mass flow rate varied between 0.014 kg/s and 0.036 kg/s. The effects of drying time and inlet air velocity on energy and exergy were evaluated.
The values of exergy loss were found to be as 10.82 W, 6.41 W, 4.92 W, 4.06 W and 2.65 W with the drying mass flow rate varied in the range, mentioned above. However, the values of energy utilization ratio were found to be as 55.2%, 32.19%, 29.2%, 21.5% and 20.5% for the above said five different drying mass flow rates. From the study it was found that the exergy loss decreases with the increase in the mass flow rate of the drying air. The maximum exergy losses occurred for 0.014 kg/s mass flow rate. After the study of thermal performance of solar dryer it had been suggested that, in order to decrease the energy utilization and exergy losses: order, structure, and moisture content of the products on the drying chamber should be taken into consideration. Also it is necessary to show the variations of exergy with drying time in order to get when and where the maximum and minimum values of the exergy losses occur during the drying process.

Akpinar and Kocyig˘it [27] designed, fabricated and experimentally investigated a new type of solar air heater with and without obstacles. The experiments were carried out at two different air mass flow rates of 0.0074 and 0.0052 kg/s. It was found that the efficiency of the solar air collectors depends on different parameters such as solar radiation, surface geometry of the collectors and extension of the air flow line. The energy efficiency were found to be varied between 20% and 82% while those of exergy efficiency changed from 8.32% to 44.00% at the above said mass flow rates. The highest efficiency was found to be for the solar air heater (SAH) with absorbent plate in flow channel duct for all operating conditions, whereas the lowest values were obtained for the SAH without obstacles. Also the efficiency of the collector has been found to be increasing function of mass flow rate. This shows that the exergy loss of the system decreased due to the increase in the collector efficiency. Reverse relationship between dimensionless exergy loss and
heat transfer were also found in the study. The deciding parameters in order to decrease the exergy loss were the collector efficiency, temperature difference of the air. New relations were proposed to evaluate of the energy and exergy analysis of SAH. It is concluded that the proposed procedure can be successfully employed for predicting the SAH performance.

Alta et al [28] investigated the energy and exergy efficiency of three different types of solar air heaters, two having fins and one without fins besides one heaters with fins has single glass cover while the other two have double glass cover. The energy and exergy output rates of the solar air heaters were evaluated at different air flow rates viz. 25, 50 and 100 m$^3$/m$^2$ h, tilt angle at 0º, 15º and 30º and temperature conditions versus time. They found that the heaters with double glass covers and fins are more effective and the difference between the input and output air temperature is higher than that of the other cases. It was also found that the lower air flow rates will be beneficial in applications where higher temperature differences are more important. Besides it has also been observed that using more transparent cover and fins increases the values of temperature differences. While transparent cover decreases convection heat losses, fins obtain more heat because of an increase in the heating time by circulating air inside.

Ezan et al. [29] has investigated the energetic and exergetic performances of a latent energy storage system based on the shell and-tube TES unit during charging (solidification) and discharging (melting) processes. The experimental system consists of a heat exchanger section, a measurement system and flow control systems. The inlet temperature varied from −5 ºC to −15 ºC for the charging mode,
and the volumetric flow rates varied from 2 to 8 Lt/min. The experiments were performed for three different tube materials, copper, steel and PE32 with two different shell diameters of 114 mm and 190 mm respectively, and the effects on energetic and exergetic efficiencies were investigated. They concluded that the exergetic efficiency increased with the increase in the inlet temperature and flow rate during charging period while during the discharging period, the irreversibility increased as the temperature difference between the PCM and the inlet heat transfer fluid (HTF) increased.

Prommas et al. [30] worked on the energy and exergy analyses in drying process of porous media using hot air. The main objectives of the study were as follows: (i) exergy input and the distributions of the exergy losses of the different drying operations (ii) the exergy losses of two operations porous packed bed and (iii) the effect of operating parameters on exergy losses. From the study it was found that as the drying time increases, the exergy efficiency of the drying chamber also increases which is due to the fact that as the drying time increases the available energy in the drying chamber also increases. They also presented the effect of the other particle size on the drying time as well as the exergy efficiency of the drying system. Furthermore, it was found that the exergy efficiencies of C-bed were higher than of the F-bed about 10% after 60 min of drying time with parallel to the end of drying process.

Panwar et al. [31] reviewed the literature on energy and exergy analyses of solar drying systems and suggested that for utilizing low grade energy to dry agricultural produces solar drying is the promising option. In their study they found that the exergy efficiency is actual efficiency of the process due to irreversibility associated with the system. Therefore it can be said that exergy analysis is a tool to
access the efficient usage of solar energy. It is the property of the system, which gives the maximum power that can be obtained from the system when it is brought to a thermodynamic equilibrium state from a reference state. The energy used in drying of agricultural and industrial produce is significant and, therefore, represents an often reducible element of process cost.

