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Parametric evaluation of a cascaded novel system based on biomass, solar, and SCO_2 power cycle

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ABSTRACT

The Renewable energy source is pivotal to clean power generation. The present work comprises solar and biomass as leading energy sources for a sCO2/ORC-based combined power plant. A comprehensive thermodynamic performance assessment of a supercritical Brayton cycle (SBC) and organic Rankine cycle (ORC) system is performed. The system is modelled and the Mini-RefProp program is used to obtain the thermodynamic properties of the working fluids. The system's performance is quantified in terms of its net power output, thermal efficiency, and exergy efficiency. The use of solar and biomass energy sources also contributes to the sustainability of the system. The results show that the integration of the SBC and ORC cycles leads to a significant increase in the net power output and thermal efficiency of the system. Furthermore, the results show that the thermodynamic properties of the working fluids significantly affect the performance of the system. The exergy efficiency for topping cycle has achieved the highest among all the three cases i.e., 25.5% and the overall exergy efficiency i.e., 34.81%. This shows that biomass can be one of the best sources of energy source. Also, the Levelized cost of electricity was calculated for the overall system which resulted in US$8.42 kW/hr. Altogether, the study delivers significant insights into the feasibility of a unified SBC and ORC system for efficient harnessing of solar and biomass energy sources.

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1. Introduction

Solar and biomass power sources represent two promising approaches to attaining sustainable and renewable energy alternatives. With the global population on the rise, energy demand is expected to surge, underscoring the necessity of identifying eco-friendly and cost-effective energy alternatives. Solar power is generated from sunlight and can be captured through various technologies, including photovoltaic cells, solar thermal systems, and concentrated solar power (CSP). Biomass energy, in contrast, is derived from organic matter like wood, crops, and agricultural residues, and can be transformed into multiple energy forms, including electricity, heat, and biofuels. This paper examines the potential of solar and biomass energy as sustainable substitutes for

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fossil fuels, assessing their economic, environmental, and social implications.

The S-CO2 Brayton cycle, which is being explored for use in next-generation nuclear reactors due to its high efficiency and compact design, is examined Ahn et al [1]. Various heat sources, such as nuclear, fossil fuel, waste heat, and renewable heat sources like solar thermal or fuel cells, are identified by the author as compatible with the S-CO2 cycle. The study compares the performance of different S-CO2 cycle configurations. The report provides an overview of the S-CO2 cycle's current development status. Unlike traditional steam Rankine cycles, non-supercritical Brayton cycles, or geothermal power cycles, supercritical CO2 (sCO2) power cycles are analysed in this research. The authors discuss several sCO2 Brayton cycle designs and emphasise how these might lead to improved cycle efficiency. The study offers a review of prior studies on sCO2 power cycles and their uses in various industries. Haffejee et al [2] The integrated performance of a modular biomass boiler is analyzed for its application in an existing industrial Rankine steam heat and power cycle, with a supplementary supercritical carbon dioxide (sCO2) Brayton cycle. The model quantifies the impact of the sCO2 heaters, which result in reduced heat uptake for downstream boiler heat exchangers. Jamil and Ali [3] discussed the system is best suited for direct steam injection applications requiring high temperatures and pressures, such as solar thermal enhanced oil recovery for the extraction of heavy oils. Pantaleo et al [4] performed literature study that examines the difficulties in creating biomass power plants for the requirement of steady and economical supply of biomass. The assessment emphasises the potential advantages of combining two energy sources—solar thermal and biomass—that work well together seasonally and throughout the day. The research also makes reference to a prior study that suggests a hybrid Brayton solar plant that uses natural gas combustors to guarantee steady electricity supply. [5] To determine the gap of work in various systems and the possible advantages are suggested through a system, by conducting literature review. In order to generate power, the study suggested a novel system that combines supercritical CO2, solar energy, and biomass. They discovered that while the suggested system may run at greater temperatures and reach better efficiencies, traditional molten salt systems have temperature and efficiency restrictions. The authors discovered that biomass may give the power cycle a reliable supply of heat and increase operation time. Milani et al [6] described the modelling and control methods of a 10 MW solar-assisted recompression sCO2 Brayton cycle in Port Headland, Northwest Australia. It contrasts the performance of two different scenarios: a direct cycle where sCO2 flow is heated directly in the central receiver without TES, and an indirect solar-assisted cycle outfitted with thermal energy storage (TES). The work-focused to increase the contribution of the solar field while reducing the use of the AFB heating system. Wang and He [7] investigated a S-CO2 Brayton cycle-integrated molten salt solar power tower system. The authors have examined the impacts of significant thermodynamic factors on the system's exergy efficiency using a parametric study. To get the maximum energy efficiency, they also used a genetic algorithm for parameter optimisation. According to the study, a unique salt with a higher maximum permissible temperature is required to boost system effectiveness further. Liang et al [8] discussed an organic Rankine cycle and a supercritical CO2 Brayton cycle coupled with a molten salt solar power tower plant are optimised. The suggested technique optimises the integrated system's flowsheet mass/heat equilibrium and stream thermodynamic characteristics. According to the findings, the suggested strategy improves thermal efficiency up to 3.6% compared to the literature values. The findings indicate that the condenser and turbine thermo-economic performances are improved by the RORC and DORC arrangements, respectively. The work also emphasises upon fuel cost rate and power output. Manente and Lazzaretto [10] The possibility of employing a supercritical closed CO2 Brayton cycle (s-CO2) to turn biomass sources into power is investigated in this research. The s-CO2 system has two cascaded supercritical CO2 cycles that make it possible to efficiently use all of the heat that is present in flue gases. To examine the thermodynamic performance of such systems, the research examines four boiler configurations. According to the results of the optimisation process, a cascaded configuration with a part flow topping cycle can produce a maximum biomass to electricity conversion efficiency of 36%, which is about 10% points higher than that of the existing biomass power plants in the small to medium power range. Mehrpooya et al [11] The study proposed a revolutionary integrated system that integrates water regeneration, solar collectors with flat plates (FPC), and the Kalina power cycle with the water scrubbing biogas upgrading process. The system generates the electrical power needed for the enhancement of biogas process using solar thermal energy. In the biogas upgrading cycle, any extra heat is captured and fed into the Kalina cycle. On the basis of actual solar data for Bushehr city, the suggested system was modelled using Aspen Hysys. The CO2 and H2S concentrations could be eliminated during the water scrubbing process, which also produced improved biogas. The suggested integrated system's exergy efficiency was determined to be 92.36%. The FPCs were where the greatest amount of energy was destroyed, accounting for 73% of all energy loss. The steam turbine and desorption column both have the second and third greatest rates of energy destruction. Study and discussion also included the impacts of collector number and minimum approach temperature on exergy efficiency, improved biogas production, Kalina cycle efficiency, and exergy destruction. Xing et al [12] performed the study on a combined cooling and power (CCP) system that makes use of waste heat from an internal combustion engine is presented in this article. A CO2 Brayton cycle, an organic Rankine cycle, and an ejector refrigeration cycle make up the system. The performance of the system is examined in terms of the impact of five important parameters using thermodynamic and exergo-economic studies. The findings demonstrate that raising the ORC turbine inlet pressure, ejector primary flow pressure, and turbine inlet temperature improves the CCP system's thermodynamic and exergo-economic performances. However, lower system performances will result from raising the compressor pressure ratio and compressor inlet temperature. From an exergo-economic perspective, a single-objective optimisation is used to find the system performance that is best. Through optimisation, the system's average expense per unit of energy product is reduced to the lowest possible level. Delgado-Torres and L. García-Rodríguez [13] conducted a study, the efficiency of the solar Rankine cycle was optimised using various working fluids and sun collectors. The study is carried out for direct vapour generation and heat transfer fluid configurations of the solar power cycle, as well as for non-regenerative and regenerative Rankine cycles. Analysis also checked on how these variables affect the aperture area per unit of net mechanical power supplied by the solar cycle. The findings may be helpful for technoeconomic analysis, system size, working fluid selection, and solar power cycle design evaluation. Pasetti et al [14] presented in the study, an experimental setup for examining fluids' thermal stability, coupled with an enhanced statistical analysis of the experimental data. The researchers used vapour pressure deviations to predict the breakdown rates of three fluids relevant to ORC applications. According to the findings, there were differences in the thermal stability of the fluids, with one fluid being more stable than the others. Estimates of the decomposition rates were more precise due to the revised analytical procedure.

Puig-Arnavat et al [15] presented the analysis of alternative gasification trigeneration plant designs under the Polycity project. In Cerdanyola del Vallès, close to Barcelona, a new urban development area dubbed "Parc de l'Alba" was the target of the project, which planned to set up a high-efficiency energy system to produce power, heating, and cooling.

