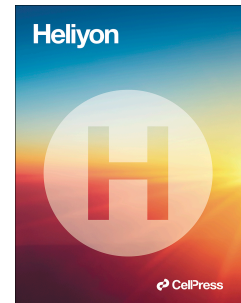


Journal Pre-proof

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PII: S2405-8440(23)10278-7

DOI: <https://doi.org/10.1016/j.heliyon.2023.e23070>

Reference: HLY 23070

To appear in: *HELIYON*

Received Date: 24 July 2023

Revised Date: 6 November 2023

Accepted Date: 25 November 2023

Please cite this article as: , Energetic, exergetic, economic and environmental performance of a rice husk gasification based carbon negative combined power and cooling plant, *HELIYON* (2024), doi: <https://doi.org/10.1016/j.heliyon.2023.e23070>.

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Title: Energetic, Exergetic, Economic and Environmental Performance of a Rice husk Gasification based Carbon Negative Combined Power and Cooling Plant

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Energetic, Exergetic, Economic and Environmental Performance of a Rice husk Gasification based Carbon Negative Combined Power and Cooling Plant

Abstract

This article presents the proposed configuration of a biomass gasification based carbon-negative combined power and cooling system. Parametric alteration of the response variables with respect to the individual input variables as well as the interaction of the input variables on response have been studied. Detailed analysis of variance has been carried out for the response variables (exergy utilization factor and modified unit electricity cost) and optimization of the whole plant has been performed employing response surface methodology. At the optimum operating condition, for both power and cooling, the plant utilizes 32.39% of input exergy at an effective electricity cost of 0.1186 \$/kWh (including the cost of CO₂ capture), having a desirability of about 1. CO₂ capture and the environmental benefit due to CO₂ cutting at optimum operating condition found to be 1.517 M ton/yr and 0.2275 B\$/yr respectively.

Keywords: Biomass, Molten carbonate fuel cell, Carbon capture, Optimization, Response surface methodology

1. Introduction

Economic development and population growth has been aiding increase in global energy consumption. Currently, significant share (almost 80%) of the fuel demand is met by fossil fuels [1] and it is already known that one of the leading causes of global warming and associated climate change is due to the release of CO₂ by power plants. Moreover, the depletion of fossil fuels is also a matter of concern. So, employing renewable forms of energy, waste heat recovery for improving efficiency, and CO₂ capture from the plant exhaust are the key areas to be worked on. The best alternative to the usage of fossil fuel is indeed the renewable resources of energy. The most abundant and readily available source of renewable energy is solar energy.

Still, the intermittent nature of availability during the day or seasonal variation of solar energy [2] does not seem very appealing to be used in a power-producing plant. Another type of renewable energy, biomass, seems more suitable to avoid intermittency and provide stability in power production. Moreover, biomass is sufficiently accessible in most places and is a carbon-neutral or zero-carbon energy source as it emits an approximately equal amount of CO₂ when combusted fully as it inhaled from the environment during its lifespan. So, CO₂ capture from the flue gas of a biomass-based plant would result in a carbon-negative plant [3].

Biomass to useful energy transformation may be performed employing routes like thermal and thermochemical conversion (direct combustion, gasification, liquefaction, and pyrolysis) and biological conversion (fermentation and anaerobic processes). And out of different biomass to energy conversion methods, incineration (direct combustion) of biomass and gasification are the two most common technologies for power plant applications. Direct combustion is the most common way of biomass energy conversion to useful energy. However, biomass has certain disadvantages when it is used directly as a fuel to generate power via incineration, as biomass has a high moisture content, low calorific value, and higher volume-to-mass ratio. On the other hand, biomass gasification allows various hybrid integration options for power plants including efficient technologies like fuel cells [4–6] as syngas produced from gasification of biomass can act as a versatile fuel for different power plant modules. And in many cases, gasification-based configurations help carbon capture as well, as done in the present study. So, gasification technology is now being employed widely to achieve clean and efficient power production.

The process of biomass gasification requires a gasifying agent (air/steam/CO₂, or a combination of these agents). In terms of the quality of gas produced, steam gasification yields better quality syngas than other types of gasification agents. Syngas obtained from air-gasification can yield LHV up to 6 MJ/ Nm³ [8] as it produces gas with high N₂ content and steam-gasification can produce syngas having LHV as high as 12-18 MJ/Nm³ [9] as better

syngas composition i.e., H_2 -rich syngas is produced in this case due to water gas shift and steam-methane reforming reactions. As almost N_2 -free syngas is generated when steam is used as the gasifying media, the process of CO_2 separation from the exhaust of the plant becomes easier before emitting to the atmosphere. Better power production from fuel cells was witnessed when steam gasification was integrated than air gasification [10].

But using biomass as fuel yields certain disadvantages like reduced system efficiency than fossil-fuelled power plants. CO_2 capture from the exhaust of any power plant is a vital aspect to minimize the environmental hazards caused by the power plant, but CO_2 capture further reduces the efficiency of a plant as it is an energy intensive process. So, to enhance the efficiency of biomass-based power plants, various system integrations and waste heat recovery techniques must be studied before finalizing a particular system integration.

Cebrecan et al. carried out the performance analysis of integrated sub-critical and super-critical coal-fired power plants co-fired with biomass with and without CO_2 capture [11]. More than 9% reduction in plant efficiency was observed when the plant was operated with 30% biomass co-firing for 90% CO_2 capture. Negative values of CO_2 emission was observed for the plants co-fired with biomass. Carapellucci et al. studied various configurations of steam power plants based on natural gas retrofitted with post-combustion CO_2 capture [12]. The power requirement for CO_2 capture was made available by steam extraction from the low-pressure steam turbine. A substantial penalty in plant efficiency was observed due to steam extraction to power the CO_2 capture unit. Zang et al. modelled and studied the techno-economic comparative investigation of different BIGCC systems with and without CO_2 capture [13]. They considered air gasification and oxygen gasification, internally and externally fired GT, and with and without CCS arrangements. Post-combustion CO_2 capture using MEA was performed when air was considered as the gasifying agent and for mixture of oxygen and steam as the gasifying agent, pre-combustion CO_2 capture was done using Selexol and WGSR.

Hosseinpour et al. carried out a parametric study and optimization of a biomass-gasification integrated solid oxide fuel cell plant [14]. For the CHP plant, the least exergy destruction rate for the gasifier was observed when steam was employed as the gasifying medium, and maximum exergy efficiency of 43% was observed for the plant for the oxygen-blown plant, having a total exergy unit cost of 3.02 cent/kWh. Moradi et al. modelled a micro-CHP system integrating a gasifier unit and a mGT, and for waste heat recovery, an ORC was employed [15]. Higher net electrical power production than nominal operation was witnessed due to steam injection to the combustion chamber and heat recovery through an ORC unit. 127.6 kWel power with 23.6% electrical efficiency was observed for the system when steam is injected into the combustion chamber at a rate of 25 g/s. Doherty et al. carried out simulation of a biomass fuelled SOFC integrated system employing Aspen Plus software [16]. A tubular SOFC configuration was considered and Gibbs free energy minimization approach was considered to develop the model. Under realistic operating design configuration, 37.04% net electrical efficiency and gross efficiency of 42.53% were observed.

Gas turbines have widely been employed in plants for power generation. However, an externally fired gas turbine (EFGT) has certain advantages over a simple GT unit. EFGT units generally have longer life since the post-combustion gas does not come in contact with the GT blades. Vera et al. studied the comparison of two small-scale CHP systems [17]. One of the systems was the integration of a biomass gasifier and a GT unit. The other one consisting of a combustor and an EFGT unit. Both systems utilized wastes from olive industry and higher overall and electrical efficiencies for the EFGT system has been observed than that of the gasification integrated GT system. Akkaya et al. studied the exergy performance of a CHP system consisting of SOFC, GT, and a HRSG unit to produce saturated steam utilizing the left-over heat energy [18]. For performance assessment, they considered exergy output and exergy efficiency and introduced the exergetic performance coefficient (EPC). It was found that

substantial advantages in terms of the least rate of entropy generation for given total exergy output are achieved when the plant is operated at maximum EPC conditions.

The majority of the works done on the power plants, as seen above, are techno-economic in nature, which do not discuss the important area of the plants' exact and suitable operating conditions to achieve maximum output from the plant. It is imperative to know the optimum input variables of any power plant, as the input variables of any power plant can have a wide range of values. Response surface methodology (RSM) effectively determines the optimum operating conditions of different processes and systems with adequate accuracy. In addition to that, RSM is a sound optimization technique which is instrumental in detailed study related to the effect of input variables and its interaction on the response variables and also identifying the influential input variables of any system [19–21]. Baghernejad et al. studied the exergo-economic analysis and optimization of solar integrated combined cycle system using a generic algorithm technique [22]. For the designed plant capacity of 400 MW, a 27.34% increase in overall exergo-economic factor was observed. 14.82% decrease in exergy destruction cost and an increase in exergy efficiency of the plant from 43.79% to 46.8% have been achieved operating the plant at optimum condition. Mahmoudi et al. performed a techno-economic analysis and multi-objective optimization of a system integrating MCFC, supercritical CO₂ cycle and ORC considering liquefied natural gas as the heat sink [23]. The combined optimization case showed 64.6% of exergy efficiency and 0.0451 cents/kWh of UEC. Duan et al. carried out part-load performance analysis and optimization of a power system consisting of MCFC and steam turbine [24]. Reduction in total exergy loss was observed for the new system compared to the benchmark system and 6.37% increase in net system efficiency was observed for the new system than the benchmark system. Mojaver et al. studied RSM multi-objective optimization and exergy analysis of a biomass gasification integrated SOFC and a high-temperature Na heat pipe system [5]. 353 kW of power and 44.22% of exergy efficiency

were witnessed at the optimum operating state of the system. Hosseinpour et al. conducted exergy analysis and optimization of a SOFC integrated Stirling engine cogeneration system [5]. CH₄ was used as the fuel for the system and 56.44% of exergy efficiency was observed at optimum condition.

Although apparently complex, the conceived configuration of the plant offers a unique integration of an EFGT, an MCFC, and an ORC as well as a vapour absorption refrigeration (VAR) system with biomass steam gasification so as to render an efficient carbon negative co-generation plant giving power and cooling. The presence of MCFC and the post-combustion moisture separation make the capture of CO₂ possible without any elaborate and conventional CO₂ removal system. Moreover, Response Surface Methodology (RSM) has been employed in this complex configuration to perform a multi-objective optimization study.

