Thermodynamic and financial assessment of concentrated solar power plant hybridized with biomass-based organic Rankine cycle, thermal energy storage, hot springs and CO₂ capture systems

Suresh Baral*
School of Engineering, Pokhara University, Pokhara-30, Dhunepatan, Kaski, Nepal

Abstract
The present study aims to investigate the thermodynamic and financial aspect of concentrated solar power (CSP) plant hybridized with biomass-based organic Rankine cycle (ORC), thermal energy storage (TES), hot springs and CO₂ capture systems. The organic working fluids namely R123, R235fa, D4 and MDM are selected for designing the hybrid system at different operating conditions. The nominal power capacities of the CSP and biomass ORC plants are 1.3 MW and 730 kW respectively. Additionally, a parametric study has been carried out to understand the influencing parameters that affect the system’s performance. From the results, it is revealed that the biomass ORC plant with a hot spring system alone can develop a power of 720 and 640 kW for D4 and MDM respectively. Furthermore, the power generation can be increased with addition of TES in the CSP plant. From the economic point of view, the hybrid system with special focus on CO₂ capture could be very profitable if the levelized cost of electricity (LCOE) is fixed at 0.24$/kWh. In this scenario, the payback period is 8 years with an internal rate of return (IRR) more than 8%. Therefore, the hybrid system is thermodynamically and financially attractive for dispatchable electricity.

Keywords: biomass ORC; hot springs; CO₂ capture; TES; power generation; financial assessment

1 INTRODUCTION
Concentrating solar power (CSP) plants are the most promising technologies for utilizing the solar energy potential worldwide today. The annual world energy consumption is only one-third of the solar energy falling on the earth [1]. The renewable energy utilization through CSP technology leads to production of cleaner power generation, thereby reducing emissions and dependency on usage of polluting fossil fuels [2]. The concept for power production from the technology had been established a few decades ago. It needs significant financial investment, human resources and materials for development and operation of each conventional power plant. Besides, hybridizing is now essential for efficiency improvement or retrofitting of the existing system. The potential viability for integrating CSP systems has great advantages and is an attractive way for reduction in capital costs, operation and maintenance costs and environmental issues relating with CO₂ emission [3–4]. Furthermore, CSP plants have a large number of benefits but the solar energy is intermittent so there is no power generation during cloudy days and night time. In order to match the power requirements for the end users, the CSP plants should be hybridized with other renewable energy source technology such as biomass, geothermal, waste heat and thermal energy storage systems [5].

In this context, various authors have described a variety of configurations for hybridizing the solar energy source plants for a stable and robust supply of power generation. Among them, the biomass-fired plants with organic Rankine cycle (ORC) have been discussed in several literatures. The most commonly used solar technologies include solar towers, flat and evacuated tubular solar collectors, concentrated solar power plant and parabolic trough solar collectors for the hybrid configuration with biomass-driven
plants [6–7]. The biomass feedstock can be used as supplementary fuel for achieving the constant load when needed. Literature regarding the hybrid configuration on solar and biomass-powered plants has been reported by various authors.

Francesco et al. [8] designed a hybrid system which consists of a compound parabolic trough solar collector, LiBr-H₂O absorption chiller and vegetable oil fed reciprocating engine. It was concluded that the hybrid system can be very profitable for some EU countries with a payback period of 5 years. Sahoo et al. [9] investigated the polygeneration system which contains solar and biomass systems to produce steam and later with the vapor absorption refrigeration system for cooling. The hybrid system could save primary energy up to 15.3%. Karella and Braimakis [10] analyzed a tri-generation ORC-VCC hybrid system powered by biomass and solar and reported that nominal and exergetic efficiencies were 5.54 and 7.56% respectively with a payback period of 7 years and solar and reported that nominal and exergetic efficiencies were 5.54 and 7.56% respectively with a payback period of 7 years and IRR to be 21.77%, respectively, and the payback period was 5.13 years with IRR 21.26%. Kasra et al. [11] proposed a solar-driven biomass gasification hybrid system for electrical and methanol production along with thermodynamic and economic assessment. The results indicated the highest energy and exergy efficiency of the proposed polygeneration system achieved to 56.09 and 54.86%, respectively.

