





Case Study

Techno-economic analysis and eco-efficiency indicators of a biomass-solar hybrid renewable energy system for João Pinheiro City

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Abstract

The study aims to rapidly scale up Hybrid Renewable Energy System (HRES) specifically emphasizing bioenergy generation for isolated rural communities. It aims to identify the most profitable and efficient configuration for HRES biomass-solar in João Pinheiro, taking advantage of local eucalyptus production to reduce costs associated with the transport of biomass waste, considering energy, economic and ecological indicators. Eucalyptus waste was chosen as the source of biomass as fuel, the Downdraft gasifier with air as the gasification agent, and monocrystalline silicon technology was selected for photovoltaic modules. Two case study scenarios were proposed based on global efficiency calculations. The techno-economic analysis was applied based on the First Law of Thermodynamics and the Levelized Cost of Electricity (LCOE) method. Case 2 showed the overall energy efficiency of 17.43% and LCOE 0.034 US\$/kWh more suitable for HRES solar-biomass technology. Additionally, the eco-efficiency indicator based on the calculated Net Present Value and ecological efficiency indicator, allowed evaluation of the relationship between added value and the environmental impacts associated with the studied configurations, with case 2 presenting $9.28e-05$ kgCO₂/US\$ as best result. The conclusions show that the techno-economic analysis applied to the HRES syngas-solar, along with the eco-efficiency indicator, presents the viability of decentralized bioenergy supply, particularly in isolated rural communities. This innovative approach encourages sustainable measures to meet energy needs in isolated regions with climatic, environmental and biomass supply conditions like those of João Pinheiro.

Highlights

- Overall efficiency of the Biomass-Solar HRES can range from 14% to 17.8%.
- Biomass-solar HRES makes LCOE smaller compared to isolated subsystems.
- The higher the pollutant indicator, the lower the environmental efficiency.
- Syngas has better eco-efficiency than diesel, and B20 biodiesel.
- Biomass-solar HRES can meet energy demands of isolated regions with local resources.

Keywords Hybrid · Biomass · Solar · Techno-economic · Eco-efficiency

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1 Introduction

The contemporary world suffers with energy consumption issues, particularly due to the rapid population growth, leading to increase counting on fossil fuels. However, depending on nonrenewable sources increases the risk of depleting finite energy reserves [1, 2]. Another concern arises from the unequal access to and consumption of energy, which is especially prevalent in remote areas where a substantial number of people are deprived of energy resources [3].

To achieve the Sustainable Development Goal (SDG) of universal to affordable, reliable, sustainable, and modern energy in a universal way [4, 5], making studies on energy sources increasingly attractive for the economy and industrial activities [6]. Recently, the World Bank reported that around 789 million people live without electricity, with 84.2% of these people living in rural areas isolated from the electricity grid [7]. Given this, rural electrification supports social and economic development by not only improving the quality of life through meeting people's health and education needs but also enabling the enhancement of fundamental activities in small rural industries. This includes extending the number of working days using lighting and irrigation, leading to increased productivity and, consequently, providing economic stimulus to the region [8]. On the other hand, that use renewable sources is considered a viable and efficient option for distributed energy generation in remote areas, such as photovoltaic systems and biomass gasification plants, since these areas have areas for installing panels, local irradiation and biomass resources available for exploitation [3, 9].

The Brazilian energy sector presents a diverse range of renewable sources, mainly due to the presence of an extensive Brazilian hydrographic basin [10]. According to the National Energy Balance (BEN, 2022), the Brazilian scenario presented a distribution of 78.07% in renewable sources (56.8% hydroelectric, 10.6% wind, 8.2% biomass, 2.47% solar) and only 21.93% of its energy matrix from non-renewable sources (12.8% natural gas, 2.2% nuclear, 3.9% coal, 3.0% diesel oil and fuels and 0.03% from other non-renewable sources) [11].

The renewable energy technologies are mature systems that allow the progressive replacement of conventional fossil technologies [12, 13]. However, due to economic issues, the feasibility and reliability of implementation may not be attractive when compared to conventional ones [14]. One of the possible solutions to reduce CO₂ emissions and address issues of economic viability is through Hybrid Renewable Energy Systems (HRES), which combines several technologies and Renewable Energy Sources (RESs) to implement the most suitable approach for each case, reducing intermittency problems and costs, meeting energy demands, and minimizing CO₂ emissions [15, 16]. Furthermore, HRES are growing at a fast pace, making them an interesting topic discussed by several authors [17–19].