Saidur et al. [32] reviewed the literature on exergy analysis of solar energy applications viz. solar photovoltaic, solar pond, solar air conditioning etc. From their study they found that the thermal efficiency is not sufficient to choose the desired system therefore it is necessary to apply the concept of exergy for specific design of the systems. The highest exergy destruction was observed in solar collectors in most of the solar heating devices and solar air conditioning systems. Increasing the mass flow rate leads to an increment in exergetic efficiency in photovoltaic thermal systems. Exergy efficiency of solar systems is highly dependent on the daily solar radiation and radiation intensity.

2.2.2 Solar Water Heater

Use of solar energy for water heating is the most common application, mostly three types of solar collectors based solar water heaters (SWH) are available in the market viz. flat plate collector (FPC), evacuated tube collector (ETC), compound parabolic collectors (CPC). Dharuman et al. [33], designed, constructed and did the experiments on water heating device and its performance was evaluated under various typical operating conditions. Nahar [34], did the comparative analysis of Cu–Al fin with Cu–Cu fin in flat-plate collectors to test solar water heater. Anant et al. [35], investigated and analyzed the performance of thermal energy storage based

Morrison et al. [37] evaluated the characteristics of evacuated tube based solar water heaters also made an assessment of the circulation rate through single ended tubes. Assuming that there was no interaction between adjacent tubes in the collector array they developed a numerical model of the heat transfer and fluid flow inside a single ended evacuated tube and the simulation study had been performed. The computational domain used in this study was single-ended thermosyphon with a constant pressure condition applied across the open end. In this study the computational fluid dynamics (CFD) model was validated against Particle Image Velocimetry (PIV) measurements. Experimental and simulation results showed that there was a good agreement in a number of qualitative and quantitative parameters, such as the location of the peak velocity, the peak velocity of the heated fluid stream, the cross-over point between the two opposing streams and the flow structure as the hot fluid rises up the tank.

Xiaowu and Ben [38] evaluated the performance of domestic scale solar water heater based on exergy analysis. Three procedure theory as presented in the paper exhibits great advantages as compared with other theories of energy analysis. From the study, it was shown that the proper insulation of collector and storage barrel were important as exergy losses due to imperfectly thermal insulation in collector and exergy losses due to imperfectly thermal insulation in storage barrel cannot be avoided. The exergetic efficiency of domestic-scale water heater was found to be small due to low quality of output energy and exergy losses storage barrel.

Luminosu and Fara [39] determined the optimal operation mode of flat plate collector using exergy analysis through simulation. In this study the exergy analysis
of a flat-plate solar collector based on the assumption that temperature at inlet fluid =
environment temperature = constant has been developed. The statistical data for the
solar radiation of a given area was used and the optimal values for the characteristic
quantities of the flat-plate solar collector had been obtained by developing the exergy
analysis for the selected model. The hot water supplied by this collector would be
used either directly, for example, for retarded, or showers, storing it in an insulated
tank. Another interesting application of this approach would use the swimming pools
model: alternatively, the hot water supplied by the solar collector would be
discharged in one of the swimming pools. That is open circuit condition for the use of
this solar collector is recommended.

Budianto et al. [40] developed a correlation for natural circulation flow rate
through single ended water-in-glass evacuated tubes mounted over a diffuse
reflector. Further, the numerical simulation showed that when the heat input was
concentrated on the top circumference of the tube, as in the case with collectors
mounted over a diffuse reflector. The effect of circumferential heat flux distribution on
the circulation flow rate through the tubes was not significant; therefore, the
correlation could be used to predict the flow rate at any time of day. Different flow
structures were observed in the tube when a concentrating reflector was used
underneath the collector.

Gunerhan and Hepbasli [41] studied the performance evaluation of solar water
heating system based on exergy analysis. The experiments were carried out under
the climatic condition of Izmir province (Turkey). Their main objective was basically
to analyse the different components of the system viz. flat plate solar collector, a
heat exchanger (storage tank) and a circulating pump, besides to investigate the
effect of variation in water inlet temperature on exergy efficiency of different
components and the overall system. The exergy efficiency on a product/fuel basis was found to be varying between 2.02 and 3.37% for the solar collector, 16 and 51.72% for the heat exchanger, 10 and 16.67% for the circulating pump, while for overall system it was found to be in the range of 3.27 to 4.39%.