Similarly, Joseph et al. [12] showed an advanced exergoeconomic method for the hybrid solar biomass ORC cogeneration plant. The results suggested that more than 50% of the total irreversibility rates can be avoided and economic losses in ORC plant were more endogenous. Sorn et al. [13] investigated the performance of a 10-kW ORC hybrid plant where the heat source was generated by a biomass boiler for the R245fa working fluid. The simulation results revealed that the unit costs of power generation of the system were 0.104 and 0.098 $/kWh for solar-assisted and non-solar-assisted heat sources, respectively.

Likewise, Joseph et al. [14] developed the optimization model for the thermo-economic assessment of a solar ORC plant retrofitted by a biomass unit plant. The analysis showed that 0.133 kg/s of biomass of 57€/hr was the optimal value for the biomass retrofit scheme.

In another study conducted by Patel et al. [15], a solar-biomass ORC plant powered by a cascaded vapor compression–absorption system for cooling applications had been proposed and analyzed. A fully powered biomass system was economically profitable as compared to a solar-biomass system which had a payback period of 5.4 and 7.71 years, respectively. Antonio et al. [16] presented thermodynamic and economic assessment of a hybrid solar-biomass configuration system which consists of externally fired gas turbine powered by wood chips and a bottoming ORC plant in the Mediterranean area. The result showed that a dedicated subsidy framework should be implied for the hybridization configuration due to high investment costs. The LCOE was proposed to be 140 €/MWh and with 15% IRR based on Italian tariffs.

Furthermore, Bellos et al. [17] designed and presented a poly-generation system that consists of solar and biomass plants. The study found that exergy and energy efficiency were 51.26 and 21.77%, respectively, and the payback period was 5.13 years with IRR 21.26%. Kasra et al. [18] reviewed different aspects of hybrid solar-powered polygeneration systems and presented the development of a hybridization technique along with the applications and potential benefits. Besides, the article suggested designing prototypes and test rigs for experimental assessment for different types of hybridization configuration. Khalid et al. [19] demonstrated that the integration of thermal energy storage and natural gas with the CSP plant would regulate the power production during the daytime, but the levelized cost of electricity was higher as compared to single natural gas. The LCOE was 0.086$/kWh for the hybrid system.

Joseph et al. [20] studied techno-economics for siloxane mixtures for improvement in net power and exergy efficiency. The study concluded that the mixtures could increase the net power by 2%. Yilin et al. [21] assessed the thermodynamic and thermo-economic viewpoint for the biomass-based ORC system hybridized with CO₂ capture systems. Monoethanolamine (MEA)-based CO₂ capture was designed in the biomass ORC system for feasibility analysis with eleven working substances.

Regardless of the various configurations of solar-biomass plants that had been previously reported, the studies on the CSP plant hybridized with biomass ORC, thermal energy storage, hot springs and CO₂ capture has not been given sufficient attention. The primary goal of this study was for improvement of performance of a hybrid system by assessing thermodynamically and technoeconomically. In order to achieve this goal, the following steps were performed.

- Developed the model and simulated the hybrid system
- Assessed the operating parameters that influence the system’s performance
- Determined the economic feasibility of the hybrid system which included levelized cost of electricity (LCOE), payback period, internal rate of return and sensitivity analysis

2 SYSTEM DESCRIPTION

Figure 1 demonstrates a CSP plant hybridized with thermal energy storage, biomass ORC, hot springs and CO₂ capture systems. The CSP plant with thermal energy storage (TES) systems can be used for prolonging power generation even in sunsets. Furthermore, when thermal oil provided by a solar field could not maintain the demand of power generation, TES could act as an additional source of heat for the regular power supply. TES can also be used as a heat source for the biomass ORC system. Besides, the hot springs from the geothermal source can be used as a heat source for the ORC system. The innovative aspect of this configuration is the hybridization of the biomass ORC system with TES and hot springs that can be alternatively used as a heat source. In addition, the MEA-based chemical absorption system for the CO₂ capture system is integrated for combustive gas produced from the burning of biomass (wood pellet).