Five different configurations for the production of heat, cold, and electricity models of a biomass gasification trigeneration plant proposed. The models were a useful tool for evaluating the performance of trigeneration plants since it can analyse the outputs for various biomass kinds and operating circumstances. Datta et al [16] The thermal performance and size of a biomass-based, decentralised power plant powered by an externally fired gas turbine (EFGT) are examined in this study at various cycle pressure ratios, turbine input temperatures, and cold end temperature differential in the heat exchanger. According to the study, based on the temperature differential between the heat exchanger cold end and the turbine inlet, the thermal efficiency of the EFGT plant achieves its maximum at the ideal pressure ratio. With an increase in pressure ratio, the specific air flow, which is correlated to the size of the plant equipment, falls. While a change in the temperature differential between the heat exchanger's cold and hot ends does not affect the specific air flow, an increase in the turbine's input temperature does. A trade-off in the operating condition is achieved after analysing the performance of a 100 kW EFGT plant for three sets of operating parameters using this comparison.

Liu, et al [17] examined a liquid carbon dioxide energy storage system with 10 MW of output power generation. New energy-based concepts are introduced in the paper, including investment costs, exergy destruction costs, and endogenous and exogenous exergy destruction. Engineers' understanding of the proposed system's energy conversion processes and the accuracy of the results can both be improved by the enhanced exergy-based assessments. The findings imply that the expander is the most important element with the greatest priority for development. In the proposed system, the preventable endogenous value for total exergy destruction, total exergy destruction costs, and total investment costs is ~~only~~ 42.1%, 43.42%, and 55.43%, respectively. Sharifishourabi and Arab Chadegani [18] described a thermodynamic system that can produce electricity, dry air, hot water, heating, cooling, and hot water from a single clean energy source. A triple-effect absorption chiller using LiBr-H2O as its working fluid is merged with an organic Rankine cycle powered by solar energy. An energetic and exergetic examination of the system, as well as a review of the surroundings, are all included in the research. Based on producing 428 kW of energy, the results reveal that the system has an energetic COP of the absorption chiller of 1.34 and an exergetic utilisation factor of 0.39. The organic Rankine cycle has energy and exergetic efficiencies of 14.4 and 26%, respectively. Low ambient temperatures can enhance the system's environmental benefits. Akrami et al [19] described in the study which produces hydrogen, power, heating, and cooling using geothermal energy. The system consists of a proton exchange membrane electrolyzer, an organic Rankine cycle, a household water heater, and an absorption refrigeration cycle. In addition to examining the impacts of different variables on the system's efficiency, load, power output, hydrogen generation, and unit cost, the study analyses the system's energetic, exergetic, and exergoeconomic performance. The outcomes demonstrated that the suggested system is effective and affordable, and it may be a good replacement for systems that rely on fossil fuels. Yilmaz [20] studied an integrated plant for the production of hydrogen and heat using geothermal energy is proposed. Dual organic Rankine cycles (ORCs), an absorption chilling period, and a membrane that exchanges protons electrolyzer are all components of the system. According to the research, which assesses the planned plant's thermodynamic and environmental effects, it has an overall energy efficiency of 63.28% and an exergy efficiency of 55.99%. It is discovered that the hydrogen generation rate, cooling load, and heating load are each 806.4 kW, 758 kW, and 9.0036 kg/h, respectively. If coal is employed as the plant's fuel source for electricity production, the simulated cycle reduces CO2 emissions by around 26421 t per year. Borsukiewicz-Gozdur [21] described method to generate heat and power for a drying chamber, a CHP plant that employs sawmill biomass as fuel, is shown in the study. Four distinct working fluids were analysed: octamethyl-tri-siloxane, methylcyclohexane, methanol, and water. The findings demonstrate that the system's performance may be tailored to the requirements and goals of the plant investor by selecting the proper operating fluid and regeneration version. The system with internal regeneration and methylcyclohexane used as the "dry" working fluid produced the highest electric power, while the system with external regeneration and octamethyl-trisiloxane used as the working fluid produced the highest temperature to supply the drying chamber.

The important attribution of this present work is to reveal the true potential of solar and biomass energy resources that can be used to energize the power plant. The usage of biomass source as municipal solid waste contributes to a dual purpose- providing energy as well as cleaning the environment. The novelty of this presented work is about hybrid power plant that will be powered by dual thermal energy sources- CSP and a biomass furnace. This study is based on analysis and a parametric study that examines the parameters for the overall performance of the system. Through this study, it helps to realise the study gap, including the addition of biomass energy and solar energy source for a hybrid power plant and therefore find its true potential.

Nomenclature

C_1	*investment to build total system*
C_{OM}	*cost of annual operation and maintenance for* $S-CO_2$ *system*
C_t	*annual cost of biomass fuel*
H	*operation hours in a year*
P_e	*stands for electricity output in an hour*
β_{om}	*proportion of annual operation and maintenace of total investment*
I	interest rate
m_{in}	*mass rate flowing in tank*
m_{out}	*mass rate flowing out of tank*
$Q_{loss\ in\ tank}$	*heat loss wrt to ambient temp*
η_{field}	field efficiency
ϕ	*useful radiation work*
T_s	*temp of sun*
δ	*sun cone angle*
R_{view}	*radiative view factor*
I_0	*solar radiation*
C	*concentration ratio*
T_r	*surface temperature*
α	*absorptance*
C_{conv}	Convective heat loss factor
ε	*thermal emittance*
NPV	net present value

2. Process Flow Chart

The flow chart for the new hybrid cycle is shown in Fig. 1. Figure 1 depicts the simulation process required to analyse the proposed hybrid system. -As per the literature review, a suitable layout of the power generation system is proposed. This proposed system is then modelled based on the thermodynamic laws. Numerous techniques, including mathematical modelling and computer simulation, can be used to accomplish this investigation. The input and output variables associated with the thermodynamic model were investigated using the code developed in MATLAB. The open-source software mini refprop is used for the evaluation of the sCO2 cycle for getting its thermophysical properties. Analysis of the system and the outcomes from the code reveals results for the proposed system. This will entail assessing the model's correctness and locating any potential issues. If there are some issues obtained, then the iteration will start with a selection of new input parameters.

This flow process assists in identifying potential obstacles and guiding the research design. The complexity of the system and the expected accuracy will determine the size of the accurate data set selected.

2.1. Description System

The suggested layout of the novel system is shown in Fig. 2. The process begins with heat received from a source, primarily solar energy. Biomass is a backup energy source that only comes into play when necessary, often at night, during the winter, or on overcast days. The concept of intermittent energy is eliminated by biomass. Therefore, this energy as a source of power is crucial to use for continuous energy requirements.

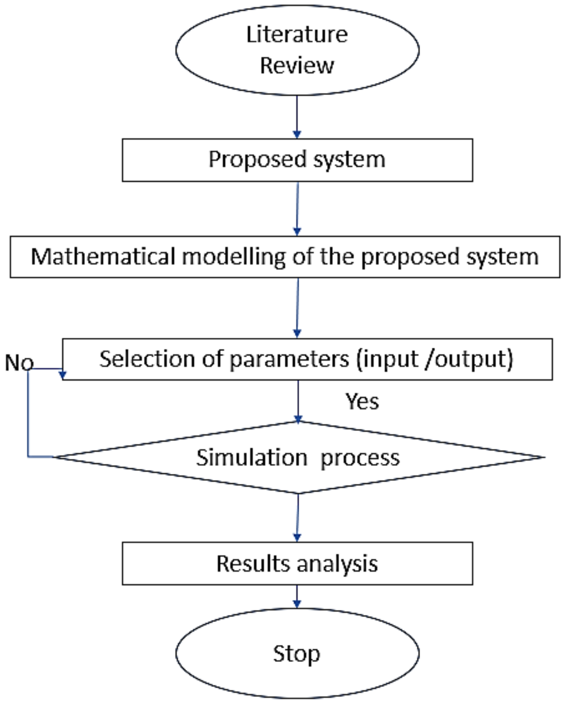

Fig. 1. Process flow chart

Heat is transferred to s-CO_2 (working fluid), which is already in a supercritical state at this point in the cycle. It then enters the turbine, expands to a low pressure and low temperature, providing work output. The working fluid is then sent via a condenser to exchange leftover heat with the bottoming cycle (ORC cycle) after the expansion.

After extracting work in the topping cycle, the working fluid (sCO2) is passed through the primary compressor. Then a recompressor stage, their second half of compression starts. When the working fluid from two compression stages joins at the recuperator, it picks up heat from the temperature of the exhaust from the turbine, improving process efficiency. One thing to keep in mind in this situation is that the turbine exhaust temperature shouldn't be lower than the compressor outlet. If it is, further recuperation is impossible because the heat capacity has been exceeded, and it will only function as a condenser or gas cooler. In the meantime, the bottoming cycle's procedure is straightforward because, as with a straightforward Brayton cycle, heat is produced in the topping cycle through the turbine's exhaust. Here, additional expansion involves a turbine, which generates effort to continue rotating the generator and generate power. Compression and expansion are then used to this process to move it along. Solar and biomass energy sources are used to create the energy. Municipal solid waste is used by biomass to provide energy that can power the turbine.