2. Material and methods

The syngas has been generated employing an Aspen Plus model [20,21] where a wide variety of biomass feed were considered for analysis and optimization of the steam gasification process. Aspen Plus is a market-leading process simulation software, which is used by researchers as well as chemical industries to perform process modelling of individual chemical processes (which help validating the processes) as well as system modelling. The plant has been modelled using Cycle-tempo simulation software and EES (Engineering Equation Solver) software has been employed to obtain the thermodynamic results along with economic and environmental outcomes. Further, Minitab software has been used to execute the optimization study.

Following sub-sections portrays system description, 4E modeling, performance parameters, and optimization strategy.

2.1 System description and assumptions

2.1.1 Assumptions

Certain assumptions were made for the plant modelling-

- ❖ Steady state was considered for the analyses.
- ❖ Gas streams were assumed to be perfect gas.
- ❖ Temperature and pressure at ambient condition were considered to be 298.15 K and 1.013 bar respectively.
- ❖ The MCFC unit was supposed to be insulated, etc. are some of the assumptions.

2.1.2 System description

The fundamental units which constitute the combined power and cooling plant are: A gasifier (G) along with a gas cleaning unit (GCU); a combined combustor (CC) and heat exchanger (HX) unit, which drives the externally fired GT (EFGT); an internal-reforming type MCFC unit; a HRSG unit, which supplies the heat required by the generator (GEN) of the VAR cycle through generated steam; an organic Rankine cycle (ORC), which is driven by the MCFC anode exhaust gas heat; and a CCU as shown in **Fig. 1**. EFGT, MCFC and the ORC are accountable for power generation and VAR cycle is employed for required cooling.

Gasification of biomass occurs in the gasifier considering steam as the gasifying medium. The necessary steam for the gasification of biomass is taken from the steam generated by the HRSG unit for the generator of the VAR cycle. After the syngas is conditioned in the GCU, it gets split between the MCFC and the EFGT units. The fuel split takes place in such a way that the air turbine (AT) of the EFGT unit always produces 1 MW output, and the rest of the fuel is supplied to the anode side of MCFC via the fuel preheater (FPH). The exhaust from the EFGT unit enters the cathode of the MCFC, and the MCFC unit uses the CO₂ present in the exhaust of the EFGT stream to generate carbonate ions, which are then transported to the anode side

and where the carbonate ions react with the syngas to produce power. The anode exhaust of MCFC contains the unutilized fuel, which is after-burnt with pure O_2 produced by the ASU.

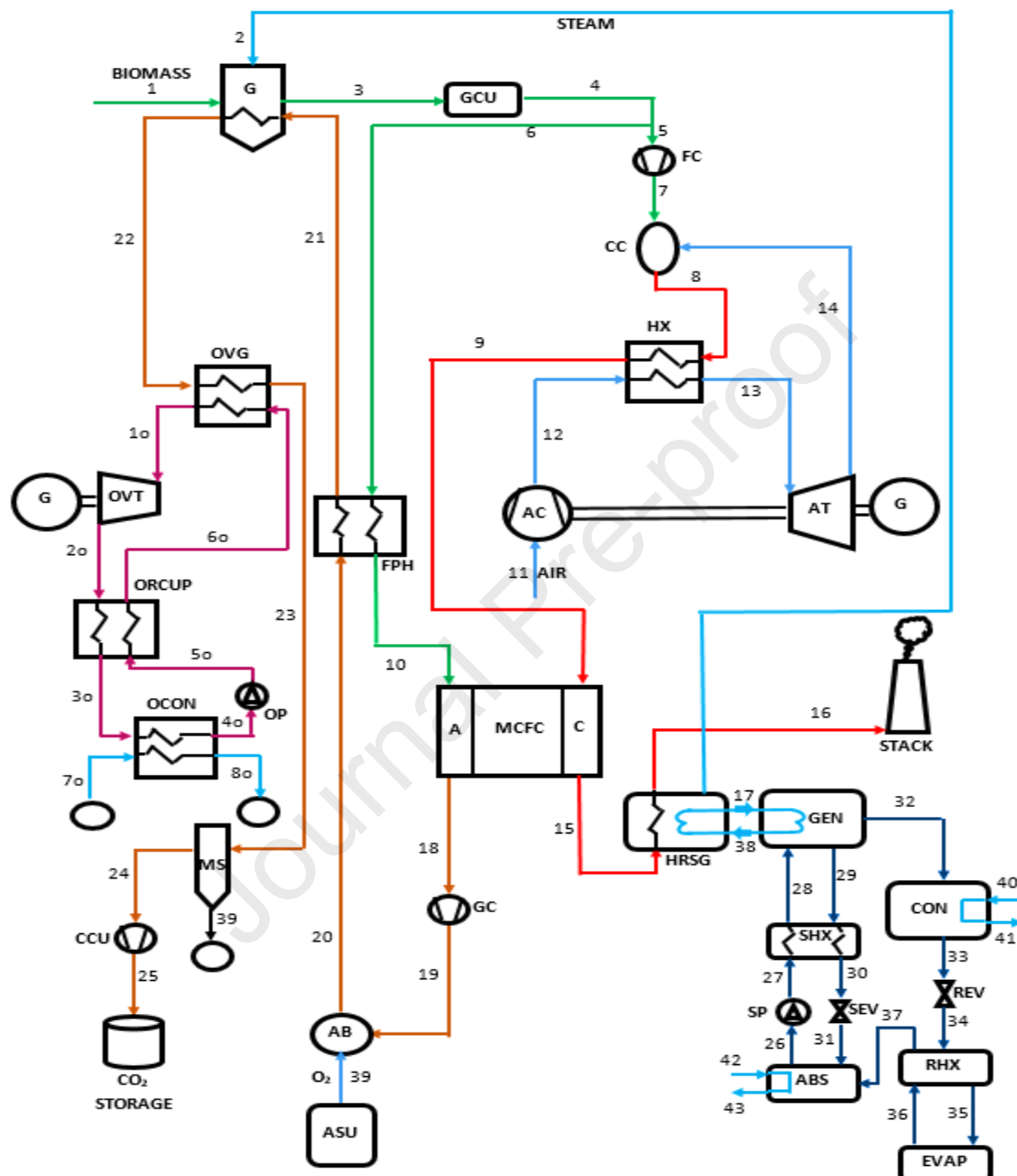


Fig. 1. Schematic diagram of the proposed combined power and cooling plant

The after-burnt gas contains high heat content, which is then utilized to preheat the fuel to anode of MCFC. After that the gas stream supplies heat to the gasifier unit via the gasifier jacket, and the remaining heat is recovered by the ORC. As after combustion of the anode

exhaust gas with pure O₂ the gas stream contains only H₂O and CO₂, the CO₂ is captured at a high pressure condition of 110 bar after separating the H₂O by a moisture separator (MS).

The separation of CO₂ from cathode stream of the MCFC, combined with the post-combustion CO₂ capture in the carbon capture unit (CCU) makes the proposed plant a net absorber of atmospheric CO₂ and hence the plant can indeed be termed carbon negative.

2.2 4E modeling

4E analysis is denoted for energy, exergy, economic and environmental analyses of the proposed plant. The techno-economic and environmental analyses modeling of the plant and energy modeling of the key units, which constitute the building blocks of the plant has been discussed in this section. Individual model for energy, exergy, economic and environmental analyses are discussed in detail in subsections 2.2.1-2.2.4 respectively.

2.2.1 Energy

Energy analysis is done to estimate some of the key performance parameters like individual power output by any unit, net power produced by the system, and electrical efficiency for any system. Moreover, energy analysis acts as the foundation for other analyses like exergy, economic and environmental analyses.

1st law analysis is performed to evaluate the work and heat interaction for any unit of a system. To carry out the 1st law analysis, steady state and control volume methods have been assumed. For each component of the plant, a steady flow energy equation with negligible change in potential and kinetic energy has been carried out. Unit-wise mass balance has been carried out and the energy balance relation for each model component is denoted by **Eq. 1** as follows:

$$\dot{Q} + \sum_{i=1}^n \dot{m}_{in} h_{in} = \dot{W} + \sum_{i=1}^n \dot{m}_{out} h_{out} \quad (1)$$

Where, $\dot{Q}$ is the heat input to a component and $\dot{W}$ is the power produced by any component ($\dot{W}$ will be negative for a power-consuming device). Component wise 1st law analysis is listed in **Table A. 1** (denoted by **Eq. 2 to 26**) in Appendix A.

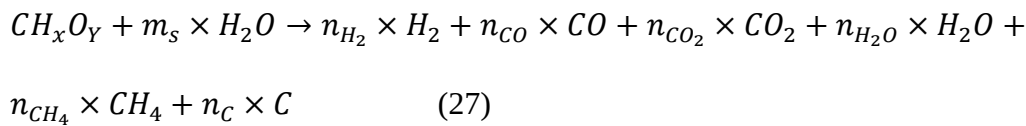
2.2.1.1 Steam-gasification model

The biomass composition used for this analysis is specified in **Table 1** with regard to proximate and ultimate analyses.

Table 1. Composition of biomass used (Rice husk) [25]

Parameters	Composition
Proximate analysis	
FC	14.99%
VM	55.54%
Moisture	9.95%
Ash	19.67%
Ultimate analysis	
C	38.43%
O	36.36%
H	2.97%
S	0.07%
N	0.49%
Ash	21.68%

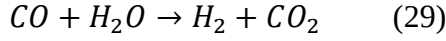
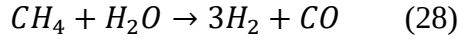
The overall reaction for the biomass steam-gasification process is represented by **Eq. 27** as follows:



Steam-gasification is modelled considering a Gibbs reactor as the main reactor, which works based on the principle of Gibbs free energy minimization. The detailed process modelling, validation, and optimization of the gasifier are explained in the previous works [20,21].

2.2.1.2 Molten carbonate fuel cell model

The MCFC unit considered in this work is of in-house reforming type, implying both water gas shift (**Eq. 29**) and steam-methane reforming (**Eq. 28**) reactions taking place in the MCFC unit itself.



The global mass balance of MCFC is stated by **Eq. 30** as follows:

$$\dot{m}_{an,in} + \dot{m}_{ca,in} = \dot{m}_{an,out} + \dot{m}_{ca,out} \quad (30)$$

Here, $\dot{m}_{an,in}$ and $\dot{m}_{an,out}$ represents mass flow rate of gas at the inlet and outlet respectively of the anode of MCFC. Similarly, $\dot{m}_{ca,in}$ and $\dot{m}_{ca,out}$ represents the mass flow rate of flue gas at the inlet and outlet respectively of the cathode of MCFC.