Zambolin and Del Col [42] carried out the thermal performance evaluation of two different types of solar collectors viz. glazed flat plate collector and an evacuated tube collector. Both the collectors were installed in parallel and tested at the same working conditions while the evacuated collector was a direct flow through type with external compound parabolic concentrator (CPC) reflectors. The main objective of this experimental work was the comparison of results between steady-state and quasi-dynamic test methods for both the solar collectors i.e. for flat plate and evacuated tube collectors. Also the objective of the study was to characterize and compare the daily energy performance of the above mentioned collectors. The efficiency has been plotted against the average reduced temperature it was also shown that the daily efficiency can be estimated by using the parameters of the quasi-dynamic model. Optical efficiency of the flat plate collector in the morning and in the afternoon hours has been found to be decreasing due to more reflection losses. While efficiency loss is reduced in the vacuum tube collector because of its geometry, the most of the absorber area is exposed to quasi-normal incidence radiation for a longer period of the day. Finally evacuated collector has been found to be better than that of flat plate collector.

Hayek et al. [43] investigated the performance evaluation of two different types of evacuated tube solar collectors viz. water-in-glass tubes and the heat-pipe designs under local weather conditions as encountered along the eastern coast of the Mediterranean Sea. The experiments were performed during the months of
November to January, i.e. under winter-like conditions, for a clear sky days of the months. Total 20 numbers of evacuated tubes along with a tank and a circulation system with measurement tools, was constructed and used for the experimental observation. The experimental study showed that the performance of ETC with heat pipe design was better than that of water-in-glass designs and their efficiency has been found to be almost 15 to 20% higher. However, their payback periods was found to be much higher owing to their larger initial cost in the local market.

Ayompe et al. [44] represented the performance evaluation of two different types of solar water heaters viz. flat plate collector (FPC) and heat pipe evacuated tube collector (ETC) in temperate climate of Dublin (Ireland). The energy analysis on daily, monthly and yearly basis was carried out and the performance of the above mentioned systems were compared. Total 1984 kWh and 2056 kWh of heat energy were collected by the 4 m$^2$ FPC and 3m$^2$ ETC systems respectively, for an annual solar radiation of 1087 kWh/m$^2$. The annual average collector efficiencies were found to be 46.1% and 60.7%, while the system efficiencies were found to be 37.9% and 50.3% for the FPC and ETC respectively. Also from the economic analysis it was found that both the systems are not economically viable and the simple payback period varied between 13 years and 48.5 years for the FPC and ETC respectively.

Gang et al. [45] studied the compound parabolic concentrator (CPC)-type solar water heater with a U-pipe and investigated its performance in meeting higher temperature requirements. The experiments were carried out at Hefei (31º53’ N, 117 º15’ E), in the eastern region of China in the month of December. Keeping the fact in the mind that the conventional solar water heaters based on flat collectors has low efficiencies in attaining higher temperatures particularly above 50 ºC. They also found that such types of systems are not useful for higher temperature applications
such as heat-powered cooling, building heating, industrial heating, seawater desalination and so on. Therefore in this study the compound parabolic concentrator (CPC)-type solar water heater with a U-pipe has been investigated. They found that when the water temperature was heated from 26.9 °C to 55, 65, 75, 85, and 95 °C, thermal efficiency was found to be decreasing function. In other words, the lower thermal efficiency has been found at 95 °C and found to be above 49%. The exergetic efficiency has been found to be increasing in nature i.e. highest efficiency was found to be at 55 °C and found to always above 4.62%.

Ceylan [46] developed a new temperature controlled solar water heater (TCSWH) and studied it based on energetic and exergetic analyses. Experiments have been carried out at 40 °C, 45 °C, 50 °C and 55 °C and the designed system was also compared with the thermosiphon system. A detailed comparison between TCSWH and thermosiphon system were performed by calculating stored energy, storage tank water temperatures, amount of water in the storage tank and system efficiencies for both of the systems. The highest amount of water had been found to be 108 kg by setting the control device at 40 °C. The average energetic efficiency was found to be 65% for the TCSWH and 60% for the thermosiphon system respectively, thus, TCSWH was found to be better than that of thermosiphon system for the same set of operating parameters.

2.3 Solar Photovoltaic Systems

Solar energy reaching the earth surface can be utilised directly in two ways, firstly, by converting directly into electricity by the means of solar photovoltaic (SPV) modules and secondly, by heating the medium by means of solar collectors for low temperature heating applications. Presently, most of the SPV modules are based on
crystalline silicon technology which is basically divided into three technologies viz. Mono-cristalline silicon (m-Si), multi-crystalline silicon (mc-Si) and ribbon silicon. In general it has been found that the mono-cristalline silicon wafer is more expensive than that of multi-crystalline silicon wafer and as far as the efficiency is concerned, m-Si based module is better than that of mc-Si module. The single crystal silicon is made of a cylindrical ingot and the crystal lattice of the entire sample is continuous with no grain boundaries. On the other hand, the multi-crystalline are made of square ingot and composed of multiple small silicon crystals [47]. The conversion efficiency of commercial types of mc-Si cells are found to be in the range of 12–15% however, it can be enhanced up to 20% by using more sophisticated solar cell designs [48].