Because of their abundance of resources and low environmental impact, biomass and solar energy are increasingly highlighted, researched, and promoted. Nevertheless, each has its own limitations and challenges. While solar energy is characterized by its intermittent nature, as it depends on sunlight and limits it as a daytime source, biomass faces the challenge of constant availability of resources at affordable values affected by seasonality [20]. However, the combination of these two energy sources is considered a solution where one complements the other in their efficiency weaknesses [21].

The main advantages of biomass-solar hybridization for practical applications include reduced space requirements for solar collectors and minimized biomass supply constraints, as the fixed plant size requires lower fuel input [22].

Recently, modeling with the Epsilon Professional software was applied by Roman [23], with the purpose of analyzing a hybrid generation system with a municipal waste gasification installation, photovoltaic system, and wind farm in order to meet a maximum power demand equal to at 10 MW. The hybridization factor for biomass technology was 55.41%, 35.05% for wind and 9.54% for solar. The net energy efficiency found based on the First Law of Thermodynamics was 16.70%. As a result of economic analysis, the results showed the cost of electricity varied from 0.115 to 0.240 \$/kWh, thus showing that the gasification of municipal waste can be used to adjust generation with demand, in addition to being economically advantageous [23].

Xue and Li [24] proposed in their studies the development of an energy generation system based on the co-combustion of agricultural biomass and dry sludge by solar energy. This integration is achieved by injecting heat collected from sunlight by parabolic trough collectors into the sludge dryer via the feed water. The total energy efficiency of the entire plant is 30.47%. The economic evaluation showed the levelized cost of electricity of 0.0834 \$/kWh, the payback is 3.73 years and the net present value of 34,806.00 kUSD achievable due to the incorporation [24].

The Hybrid Optimization Model for Renewable Energy (HOMER) was presented for Aditya [25], to find the most economical and energy efficient configurations for a hybrid system composed of photovoltaics, batteries and palm kernel biomass gasifiers, located in the remote village of Long Pahangai, in Indonesia. The hybridization factor for the solar energy system was 50.40%, and 49.60% for the biomass technology, with an energy efficiency of 16.70%

and LCOE of 0.163 \$/kWh, suggesting that a PV system -Diesel-Gasifier-Battery is the best ideal project for Long Pahangai in terms of energy cost [25].

The study carried out by Mouaky [26] showed the thermodynamic performance of a hybrid biomass-solar plant producing electricity, fresh water and domestic hot water (DHW) for a community of 40 residences located in the semi-arid region of Benguerir, in Morocco. Unlike the other cases, composite parabolic collectors and combustion boilers that use olive waste as biomass are combined sequentially to drive a 46 kW Organic Rankine Cycle and a reverse osmosis unit, with a solar energy hybridization factor of 11.42% and biomass of 88.58%. The overall energy efficiency of the plant was found to range between 11.35 and 16.32%, and the specific electricity costs found were 0.231 \$/kWh, being considered competitive in the off-grid context [26].

Recently, a techno-economic evaluation was proposed for Pantaleo [20] for a new configuration of a hybrid solar-biomass energy generation system composed of an externally driven gas turbine powered by 70% biomass (wood chips) and a bottom organic Rankine cycle, achieving heat recovery from turbine exhaust gases via thermal energy storage and heat integration from a field of parabolic collectors with molten salts as a heat transfer fluid. The results showed an energy efficiency of 29% and the LCOE of the proposed system is around 0.140 \$/kWh, with IRR is around 15%, based on Italian electricity subsidy tariffs [20].

A study conducted by Anvari [27] evaluates a combined cycle based on a new biomass-solar hybrid energy configuration to produce 13.4 MW of power in three sections (biomass section, solar section and steam turbine section), with respective hybridization factor: 8%, 49% and 43%. In order to estimate the economics of the proposed cycle, the calculated LCOE costs were 0.049 \$/kWh. The results showed that the addition of the solar section to the biomass-based system brings an increase of around 25% in energy production, with an energy efficiency of 29% [27].

Zhang [28] proposed, in his studies, a hybrid biomass-solar energy supply system, stating that for biomass technology, the combustion of agricultural waste was used, with a hybridization factor of 73.31%. For solar energy technology, parabolic collectors were used, with hybridization of 23.69%. To evaluate thermodynamic performance, the First Law of Thermodynamics was applied, obtaining average annual energy efficiency results of 25.18%. The system showed good profitability with a payback period of 5.15 years [28].