Current flow through MCFC (i_{flow}) is assessed using **Eq. 31** as follows:

$$i_{flow} = \frac{\dot{m}_{an,in}}{M_{mol,an}} \times 2F \times (x_{H_2} + 4x_{CH_4} + x_{CO}) \quad (31)$$

Here, F represents Faraday's constant and x denotes the partial pressure of gas components.

Practically only a portion of syngas can be utilized by the MCFC. The ratio between the actual and maximum possible transformation is represented by the fuel utilization factor (Uf). The actual current flow (i) is assessed considering **Eq. 32** as follows:

$$i = i_{flow} \times Uf \quad (32)$$

It is expected that current density is related to the voltage deficit. The proportionality constant is represented with the cell resistance equivalent (R_{eq}) by correlating with Ohm's law. The cell voltage (V) of the MCFC is calculated using **Eq. 33** as below [26]:

$$V = \frac{\Delta G_T}{2F} + \frac{RT_{cell}}{2F} \ln \left(\frac{x_{O_2,ca}^{0.5} \times x_{H_2,an}}{x_{H_2O,an}} \times P_{cell}^{0.5} \right) - iR_{eq} \quad (33)$$

Here, $\Delta G_T = (45.8 \times T_{cell}) - 242000$, is the change in Gibbs free energy; $F=96487$ C/mol, is the Faraday's constant and R_{eq} is the summation of resistance at anode, cathode and Ohmic loss.

The electrical power produced by the MCFC stack ($\dot{W}_{MCFC}$) can be calculated considering **Eq. 34** as follows:

$$\dot{W}_{MCFC} = V \times i \times \eta_{DC/AC} \quad (34)$$

Where $\eta_{DC/AC}$ is the inverter DC/AC transition efficiency.

Net power produced, electrical efficiency, and effective electrical efficiency are the performance parameters obtained from energy analysis model, which are estimated as per **Eq. 51, 53, and 54** (shown in section 2.3) respectively.

2.2.2 Exergy

Exergy analysis is carried out to know the maximum work transferred by the plant and it also helps improving the plant performance by identifying the critical areas of the system where maximum exergy destruction takes place. Exergy analysis for an individual equipment is performed considering work and heat interactions along with the stream exergy values. **Eq. 35-42** are employed to obtain the performance parameter related to exergy analysis.

The exergy of any stream is the summation of physical (E_{ph}) and chemical (E_{ch}) exergy values, as shown below:

$$E = E_{ch} + E_{ph} \quad (35)$$

The physical and chemical exergy calculating equations are as follows:

$$E_{ph} = \sum_j \dot{N}_j \{ (\bar{h}_j - \bar{h}_{ref}) - T_0 (\bar{s}_j - \bar{s}_{ref}) \} \quad (36)$$

$$E_{ch} = \sum_j \dot{N}_j \{ \sum_j x_j \times \bar{e}x_{che} - RT_0 \sum_j x_j \times \ln x_j \} \quad (37)$$

The exergy destruction at any component throughout a process is computed as follows:

$$E_{Dex} = \sum_j \left(1 - \frac{T_0}{T_j}\right) \dot{Q} - \dot{W}_{cv} + \sum_{in} \dot{m}_{in} ex_{in} - \sum_{ex} \dot{m}_{ex} ex_{ex} \quad (38)$$

Net input exergy to the plant is basically the fuel exergy (i.e., biomass) (E_{biom}), which can be estimated as follows:

$$E_{biom} = m_{biom} \times E_{ch,biom} \quad (39)$$

The chemical exergy of biomass ($E_{ch,biom}$) is assessed employing the following relation:

$$E_{ch,biom} = \xi \times LHV_{biom} \quad (40)$$

Where ξ is the chemical exergy co-efficient of biomass and is determined employing the relation given below[21]:

$$\xi = \frac{1.044 + 0.016 \frac{H_{BM}}{C_{BM}} - 0.34493 \frac{O_{BM}}{C_{BM}} \left(1 + 0.0531 \frac{H_{BM}}{C_{BM}}\right)}{1 - 0.4124 \frac{O_{BM}}{C_{BM}}} \quad (41)$$

LHV of biomass (LHV_b) is obtained following relation[20]:

$$LHV_b = HHV_b - 21.97[H] \quad (42)$$

The defined exergy utilization factor (estimated as per **Eq. 55**) is the performance parameter obtained performing the exergy analysis.

2.2.3 Economy

It is imperative to perform the economic analysis of any plant to understand the economic viability of the proposed plant. Unit cost of electricity is basically the performance parameter as per economic analysis is concerned. The yearly capital cost (which is estimated from total equipment cost), operations and maintenance cost, and fuel cost are calculated first to estimate the unit cost of electricity. **Eq. 43-48** are employed to obtain the performance parameters related to economic analysis. For economic analysis, the NETL (National Energy Technology

Laboratory) approach has been considered [27]. The key parameters for the economic evaluation are listed in **Table 2**.

Table 2. Key data assumed to perform the economic study of the system

Parameter	Value	Reference
Year	30 years	[26]
H	8000 hours	[28]
CF	0.85	[13]
T _L	4%	[29]
$\dot{C}_{fuel}$	2 \$/GJ	[30]
in_{year}	8%	[26]
ζ_1	20.20%	[26]
ζ_2	52.5%	[26]
ζ_3	9%	[26]

The yearly capital cost (TYCP) is estimated by equation given below [26]:

$$TYCP = \{TEP \times (1 + \zeta_1) \times (1 + \zeta_2) \times (1 + \zeta_3)\} \times fn_{CRF} \quad (43)$$

Here, ζ_1 : adjustment element used for overnight cost; ζ_2 : adjustment element used for the plant cost; ζ_3 : adjustment element used for engineering, construction and procurement cost; TEP: total equipment rate; and fn_{CRF} : capital recovery function

The summation of all the equipment costs leads to the total equipment cost (TEP) and is estimated as follows:

$$TEP = \sum C_{equipment} \quad (44)$$

The capital regaining function (fn_{CRF}) is estimated using the following relation [10]:

$$fn_{CRF} = \frac{in_{year}(1+in_{year})^{year}}{(1+in_{year})^{year}-1} \quad (45)$$

Here, “ in_{year} ” and “ $year$ ” are “interest rate per year” and “years of operation”, correspondingly.

MCFC needs replacement four times over the lifespan of a plant. An extra 5% MCFC substitute cost has been considered to cope with the short longevity of the MCFC unit [26]. Total cost of operation and maintenance (OM) for the plant is estimated as follows:

$$OM = (0.04 \times TYCP) + C_{MCFC} \times (4 \times 0.05) \quad (46)$$

The yearly fuel cost is calculated as follows:

$$FC = \dot{C}_{fuel} \times \dot{m}_{fuel} \times LHV_{biom} \times H \times 3600 \quad (47)$$

The equipment cost of any plant is usually a function of capacity, size, and mass flow rate. The component cost of the plant's equipment are listed in **Table A. 2** in Appendix A. The cost of each component is updated employing the Cost Index for Chemical Engineering Plant (CEPCI). 2019 has been taken as the current year for the present study. The component cost of the k^{th} unit concerning the reference year is calculated as below [26]:

$$C_{k,CY} = C_k \times \frac{CEPCI_{CY}}{CEPCI_{OY}} \quad (48)$$

Where, $CEPCI_{CY}$ and $CEPCI_{OY}$ are the cost indices for the recent and the original years, individually.

Unit electricity cost and the modified unit electricity cost as in **Eq. 57** and **58** are the two performance parameters obtained performing the economic investigation of the proposed plant model.

2.2.4 Environment

As regulations related to environmental impact due to power generation are getting stringent day by day, it is necessary to perform the environmental analysis as well for the proposed plant. As power plants mostly emit CO₂ to the atmosphere in bulk and as the proposed plant is modelled as a CO₂ negative plant, environmental analysis considering CO₂ capture is

performed for the proposed plant. Environmental profit achieved by the biomass-based system has been evaluated corresponding to the extent of CO₂ captured and the environmental gain owing to CO₂ capture.

The key input parameters needed for environmental investigation are as follows:

Discharge from standard coal-powered sub-critical steam plant = 0.8552 kg of CO₂/kWh[12]

Environmental damage rate occurred due to the CO₂ emission (EDC_{CO2}) = 150 \$/ ton of CO₂[31]

Total CO₂ capture per annum (TACC) from the system is estimated considering the following equation (**Eq. 49**):

$$TACC = MFR_{abg} \times x_{abg} \times M_{CO_2} \times \left(Hr \times \frac{3600}{1000} \right) \quad (49)$$

Here, MFR_{abg} symbolizes the mass flow rate of after-burnt gas, x denotes molar fraction, and M represents the molar mass.

The environmental gain for CO₂ capture per annum (AEBCC) by the present system is assessed by the following relation (**Eq. 50**):

$$AEBCC = TACC \times EDC_{CO_2} \quad (50)$$

Total CO₂ capture per annum and environmental gain for CO₂ capture per annum are the performance parameters obtained from environmental analysis of the plant.

2.3 Performance parameters

The net power generated by the system is estimated as below:

$$\dot{W}_{net} = \dot{W}_{AT} + \dot{W}_{MCFC} + \dot{W}_{OVT} - \dot{W}_{Auxiliary} \quad (51)$$

$$\dot{W}_{Auxiliary} = \dot{W}_{AC} + \dot{W}_{SP} + \dot{W}_{OP} + \dot{W}_{GC} + \dot{W}_{FC} + \dot{W}_{ASU} + \dot{W}_{CCU} \quad (52)$$

The power spent by the auxiliary units of the system is estimated using **Eq. 52**.