Smestad [49] examined concepts of hot carrier and light converter, indicating that electrons are ejected not only as heat but also as light. Carnot factor in solar cell theory was investigated by Landsberg and Markvart [50], they obtained an expression for the open-circuit voltage which is equal to the band gap multiplied by the Carnot efficiency. Thermodynamics and reciprocity of solar energy conversion was also discussed by Markvart and Landsberg [51] by taking into consideration the PV, photochemistry and photosynthesis. Sahin et al. [52] investigated the thermodynamic characteristics of the solar photovoltaic (PV) cells using exergy analysis. They developed and applied the new approach for the assessment of PV cells and found that the presented approach was realistic as it accounts for thermodynamic quantities such as enthalpy and entropy. They also analysed the PV cells on the basis of the energy and exergy efficiencies, the energy efficiency was found to be varying between 7-12% during the day while, the exergy efficiency was found to be varying between 2-8%.
Bisquert et al. [53] investigated the physical and chemical principles of SPV conversion systems. They found that the open-circuit voltage and chemical potential of a SPV cell is dependent on Carnot and statistical factors. Joshi et al. [54] investigated the performance characteristics of a photovoltaic (PV) and photovoltaic-thermal (PV/T) system using energy and exergy analysis for the New Delhi, India. They found that in the case of PV/T, the energy efficiency varies between 33-45%, while the corresponding exergy efficiency varies between 11-16%. On the other hand, for PV alone, the exergy efficiency was found to be varying in the range of 8-14% for a typical set of operating parameters. They also calculated the fill factor in order to know the behaviour of the exergy efficiency of the SPV systems and found that the higher the fill factor better would be the exergy efficiency. Hepbasli [55] has done a literature review on exergy analysis of several solar energy systems especially photovoltaic thermal systems and gave similar expressions as given by Fujisawa and Tani [56] and Saitoh et al. [57].

Joshi et al. [58] did the thorough review on performance evaluation of photovoltaic (PV) and photovoltaic thermal (PV/T) systems based on electrical as well as thermal output e.g., electrical, thermal, energy, and exergy efficiency. Work done by different authors on Photovoltaic systems and their applications were also revealed in this study. Applications of PV systems were classified according to their use, i.e., electricity production and thermal applications. A case study for PV and PV/T system based on exergetic analysis was also presented. From the extensive literature review, they found that the exergy efficiency of PV/T systems is higher than those of PV alone system as the PV/T systems gives useful thermal output apart from electricity. Also it has been observed from the study that electrical as well as thermal efficiencies can be increased by using reflecting surfaces because by using
reflector more incident radiations can be used. The thermal efficiency of PV/T water collector has been found to be more than that of PV/T air collector which is an obvious case as the density of water is higher than that of air.

Sarhaddi et al. [59] worked on performance analysis of solar photovoltaic thermal (PV/T) air collector using exergetic analysis. For the estimation of the electrical parameters of a PV/T air collector an improved electrical model was used in the present study and then in terms of design and climatic parameters a modified equation for the exergy efficiency of a PV/T air collector is derived. For calculating thermal and electrical parameters of a PV/T air collector had also been developed. Numerical simulation results and modified exergy efficiency obtained in the present study showed the good agreement with the experimental measurements noted in the previous literature. For a sample climatic, operating and design parameters, the thermal efficiency, electrical efficiency, overall energy efficiency and exergy efficiency of PV/T air collector were found to be 17.18%, 10.01%, 45% and 10.75% respectively.

Tiwari et al. [60] did the literature survey on thermal modelling of photovoltaic (PV) modules and their applications. In the review article different applications of PV module based on electrical and thermal output has been covered. Also in that article they covered the detailed description and thermal model of PV and hybrid photovoltaic thermal (HPVT) systems, using water and air as the working fluid. The numerical modelling and analysis of thermal and electrical output of PV and HPVT in terms of an overall thermal energy and exergy has been carried out in this study. From their extensive literature review, they found that the photovoltaic-thermal (PVT) modules were very promising devices and there exists a lot of scope to further improve the performances. The CIGS solar cells in the BIPVT system are the most
suitable from the energy payback time (EPBT) and energy production factor (EPF) point of view. However, mono-crystalline solar cells in the BIPVT system were found to be the most suitable from the life cycle conversion efficiency (LCCE) point of view.

Vats and Tiwari [61] carried out the performance study of a building integrated semitransparent photovoltaic thermal (BISPVT) system integrated on the roof of a room based on energy and exergy analysis. Six different types of SPV modules viz. monocrystalline Silicon (m-Si), polycrystalline Silicon (p-Si), amorphous silicon (a-Si), Cd-Te, CIGS and heterojunction with intrinsic thin layer (HIT) have been used for comparative performance evaluation. They found that as the cell temperature increases the exergy efficiency decreases and the maximum annual electrical energy produced by HIT was found to be 810 kW h, and suggested that this module suitable for generating electricity. However, maximum annual thermal energy produced by a-Si was found to be 464 kW h and it was also found that to be suitable for space heating applications while the efficiency was found to be 16.0% for HIT and 6.0% for a-Si respectively.