A comprehensive energy analysis in a hybrid solar-biomass and steam turbine system was studied by Anvari [29]. With the parametric evaluation, the effect of thermodynamic parameters on the overall performance of the system was verified by the First Law of Thermodynamics. The biomass chosen was wood, undergoing the thermochemical transformation process of gasification, responsible for 9% of production, while steam turbine technology was responsible for 38% of production. Solar energy technology used solar towers with a hybridization factor of 53%. The results indicated that when adding the solar unit to the biomass section, the power increases by 30%, obtaining an energy efficiency of 22.30% and an LCOE of 0.042 \$/kWh [29].

Two new hybrid solar-biomass energy generation systems are proposed, modeled and compared to each other by Sarkis [21]. The wood biomass is first gasified in a gasifier and then the syngas is used in a gas turbine power plant combined with a Rankine cycle. Solar energy is used in the bottoming Rankine cycle, where the first system uses it indirectly to heat the feed water before the deaerator, while the second system adopts solar energy in direct steam generation mode to generate additional steam for low temperatures. The hybridization factor of the first system is 91.48% and 8.52% for biomass and solar energy, respectively, while for the second system it is 64.44% and 35.56% for biomass and solar energy, respectively. The results of the economic evaluation, through the levelized cost of electrical energy and results of the energy analysis for the first and second proposed configurations were 0.0749 and 0.0799 \$/kWh and 45.06% and 40.12%, respectively [21].

A 2.1 MW and 960 kW hybrid solar-biomass combined heat and power system consisting of an externally driven 1.4 MW gas turbine and an Organic Rankine Cycle power plant with a capacity of 0.7 MW was evaluated techno-economically by Pantaleo [22]. The results reported an energy efficiency of 25% and levelized energy costs from about \$0.100/kWh to above \$0.220/kWh, along with net present values (NPVs) of about 13,000 to 3000 kUSD and internal rates return (IRRs) from 30% to almost zero when prioritizing the generation of electrical energy [22].

In previous studies, a variation can be observed for the values found in energy efficiency analysis studies of HRES biomass-solar, ranging from 11.35% to 45.06%, as well as for the values found in LCOE analyses, ranging from 0.042 US\$/kWh to 0.247 US\$/kWh. This is related to the variation in the hybridization factor in each case, variation in the type of biomass and solar technology applied, as well as the fact that in some studies they are optimized with the recovery of residual heat from the process, increasing the efficiency value found, compared to lower values from other studies.

Therefore, it is important to highlight that, despite continuous efforts to implement HRES biomass-solar technologies around the world, their technical–economic and ecological efficiency studies, no studies were found in the scientific literature that specifically address a combined technical–economic analysis, with an assessment of eco-efficiency indicators for HRES.

The main objective of this article is to evaluate energy, economic, and ecological aspects, and calculate the eco-efficiency indicator of a HRES biomass-solar generation process in a remote community without access to conventional grid electricity, and from this, fill the literary gap with the eco-efficiency indicator of the generation process calculated based on the net present value obtained by technical–economic analysis and the CO₂ emission factor, obtained by ecological analysis, so that in addition to the technical and economic indicators evaluated, there is also a survey of economic and ecological indicators for evaluation.

2 System description

The proposed system is a HRES that combines biomass and solar PV technologies. The biomass subsystem consists of a gasification technology coupled to an internal combustion engine and generator (gasification-ICEG). The gasification subsystem—ICEG includes a downdraft gasifier, heat exchanger, filter, internal combustion engine, and generator. Eucalyptus biomass is thermally converted in the gasifier at high temperatures, producing syngas. Subsequently, the syngas passes through the filter and heat exchanger before driving the 100 kW generator engine. In a hybrid configuration, the solar-PV subsystem comprises photovoltaic panels that convert solar radiation into electrical energy. The generated electricity is directed to the charge controller, then to the inverter, and finally stored in batteries before being supplied to the end consumer. Fig. 1 illustrates the flowchart of the HRES biomass-solar.

2.1 Gasification of biomass

Gasification is a thermochemical technology that converts biomass into a low calorific fuel gas called syngas, using an oxidizing agent [30, 31]. Syngas can then be utilized to produce heat or mechanical energy, powering systems such as internal combustion engines and gas turbines [32].