The electrical efficacy of the plant is computed considering only the net power generated as follows:

$$\eta_{elect} = \frac{\dot{W}_{net}}{\dot{m}_{fuel} \times LHV_{biom}} \quad (53)$$

As the plant is having both power and cooling units, therefore, the 1st law performance of the plant has also been judged by calculating its effective electrical efficiency. While calculating the effective electrical efficiency, equivalent work requirement to drive a standard vapor compression refrigeration system of the same capacity (as that of the modelled VAR) is taken into account along with the net electrical power ($\dot{W}_{net}$) produced. Thus, effective electrical efficiency is estimated considering effective output energy, i.e., both power and cooling effect, and is calculated as follows:

$$\eta_{effect} = \frac{\dot{W}_{net} + \dot{Q}_{EVAP} / COP_{VCR}}{\dot{m}_{fuel} \times LHV_{biom}} \quad (54)$$

The exergy utilization factor of the model is computed considering effective exergy from the power and cooling effect produced by the combined power and cooling plant and is estimated using following relation:

$$EUF = \frac{\dot{W}_{net} + E_{cooling}}{\dot{m}_{biom} \times E_{biom}} \quad (55)$$

Here $E_{cooling}$ is the exergy associated with the cooling effect, estimated using **Eq. 56** as follows:

$$E_{cooling} = \left(\frac{T_0}{T_{EVAP}} - 1 \right) \dot{Q}_{EVAP} \quad (56)$$

Where T_0 and T_{EVAP} are atmospheric and evaporator operating temperatures, respectively.

The unit electricity cost is estimated considering the following relation:

$$UEC = \frac{(TYCP + OM + FC)}{\dot{W}_{net} \times CF \times H \times (1 - T_L)} \quad (57)$$

As no extra energy is required to produce the cooling effect, the economic gain from the cooling is considered while estimating the modified unit cost of electricity. The MUEC is assessed as follows:

$$MUEC = \frac{(TYCP+OM+FC)}{W_{net} \times CF \times H \times (1-T_L) + AEC} \quad (58)$$

Where AEC in “kWh” is the avoided electricity for cooling, is the extent of electricity needed to yield the same amount of cooling effect by a standard VCR cycle and is estimated employing **Eq. 59** as follows:

$$AEC = \frac{\dot{Q}_{EVAP}}{COP_{VCR}} \times 8000 \quad (59)$$

2.4 Optimization methodology

Response surface methodology (RSM) is an extensively used technique to optimize the performance parameters of an existing or newly developed process or system. Effective design of experiments (DOE) comes in handy optimizing any model performing the least number of simulations or experiments as it works as a partial factorial design, resulting in time and energy savings and reduction in cost. Several input variables such as R_p , $ITAT$, j , and U_f have been taken into account to optimize the developed plant considering EUF and $MUEC$ as the response parameters. The multi-objective optimization has been executed in Minitab software, and the regression equation for individual response variables is developed by RSM performing analysis of variance (ANOVA). Detailed discussion about optimization is mentioned in earlier works [20,21].

To create the relation between response and input variables, a second-order quadratic relation (**Eq. 60**) is used as shown below [20]:

$$r = \beta_0 + \sum_{i=1}^n \beta_i v_i + \sum_{i=1}^n \beta_{ii} v_i^2 + \sum \sum \beta_{ij} v_i v_j \quad (60)$$

Here, “ r ” implies response; “ v ” indicates variable; “ n ” is the count of variables; $\beta_0, \beta_i, \beta_{ii}, \beta_{ij}$ is the constant, linear, square and interaction items correspondingly.

The coefficient of regression (R^2) is calculated employing the relation (**Eq. 61**) as follows [20]:

$$R^2 = \frac{\sum_{i=1}^k (r_{i,p} - r_m)^2}{\sum_{i=1}^k (r_i - r_m)^2} \quad (61)$$

The following equation (**Eq. 62**) is employed to calculate the adjusted regression coefficient (

R_{adj}^2) [20]:

$$R_{adj}^2 = 1 - \frac{\sum_{i=1}^k (r_{i,p} - r_m)^2}{\sum_{i=1}^k (r_i - r_m)^2} \times \frac{(k-1)}{(k-n-1)} \quad (62)$$

Here, k implies the number of experiments; r_i , $r_{i,p}$, and r_m are experimental, predicted, and mean values correspondingly.

The broad flowchart for the thermo-economic assessment and optimization method of the proposed model is exhibited in **Fig. 2**.

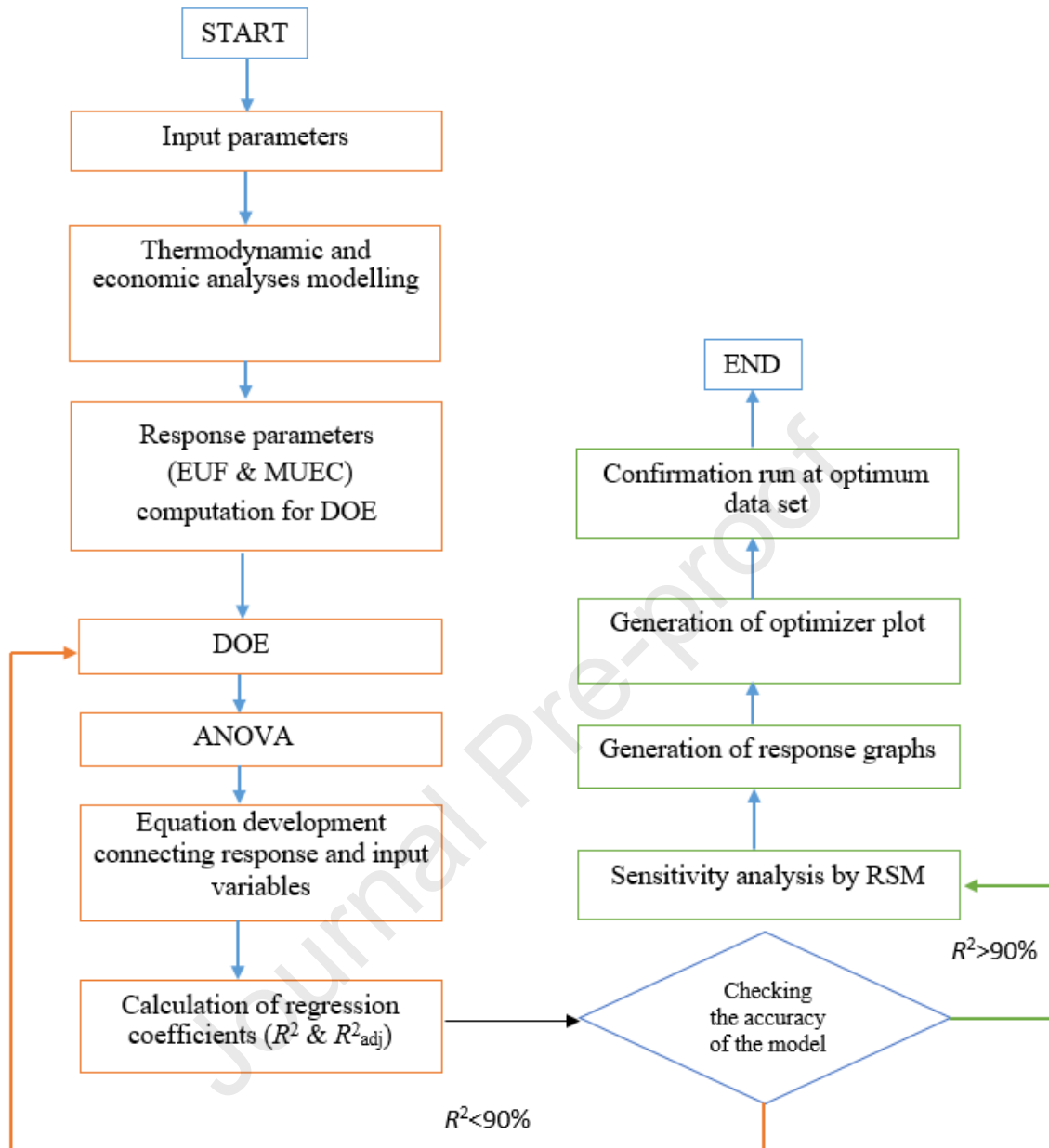


Fig. 2. Flowchart for complete investigation and optimization of the proposed model

3. Results and discussion

3.1 Validation of results for important plant constituents

Before simulating the plant at the base-case operational state and optimizing the whole plant, it is important to validate the results of key plant units, like the gasifier unit and MCFC unit.

The complete details of the model description, validation, and optimization of the gasifier unit can be found in our previously published works [20,21].

The results of the MCFC unit have been matched with the experimental and simulation work by Liu and Weng [32]. The variation of cell voltage with current density of the developed MCFC unit has been equated with the mentioned experimental study and is presented in **Table 3**.

Table 3. Comparison of developed MCFC model results with published experimental work [32]

Current density	Cell voltage (present study)	Cell voltage (theoretical modeling)	Error (%)	Cell voltage (experimental results)	Error (%)
1200	0.8407	0.84	0.08	0.78	7.78
1300	0.8303	0.83	0.03	0.77	7.83
1400	0.8198	0.82	0.02	0.76	7.86
1500	0.8092	0.81	0.09	0.75	7.89
1600	0.7985	0.80	0.18	0.74	7.91
1700	0.7877	0.79	0.29	0.73	7.90
1800	0.7768	0.78	0.41	0.72	7.88

Table 3 displays that the variations of the cell voltage with the change in current density are at par with both the modeling as well as experimental studies performed by Liu and Weng. The deviancy is well within the agreeable limit. Thus, it can be understood that the developed MCFC unit is well authenticated and can reasonably predict the outcome. The variance between model estimates and experimental results can be illuminated as parasitic currents within the electrodes depending on specific cell fabricating structures, which are challenging to be evaluated by the simulation works [26]. A similar deviation between the simulation and experimental outcomes was experienced in the referred work too.

3.2 Base-case analysis

Before parametric variation and statistical analysis for optimization, the base-case performance analysis of the plant was carried out to check whether the plant model is viable or not. The operational parameters for the base-case condition have been considered as $R_p = 4$, $ITAT = 1000$ °C, $j = 1500$ A/m², and $U_f = 0.75$. For the economic analysis at the base case condition, input data as shown in **Table 2** have been considered and the detailed outcome of the proposed plant at the base-case state are listed in **Table 4**.

Table 4. Performance of the plant at base-case state

Parameters	Results
EFGT Power	1000 kW
MCFC Power	1339 kW
ORC Power	146.4 kW
Refrigeration Capacity	391.72 TR
COP	0.5867
$\dot{W}_{net}$	2121 kW
$\eta_{eff\ elect}$	34.67%
EUFC	0.2729
MUEC	0.1315 \$/kWh
CO ₂ Cutting	2.147 M ton/yr
AEBCC	0.3221 B\$/yr

The utilization of fuel exergy input at the base-case state is shown in **Fig. 3**. Of the total input exergy, 27.29% exergy is utilised, 9.59% is the exergy loss through the stack and 63.12% of input exergy is destructed.

Feasible performance parameters at the base case suggests that the proposed power cooling plant model is worth conceiving for further study.