In the present study, the hybrid system has been designed for a power capacity of 1.3 MW when the solar insolation is around 800 W/m². In this system, the CSP plant is designed to heat the
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Figure 1. Schematic diagram of a hybrid system.

Figure 2. T–s diagrams for the selected working fluids in the hybrid system.
The properties such as high latent heat, low specific heat and high density are appropriate for the ORC systems. These selected compounds have higher latent heats which provide higher unit work output during the expansion process in the hybrid system. Another advantage is that it can provide the same power outputs with the small-sized plant. Also, the critical temperatures of those working substances are lower as compared to others. Table 1 shows the detailed characteristics of the organic fluids that have been investigated for biomass ORC plant with TES and hot springs. The system can be modified or retrofitted after several years of operations from the CSP plant to the solar-biomass ORC plant. In the biomass ORC system, the working fluids are subjected to a maximum temperature of 720 and 410 K for R123 and MDM, respectively. In addition, it is assumed that the biomass furnace can produce almost half of the thermal energy for running the ORC plant as an input [23]. Lastly, the hybrid plant consists of a CO₂ capture system for detaining CO₂ from the biomass ORC plants so that it is not released to the environment. This CO₂ gas is then captured by chemical absorption known as monoethanolamine (MEA) which is commonly used as a solvent.

### 3 MATERIALS AND METHODS

#### 3.1 Thermodynamic modeling

In the thermodynamic analysis of the hybrid system, the preliminary step is to calculate the unknown parameters such as temperature, pressure, entropy, enthalpy and quality for each state in the system. These crucial parameters are not easily defined unless thermodynamic modeling is carried out. For this, it is important to model the components of the hybrid system by commercial software. The approach of the modeling the hybrid system in the present article is conducted by Engineering Equation Solver (EES) software. The energy and mass balance equations are the most fundamental governing expression for the thermodynamic assessment of the hybrid system. For modeling, each sub-system is taken as one block and the EES evaluates the performance of the systems. The outputs of the each model are combined to evaluate the net power output, thermal efficiency, overall efficiency, mass flow rate and shaft power. The thermodynamic behaviors in the performance of the hybrid system are also assessed by changing the thermodynamic parameters. The flowchart for the estimation of the various thermodynamic and economic parameters is shown in Figure 3.
The required governing expressions for the assessment of the system are summarized in Table 2. The TES tank acts as a heat source for both cases (CSP and ORC plant). The biomass ORC plant is designed to operate for 10 h per day with TES and hot springs. Typically, the hot spring temperature found was around 343 K. The major locations of hot springs in Nepal are Bhurung Tatopani, Sadhu Khola and Srinagar with solar insolation around 600 W/m² on average [29–30]. The time of operation during the year is 7680 h. The annual energy production is estimated based on this assumption. The main design parameters used in this study are summarized in Table 3. The TES tank acts as a heat source for both CSP and ORC plant. The biomass ORC plant is designed to operate for 10 h per day with TES and hot springs. Typically, the hot spring temperature found was around 343 K. The major locations of hot springs in Nepal are Bhurung Tatopani, Sadhu Khola and Srinagar with solar insolation around 600 W/m² on average [29–30]. The time of operation during the year is 7680 h. The annual energy production is estimated based on this assumption. The main design parameters used in this study are summarized in Table 3. The TES tank acts as a heat source for both CSP and ORC plant. The biomass ORC plant is designed to operate for 10 h per day with TES and hot springs. Typically, the hot spring temperature found was around 343 K. The major locations of hot springs in Nepal are Bhurung Tatopani, Sadhu Khola and Srinagar with solar insolation around 600 W/m² on average [29–30]. The time of operation during the year is 7680 h. The annual energy production is estimated based on this assumption. The main design parameters used in this study are summarized in Table 3. The TES tank acts as a heat source for both CSP and ORC plant. The biomass ORC plant is designed to operate for 10 h per day with TES and hot springs. Typically, the hot spring temperature found was around 343 K. The major locations of hot springs in Nepal are Bhurung Tatopani, Sadhu Khola and Srinagar with solar insolation around 600 W/m² on average [29–30]. The time of operation during the year is 7680 h. The annual energy production is estimated based on this assumption. The main design parameters used in this study are summarized in Table 3. The TES tank acts as a heat source for both CSP and ORC plant. The biomass ORC plant is designed to operate for 10 h per day with TES and hot springs. Typically, the hot spring temperature found was around 343 K. The major locations of hot springs in Nepal are Bhurung Tatopani, Sadhu Khola and Srinagar with solar insolation around 600 W/m² on average [29–30]. The time of operation during the year is 7680 h. The annual energy production is estimated based on this assumption. The main design parameters used in this study are summarized in Table 3. The TES tank acts as a heat source for both CSP and ORC plant. The biomass ORC plant is designed to operate for 10 h per day with TES and hot springs. Typically, the hot spring temperature found was around 343 K. The major locations of hot springs in Nepal are Bhurung Tatopani, Sadhu Khola and Srinagar with solar insolation around 600 W/m² on average [29–30]. The time of operation during the year is 7680 h. The annual energy production is estimated based on this assumption. The main design parameters used in this study are summarized in Table 3.
Figure 4. Comparison of heat input for various biomass fuel for the ORC system.