3. Thermodynamic Modelling

The proposed system consists of renewable energy sources (solar and biomass), which is equipped with thermal energy storage. The energy from these sources is utilized to power sCO2 Brayton cycle to generate power. The energy potential left from the topping cycle is further tapped by the ORC cycle as a bottoming cycle. The following assumptions are incorporated to create the mathematical model: The system is considered to be working under steady-state conditions. The kinetic and potential energy of the hybrid system is neglected. The pressure drop in the sCO_2 Brayton and Organic Rankine cycles are neglected. Isentropic efficiency and effectiveness for heat exchangers are taken from the given references, and the heat losses in various components of the cycles are not considered.

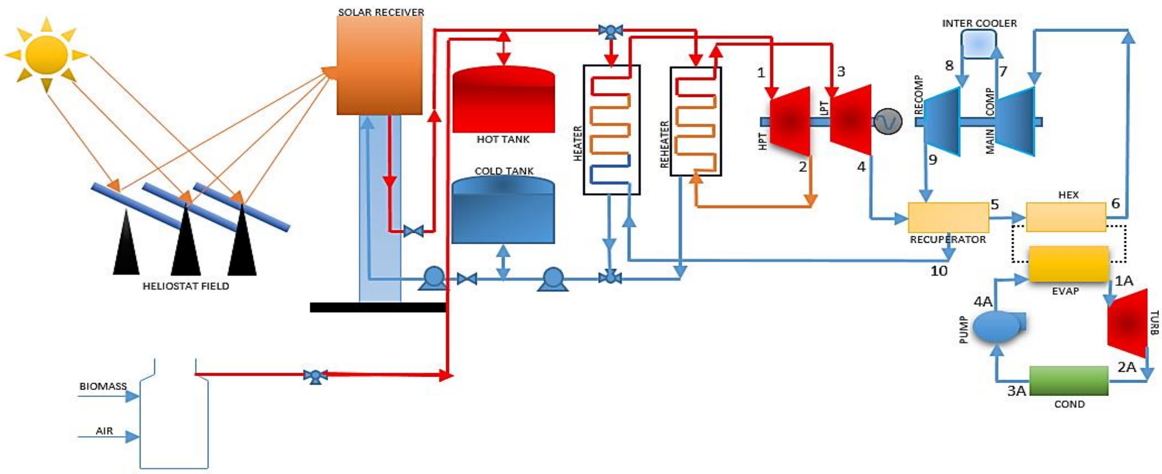

Fig. 2. Proposed layout for the overall system

3.1. Energy modelling

The energy balance for each sub-component of the system based on the first law of thermodynamics laws as shown in equation (1):

$$Q_{cv} - W_{cv} + \sum m_{in} * h_{in} - \sum m_{out} * h_{out} = 0 \quad (1)$$

3.1.1. Molten salt receiver

The heat energy received from the tower receiver may not be fully utilized due to some transportation losses that will take place while passing through the tubes. Due to these losses, conduction, convective, and radiation heat losses are considered.

The equation is given by Eqs. (2) and (3):

$$Q_{out} = Q_{tr} - Q_{opt\,(loss,conv,rad)} \quad (2)$$

$$Q_{opt\,(loss,conv,rad)=} \left(1 - \eta_{opt} * Q_{tr}\right) \quad (3)$$

3.1.2. Molten salt thermal energy storage (TES)

In the present work energy coming out from the solar tower will be divided into two stages, one part of energy will be utilized in plant while the other half of energy will be stored in molten salt thermal storage for use in when availability of energy is not possible.

Thermal energy storage is an energy storage device that has the capability to store energy up to 8 hours [23]. This type of system is usually implemented to enhance the energy production in case of absence of energy supply. It acts as the reserve for energy mostly at night or in cloudy/winter season. TES serves to capture heat energy and supply the heat energy from hot storage tank to convert it into electricity. After giving off the heat to heater and re-heater, the condensed liquid is pumped back to cold storage tank where it is kept to absorb energy and raise its temperature again. The basic input parameters for TES are shown in Table1.

Based on this the equation is written as:

$$Q_{out} = Q_{in} + Q_{tes} \quad (4)$$

Energy equation for TES is given as:

$$Q_{tes} = \left(m_{in} * h_{in} - m_{out} * h_{out}\right) - Q_{loss\ in\ tank} \quad (5)$$

3.1.3. Solar system modelling

This system consists of a number of heliostats, The energy received from them is given by the equation for heat energy obtained from the tower receiver is given as:

$$Q_{tr} = DNI * A_{hs} * no\,of\ heliostat \quad (6)$$

3.1.4. Biomass system modelling

The heat energy obtained through municipal waste in the form of biomass, according to the first law of thermodynamics, is given by the equation:

$$Q = m_f * LHV \quad (7)$$

Table 1. Input parameters for thermal energy storage [23]

Parameters	Value
TES hot tank temp	565 °C
TES cold tank temp	290 °C
Storage capacity	0.635MWh
Time storage	8 hr
Density	1900 kg/m^3
Specific heat	1.950 kJ/kgK
Viscosity	3.26 poise
Thermal storage effectiveness	0.97
Inlet charging flow rate	10 kg/s
Surrounding temperature	298K

Table 2. Chemical composition of biomass as MSW [22]

		MSW
Proximate analysis (%)	Moisture	60
	Fixed C	9
	Volatile	20
	Ash	11
Ultimate analysis (%)	Carbon	52.5
	Hydrogen	6.4
	Nitrogen	9.2
	Sulphur	0.8
	Oxygen	31.1
Heating value (MJ/kg)		7.16
Metals content (mg/kg of dry mass)	Ca	70.9
	Mg	9.2
	Cr	43.3
	Hg	1
	Cd	1.1
	pb	53.8

3.1.5. Super Critical Brayton Cycle

Carbon dioxide in supercritical phase is one of the most important working fluids used in this study. It normally behaves as a gas at standard temperature and pressure, but when compressed to high pressure, temperature normally above its critical state, then it will act as both gas and liquid. at that stage above its critical state, it behaves like a gaseous substance but has a property of a liquid. It is observed that a small change in its pressure and temperature brings a major change in its density value, hence making compression work less in this case. Carbon dioxide in its critical form is used because it is able to yield high efficiency, and apart from that, due to its stable chemical properties. Super critical Brayton cycle is chemically non-flammable because it does not leave any type of toxic element in the atmosphere, stable and reliable due to its low-cost maintenance.

This cycle consists of sCO2 turbine, compressors, a recuperator, a cooler, an intercooler, a heater and a reheater. The mathematical model for these systems is discussed below.

Table 3. Input parameter for supercritical Brayton cycle [23]

Input parameters	Value taken
Efficiency turbine	90%
Efficiency compressor	88%
Effectiveness high temp recuperator	93%
Temperature1	800 °C
Max cycle press	25 MPa
Min cycle press	7.25 MPa
Rated power	1.5 MW
Effectiveness of heat exchanger	90%

sCO2 Turbine (SBC): the energy equations to estimate the expansion work from sCO_2 turbine considering same isentropic efficiency is given as:

$$W_{act1} = \left[m_{CO2}\left(h_1 - h_2\right)\right] * \eta_{turb} \tag{8}$$

$$W_{act2} = \left[m_{CO2}\left(h_3 - h_4\right)\right] * \eta_{turb} \tag{9}$$

$$W_T = W_{act1} + W_{act2} \tag{10}$$

sCO2 Compressor: the energy equation to estimate the compression work from sCO_2 compressor and re-compressor considering same isentropic efficiency is given as:

$$W_{comp1} = \left[m_{CO2}\left(h_6 - h_5\right)\right] * \eta_{comp} \tag{11}$$

$$W_{comp2} = \left[m_{CO2}\left(h_8 - h_7\right)\right] * \eta_{comp} \tag{12}$$

$$W_c = W_{comp1} + W_{comp2} \tag{13}$$

$$W_{network(act)} = W_T - W_c \tag{14}$$

Recuperator: it is a type of heat exchanger where some of its exhaust heat gases is utilized in gaining the heat for the heater inlet. This in turn reduces fuel consumption, increases mean temperature of heat addition and overall increases the efficiency.

$$Recuperator = m_{CO2}\left(h_4 - h_{10}\right) = m_{CO2}\left(h_9 - h_8\right) \tag{15}$$

Cooler and intercooler: this is also a type of heat exchanger where the exhaust heat is rejected by running cooling water from a different system.

$$Cooler = m_{CO2}\left(h_{11} - h_8\right) = m_{water}\left(h_{11} - h_8\right) \tag{16}$$

Heater: it is a type of heat exchanger that mainly supplies the energy to the cycle for its overall working. This has two sources mainly from solar and biomass for this this study.