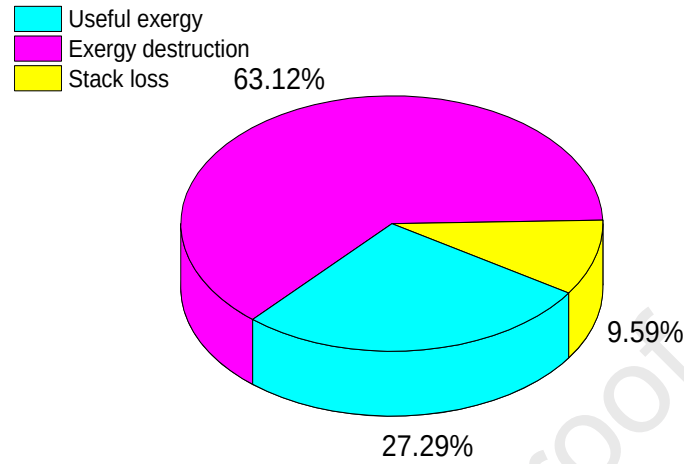


Fig. 3. The utilization of the total input fuel exergy

3.3 Parametric variation of response variables with input parameters

Detailed parametric variation of performance parameters like exergy utilization factor from exergy model and modified unit electricity cost from economic model have been portrayed in this section. The main energy model performance parameter i.e., effective electrical efficiency largely follows the exergy utilization factor trends. However, the effect of alteration of input variables on other performance parameters from energy model like individual as well as net power by the power and cooling plant have been discussed in details. The variation of the mean exergy utilization factor with the alteration in input variables is shown in **Fig. 4**. For both cases, X-axis represents the input variables and Y-axis represents the response variable respectively. With the surge in R_p , power generated by the air turbine should rise first, reach a maximum value and then decline again. However, since the power generated by the EFGT unit has been fixed to 1MW, so the fuel consumption will decrease first, reach a minimum point and then increase. As the MCFC unit and both the heat recovery units (ORC and VAR systems) depend on the fuel input to the whole plant, so the net power produced will also vary in sync with the fuel consumption by the plant. As the effect of fuel input variation is more dominant than the

variation in net power output, so the EUF will increase, reach a maximum point, and then decrease as the R_p value is raised from 4 to 16.

As ITAT is increased, the power generated by the EFGT unit should rise. As the power production by the EFGT unit is unchanging, so the biomass requirement by the plant decreases as ITAT is raised, hence the net power produced by the plant also decreases. But the decline in fuel input to the plant is more dominating when compared to the decline in net power production. As an outcome, the EUF surges as the ITAT is raised from 900 °C to 1100 °C.

With the ascent in current density, the voltage losses rise, resulting in less net voltage output and less power production by the MCFC module, the biomass supply to the plant remaining the same. As the alteration in current density does not disturb the EFGT unit or any other unit, so the net power produced by the plant decreases with the rise in current density, resulting reduction in the EUF of the plant.

Conversely, an increase in fuel utilization factor means the MCFC unit's ability to deliver the same power at the expense of less fuel. Alteration in U_f does not affect any other unit of the plant other than the ORC unit. Due to less fuel intake by the MCFC unit, the anode exhaust of the MCFC unit contains less heat energy which powers the ORC. As a result, the net power produced by the plant decreases. But the MCFC's fuel consumption reduction is more influential than the net power output reduction. As a result, with increase in U_f from 0.6 to 0.8, the EUF of the whole plant increases.

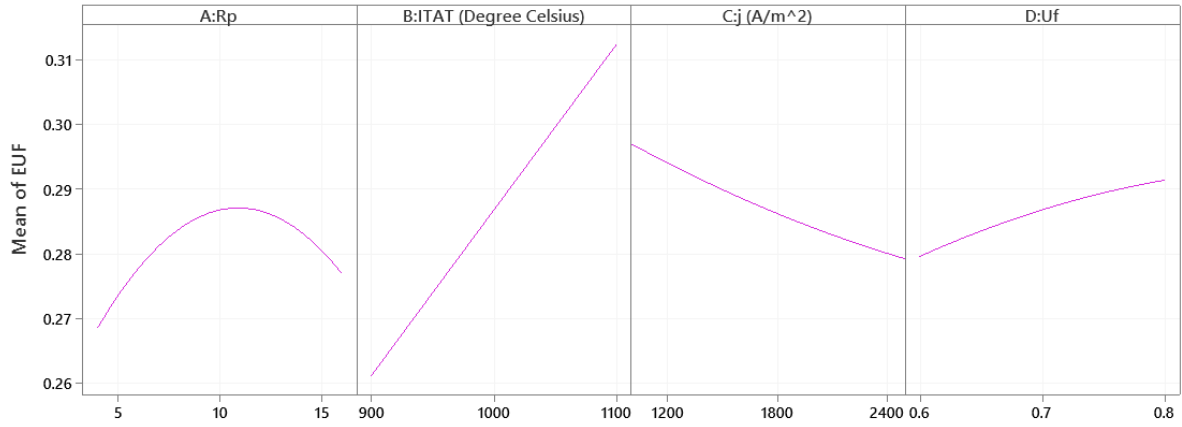


Fig. 4. Parametric variation of mean EUF with input variables

The variation of mean modified unit electricity cost with the alteration in input variables has been shown in **Fig. 5**. More the plant is efficient, lesser will be the unit cost of electricity production, i.e., system efficiency is inversely proportional to the MUEC. Hence the trends of MUEC for all input variables are just the reversal of EUF except for the current density. The net power generated by the plant reduces with the increase in current density. But as j is increased, the MCFC area requirement gets reduced, resulting in significant capital cost cutting for the MCFC unit, which in turn helps the overall economy of electricity generation. Hence, with the increase in j , MUEC decreases.

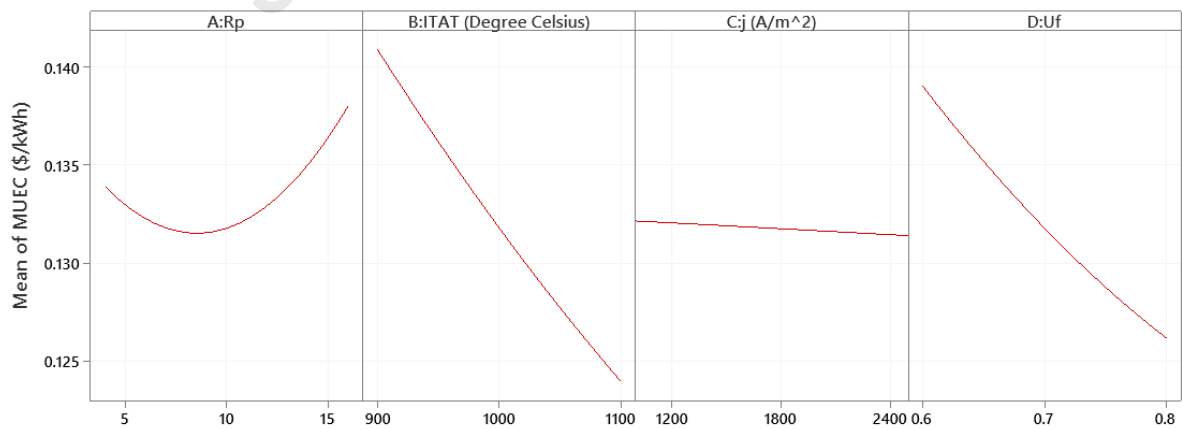


Fig. 5. Parametric variation of mean MUEC with input variables

The parameters which affect both response variables EUF and MUEC the most are clearly ITAT and Uf. Other input variables (Rp and j) are also having a fair amount of influence on the response variables. So, it is very important to carry out the optimization of the whole plant considering the above input parameters and understand the most beneficial operating condition to achieve maximum EUF along with the minimum expense of electricity generation.

3.4 Statistical analysis

In this section, a detailed analysis of variance has been discussed after the complete base-case analysis, and optimization of the proposed combined power and cooling plant employing response surface methodology has also been discussed in this segment. The key operating parameters were considered as input variables and output parameters like exergy utilization factor and modified unit cost of electricity were reflected as the response variables.

3.4.1 Analysis of variance

3.4.1.1 ANOVA for exergy utilization factor (EUF) as a response variable

The summary of ANOVA for EUF as a response variable is as follows:

$$R^2 = 0.9968, \text{ Adjusted } R^2 = 0.9935 \text{ and Predicted } R^2 = 0.9814$$

Obtained R^2 and Adjusted R^2 values are sufficiently high to realize that the model can forecast the response variable accurately.

Table 5. ANOVA results for exergy utilization factor

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	0.0110	14	0.0008	309.02	< 0.0001 significant
A (Rp)	0.0002	1	0.0002	81.60	< 0.0001
B (ITAT)	0.0078	1	0.0078	3078.56	< 0.0001
C (j)	0.0009	1	0.0009	369.60	< 0.0001
D (Uf)	0.0004	1	0.0004	163.34	< 0.0001
AB	0.0002	1	0.0002	69.04	< 0.0001

AC	1.000E-08	1	1.000E-08	0.0039	0.9509
AD	3.600E-07	1	3.600E-07	0.1416	0.7124
BC	0.0000	1	0.0000	0.0000	1.0000
BD	9.610E-06	1	9.610E-06	3.78	0.0723
CD	0.0000	1	0.0000	6.29	0.0251
A ²	0.0013	1	0.0013	501.15	< 0.0001
B ²	1.802E-09	1	1.802E-09	0.0007	0.9791
C ²	0.0000	1	0.0000	4.28	0.0575
D ²	0.0000	1	0.0000	4.34	0.0561
Residual	0.0000	14	2.543E-06		
Lack of Fit	0.0000	10	3.560E-06		
Pure Error	0.0000	4	0.0000		
Cor Total	0.0110	28			

The ANOVA results considering the exergy utilization factor as the response variable is displayed in **Table 5**. The Model F-value of 309.02 suggests the model is noteworthy. p-values less than 0.0500 imply that the model terms are significant. In this case, A, B, C, D, AB, CD, and A² are effective model terms. Values more than 0.1000 imply the model terms are not significant. It is clear from **Table 5** that ITAT and j are highly impactful while estimating the response variable having F-values of 3078.56 and 369.6, respectively, and p-values of less than 0.0001 for both parameters.