The downdraft gasifier model HBF– 300 W from Pulita New Energy Technology Co., Ltd. [33] has a production capacity of up to 100 kW, with an average consumption of 120–150 kg/h of biomass, offers advantages such as low tar production and minimal particulate matter, in addition to low cost and operational simplicity [35]. The hopper is fed with biomass from the top, while air is introduced from the side of the reactor at the top of the grate, and syngas is discharged below the grate. The biomass first enters the drying zone, where moisture is removed by rising heat from the oxidation zone. In the pyrolysis zone, thermal decomposition of biomass occurs in an inert atmosphere, producing tar and condensable and non-condensable gasses. Shortly thereafter, oxidation reactions provide energy for endothermic reactions in pyrolysis and the reduction zone. Finally, in the reduction zone, tar and carbonized material are converted into a gaseous product through a reaction with high temperature gases. This reduces the need for gas purification and makes the gas suitable for a wide range of applications [35].

The Cyclone Filter is an efficient filter even at high temperatures [36]. Its cylindrical shape with a conical base causes particle to be thrown against the wall by centrifugal force, then descend by gravity and are discharged by a rotary valve at the lower opening of the base. Clean syngas exits through the top opening [37]. Subsequently, syngas can be collected for analysis or directed into the gas–water heat exchanger and then into the ICEG. The HBF-300 W downdraft gasifier is

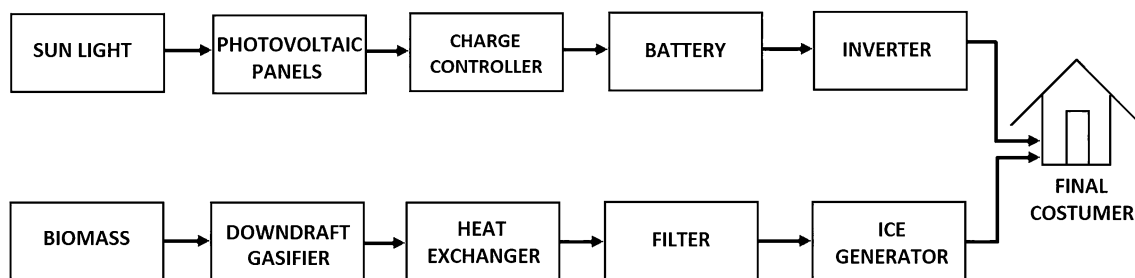


Fig. 1 HRES biomass-solar PV flowchart Source: Prepared by the author

Fig. 2 Downdraft Gasifier represented by a control volume diagram Source: Adapted of Copa et al. [36]

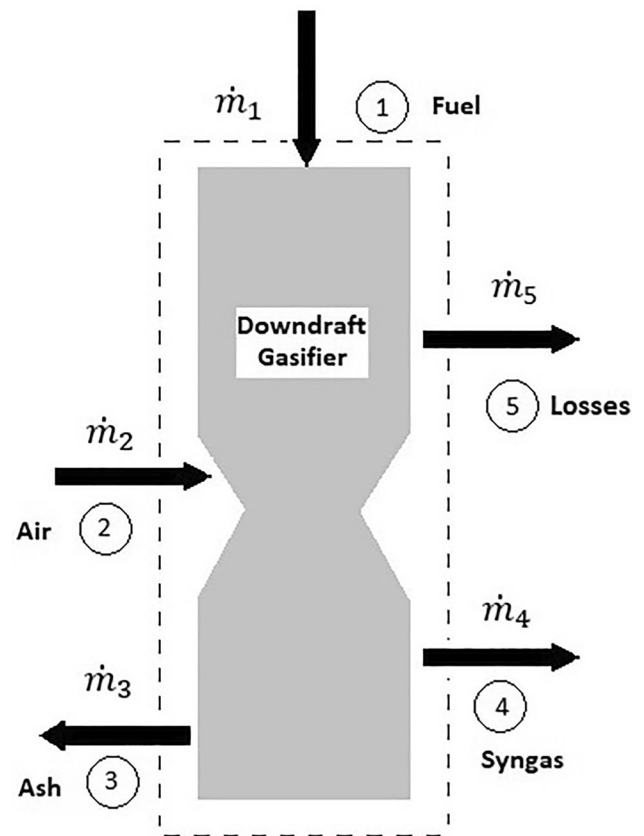


Table 1 Elementary and immediate composition of eucalyptus biomass

Eucalyptus			
Elemental composition (wt.%, Dry Basis)		Immediate composition (wt.%, Wet Basis)	
C	49.0	Moisture	11.3
H	6.3	Ash	0.8
N	0.2	Volatile matter	72.7
S	0.1	Fixed carbon	15.2
O (by difference)	44.4	LHV (MJ/kg)	18.4