$$Heater = m_{CO2}\left(h_9 - h_1\right) = Q_{in} \tag{17}$$

Re-Heater: it is a type of heat exchanger that mainly supplies the energy to the cycle for its overall working. This has two sources mainly from solar and biomass for this study. Energy equation is given

$$Re - Heater = m_{CO2}\left(h_3 - h_2\right) = Q_{in} \tag{18}$$

3.1.6. Organic Rankine Cycle

The organic Rankine cycle (ORC) consists of, ORC turbine, condenser, pump and evaporator. The energy equation for various components is written based on the energy conservation of the first law of thermodynamics. The energy is conserved for input and output of components and based on this the equations are given as:

Turbine (ORC): the energy equation for turbine is given by the isentropic efficiency of turbine as follows:

$$\begin{aligned} W_{act\,turb3} &= m_{wf}\left(h_{11} - h_{22}\right) * \eta_{turb} \\ W_{ORC} &= W_{act\,turb3} \end{aligned} \tag{19}$$

Pump: the energy equation for compressor is given of pump as follows:

$$Actual\ work\ of\ pump = \left[v_s * \left(dp\right)\right] / \eta_{pump} \tag{20}$$

3.2. Exergy Modelling

The exergy balance for system is calculated according to the following equation.

$$\begin{aligned} \frac{dE_{cv}}{dt} = \sum_j E_{qj} - W_{cv} + \sum_i m_i * e_i - \\ \sum_i m_o * e_o - E_d - E_{loss} \end{aligned} \tag{21}$$

Table 4. Parameters for Organic Rankine Cycle [23]

Parameters	value
Pump isentropic efficiency	85%
Pinch point evaporator	10-50 °C
Pressure ratio	15
Mass rate	1 kg/s
Turbine isentropic efficiency	90%

3.2.1. Solar exergy modelling

For this work a hybrid system was modelled which is sourced by one its solar components which in this case is solar receiver. So, the input exergy by the radiation towards the solar receiver is given by the Eq. (22):

$$E_{solar} = \frac{Q_{hr} + Q_{rhr}}{\eta_{field} * \eta_{th}} * \phi \quad (22)$$

For an ideal process the useful radiation work (ϕ) is calculated as Eq. (23) [24]:

$$\phi = 1 - \frac{4}{3} * \frac{T_0}{T_s} * \left(1 - (1 - \cos\delta)^{\frac{1}{4}} + \frac{1}{3} * \left(\frac{T_0}{T_s} \right)^4 \right) \quad (23)$$

The thermal efficiency for the solar system (central receiver) is calculated as given below equation [25]:

$$\eta_{th} = \alpha - \frac{\varepsilon * \sigma * R_{view} * T_r^4 + C_{conv} * h_{conv} * (T_r - T_{air})}{\eta_{field} * I_0 * C} \quad (24)$$

where T_r is the surface temperature of solar receiver given by equation[26], [27]:

$$T_r = T_{in,turbine} + \Delta T_r \quad (25)$$

The modelling of heliostat field selected is already shown in Table 5.

3.2.2. Biomass exergy modelling

Input exergy from biomass is given by equation:

$$E_{input\ biomass} = m_{biomass} * e^{ch}_{x\ biomass} \quad (26)$$

Amount of biomass fed into furnace is given by equation:

$$m_{biomass} = \frac{Q_{hr} + Q_{rhr}}{LHV_{biomass}} \quad (27)$$

Chemical exergy for ideal gas is given by equation:

$$e^{ch}_{x\ biomass} = \beta * LHV_{biomass} \quad (28)$$

where β is determined by given equation:

$$\beta = \frac{1.0414 + 0.0177\left(\frac{H}{C}\right) - 0.3328\left(\frac{O}{C}\right)\left[1 + 0.053 * \left(\frac{H}{C}\right)\right]}{1 - 0.4021 * \left(\frac{O}{C}\right)} \quad (29)$$

3.2.3. Exergy modelling for Super critical Brayton cycle and organic Rankine cycle:

Heat transfer exergy is given by equation:

$$E_{in} = \left(1 - \frac{T_0}{T_k}\right) * Q_k \quad (30)$$

where T_0 and T_k are reference and component temperature respectively. The calculation of physical exergy is also carried by given equation:

$$e = (h - h_0) - T_o * (s - s_o) \quad (31)$$

In this study the reference temperature and pressure are taken as 25 °C and 101.23KPa.

Table 5. Parameters to Obtain Thermal Efficiency of Receiver [23]

Parameter	Value Taken
Absorptance, $\boldsymbol{\alpha}$	0.95
Thermal emittance, $\boldsymbol{\varepsilon}$	0.85
Radiative view factor, $\boldsymbol{R_{view}}$	1
Solar receiver temperature, $\boldsymbol{\Delta T_r}$	150
Convective heat loss factor, $\boldsymbol{C_{conv}}$	1
Equivalent temperature of sun, $\boldsymbol{T_s}$	5800
Concentration ratio	900
Cone angle of sun, $\boldsymbol{\delta}$	0.05
Annual heliostat field efficiency, $\boldsymbol{\eta_{field}}$	0.60
Convective heat transfer coefficient, $\boldsymbol{h_{conv}}$	10

Table 6. Exergy equations for hybrid plant

Components	Exergy Equations
Turbine1	$\left(E_1-E_2\right)-W_{t1}=E_{1D}$
Turbine2	$\left(E_3-E_4\right)-W_{t2}=E_{2D}$
Compressor1	$W_{c1}-\left(E_6-E_5\right)=E_{3D}$
Compressor2	$W_{c2}-\left(E_8-E_7\right)=E_{4D}$
Heater	$Q_{hr}*\left(\frac{\alpha}{\eta_{th}}-1\right)*\left(1-\frac{T_0}{T_r}\right)=E_{1,hr}$
	$\frac{Q_{hr}}{\eta_{th}}*\phi-E_{1,hr}+\left(E_9-E_1\right)=E_{hr,D}$
Re-heater	$Q_{rhr}*\left(\frac{\alpha}{\eta_{th}}-1\right)*\left(1-\frac{T_0}{T_r}\right)=E_{1,rhr}$
	$\frac{Q_{rhr}}{\eta_{th}}*\phi-E_{1,rhr}+\left(E_3-E_2\right)=E_{rhr,D}$
Cooler	$\left(E_{10}-E_5\right)-\left(E_{4a}-E_{1a}\right)=E_{cool\ D}$
Recuperator	$\left(E_4-E_{10}\right)-\left(E_9-E_6\right)=E_{rec\ D}$
ORC turbine	$\left(E_{1a}-E_{2a}\right)-W_{t1a}=E_{orc\ D}$
ORC condenser	$\left(E_{2b}-E_{3c}\right)-\left(E_{cw1}-E_{cw2}\right)=E_{cond\ D}$
ORC pump	$W_{p1}-\left(E_{4d}-E_{3c}\right)=E_{pump\ D}$
ORC evaporator	$\left(E_{10}-E_5\right)-\left(E_{4a}-E_{1a}\right)=E_{cool\ D}$

3.2.4. Perfformance Parameters

The energy efficiency is calculated as shown in below equations:

$$\eta_{sbc}=\frac{W_{sbc}}{Q_{sol}}$$
$$\eta_{orc}=\frac{W_{orc}}{Q_{orc}} \tag{32}$$
$$\eta_{over}=\frac{W_{sbc}+W_{orc}}{Q_{sbc}+Q_{orc}}$$

and the exergy efficiency is calculated as:

$$\eta_{sol-sbc}=\frac{W_{sbc}}{E_{sol}}$$
$$\eta_{bio-sbc}=\frac{W_{sbc}}{E_{bio}} \tag{33}$$
$$\eta_{over}=\frac{W_{sbc}+W_{orc}}{E_{sol}+E_{bio}}$$

4. Economic Modelling

Economic evaluation for a thermal plant usually involves using metrics such as the levelized cost of electricity (LCOE) because it offers a uniform means for assessing the expenses of different power production technologies and projects.

The LCOE considers both the amount of electricity produced by a power plant and the total cost of developing, running, and maintaining it over its lifetime. It compares the cost per unit of energy across various technologies and projects by dividing the overall cost by the total quantity of power produced.

By giving an estimate of the cost of energy during the plant's lifespan, which can be used to compare various technologies or projects, this study can assist in guiding investment decisions. The LCOE may assist investors and power plant designers in determining the most affordable and environmentally responsible ways to generate energy by taking into consideration things like fuel prices, investment costs, and environmental effects.

Overall, using economic analysis techniques like LCOE given by Eq. (34) and taken from [32] Making decisions about the investments in power plants is crucial since it ensures that the projects are long-term sustainable and economically feasible.

$$LCOE = \frac{NPV\ ENERGY}{NPV\ COST}$$
$$LCOE = \frac{C_1 + C_{OM} * 1.2\% + C_t}{H * P_e * i} \tag{34}$$

Here,

$C_1 = \left(C_{POWERBLOCK} + C_{TOWER\ AND\ RECEIVER} + C_{LAND}\right)$

$C_{POWERBLOCK}, C_{TOWER\ AND\ RECEIVER}$ and C_{LAND} $= investment\ in\ power\ block, heliostat, solar\ tower\ and\ receiver\ and\ land\ resp$

Cost of annual operation and maintenance for sCO_2 $system$ can be calculated by:

$C_{OM} = C_1 * \beta_{om}$ check these equations and explain terms used n= system life

5. Results and Discussion

5.1. Exergy destruction for the proposed system

The exergy destruction for the heater and re-heater is highest amongst all other components exergy destruction because the heat exergy transferred in this is highest, and sufficient heat transfer does not take place. Hence, it is important to take note for the above case as shown in Fig. 3.