2.4 Renewable Energy Cooking Devices

Literature review of Renewable energy cooking devices has been divided into two parts viz. solar cooker and biomass cook stoves.

2.4.1 Solar Cooker

The standard proposed by Mullick et al. [62] is more complicated and less universal than the one being evaluated, though the characteristic curve they developed is a good predictive tool. Grupp et al. [63] employ a test procedure that presents much useful information especially for Europe. In recent years several
authors have investigated methodologies for the evaluation and comparison of solar cookers [62-65]. Traditional methods of characterizing the performance of solar cookers are based on energy analysis [67–68] as they are based on the first law of thermodynamics and provide information about the total quantity of energy without investigating the quality and the availability of energy. The exergetic analysis of low cost parabolic type and box type solar cooker was conducted by Ozturk [69] for the first time in 2004. Inspired from the study of Ozturk [69], Petela [70] in 2005 carried out the performance evaluation of a cylindrical trough shape solar cooker based on the exergetic analysis. Comparative study on energy and exergy efficiency for Box type and parabolic type solar cookers was conducted by Oztruk [71] under the climatic conditions of Turkey.

Buddhi and Sahoo [72] designed a box-type solar cooker having latent heat storage and showed that it is possible to cook the food, even in the evening hours with latent heat storage. Nahar [73] designed, developed and tested a novel solar cooker that does not require any tracking and its performance was compared with a hot-box type solar cooker. The overall efficiency of the novel solar cooker was found to be 29.5% and the payback period was found to be between 1.30 and 3.29 years depending upon the fuel it replaces. Gaur et al. [74] made a performance study of the box-type solar cooker with special emphasis on the shape of lid of the utensils used. The study revealed that the performance of a solar cooker could be improved if a utensil with a concave shape lid is used instead of a plain lid generally provided with the solar cookers. Buddhi et al. [75] also analyzed the thermal performance of a box type solar cooker on the basis of first and second figure of merit with and without load respectively and found that the second figure of merit depends on the quantity
of water loaded in the solar cooker and emphasized that the test method should specify the amount of water to be taken.

Petela [70] worked on the exergetic analysis of simple parabolic type solar cooker (SPC) of the cylindrical trough shape. Cooking pot, reflector and imagined surface making up the system are the foremost important parts of the solar cooker study therefore the equations for heat transfer between these three surfaces were developed. The model allowed the theoretical estimation of the energy and exergy losses: unabsorbed insolation, convective and radiative heat transfers to the ambient. Besides, the exergy losses: the radiative irreversibilities on the surfaces and the irreversibility of the useful heat transferred to the boiling water. Detailed methodology for the exergy analysis of SPC and the distribution of the exergy losses had been presented in this study and he also explained the method of determining exergy loss on the radiating surface specifically, when the surface absorbs radiation fluxes at different temperatures. From the study it had been observed that for the enhancement of the energy and exergy efficiencies of the cooker optimization of different parameters is important. Due to the escape of a large amount of insolation which is not absorbed, and due to the heat loss to the ambient energy efficiency were found to be very low. As far as exergy is concerned, the exergy efficiency had been found to be lower than that of energy efficiency which is due to the fact that, energy efficiency is based on first law of thermodynamics while the exergy efficiency on second law of thermodynamics which considers all the losses due to irreversibility and entropy generation. Besides, the losses due to absorptance of radiation on the surfaces of the reflector and the cooking pot. The energy efficiency of the SPC was found to be in the range of 6% to 19% while the exergy efficiency was found to be below 1 %, which is due to the fact as explained above.
Kaushik and Gupta [76] studied the performance analyses of community-size and domestic-size paraboloidal solar cooker based on energy and exergy analyses. The study showed that the community-size solar cooker (CSC) has the high energy, exergy efficiencies and low characteristic boiling time as compared with the domestic-size paraboloidal solar cooker (DSC). In other words, the performance of CSC was found to be better than that of the DSC. They also suggested that the exergy efficiency can be increased only up to some extent by increasing the reflectivity of the reflectors, proper designing of cooking place and using a suitable cooking pot. The time required to heat the water up to boiling temperature was also estimated and this indicated that such cookers are suitable to cook a meal faster besides the quality of the meal cooked was found to be better than that cooked by traditional cookers. The low efficiency of DSC was found to be lower due to the optical and thermal losses from the reflector and pot. As the solar radiation is rich in exergy and being utilized in the form of heat at low temperature therefore, the exergy efficiency of any solar cooker or solar thermal device is very low.