The model equation which estimates EUF in terms of the input variables is as follows:

$$\begin{aligned}
 EUF = & 0.0961241 - 0.00289213 \times Rp + 3.98333 \times e^{-5} \times ITAT - 1.08519 \times e^{-6} \times j + \\
 & 0.128083 \times Uf + 1.10417 \times e^{-5} \times Rp \times ITAT - 1.11111 \times e^{-8} \times Rp \times j + 0.0005 \times \\
 & Rp \times Uf - 8.03096 \times e^{-22} \times ITAT \times j + 0.000155 \times ITAT \times Uf - 2.66667 \times e^{-5} \times j \times \\
 & Uf - 0.000389352 \times Rp^2 - 1.66667 \times e^{-9} \times ITAT^2 + 2.3037 \times e^{-9} \times j^2 - 0.130417 \times \\
 & Uf^2
 \end{aligned}
 \quad (63)$$

Eq. 63 can be used to estimate the EUF of the plant without the need for any simulation. The equation is capable of correct forecasting of exergy utilization factor once the input variables or the operating condition of the plant is fixed.

3.4.1.2 ANOVA for modified unit electricity cost (MUEC) as a response variable

The summary of ANOVA considering modified unit electricity cost as a response variable is as follows:

$$R^2 = 0.9989, \text{ Adjusted } R^2 = 0.9978 \text{ and Predicted } R^2 = 0.9935$$

Both R^2 and Adjusted R^2 values for modified unit electricity cost are more than 90%, indicating the model can predict the response with high accuracy.

Table 6. ANOVA results for MUEC

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	0.0015	14	0.0001	888.94	< 0.0001 significant
A (Rp)	0.0001	1	0.0001	412.58	< 0.0001
B (ITAT)	0.0009	1	0.0009	6897.34	< 0.0001
C (j)	1.688E-06	1	1.688E-06	13.58	0.0024
D (Uf)	0.0005	1	0.0005	3966.96	< 0.0001
AB	0.0000	1	0.0000	197.24	< 0.0001
AC	1.225E-07	1	1.225E-07	0.9861	0.3376
AD	6.400E-07	1	6.400E-07	5.15	0.0395
BC	1.225E-07	1	1.225E-07	0.9861	0.3376
BD	4.000E-08	1	4.000E-08	0.3220	0.5794
CD	6.250E-08	1	6.250E-08	0.5031	0.4898
A ²	0.0001	1	0.0001	913.78	< 0.0001
B ²	2.602E-06	1	2.602E-06	20.94	0.0004
C ²	1.126E-10	1	1.126E-10	0.0009	0.9764
D ²	4.370E-06	1	4.370E-06	35.18	< 0.0001
Residual	1.739E-06	14	1.242E-07		
Lack of Fit	1.739E-06	10	1.739E-07		
Pure Error	0.0000	4	0.0000		
Cor Total	0.0015	28			

The ANOVA results considering modified unit electricity cost as a response variable are shown in **Table 6**. The Model F-value of 888.94 suggests the model is significant. p-values less than 0.0500 imply that the model terms are noteworthy. In this case, A, B, C, D, AB, AD, A², B², and D² are significant model terms. Values greater than 0.1000 imply the model terms are not significant. For MUEC, ITAT is the most dominant input variable having an F-value of 6897.34 and a p-value of less than 0.0001. Uf is the following impactful input parameter having an F-value of 3966.96 and a p-value of less than 0.0001.

The relation which estimates MUEC in terms of the input variables is as follows:

$$\begin{aligned}
 MUEC = & 0.345519 + 0.00174676 \times Rp - 0.000181 \times ITAT - 1.25185 \times e^{-6} \times j - \\
 & 0.19275 \times Uf - 4.125 \times e^{-6} \times Rp \times ITAT - 3.88889 \times e^{-8} \times Rp \times j + 0.000666667 \times \\
 & Rp \times Uf + 2.33333 \times e^{-9} \times ITAT \times j + 1 \times e^{-5} \times ITAT \times Uf - 1.66667 \times e^{-6} \times j \times \\
 & Uf + 0.000116204 \times Rp^2 + 6.33333 \times e^{-8} \times ITAT^2 - 7.40741 \times e^{-12} \times j^2 + 0.0820833 \times \\
 & Uf^2 \quad (64)
 \end{aligned}$$

Eq. 64 can be used to predict the modified unit cost of electricity for the plant for any given set of input parameters with adequate accuracy without having to do any simulation and post-simulation calculations.

3.4.2 Interaction effect of input variables on response

This segment discusses the interaction effect of any two input variables (keeping all other input variables constant) on the response.

3.4.2.1 Interaction effect of input variables on exergy utilization factor (EUF)

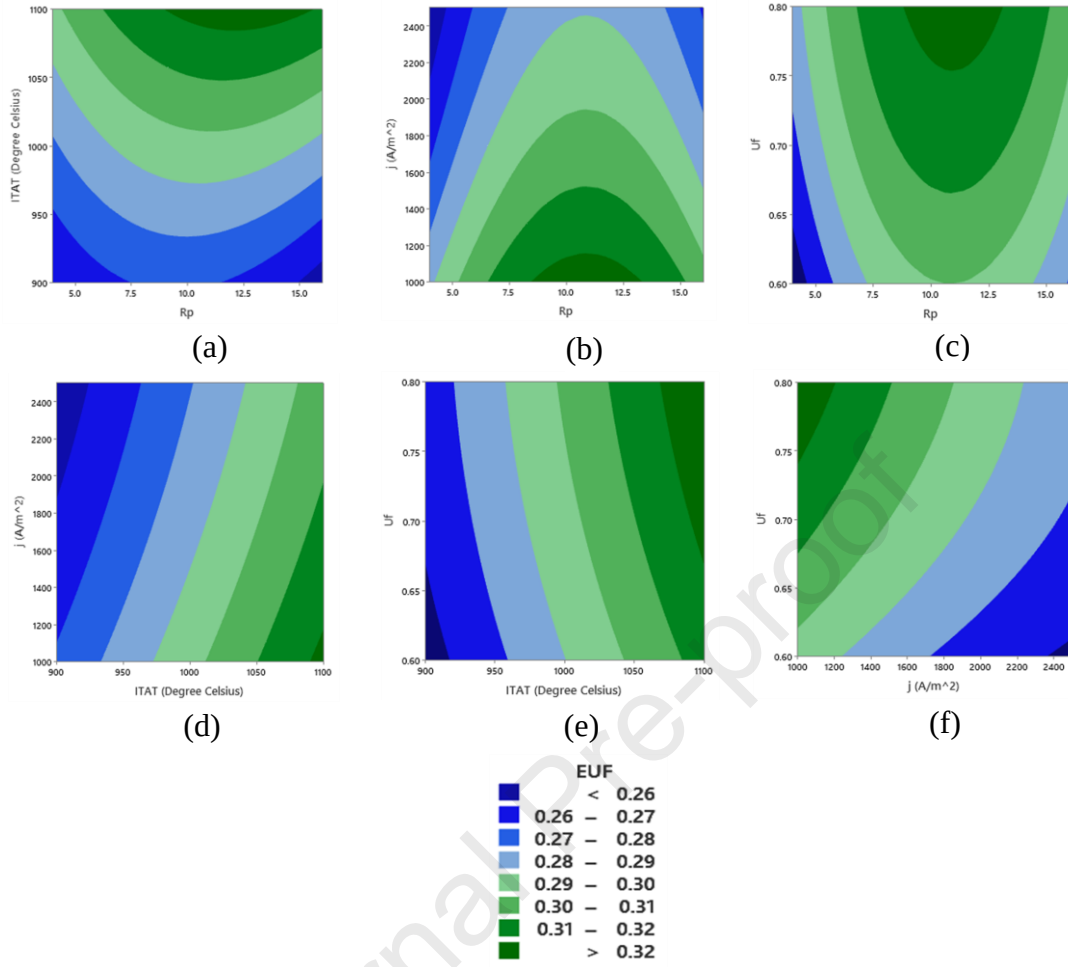


Fig. 6. Interaction outcomes of conceivable combination of input variables on EUF: (a) R_p , ITAT V/S EUF (b) R_p , j V/S EUF (c) R_p , U_f V/S EUF (d) ITAT, j V/S EUF (e) ITAT, U_f V/S EUF (f) j , U_f V/S EUF

Fig. 6 shows the interaction outcomes of all conceivable combinations of input variables on the exergy utilization factor. To check the interaction effects of any two input variables, other input variables are kept constant at the hold values ($R_p=10$, $ITAT=1000$ °C, $j=1750$ A/m² and $U_f=0.7$) as shown in **Fig. 6**. It is visible from all the interaction plots for the response EUF, the maximum value of EUF (more than 0.32) is obtained when the plant is operated at high ITAT (around 1100 °C) and low j (around 1000 A/m²). Subsequently, EUF between 0.30 to 0.32 is obtained when the plant is operated at; (a) ITAT more than 1050 °C and R_p more than 6, (b) ITAT more than 1020 °C over an entire range of j , (c) ITAT more than 1040 °C over an entire

range of U_f and (d) more than 0.75 of U_f and less than 1200 A/m^2 of j . So, from the discussion of the interaction effects of input variables on the exergy utilization factor, it can be concluded that the plant needs to be run mainly at a high ITAT value to utilize maximum input exergy.