Source: Adapted of Sales et al. [38]

supplied with 120 kg/h of biomass, with an estimated syngas generation of 398 m³/h [33]. Fig. 2 shows the control volume of the gasifier, and provided elementary and immediate composition values for the eucalyptus biomass, as shown in Table 1, as well as the calorific value of the synthesis gas (LHV) used in the calculations.

The Gas–Water Heat Exchanger employs forced convection to cool the gas through a large area in contact with water. It utilizes a “Cooler” type of heat exchanger, with one flow as the process fluid and the other as a colder utility, such as cooling water [39].

The double-tube heat exchanger consists of two concentric tubes, made of stainless steel material, with the inner tube measuring 0.012 m in diameter and the outer tube measuring 0.088 m in diameter. Synthesis gas flows through the inner tube, with an inlet temperature of 400 °C and an outlet temperature of 40 °C. Water flows through the annular portion between the tubes in countercurrent at a flow rate of 0.002 m³/s, at a temperature of 25 °C (ambient temperature) [39]. The cooling liquid (water) absorbs heat when it encounters the heated liquid tube (syngas) and, after condensation, drains back to the bottom of the heat exchanger [39]. This type of heat exchanger is simple, with a good heat transfer coefficient, suitable for high pressures, and easy to maintain [39]. Fig. 3 shows the control volume of the heat exchanger.

The ICEG group consists of an internal combustion engine coupled to an electrical energy generator [33]. The ICEG control volume is represented in Fig. 4 and the main characteristics of the generation system are shown in Table 2.

Fig. 3 Control volume of the heat exchanger. Source: Prepared by the authors

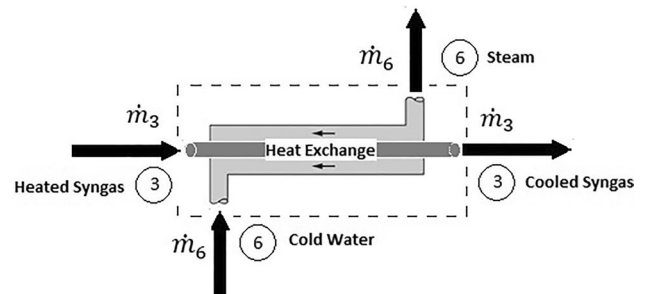


Fig. 4 Control volume of ICEG. Source: Prepared by the authors

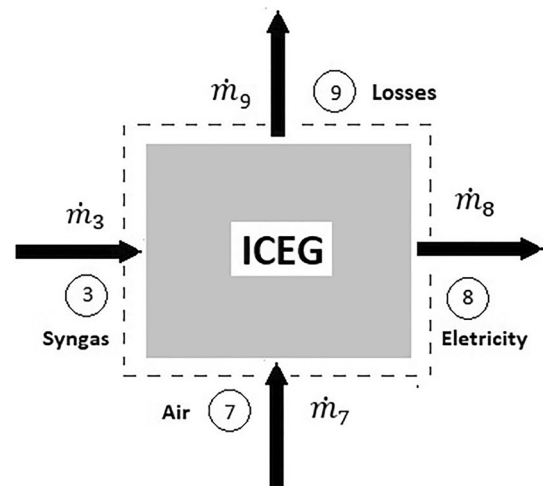


Table 2 Main technical parameters of the generator set

Generator model	HTG-100 GF
Rated power	100 kW
Rated voltage	220/110 V
Rated frequency	60 Hz
Rated speed	1800 rpm

Source: Adapted from Pulita Energy, 2022 [33]

The model of the motor-generator set was chosen based on a capacity and power of 100 kW in order to meet the demand of 80 kW. Also, the suggestion from the Pulita New Energy Technology Co., Ltd. catalog [33] was taken into consideration, together with the HBF-300W downdraft gasifier model.