Mawire et al. [77] had worked on the thermal energy storage (TES) system of an indirect solar cooker using simulated energy and exergy analyses, an oil–pebble bed was used as the TES material in their study. For the performance analysis of the TES system using energy and exergy analyses two different charging methods were used. The constant flow rate for charging the TES system was used in first method however, in the second method, the flow rate was made variable to maintain a constant charging temperature. From their study it was found that the energy stored in constant-temperature charging method had larger than that of constant-flow rate charging method. The energy and exergy rates for the constant- temperature method were found to be slightly lower than that of the constant-flow rate method for
lower solar radiation conditions. However, the best results for exergy rates and exergy efficiencies were obtained by using the constant-temperature method at high solar radiation conditions. For both methods, the exergy efficiencies were found to be smaller than that of the energy efficiencies. Therefore, from the study it was concluded that the constant-temperature method performs better than that of the constant-flow rate method at high solar radiation conditions. While, the performance of solar cooker at constant-flow rate method was found to be better for low solar radiation conditions.

Mawire et al. [78] also studied the mathematical models for thermal energy storage (TES) system and thermal energy utilization (TEU) system of an indirect solar cooker to perform the discharging simulations in an indirect solar cooker. Discharging results of the TES system were presented using two different methods. In the first method, the discharge of the TES system was at a constant flow-rate while in the second method, the flow-rate was varied in order to maintain a desired power at a constant inlet temperature. The results of discharging the TES system at a constant flow-rate indicated a higher rate of heat utilization which was not found to be beneficial due to the cooking process since, the maximum cooking temperature could not be maintained for the duration of the discharging period. On the other hand, the controlled load power discharging method had a slower initial rate of heat utilization but the maximum cooking temperature was maintained for most of the discharging process which is the desirable condition for the cooking process.

Kumar et al. [79] worked on the truncated pyramid type solar box cooker (TPSBC) and presented an exergy analysis based on the test protocol. The energy and exergy balance for two different types of solar cooker viz. TPSBC and box type solar cooker (SBC) was carried out and the variations in their values with time and
temperature difference were also compared. The variations in the exergy loss with temperature difference was analysed for the selected water temperature range from 60 °C to 95 °C. The peak exergy, quality factor, and the heat loss coefficient were found to be 7.124W, 0.15, 4.09 W/m²K, respectively, for TPSBC and 9.95W, 0.14, 4.89 W/m²K, respectively, for SBC. These parameters for the first time were proposed to be the performance indicators for solar cookers. From the results of the study it was concluded that the exergy analysis of box type solar cookers is a practical, comprehensive and realistic tool for solar cookers’ performance evaluation as it emphasized on the quality of energy.

Kumar et al. [80] also studied the solar cookers of different geometries and presented an exergy based unified test protocol. In this study, four exergy based parameters viz. peak exergy, quality factor, exergy temperature difference gap product and heat loss coefficient were proposed for solar cookers at different topological design, as their thermal performance indicators. Calculations had been made and graphs between exergy output power and temperature difference were plotted. It was observed that these parameters resemble a parabolic curve for each design and the peak exergy can be accepted as a measure of devices fuel ratings. They proposed that the quality factor of the solar cooker can be defined as the ratio of the peak exergy power gained to the exergy power lost at an instant of time. It had also been found that the exergy power lost is directly proportional to temperature difference irrespective of the topology of the device and the slope of the straight line obtained through curve fitting represents the heat loss coefficient of the cooker. It was also mentioned that the proposed parameters in this study could lead to the development of unified test protocol for solar cookers of different geometries.
2.4.2 Biomass Cook Stoves

Due to the energy crisis during the 1970s, the improvement in biomass cook stoves to save large quantity of fuel consumed by these cook stoves was considered as an urgent need and many countries across the world started working on the same. Several developing countries including India, started national level programmes on the research, development and dissemination of improved cook stoves. National Program on Improved Cook-stoves (NPIC) was initiated in the year 1983 by the Ministry of New and Renewable Energy (MNRE), Government of India. Since, than many efforts and researches were conducted to augment the thermal efficiencies of cook stoves and to reduce the indoor air pollution levels. Learning from the experiences of this programme, it was found that there is a need of new initiative on the cook stoves with a different approach considering the changes that have taken place in the society, technology and the global concerns [81, 82].