Figure 5. Effect of HTF on solar plant and overall efficiency.

where *n* is the system lifetime, *C_c* is the capital cost of the hybrid system, *O_c* is denoted as the operational cost, *i* is the interest rate and *P_e* is the electrical power generated in the year `t`.

4 RESULTS AND DISCUSSION

From the developed mathematical model, the detailed parameter was estimated based on operating pressure of 10 bar for all the sub-system in the hybrid system. The power output and thermal efficiency for all the organic fluids are shown in Table 4.

Based on the simulated efficiency of the hybrid system, the heat input for the various types of biomass fuel used in the ORC system has been evaluated. In Figure 4, the highest heat input is obtained from cypress biomass fuel where the working fluid is R123. In this case, the maximum heat input is 6 MW for generation of 730 kW of power output. The biomass fuel has been selected on the basis of reference [32].

4.1 Analysis on the CSP plant

In order to assess the performance of the hybrid system, various parameters such as solar irradiance, HTF and efficiencies were taken into consideration. The effect of HTF on the plant efficiency is shown in Figure 5.

Here, when the HTF temperature is 650 K, then the solar plant and overall system’s efficiencies are 41 and 35.8%, respectively. It is worth noting that changes in temperature of HTF results in changes in efficiency.
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Figure 6. Effect of solar heat input and mechanical work with change in collector area.

Figure 6 illustrates that the solar heat input and net mechanical work depend on the solar collector area. The larger the size of the solar collector, the more heat is gained which in turn produces more mechanical power. For producing the mechanical power of 1.2 MW, the area of the solar collector requires 5500 m$^2$ and 5.4 MW of heat input.

Similarly, Figure 7 indicates that solar insolation is one of the important factors for heat input and power output. Normally, an average of 800 W/m$^2$ solar insolation could produce 1 MW power output with 3 MW heat input.

4.2 Analysis on biomass ORC plant with TES and hot springs

The performance of the biomass ORC plant hybridized with TES and hot springs is presented in this section. The main investigating parameters were evaporating and condensing temperature for the working fluids in assessing the performance of the system. The four working fluids namely R123 and R245fa (TES), D4 and MDM (hot springs) were used in the biomass ORC system. These organic working fluids were subjected to a maximum temperature of 723 K. The thermal efficiency of the
biomass ORC plant with TES varies as HTF temperature changes. It is seen in Figure 8 that an HTF temperature of 600 K has an efficiency of 17.5 and 16.2% for R123 and R245fa, respectively. The thermal stability limitation for these compounds is around 623–673 K.