3.4.2.2 Interaction effect of input variables on modified unit electricity cost (MUEC)

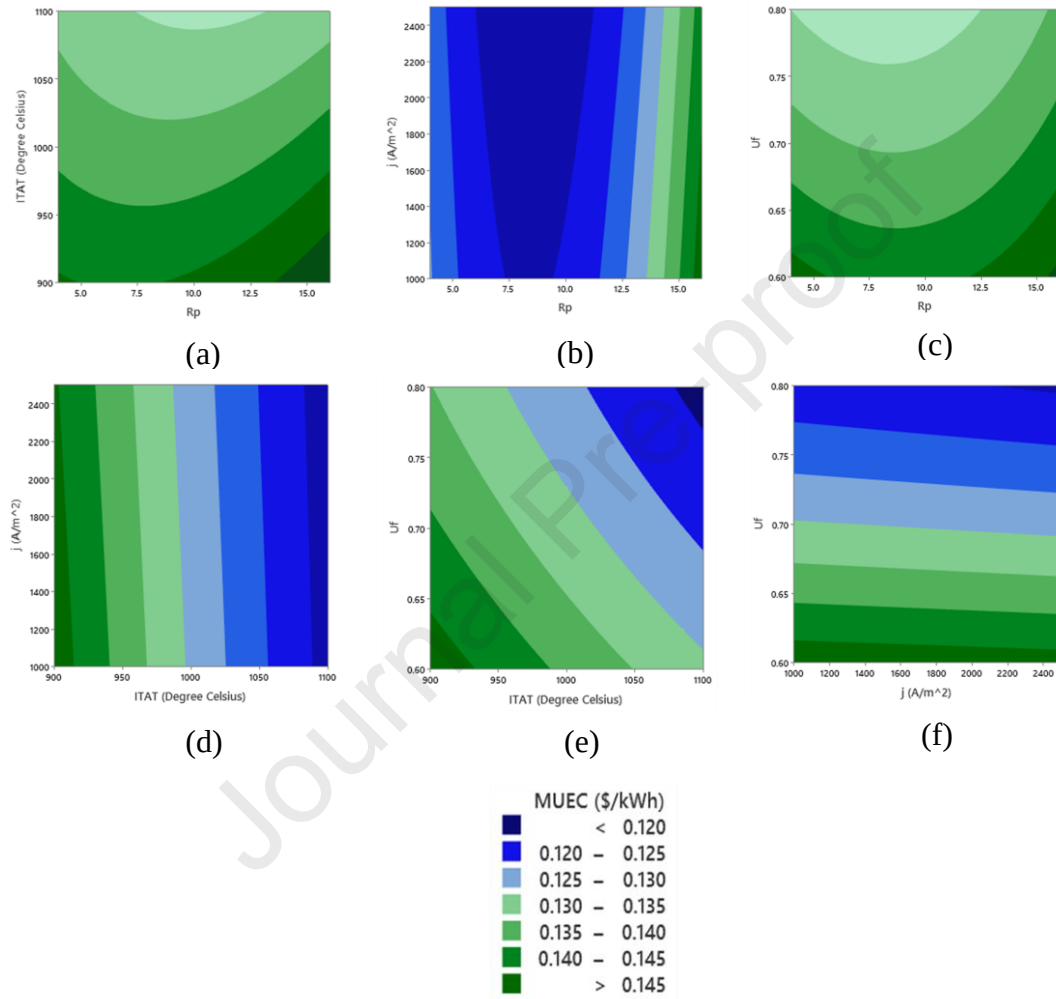


Fig. 7. Interaction outcomes of the conceivable combinations of input variables on MUEC:

(a) R_p , ITAT V/S MUEC (b) R_p , j V/S MUEC (c) R_p , U_f V/S MUEC (d) ITAT, j V/S MUEC (e) ITAT, U_f V/S MUEC (f) j , U_f V/S MUEC

Fig. 7 shows the interaction outcomes of the conceivable combinations of input variables on modified unit electricity cost. To check interaction effects of any two input variables, other input variables are kept constant at the hold values ($R_p=10$, ITAT=1000 °C, $j=1750 \text{ A/m}^2$ and

$U_f=0.7$) as shown in **Fig. 7**. It is visible from all the interaction plots for the response MUEC, minimum value of MUEC (less than 0.12 \$/kWh) is obtained when the plant is operated at high U_f (more than 0.77) and high ITAT (around 1100 °C). Subsequently, MUEC between 0.12 to 0.125 \$/kWh is obtained when the plant is operated at; (a) ITAT around 1100 °C and R_p ranging 7 to 13, (b) ITAT around 1100 °C over an entire range of j and (c) U_f more than 0.68 and ITAT more than 1020 °C. So, from the discussion of the interaction effects of input variables on modified unit electricity cost, it can be drawn that the plant needs to be run mainly at high U_f and high ITAT values to achieve minimum MUEC.

3.4.3 Optimization

Analysis of variance (ANOVA) is carried out after the design of experiments (DOE) is formed. The formation of DOE has been completed considering four input variables and a wide range was considered for each input parameter. R_p ranges from 4 to 16, ITAT ranges from 900 °C to 1100 °C, j varies from 1000 A/m² to 2500 A/m², and U_f varies from 0.6 to 0.8. The model run response parameters were evaluated at the specified set of operating parameters to complete the DOE.

The optimization has been performed considering the maximization of the exergy utilization factor and minimization of modified unit electricity cost. 0.3239 of EUF and 0.1186 \$/kWh of MUEC were found to be the optimum response variables. On the other hand, $R_p = 10.1128$, ITAT = 1100 °C, $j = 1412.64$ A/m² and $U_f = 0.799998$ is found to be the optimum operating condition, as shown in **Fig. 8**.

It is essential to carry out the desirability test to check the accuracy of the input variables and the optimization results. The desirability value ranges from 0 to 1. Closer the desirability towards 1, better is the optimization precision. It is witnessed in **Fig. 8** that the desirability

value of the combined response is almost 1, which shows the capability of the developed model to forecast the optimum response at the optimum operating state.

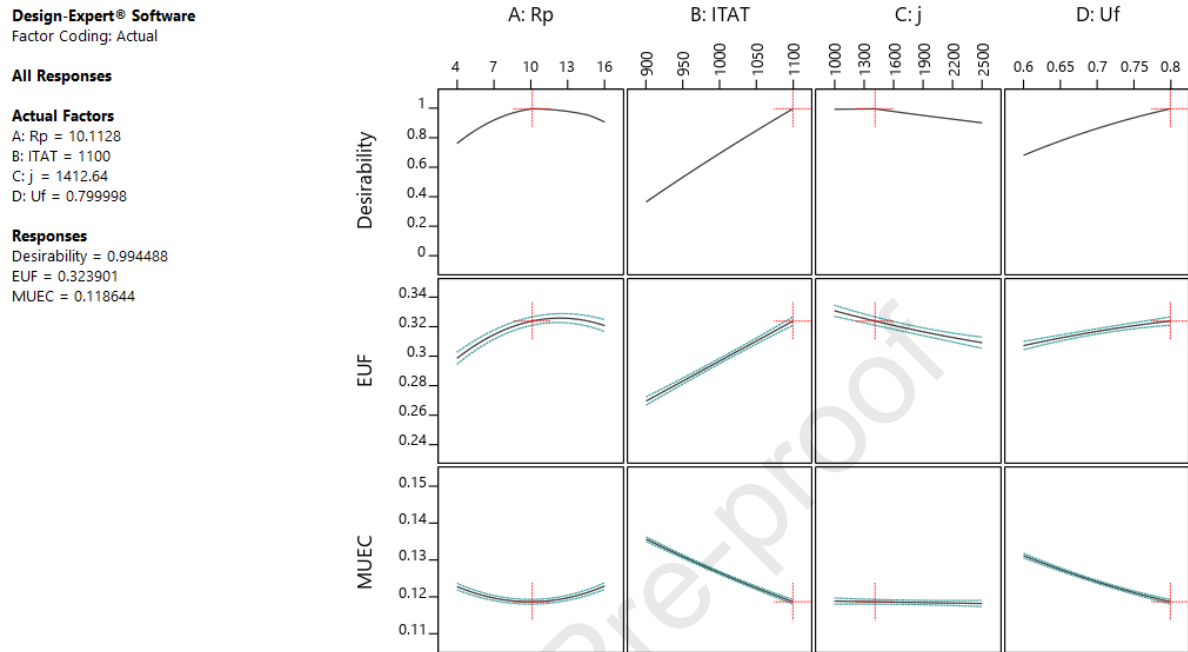


Fig. 8. Optimizer plot

A detailed confirmation-run or simulation-run has been performed at the optimum state of the plant to check the closeness of the results obtained by the model with the RSM predicted results. Very close agreement between the model-run results with the RSM predicted results implies the robustness of the developed model as well as the optimization methodology. The detailed confirmation results are listed in **Table 7**.

Table 7. Detailed plant performance at optimum operating condition

Parameters	Confirmation Results
$\dot{W}_{net}$	1791 kW
Refrigeration Capacity	283.29 TR
COP	0.5867

$\eta_{\text{eff elect}}$	40.86 %
EUFC	0.3248
MUEC	0.1188 \$/kWh
CO ₂ Cutting	1.517 M ton/yr
AEBC	0.2275 B\$/yr

3.4.4 Performance comparison

While there is hardly any similar work available on the basis of which the proposed plant's performance could be compared, some of the works based on biomass, considering CO₂ capture have been reported earlier. The reported works considered different configurations of biomass based power generation with various CO₂ capture techniques[33–36]. 23-35% (more than 40% only for select configurations) of electrical efficiency with 0.16-0.29 \$/kWh of unit electricity cost was achieved by the reported works. It is observed that very few of the works could reach the electrical efficiency level of more than 40%, and the proposed plant also easily outperformed the reported works economically with a unit electricity cost of 0.1188 \$/kWh.

4. Conclusions

In this study, a novel carbon-negative combined power and cooling plant has been conceptualized and a multi-dimensional analysis of the system is reported. Parametric deviation of the response variables with the variation in input parameters has been reported and optimization of the whole plant has been performed using RSM. The major findings of the study are stated as below-

- $R_p = 10.1128$, $ITAT = 1100\text{ }^{\circ}\text{C}$, $j = 1412.64\text{ A/m}^2$, and $U_f = 0.799998$ is found to be the optimum operating condition. 40.86 % effective electrical efficiency, 0.3248 of EUFC, and 0.1188 \$/kWh of MUEC were found to be the optimum response variables

when the plant is operated at the optimum operating condition. The CO₂ cutting at optimum operating condition was found to be 1.517 M ton/yr, and the environmental benefit due to CO₂ cutting is 0.2275 B\$/yr. While, the performance at the base case is obtained as 34.67% of effective electrical efficiency, 0.2729 of EUF, and 0.1315 \$/kWh of MUEC.

- A desirability test was performed, and the combined response desirability was found to be almost 1, indicating a brilliant outcome by the optimization process.
- A performance comparison of the developed model with published carbon-negative plants has been done, and the superior results shown by the developed model depict this work's potential for value addition in the field of carbon-negative system studies.

5. Future scope

This study deals with optimization of performance in terms of exergy utilization and unit cost of electricity of a unique carbon negative power and cooling plant considering a specific fuel type. Similar carbon negative multigeneration models, including material recovery could be proposed and analysed. In addition to that, fuel input type can also be varied (like considering municipal solid wastes) for the system to comprehend the proposed model's flexibility in operation.