Several studies on energy and exergy analysis of woody biomass, herbaceous and agricultural biomass were reported in the literature [83]. A study by Zhong et. al. [84] revealed that biomass is converted to a liquid fuel with an approximately high energy, which is called bio-crude. The maximum exergy efficiency of this process can be as high 86 % and was calculated based on the equations developed by Szargut et al. [85]. An energy analysis of rape seed oil methyl ester (RME) was investigated by Kalinc et al. [86] and it was found that the process analysis method is a common method to obtain reasonable data for energy and exergy analysis. The chemical exergy of liquid fuels was calculated and estimated and the chemical exergy of rape seed oil and RME was reported to be 44.5 MJ/kg and 50.5 MJ/kg respectively. Ojeda et al. [87] evaluated the lingo-cellulosic biomass and calculated the exergy of main stream process such as re-
treatment, fermentation and separation. According to Dincer et al. [88] to harvest good results and/or to get better thermal efficiencies of any system not only quantity but also the quality of energy should be considered. It was found the energy efficiencies are usually lower than the energy efficiencies as some of input is lost because of inevitable circumstances. Saidur et al. [89] had done the literature survey on the exergy analysis of various biomass viz. herbaceous and agricultural biomass, woody biomass, contaminated biomass and industrial biomass, aquatic biomass. In their study they found that the gasification, methanation and CO$_2$ removal were the main sources of exergy losses.

### 2.5 Exergoeconomics

In the analysis and design of energy systems, the techniques which combine scientific disciplines (energy, thermodynamic) with the economic disciplines mainly cost accounting to achieve the optimum designs are often used. For energy conversion devices, cost accounting conventionally considers unit costs based on energy [90]. Exergoeconomic evaluation is based on the concept of exergetic cost. For a thermodynamic system, the exergetic cost of an input, output or internal physical flow is defined as the amount of exergy per unit time required to produce that flow [91]. Few researchers [92–95] have recommended that costs are better distributed among outputs based on exergy than that of energy because exergy is more consistent measure of economic value of a system. In addition, most of these researchers have developed methods for performing economic analyses based on exergy, which are referred to by a variety of names e.g. thermoeconomics, second-law costing, cost accounting and exergoeconomics. Exergoeconomic evaluation has been carried out by many investigators, but recently their studies have intensified for
thermal power plant [96, 97]), cogeneration systems [98, 99] and on other thermal applications [100, 101].

Kim et al. [102] proposed the exergoeconomic analysis of thermal systems and derived the general cost-balance equation which can be applied to any component of a thermal system. The proposed exergy-costing method has been applied to a 1000-kW gas turbine cogeneration system. The exergy of a material stream was decomposed into thermal, mechanical and chemical exergy flows and an entropy-production flow in their study [102]. In their methodology a set of equations for the unit costs of various exergies has been obtained. By applying the cost-balance equation to each component of the system and to each junction the monetary evaluations of various exergy (thermal, mechanical, etc.) costs, as well as the production cost of electricity of the thermal system had been analysed. They also concluded that this exergy costing method provides information on decisions about the design and operation of the cogeneration system, besides the cost of losses of the system can also be obtained.

Ozgener and Hepbasli [103] investigated the capital costs and thermodynamic losses for devices in the solar-assisted ground-source heat pump greenhouse heating system with a U-bend ground heat exchanger. The basic objective of this experimental study was to find out the capital costs and thermodynamic losses for devices in solar assisted ground source heat pump greenhouse heating system. The experiments were carried out at the Solar Energy Institute of Ege University, Izmir, Turkey. The results showed that a systematic correlation appears to existed between the capital cost and exergy loss (total or internal) for components and the overall system. From their study it was found that the electrical, mechanical and isentropic efficiencies are the main cause of exergy destructions in the system and also point
out the attention to these equipments, because the components of less performance can reduce the overall performance of the system. The total exergy losses values were found to be from 0.010 kW to 0.480 kW for the system and most of the losses occurred in the greenhouse and compressor.

Ucar and Inalli [104] developed an exergoeconomic model for analysis and optimization of solar heating systems with residential buildings. Using MATLAB optimization toolbox, the optimum collector area and storage volume for solar-assisted heating system under the climatic condition of Elazığ, Turkey (38.7°N) were obtained. Each of the components of a solar heating system with seasonal storage was analysed using exergy analysis and the corresponding exergy losses were obtained. It was found from their study that the optimum collector area in the cylindrical storage system was larger than that of the trapeze storage system and therefore, the total cost of the cylindrical storage system is higher than that of trapeze storage system. From their study it was concluded that the size and type of storage play an important role in the seasonal storage solar heating systems.

Ozgener et al. [105] worked on the exergoeconomic analysis of geothermal district heating systems through mass, energy, exergy and cost accounting analyses and also presented a case study for the Salihli geothermal district heating system (SGDHS) in Turkey. Relations between energetic and exergetic losses and capital costs for the Salihli geothermal district heating system had been investigated. From the study it was found that a systematic correlation appears to exist between exergy loss rate and capital cost for the plant. Furthermore, a correlation appears to exist between the mean thermodynamic loss rate-to-capital cost ratios for all of the
devices in a SGDHS. The exergy destruction in the systems was found mainly due to the thermal line, heat exchangers and pumps.