Figure 9 describes the effect of condensing temperature on mass flow rate and shaft power. When the condensing temperature decreases, the shaft power increases. In order to provide more shaft work, the mass flow rate should be increased. The increased flow rate yields more heat energy for developing more torque in the expander. At 290 K, 710 and 800 kW shaft power has been developed with 8 and 11 kg/s for R123 and R245fa working fluids, respectively.

Similarly, for the ORC plant with hot springs, the working fluids namely D4 and MDM behave in the same trend as that of R123 and R245fa. When there is increase in evaporating temperature, there is increase in shaft power and thermal efficiency. In Figures 10 and 11, the maximum shaft power and thermal efficiency at temperature of 410 K are 420 kW and 11.8% and 390 kW 11% for D4 and MDM, respectively.
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The main reason for the increment in shaft power is the same amount of heat exchanges in the heat exchanger (evaporator) from the evaporation of working fluids. A higher evaporating temperature increases the drop in enthalpy in turbine and results in an increase in thermal efficiency. Likewise, the condensing temperature in the biomass ORC plant plays a crucial role in the power generation as well as in the system’s efficiency. The lower the condensing temperature, the higher is the shaft power developed and thermal efficiency.

Figures 12 and 13 show a clear profile of increment in both shaft power and thermal efficiency for two different working fluids. The thermal efficiency and shaft power output are 16.5% and 560 kW for MDM when the condensing temperature is 280 K. Similarly, for D4, the shaft power output varies from 360 to 210 kW when the condensing temperature changes from 280 to 315 K. It implies that the biomass ORC turbine backpressure rises as the condensing temperature increases. Therefore, the power output of the ORC declines and so does the thermal efficiency.
4.3 Financial assessment of the hybrid system
The yearly performance of the system is evaluated by using meteorological data on the particular location of investigation. Based on the data, the expected power production from the CSP plant with and without TES during a year is calculated. Besides, the most important financial parameter is electric power generation for all the four cases. LCOE was taken into consideration for financial evaluation over the plant life, i.e., 20 years. The operating hours of the hybrid system is assumed to be 320 days in a year. The larger the solar collector area, the longer is the duration of the storage system which eventually minimizes the LCOE.

The component-wise cost of the hybrid system is shown in Figure 14. Here, the majority of cost is occupied by a CSP plant which is 76% of the total investment followed by the biomass ORC plant and CO\textsubscript{2} capture system.

Table 5 shows the detail breakdown of costs of the hybrid system including the CO\textsubscript{2} capture system. The economic assessment of the hybrid system helps to determine how the financial change

Figure 12. Effect of condensing temperature on shaft power and thermal efficiency (D4).

Figure 13. Effect of condensing temperature on shaft power and thermal efficiency (MDM).
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Table 5. Total components wise cost for the hybrid system [19, 21, 29].

| Concentrating solar plant system               | Economic life (years) |
|-----------------------------------------------|-----------------------|
| Solar field (collector) & piping              | 480 000               | 20        |
| Thermal energy storage & molten salt          | 600 000               | 20        |
| Balance of plant                              | 110 000               | 20        |
| Heat transfer fluid                           | 1 600 000             |           |
| Components cost of Rankine cycle plant        | 1 050 000             | 20        |
| Maintenance & operation (annually)            | 157 400               |           |
| Insurance cost (annually)                     | 60350                 |           |
| Civil engineering cost                        | 3 388 500             |           |
| Area cost (land)                              | 444 350               | 20        |
| Contingency and other cost                    | 225 900               |           |
| Total CSP plant capital cost ($)              | 8 116 500             |           |