5.2. Effect of recuperator vs temperature

The recuperator effect is the capacity of a heat exchanger to transfer heat from the hot fluid to the cool fluid. As the temperature differential between the hot and cold fluids increases, the recuperator effect decreases.

Table 7. Input parameters for cost analysis[32]

Annual power generation	2890.8MWhr
Capital expenditure	US$164 million
OML	1.2% of capital expenditure
Construction period	5 years
Lifespan	25 years
Discount rate	10%
Inflation	2%

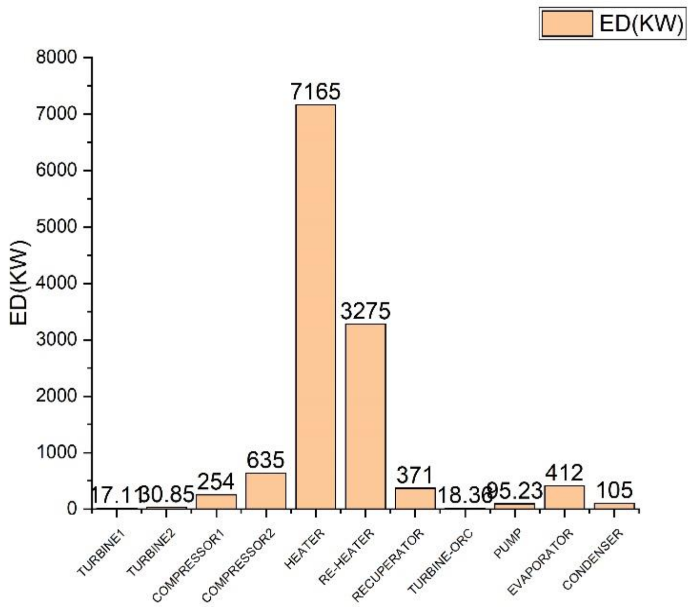

Fig. 3. Exergy destruction for various components

As can be shown Fig. 4, solar cases have a higher recuperation effect than solar and biomass cases combined. This can be explained by the fact that the rate of heat transmission decreases as temperature differences increase. This is true because the rate of heat transfer decreases according to the temperature difference between the two fluids and increases as the pushing force for heat transfer increases. However, the amount of heat provided by biomass is smaller in general. Another element influencing the decline in the recuperator effect is the fact that most materials lose thermal conductivity as temperature rises. This shows that the heat exchanger's ability to convey heat decreases as temperature rises.

At greater temperatures, the viscosity of the fluids may also change, which may affect their flow rate and heat transfer characteristics. As the temperature rises, these factors combine to lessen the recuperator effect.

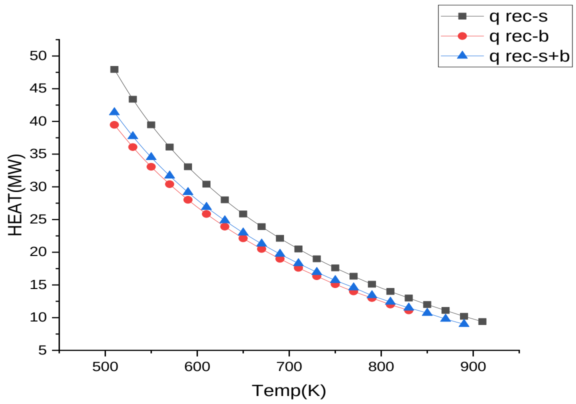

Fig. 4. Recuperator effect vs Temperature

5.3. Effect of work and efficiency vs pressure ratio

In this study's Fig. 5, solar energy produces the most heat, followed by biomass, and then the combined case. By increasing the pressure ratio, a gas turbine engine's efficiency may be increased.

The combustion temperature rises when the pressure ratio is raised, increasing the engine's thermal efficiency. As the pressure ratio increases, the compressor may squeeze more air into the same volume, increasing the mass flow rate through the engine. More fuel may be used as a result, boosting power output.

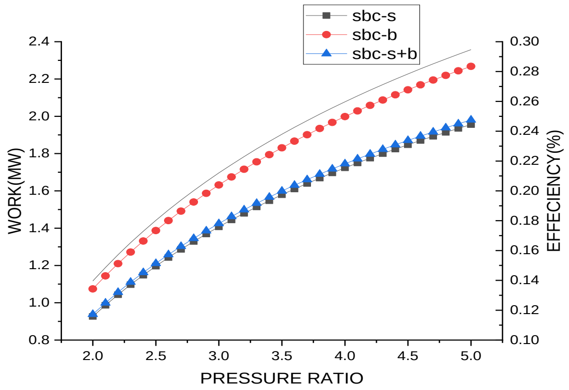

Fig. 5. work and efficiency vs pressure ratio-topping cycle

5.4. Effect of efficiency vs no of stages (turbines, compressors)

The effectiveness of compressors and turbines can be improved by adding more stages, as shown in Fig. 6. This is because a multi-stage design allows for a more consistent distribution of pressure and temperature across the stages, which can improve the device's overall performance. As the result demonstrates, efficiency naturally increases across the seasons.

A greater pressure ratio can be achieved by combining stages of a compressor, each of which is designed to lower air pressure by a particular percentage. As a result of the air being compressed more successfully, this increases engine performance and efficiency.

More energy may be captured from the hot gases that are expanding when stages are added to a turbine, which improves the efficiency of converting the fuel into mechanical energy.

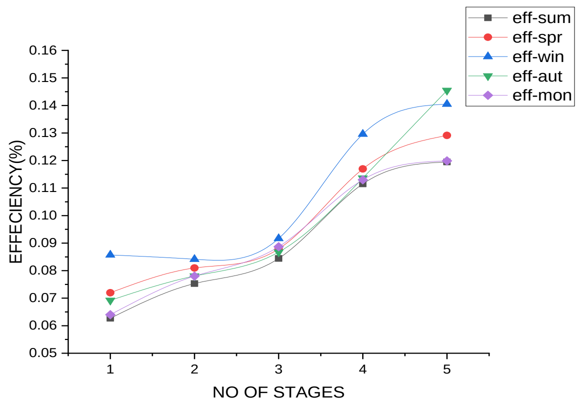

Fig. 6. Efficiency vs no of stages for compressor and turbine

5.5. Effect of average heat vs time for seasons

The quantity of heat absorbed by a surface is determined by various parameters, including surface area, surface reflectivity, and material specific heat capacity. Raising the DNI will increase the amount of solar radiation absorbed by the surface, as shown in Fig. 7, leading to an increase in the average heat received, assuming that these parameters stay constant. In this instance, spring is the season with the most heat, followed by winter, summer, and fall. As a result, this season will make the best use of the heat.

More solar energy is absorbed by the collector as the DNI rises, increasing the amount of heat produced. This might increase the solar collector's efficiency and generate more power.

The link between DNI and average heat received, however, is not necessarily linear, since other variables like the ambient temperature and wind speed may have an impact on the amount of heat received. Furthermore, practical constraints such as the capacity of the solar collector or the availability of sunlight may restrict how much DNI may be used.

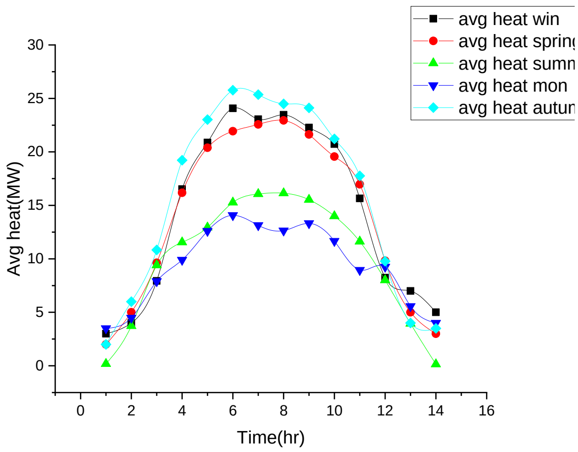

Fig. 7. Average heat received by solar radiation vs time for various seasons

5.6. Effect of exergy efficiency vs pressure

In general, as pressure increases, a system's exergy efficiency decreases Fig. 8. This is because raising the pressure might make the system more irreversible, which would decrease the amount of productive labour that could be produced. As with sunlight, there is a significant decrease in efficiency when compared to biomass.

One explanation for this is that raising the pressure may cause the system's temperature to rise, which would result in more waste heat being produced by the system. The energy efficiency of the system is decreased since this waste heat reflects energy that cannot be converted into useful work.