Nomenclature

A_{cell}	Cell area (m ²)	OM	Operation and maintenance rate (\$)
A_{DE}	Annual electricity delivery (kWh)	OY	Years of operational
Adj MS	Adjusted average of squares	P	Pressure (bar)
Adj SS	Adjusted summation of squares	$\dot{Q}$	Heat flow rate (kW)

AEBC	Environmental benefit due to carbon capture per annum (million \$/year)	R	Universal gas constant (kJ/kmol-K)
A_{HEX}	Heat exchanger area (m ²)	R _p	Pressure ratio
ASU	Air separator unit	r	Response
AT	Air turbine	R^2	Regression coefficient
BP	Boiler pressure of steam cycle	S	Sulphur
BM	Biomass	s	Entropy (kJ/kg)
C	Carbon	Seq SS	Sequential sum of squares
$\dot{C}$	Cost (\$)	T	Temperature (°C / K)
CF	Capital utilization factor	TACC	Total annual CO ₂ capture (ton/year)
CEPCI	Cost Index for Chemical Engineering Plant	TYCP	Total yearly capital cost (\$)
D	Desirability	UEC	Unit electricity cost (\$/kWh)
DF	Degrees of freedom	U _f	Fuel utilization factor
DOE	Design of experiments	ν	Variable
E	Exergy (kW)	VM	Volatile matter
EC	Cost equation	V_N	Nernst voltage (volts)
EU _F	Exergy utilization factor	W	Power (kW)
F	Faraday constant (C/kmol)	Greek letters	
fn_{CRF}	Capital recovery function	ξ	Chemical exergy co-efficient
FC	Fixed carbon	η_{elect}	Electrical efficiency (%)
H	Hydrogen	$\eta_{eff\ elect}$	Effective electrical efficiency (%)
h	Specific enthalpy (kJ/kmol)	ζ_1	adjustment element for overnight cost

h_{fg}	Vaporization latent heat (kJ/kg)	ζ_2	adjustment element for the system cost
HX	Heat exchanger	ζ_3	adjustment element for engineering, construction and procurement cost
HHV	Higher heat value (kJ/kg)	Subscripts	
I	Current (Amp)	an	Anode
ITAT	Inlet temperature of air turbine (°C)	adj	adjusted
I_{yr}	Annual interest cost (%)	Aux	Auxiliary
j	Current density (Amp/m ²)	$biom$	Biomass
LHV	Lower heat value (kJ/kg)	ca	Cathode
$LMTD$	Log mean temperature difference (K)	ch	Chemical
$\dot{m}$	Mass flow (kg/s)	Dex	Destruction
M	Molar mass (kg/mol)	ex	exit
MUEC	Modified unit electricity cost (\$/kWh)	in	inlet
N	Nitrogen	out	outlet
N	Molar flow (kmol/s)	pred.	predicted
N_{cell}	Cell count in a stack	ph	Physical
N_{MCFC}	Stacks count	sys	System
O	Oxygen		

Data availability statement

All data generated or analysed during this study are included in this article.

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Appendix A

Table A. 1. Component wise 1st law analysis of the proposed plant

Name	Equation details	Eq. no.
G	$(\dot{m}_1 * LHV_{biomass}) + (\dot{m}_2 * h_2) + (\dot{m}_{21} * h_{21})$ $= (\dot{m}_3 * HHV_{syngas}) + (\dot{m}_{22} * h_{22})$	(2)
GCU	$(\dot{m}_3 * HHV_{syngas}) = (\dot{m}_4 * HHV_{syngas})$	(3)
FC	$(\dot{m}_5 * HHV_{syngas}) + \dot{W}_{FC} = (\dot{m}_7 * HHV_{syngas})$	(4)
CC	$(\dot{m}_{14} * h_{14}) + (\dot{m}_7 * HHV_{syngas}) = (\dot{m}_8 * h_8)$	(5)
HX	$(\dot{m}_8 * h_8) + (\dot{m}_{12} * h_{12}) = (\dot{m}_9 * h_9) + (\dot{m}_{13} * h_{13})$	(6)
AC	$(\dot{m}_{11} * h_{11}) + \dot{W}_{AC} = (\dot{m}_{12} * h_{12})$	(7)
AT	$(\dot{m}_{13} * h_{13}) = \dot{W}_{AT} + (\dot{m}_{14} * h_{14})$	(8)
MCFC	$(\dot{m}_9 * h_9) + (\dot{m}_{10} * HHV_{syngas})$ $= \dot{W}_{MCFC} + (\dot{m}_{15} * h_{15}) + (\dot{m}_{18} * h_{18})$	(9)
GC	$(\dot{m}_{18} * h_{18}) + \dot{W}_{GC} = (\dot{m}_{19} * h_{19})$	(10)
AB	$(\dot{m}_{19} * h_{19}) + (\dot{m}_{39} * h_{39}) = (\dot{m}_{20} * h_{20})$	(11)
FPH	$(\dot{m}_6 * HHV_{syngas}) + (\dot{m}_{20} * h_{20})$ $= (\dot{m}_{10} * HHV_{syngas}) + (\dot{m}_{21} * h_{21})$	(12)
OVG	$(\dot{m}_{22} * h_{22}) + (\dot{m}_{60} * h_{60}) = (\dot{m}_{10} * h_{10}) + (\dot{m}_{23} * h_{23})$	(13)
OVT	$(\dot{m}_{10} * h_{10}) = \dot{W}_{OVT} + (\dot{m}_{20} * h_{20})$	(14)
RCUP	$(\dot{m}_{20} * h_{20}) + (\dot{m}_{50} * h_{50}) = (\dot{m}_{30} * h_{30}) + (\dot{m}_{60} * h_{60})$	(15)
OP	$(\dot{m}_{40} * h_{40}) + \dot{W}_{OP} = (\dot{m}_{50} * h_{50})$	(16)
OCN	$(\dot{m}_{30} * h_{30}) + (\dot{m}_{70} * h_{70}) = (\dot{m}_{40} * h_{40}) + (\dot{m}_{80} * h_{80})$	(17)
MS	$(\dot{m}_{23} * h_{23}) = (\dot{m}_{24} * h_{24}) + (\dot{m}_{H2O} * h_{H2O})$	(18)
CCU	$(\dot{m}_{24} * h_{24}) + \dot{W}_{CCU} = (\dot{m}_{25} * h_{25})$	(19)
HRSG	$(\dot{m}_{15} * h_{15}) + (\dot{m}_{38} * h_{38})$ $= (\dot{m}_{16} * h_{16}) + (\dot{m}_2 * h_2) + (\dot{m}_{17} * h_{17})$	(20)

$$\begin{aligned} \text{GEN} \quad & (\dot{m}_{17} * h_{17}) + (\dot{m}_{28} * h_{28}) \\ & = (\dot{m}_{38} * h_{38}) + (\dot{m}_{29} * h_{29}) + (\dot{m}_{32} * h_{32}) \end{aligned} \quad (21)$$

$$\text{CON} \quad (\dot{m}_{32} * h_{32}) + (\dot{m}_{40} * h_{40}) = (\dot{m}_{33} * h_{33}) + (\dot{m}_{41} * h_{41}) \quad (22)$$

$$\text{RHX} \quad (\dot{m}_{34} * h_{34}) + (\dot{m}_{36} * h_{36}) = (\dot{m}_{35} * h_{35}) + (\dot{m}_{37} * h_{37}) \quad (23)$$

$$\text{EVAP} \quad (\dot{m}_{35} * h_{35}) + \dot{Q}_{EVAP} = (\dot{m}_{36} * h_{36}) \quad (24)$$

$$\text{ABS} \quad (\dot{m}_{31} * h_{31}) + (\dot{m}_{42} * h_{42}) = (\dot{m}_{26} * h_{26}) + (\dot{m}_{43} * h_{43}) \quad (25)$$

$$\text{SHX} \quad (\dot{m}_{27} * h_{27}) + (\dot{m}_{29} * h_{29}) = (\dot{m}_{28} * h_{28}) + (\dot{m}_{30} * h_{30}) \quad (26)$$

Table A. 2. Equipment price equations

Component	Cost equations	Ref.
Gasifier	$C_G = 1600 \times (\dot{m}_{fuel} \times 0.9 \times 3600)^{0.67}$	[10]
Gas cleaning unit	$C_{GCU} = 0.05 \times C_G$	[37]
Compressors	$C_{AC} = \frac{39.5 \times \dot{m}_{air}}{0.9 - \eta_{AC}} \times \frac{P_{out}}{P_{in}} \times \ln\left(\frac{P_{out}}{P_{in}}\right)$	[10]
MCFC	$C_{MCFC} = 2600 \times \dot{W}_{MCFC}$	[38]
MCFC auxiliary	$C_{aux,MCFC} = 0.1 \times C_{MCFC}$	[38]
Combustion chamber and after burner	$C_{CC} = \frac{46.08 \times \dot{m}_{oxidant}}{0.995 - \frac{P_{out}}{P_{in}}} \times \exp\left(\frac{18}{1000} T_{out} - 26.4\right) + 1$	[38]
Heat exchangers	$C_{HX} = 130 \times \left(\frac{A_{HX}}{0.093}\right)^{0.78}$	[38]
OVG	$C_{OVG} = 6570 \times \left(\frac{\dot{Q}}{LMTD_{OVG}}\right)^{0.78} + 21276 \times \dot{m}_{ORC} + 1184.4 \times (\dot{m}_{fluegas})^{1.2}$	[39]
Air turbine	$C_{AT} = \dot{W}_{GT} \times \{1318.5 - 98.328 \times \ln(\dot{W}_{AT})\}$	[38]

ORC Condenser	$C_{OCN} = 1773 \times \dot{m}_{ORC}$	[23]
Organic Vapour	$C_{OVT} = 6000 \times \dot{W}_{OVT}$	[23]
Turbine		
Heat recovery	$C_{HRSG} = 6570 \times \left\{ \left(\frac{Q_{ECO}}{LMTD_{ECO}} \right)^{0.78} + \left(\frac{Q_{EVAP}}{LMTD_{EVAP}} \right)^{0.78} + \right.$	[39]
Steam Generator	$\left. \left(\frac{Q_{SH}}{LMTD_{SH}} \right)^{0.78} \right\} + 21276 \times \dot{m}_{water} + 1184.4 \times (\dot{m}_{fluegas})^{1.2}$	
ASU	$C_{ASU} = 36.63 \times 10^6 \times \left(\frac{\dot{m}_{O_2}}{28.9} \right)^{0.7}$	[26]
CCU	$C_{CCU} = 682870 \times \left(\frac{\dot{m}_{CO_2}}{24} \right)^{0.6}$	[12]
VAR	$C_{VAR} = 1143.3 \times (\dot{Q}_{evap})^{0.67}$	[40]

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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