Biomass-based ORC system Economic life (years)

| Thermal oil for boiler                        | 420 000               | 20        |
| Working fluid for operation                  | 180 000               | 20        |
| Cost of plant installation                   | 60 000                |           |
| Complete ORC system                          | 780 000               | 20        |
| Electrical activities                         | 90 000                |           |
| Maintenance & operation (annually)            | 31500                 |           |
| Insurance cost (annually)                     | 2100                  |           |
| Control system                               | 60 000                | 20        |
| Contingency and other                         | 300 000               |           |
| Building works (civil)                        | 210000                |           |
| Total biomass ORC capital cost ($)            | 2 133 600             |           |

Hot spring system Economic life (years)

| Storage system                                | 3500                  | 20        |
| Pumping system                                | 6500                  | 20        |
| Piping system                                 | 3000                  | 20        |
| Total hot spring system capital cost ($)      | 13 000                |           |

CO2 capture system Economic life (years)

| Cost of amine-based CO2 capture system for 700 kW ($) | 454 580 | 20 |
| Maintenance & operation (annually)                  | 9090   |   |
| Insurance cost (annually)                            | 450    |   |
| Total cost of CO2 capture system                    | 464 120 | |

**Figure 14.** Component-wise cost in the hybrid system.

occurs when there is integration of TES, hot springs and CO2 capture systems with CSP and biomass ORC plants. The CO2 capture system is integrated into the biomass ORC system to provide clean energy production, thereby capturing the emissions from the combustion of biomass products. This helps to predict the overall LCOE of the hybrid system. Furthermore, the total cost of the hybrid is found to be $10727220. In addition, the annual equivalent cost (AEC), operation and maintenance (O&M) cost and annual energy production from the subsystems have been evaluated. The total annual power generations by the CSP plant with TES and without TES are 6240 and 3120 MWh, respectively, similarly for the biomass ORC plant with TES and hot springs which are 750 and 400 MWh, respectively, with working fluids R123 and D4. Table 6 reveals the AEC, O&M cost and annual power generation from the hybrid system. It is found that addition of TES increases the annual solar energy production of the hybrid plant with no impact on the plant efficiency. The result indicates that hybridization of sub-systems leads to increase in the cost of electricity. However, the aim of this work is not to compare the cost of electricity generation with different power generation sub-systems but rather to demonstrate the idea of benefits of hybridization with different systems. The AEC of the hybrid
Table 6. Financial parameters for different sub-systems in the hybrid system.

| System description          | Annual equivalent cost ($/year) | Annual O&M cost ($/year) | Annual power generation (MWh) |
|----------------------------|---------------------------------|--------------------------|------------------------------|
| CSP plant with TES         | \(215.39 \times 10^9\)          | \(217.75 \times 10^9\)   | 6240                         |
| CSP plant without TES      | \(167.25 \times 10^9\)          | \(190 \times 10^9\)      | 3120                         |
| Biomass plant ORC with TES | \(170 \times 10^9\)             | \(33.6 \times 10^9\)     | 1200 (R123) 992 (R245fa)    |
| Biomass plant ORC with hot springs | \(165 \times 10^9\)         | \(30 \times 10^9\)       | 720 (D4) 640 (MDM)          |
| CO₂ capture system         | \(37.24 \times 10^9\)           | \(9.3 \times 10^9\)      | N/A                          |

system is higher due to the significant cost of solar collectors, ORC system and CO₂ capture system.

4.4 LCOE and sensitivity analysis

The cost of electricity generation by the hybrid system is evaluated by the ratio of all the annual equivalent costs of the hybrid system and O&M costs to total annual power generation. From this cost of electricity value, the LCOE is calculated for 20 years. The low LCOE results in a high payback period and vice versa. It is seen from Figure 15 that LCOE of 0.153$/kWh can have a payback period of 15.2 years whereas the payback is just 8 years. Therefore, if the hybrid is treated as a commercial investment, the latter can be suggested whereas for social benefit investment, the system with low LCOE is recommended.