The amount of work necessary to transport fluids or gases through the system might increase as pressure is increased, since it can also increase the resistance to flow in the system. This work represents energy lost as a result of system irreversibility, which affects exergy efficiency.

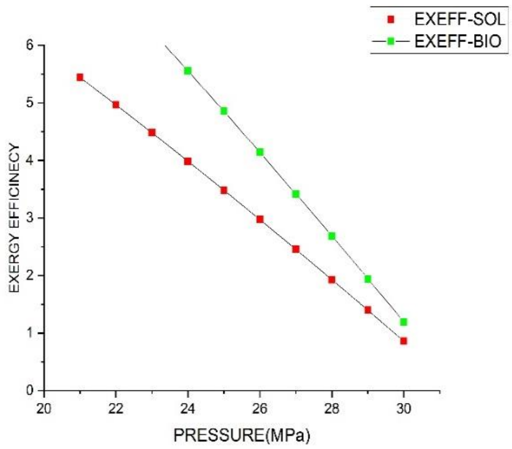

Fig. 8. Variation of exergy efficiency vs pressure

5.7. Effect of exergy efficiency vs compressor efficiency

For this case the exergetic efficiency of biomass is more in comparison to solar case this is due to because system's exergy efficiency is a measure of the usable work that can be obtained from it as shown in Fig. 9, in comparison to the greatest work that could be obtained from the same amount of energy in an idealised reference environment. The compressor is crucial to the energy conversion process because it increases the amount of energy available by compressing the fluid or gas to a higher pressure and temperature.

Less energy is lost during the compression process thanks to a more effective compressor, which also means that less waste heat is generated. Waste heat reduces the system's energy efficiency since it reflects energy that cannot be put to use.

A more effective compressor can also provide higher pressure and temperature at the exit, which results in more energy being available for use in downstream processes. This can enhance the amount of productive work that can be obtained while also improving the system's exergy efficiency.

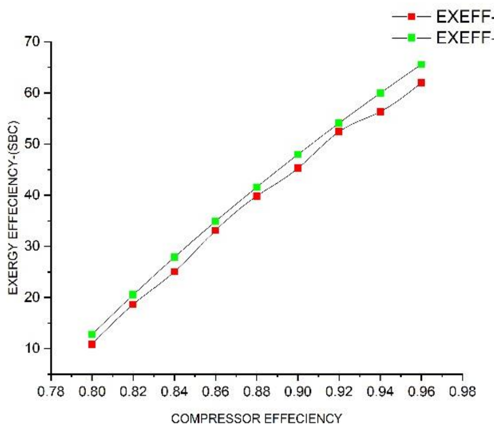

Fig. 9. Variation of exergy efficiency vs compressor efficiency

5.8. Effect of exergy efficiency vs turbine efficiency

Due to the above case study for compressor efficiency in Fig. 10 The same inference can be brought to turbine efficiency because a more efficient turbine can extract more mechanical energy from the fluid or gas, less energy is lost as waste heat during the expansion process. Waste heat reduces the system's energy efficiency since it reflects energy that cannot be put to use.

In addition, a more effective turbine may work at lower exhaust pressure and temperature, which would release more energy for use in processes farther down the line. This can increase the quantity of work that can be done productively while simultaneously enhancing the system's energy efficiency.

It should be emphasised, nevertheless, that the relationship between energy efficiency and turbine efficiency is not always clear-cut and depends on the particular system and its operating conditions. Other elements, such as compressor efficiency or heat source temperature and pressure, can all have an impact on the system's exergy efficiency.

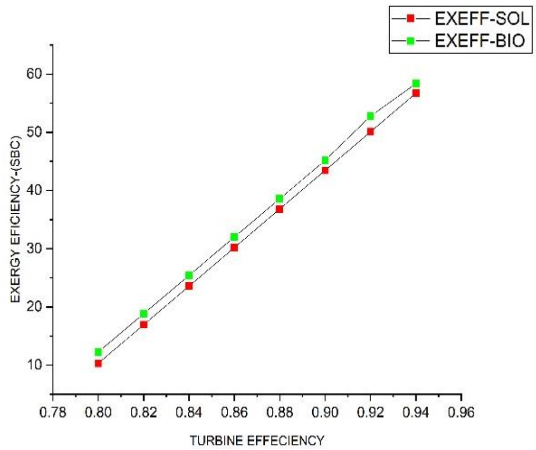

Fig. 10. Variation of exergy efficiency vs turbine efficiency

5.9. Effect of exergy efficiency vs time for different seasons:

With Direct Normal Irradiance (DNI), the exergy efficiency of a system might vary depending on the season, as shown in Fig. 11. The amount of solar radiation received per unit area and per unit time is measured by the DNI, which is typically highest in the summer and lowest in the winter. The highest is seen within this, followed by the monsoon and spring. This suggests that it is preferable to make the most of the heat that is available during this season.

The energy efficiency of a solar energy system, such as a solar thermal power plant or a photovoltaic system, is influenced by the quantity and quality of solar radiation that is available. During the summer, when DNI is maximum, the solar energy system is projected to be more efficient and capable of converting more of the available solar radiation into usable energy. As a result, seasonal fluctuations in DNI must be taken into account when developing and running solar energy systems in order to optimise performance and maximise exergy efficiency.

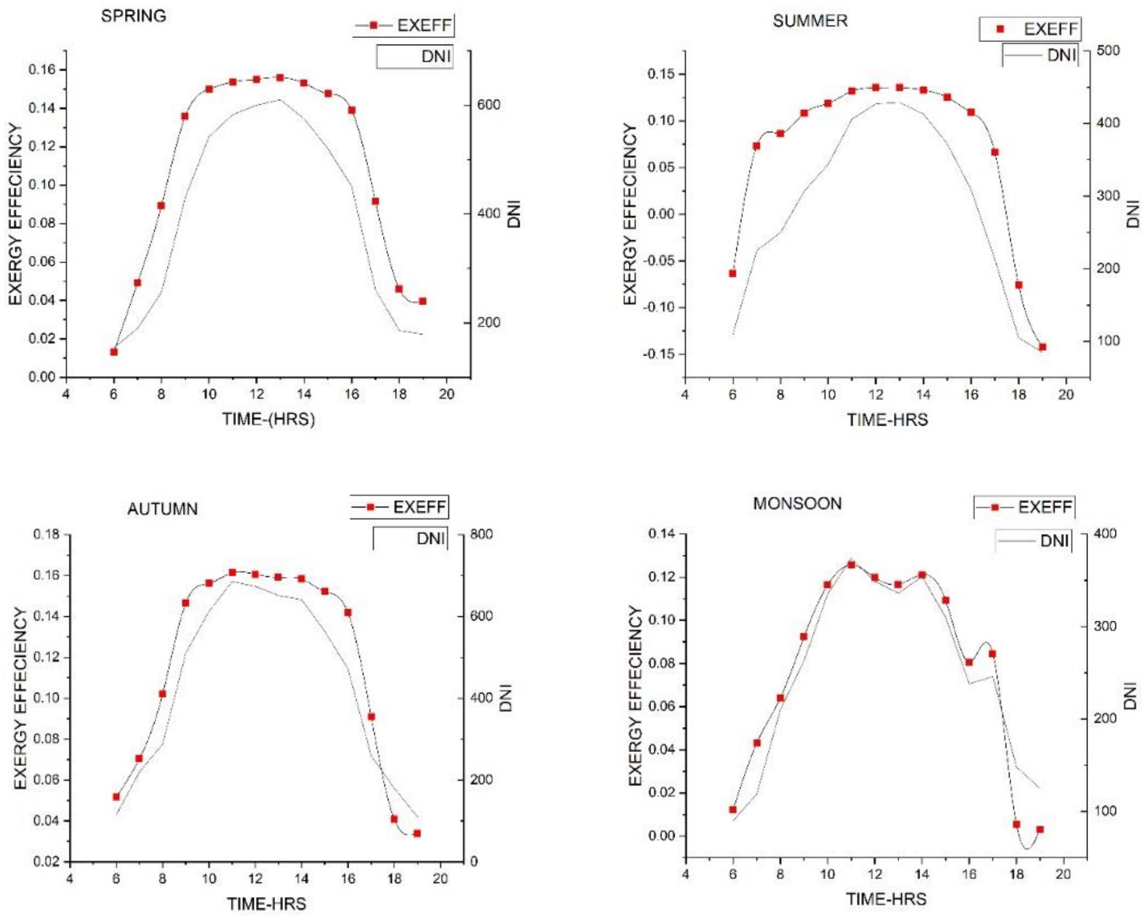

Fig. 11. Exergy efficiency and DNI vs time for different seasons

5.10. Effect of network in ORC vs approach temperature

With increasing approach temperature, the power output of an Organic Rankine Cycle (ORC) drops. The approach temperature, a crucial factor in the design of the ORC system, is the difference between the temperature of the working fluid at the evaporator output and the temperature of the heat source. According to the study mentioned above, R245fa produces the least amount of heat, while iso-butane produces the most work at low approach temperatures, as shown in Fig. 12.