Sahoo [106] carried out an exergoeconomic analysis and optimization of a cogeneration system which produces 50 MW of electricity and 15 kg/s of saturated steam at 2.5 bar. He optimized the unit using exergoeconomic principles and evolutionary programming, and showed that the cost of electricity production is 9.9% lower for the optimum case in terms of exergoeconomics compared to a base case. Sayyaadi [107] performed an exergoeconomic optimization of a 1000 MW light water nuclear power generation system using a genetic algorithm and considering ten decision variables, and showed that the fuel cost of the optimized system is greater than that for the base case and the shortcomings in the optimized system are compensated by larger monetary savings in other economic sectors.

Ameri et al. [108] worked on the energy, exergy and exergoeconomic analysis for the Hamedan steam power plant and estimated the exergy destruction and exergy loss of each component of the power plant. In order to obtain a good insight into this analysis the effects of the load variations and ambient temperature were calculated. The exergy efficiencies of the boiler, turbine, pump, heaters and the condenser are estimated at different ambient temperatures. From the energy analysis it was found that the maximum energy loss occurred in the condenser (around 70.5%) while, in the boiler the energy loss was found to be 15.5%. On the other hand, as far as exergy is concerned, the major exergy loss was found in the boiler (around 81%) of the total exergy destruction of the power plant cycle, while it was only 5% of total exergy loss in the condenser. From the exergoeconomic point of view, it has been
observed that the cost of the exergy destruction in the boiler and turbine was higher than that of the other components cost.

Ahmadi et al. [109] carried out the comprehensive exergy, exergoeconomic and environmental impact analysis and optimization of several combined cycle power plants. The analyses of the results were performed in two different parts, in the first part, the plant was analysed using thermodynamic fundamentals i.e. energy and exergy analyses, besides the effect of supplementary firing on the natural gas-fired plants. Also the effect of supplementary firing on the performance of bottoming cycle and CO₂ emissions, were carried out using the first and second laws of thermodynamics. For determining the best design parameters, a multi-objective optimization was performed to determine the accounting for exergetic, economic and environmental factors in the second part. Three objective functions were considered in the optimization viz. the total cost rate of the system products, CCPP exergy efficiency and CO₂ emissions of the overall plant. The environmental impact in terms of CO₂ emissions was integrated with the exergoeconomic objective function as a new objective function. The exergoeconomic analysis results showed that the combustion chamber has the greatest cost of exergy destruction of all components, besides increasing the gas turbine inlet temperature decreases the cost of the exergy destruction of the combined cycle power plant.

Baghernejad and Yaghoubi [110] applied the concept of exergoeconomic to optimize an integrated solar combined cycle system. An exergy-costing method was applied to a 400MW integrated solar combined cycle system to estimate the unit costs of electricity produced from the combined gas and steam turbines. They found that the objective function decreased by about 11% and the overall exergoeconomic
factor of system increased by 27.34%, while the unit cost of electricity produced by steam turbine and gas turbine reduced by about 7.1% and 1.17% respectively. This was achieved, however, with 13.3% increase in the capital investment while the exergy destruction cost reduced by 14.82% and the exergetic efficiency of the system increased by 3%.

Yucer and Hepbasli [11] carried out the exergoeconomic analysis of a dormitory heated by a conventional boiler in a central heating system. In this study some heating equipments were comprehensively evaluated based on exergetic and exergoeconomic analyses. A conventional boiler and a water heater in the central heating system were considered in the analysis. The total exergy input rate had been found to be 1455 kW, while the largest exergy loss rate was found to be 987.6 kW. The exergetic efficiencies of the conventional boiler and the water heater were found to be 15.6% and 20.4%, respectively. The exergoeconomic factors of the conventional boiler and the water heater were calculated to be 0.72% and 0.14%, respectively. These low values mean that the equipments at hand both of the conventional boiler and the water heater were to be changed by more efficient ones. The equipment efficiencies should be improved by increasing the capital investment, which behave more specific in the procurement of the equipments.

2.6 Conclusions of Literature Review

A comprehensive literature review on energy and exergy analyses of renewable energy conversion systems including solar air heater, solar water heater, solar photovoltaic and cooking devices such as solar cooker and biomass cook stoves have been carried out. Apart from the energy and exergy analyses of renewable
energy systems the literature review on exergoeconomics was also carried out which is one of the objectives of the thesis. From the literature review of exergy analysis of different renewable energy conversion systems, it was found that, there has been gaps in these areas because of the fact that the exergy analysis of the following system is scant:

- Solar thermal devices in general and solar air/water heaters in particular.
- The exergy analysis of biomass based energy systems.
- The exergy analysis of photovoltaic modules.
- The literature review on the exergoeconomics evaluation of renewable energy systems.

The gaps in the literature review helped in identifying the objectives and investigations of the proposed thesis. The proposed thesis is an attempt to fill the gaps in the above mentioned literature review especially, the renewable energy systems.

References


81. Ministry of New and Renewable Energy (MNRE), [www.mnre.gov.in]