Another parameter for financial assessment is carried by sensitivity analysis. This is conducted by varying the influencing parameters such as LCOE, operating hours, capital cost, O&M cost and interest rate in this study. The percentage of deviation from the base is 20%. Furthermore, the change in the internal rate of return (IRR) can also be estimated by this analysis. The IRR value of 5% is taken as the base for the calculation, and if it is >5%, the investment is favorable. In this study, for calculating cash flows, there are some parameters that have more influence on the net present value (NPV). From the investigation, it is observed that the most influencing parameters in NPV are change in LCOE, capital cost and operating hours. The least factors are interest rate and O&M cost. The least influencing parameters are annual cost and interest rate. In addition, Table 7 examines all different cases (NPV, IRR, payback period) for the evaluation of financial investment.

When the LCOE of hybrid system changes by 20%, there is a change in net present value from the base case. If LCOE is increased, the IRR is found to be 8% whereas the payback period is 10.2 years. Similarly, if the operating hours are increased, the IRR changes to 7% with a payback period of 11 years. Likewise, if the capital cost is decreased, the payback and IRR are 10.3 years and 7%, respectively. Figure 16 illustrates the variation of NPV for four different scenarios. The negative sign in NPV denotes that the investment is not profitable.

The LCOE of without the carbon capture system was found to be $0.17/kWh for the hybrid system.

The CO₂ emission saving from the system is also presented in this study. It is estimated that the total CO₂ emission saving
Table 7. Influencing scenario for sensitivity analysis.

| Scenario/variable | Net present value, NPV ($) | Internal rate of return, IRR (%) | Payback period (years) |
|-------------------|---------------------------|---------------------------------|-----------------------|
|                   | Increase | Decrease | Increase | Decrease | Increase | Decrease | Increase | Decrease | Increase | Decrease | Increase | Decrease |
| LCOE              | 2464659  | −2100248 | 8        | 3        | 10.2     | 16.7     |
| O&M cost          | −486274  | 489143   | 4        | 6        | 13.4     | 12.3     |
| Interest rate     | −648676  | 717195   | 5        | 5        | 13.1     | 12.9     |
| Operating hours   | 1483149  | −1268605 | 7        | 4        | 11       | 15       |
| Capital cost      | −1606217 | 169087   | 3        | 7        | 14.7     | 10.3     |

Figure 16. Variation in NPV for several variables.

Figure 17. CO₂ emission savings from the hybrid plant.
from the hybrid plant is almost 120 metric tons/year with the CSP plant. On the other hand, for the biomass-based ORC system, the emission saving is around 25 metric tons/year throughout its financial life period of 20 years. The saving in emission is shown in Figure 17. In order to produce 750 kW power out from the biomass ORC plant, it is estimated that biomass ORC could consume around 635 metric tons of biomass fuel per year.

5 CONCLUSIONS

In this study, a detailed thermodynamic and financial assessment was carried out for the CSP plant hybridized with biomass ORC, TES, hot springs and CO$_2$ capture system. The four working fluids were selected for the ORC plant for the performance analysis. The TES system and hot springs could act as a heat source for the hybrid system when there are poor sunshine days or for maintaining the load during fluctuation. The integration of hot springs and CO$_2$ capture system in the biomass ORC system added a new concept for assessing the system performance. From the results, it was seen that the thermal efficiency and power output from the CSP and biomass ORC plants were 39.5%, 1300 kW and 12% (R123), 730 kW, respectively. The biomass ORC plant with the hot spring system alone could develop a power of 720 and 640 kW for D4 and MDM, respectively. Furthermore, the power generation was increased with the addition of TES in the CSP plant. With the increase in HTF temperature in the system, the overall thermal efficiency and power generation increased.

From the economic point of view, the hybrid system can be very profitable if the LCOE could be fixed for 0.24$/kWh. In this scenario, the payback period would be 8 years with IRR more than 8%. Therefore, the CSP plant integrated with biomass ORC, TES, hot springs and CO$_2$ system is suitable for utilizing this concept in power generation and reducing pollution in the environment.

DATA AVAILABILITY

The data used to support the findings of this study are available from the corresponding author upon request.

Conflict of interest statement. The author declares that there are no conflicts of interest.

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