As the temperature of the approach increases, the temperature difference between the heat source and the working fluid reduces, which lowers the rate of heat transfer and lowers the power output of the ORC. This implies that the ORC network, or the quantity of energy that can be converted into usable work, diminishes as the approach temperature increases. In addition to decreasing system efficiency, raising the approach temperature may increase the thermal loads on the ORC components. The reason for this is that when the working fluid temperature increases, the cycle's thermodynamic efficiency decreases and the temperature at which the ORC components operate increases in Fig. 13.

In order to balance the trade-off between power generation and system efficiency and maximise the approach temperature, careful design of the ORC system is necessary. This may entail choosing a working fluid with an appropriate boiling point and thermodynamic properties, optimising the heat exchanger design, and managing the ORC operating parameters to keep the approach temperature within a suitable range.

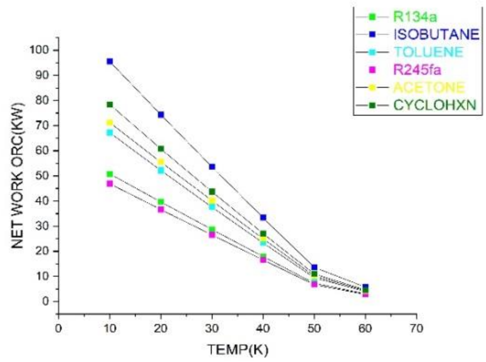

Fig. 12. Network of ORC vs Approach temperature

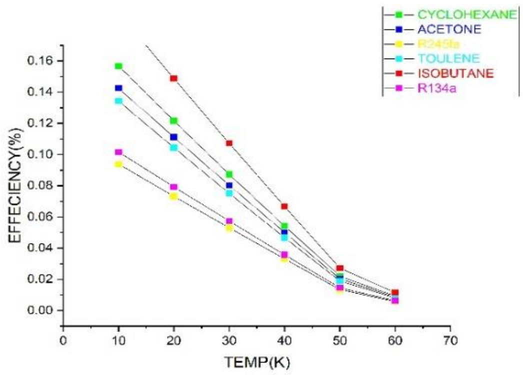

Fig. 13. Efficiency vs Approach temperature

5.11. Effect of exergy destruction vs turbine inlet temperature

Exergy destruction in a gas turbine cycle increases as turbine inlet temperature rises. This is because the thermodynamic efficiency of the cycle, which in turn affects how much irreversibility or energy destruction occurs throughout the energy conversion process, is directly influenced by the temperature of the turbine inlet, as shown in Fig. 14. The energy destruction in the biomass example is lower, making it a more efficient cycle than the solar one.

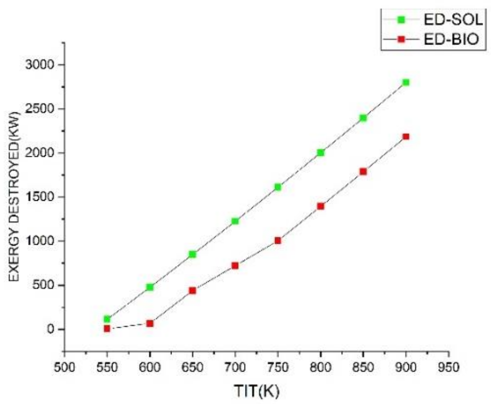

Fig. 14. Exergy destroyed vs turbine inlet temperature

A greater cycle's thermodynamic efficiency is the consequence of the working fluid's ability to transfer more thermal energy into mechanical work at higher turbine inlet temperatures. The rate of irreversibility or exergy destruction inside the cycle, as is shown in the case of solar-powered cycles, increases as the temperature rises, as does the temperature differential between the working fluid and its surroundings.

Exergy deterioration can be caused by pressure decrease, fluid friction, irreversible heat transfer, and other factors. As the temperature differential widens, these effects intensify, leading to a quicker rate of energy destruction as the input temperature of the turbine rises.

As a result, it is crucial to balance exergy destruction with thermodynamic efficiency while designing and running gas turbine cycles. This could include employing innovative materials and cooling techniques to reduce thermal stresses on turbine components and optimising operating conditions to minimise exergy destruction while maintaining high thermodynamic efficiency.

5.12. Effect of exergy destroyed vs pressure

Exergy destruction in a thermodynamic system increases with pressure increase, especially if the pressure increase is paired with a temperature increase. This is due to the fact that a rise in pressure typically generates a rise in thermodynamic irreversibility, which results in more energy being destroyed in the system. As a result, in Fig. 15, it can once again be shown that the biomass example is more efficient than the solar case in this instance.

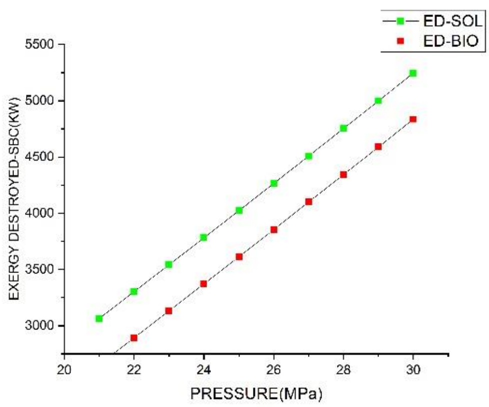

Fig. 15. Exergy destruction vs pressure

One of the main causes of exergy deterioration as pressure increases is pressure drops, which happen as a result of fluid friction when the working fluid flows through the different parts of the system. When pressure is reduced, less work is produced and more entropy is created, which accelerates the pace at which energy is destroyed.

As a result, it is critical to carefully evaluate the relationship between pressure and exergy destruction when developing and operating thermodynamic systems, and to manage the trade-off between achieving desired performance goals and minimizing exergy destruction.

5.13. Work and efficiency variations with turbine temperature for ORC cycle

The effect of turbine inlet temperature on an Organic Rankine Cycle (ORC) network and efficiency might vary based on the working fluid utilised in the cycle as shown in Fig. 16. Increasing the temperature of the turbine's intake generally enhances cycle performance by increasing network and thermodynamic efficiency.

The key finding in this study is that the majority of the work is produced by fluids like iso-butane, cyclo-hexane, and acetone within a fixed range of temperatures for all the working fluids for ORC that were put to the test.

The unique characteristics of the working fluid, such as boiling point, critical temperature, and thermal stability, dictate the impact of turbine input temperature on the ORC cycle. In some circumstances, increasing the turbine inlet temperature can improve efficiency and network performance; however, in others, it can reduce performance due to limits in the working fluid parameters.

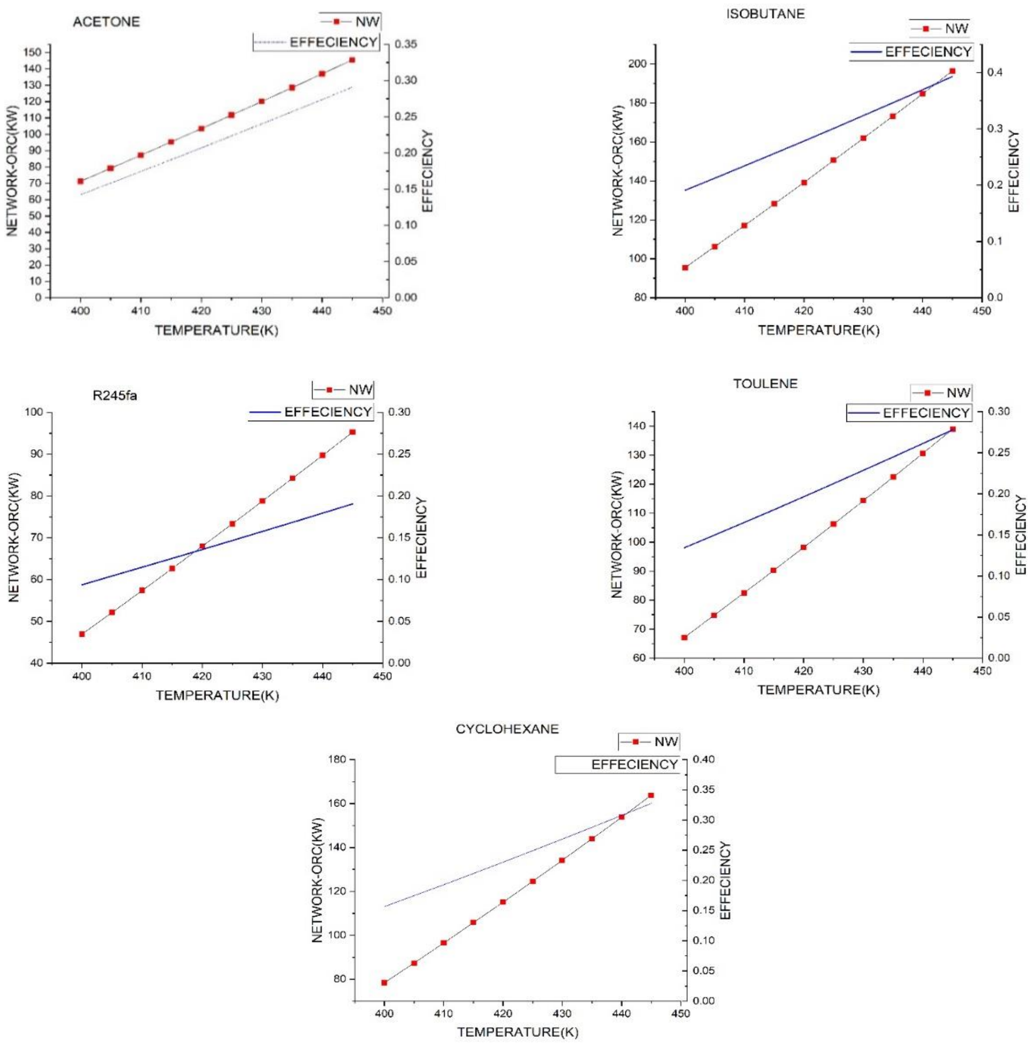

Fig. 16. Network and efficiency vs temperature for various ORC working fluid

5.14. Effect of exergy destruction vs turbine and compressor efficiency

Exergy destruction often reduces as compressor efficiency increases, as shown in Fig. 16. This is because one of the most important parts of a thermodynamic cycle for converting energy is the compressor, and the compressor's effectiveness directly impacts how much energy is wasted during compression.

Exergy destruction indicates that while exergy destruction is present in both the turbine and compressor efficiency situations in the solar scenario, less of this efficiency value should be taken into account for the process, as it would improve cycle efficiency.

The quantity of irreversibility that occurs during the conversion of energy in a thermodynamic cycle is measured by exergy destruction. As a result of irreversible thermodynamic events such as fluid friction and heat transfer losses, it refers to the quantity of energy that is lost or destroyed. Entropy growth throughout the system as a whole, which rises as component efficiency falls, is strongly related to exergy destruction.

Less energy is wasted during compression with a better compressor efficiency, which reduces the system's energy destruction and entropy growth. Because a more efficient compressor can compress the working fluid with less energy input, it has lower thermodynamic irreversibility and loses less energy as waste heat.

5.15. Effect of thermal energy storage system with time based on storage capacity

Here, in this case study, it is observed that more amount of heat can be stored from a biomass source. However, by making the inlet temperature higher the storage capacity can be increased, hence allowing to storage more energy. But through analysis, it is observed in Fig. 19. that energy storage through biomass is more efficient and provides more energy.

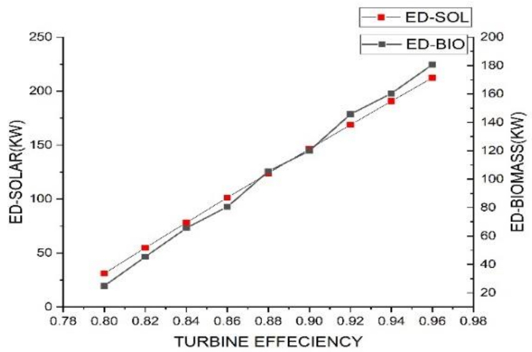

Fig. 17. Variation of exergy destruction vs turbine efficiency

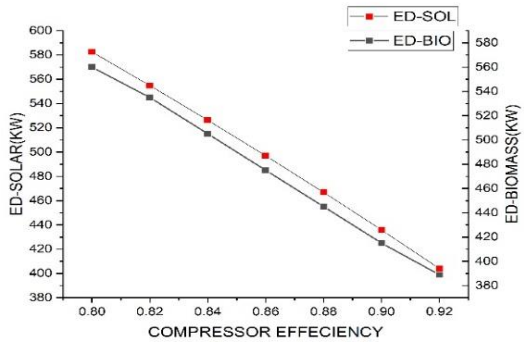

Fig. 18. Variation of exergy destruction vs compressor efficiency

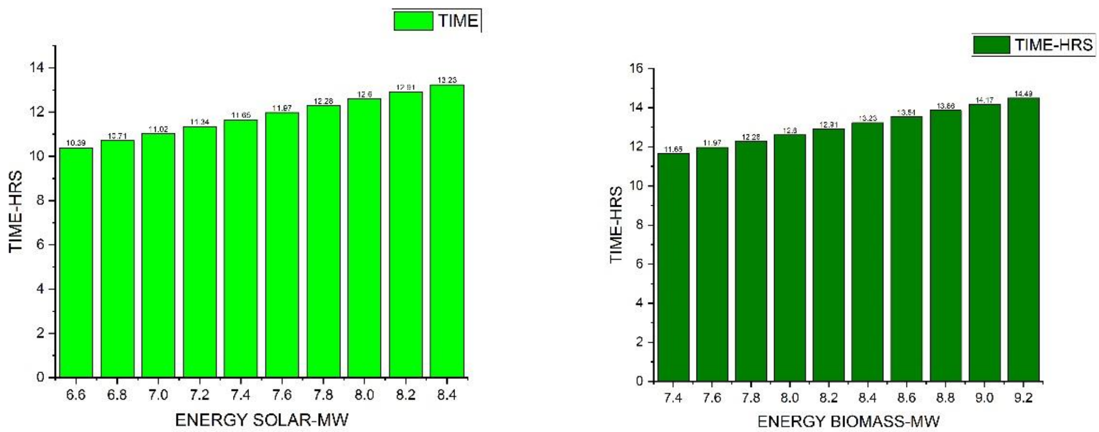

Fig. 19. TES vs energy available from the two renewable sources

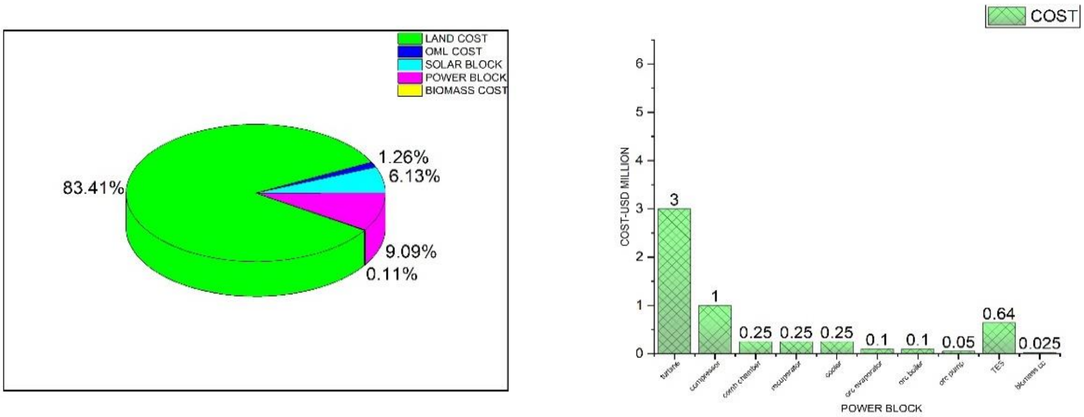

Fig. 20. Cost breakdown of various components

5.16. Comparison of cost for different components within a system

In my cost analysis, as shown in Fig. 20 it is calculated that most amount of cost is acquired by land followed by power block components. Hence, overall, the cost analysis for the power block can further be subdivided and here in this case, the maximum amount of energy is allocated to the turbine and compressor. Acquisition of this component is costly, but if invested for a time investment, it can greatly enhance the economic condition and its dependency on coal-based energy reserves in coming future.

6. Conclusions

The solar and biomass example, which has the highest energy efficiency of the cases examined, has an energy efficiency of 22.32%, according to the examination of the various renewable energy sources. The ORC instance, on the other hand, has a greater exergy efficiency of 12.5% but a lower total efficiency. The total LCOE is $8.42 kW/hr, suggesting a cost for energy generation. The findings generally indicate that there is still room for improvement in the effectiveness of producing renewable energy, and further research is required to examine the potential of various energy sources to meet the rising need for energy while minimizing environmental impact.

Additionally, a trade-off between energy and energy efficiency is evident when comparing the various renewable energy sources. A large quantity of energy is likely lost during the conversion process, even if certain examples have great energy efficiency. Other examples, however, have better energy efficiency, demonstrating a more effective energy conversion process, although their energy efficiency is significantly lower.

Notably, the ORC scenario exhibits the best energy efficiency, indicating that this technology may be further investigated as a means of enhancing the effectiveness of energy conversion. Additionally, the LCOE study implies that in order for renewable energy to be more competitive with conventional energy sources, the cost of production must be decreased.

The study's findings demonstrate the need of continuing to continue studying and develop renewable energy technologies in order to raise their effectiveness and lower their production costs. By accelerating the transition to a more sustainable energy system, these initiatives would help lower greenhouse gas emissions and lessen the effects of climate change.

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