2.2 Photovoltaic solar panel

Solar energy, as an abundant and clean source, is considered as a promising alternative to supply the existing energy demand [40, 41]. Its significant growth has improved its viability [42] and reduced system prices, providing competitiveness [43]. Fig. 5 shows the control volume of the photovoltaic array/panel module.

The photovoltaic module consists of photovoltaic cells, which are electrical devices that directly convert photon energy into direct current (DC) electricity through a chemical/physical phenomenon called the photovoltaic effect [44]. The inverter is responsible for optimizing the energy generated by the solar panels and efficiently transforming the electrical energy into the necessary format to inject it into the grid [45]. Batteries are used to store the surplus produced [45].

The technical specifications of the photovoltaic panels in this study are presented in Table 3.

Fig. 5 Control volume of the solar-PV panel. Source: Prepared by the authors

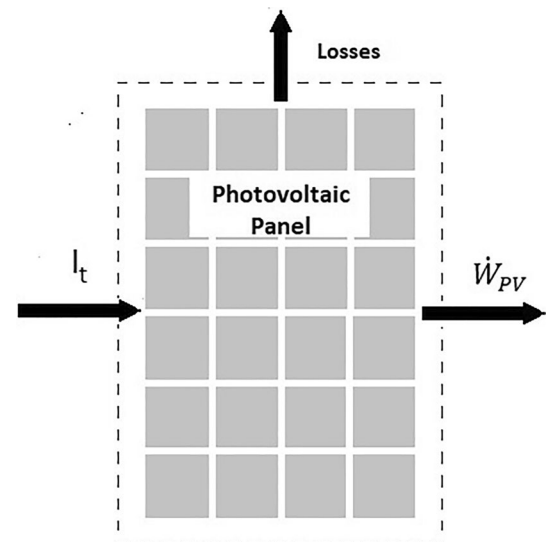


Table 3 Technical specifications solar panel

Technical specification solar panel CANADIAN SOLAR	
Model	CS3W-440
Module type	Monocrystalline
Efficiency of the photovoltaic set η_i	19.9%
Operating voltage	4.7 v
Unit area of the photovoltaic panel	2.21 m ²

Source: Adapted from (POWER; MONO; MODULE, 2015) [46]

2.3 Demand determination

The selected location for this study was João Pinheiro—MG city, which has been identified as one of the areas with the high number of households (331) without access to electricity from the grid in the state of Minas Gerais, according to IBGE's Population and Household Characteristics for the last 12 years [47]. João Pinheiro—MG is also recognized as the largest eucalyptus producer in Brazil, obtaining easy access to eucalyptus biomass residues at a lower cost due to the proximity of production [48].

Considering the IBGE CENSUS, which reports that a Brazilian family has an average of 2.79 people (considered 3 people for calculation purposes), the demand was calculated to meet 1/3 of the number of households without access to electricity which are located in nearby locations, with a total of 330 inhabitants (110 households). Considering a per capita consumption of 2612 kWh/inhabitant.year for the year 2021 in Minas Gerais State [49], with a total of 8760 h per year and considering a total of inhabitants, the proposed HRES biomass-solar needs to serve a demand of 98.4 kW. This demand will be met with 80% provided by the gasification-ICEG subsystem and 20% provided by the solar PV subsystem, since the area where the electricity generation plant is located has a large disposal of biomass and less space for solar collectors.

The hours of operation of the gasification-ICEG subsystem (H_g) were defined as 7608 h per year, considering that the plant operates in 3 shifts, 24 h a day, from Monday to Saturday, with Sundays reserved for maintenance equipment and staff rest [50]. The hours of operation of the solar PV subsystem (H_{PV}) were defined by Mahapatra [51], as 1902 h per year, with a significant electricity production averaging 6 h per day, considering an annual average solar irradiation from the inclined plane for the state of Minas Gerais equal to 4800 Wh/m² [52].

3 Methodology

The present study presents a techno-economic and environmental evaluation structure of two examined cases. The assessment was based on potential energy production, carbon footprint, life cycle cost and eco-efficiency analyses. Two cases were considered for analysis:

- Case 1—HRES without considering the thermal energy generated.
- Case 2—HRES considering thermal energy recovered from the exhaust gases of the internal combustion engine.

Case 2 uses heat from the generator engine's exhaust gases to dry the biomass, through a simple pipe, since an increase in humidity beyond the gasifier's design limits can cause instabilities in the system, such as a decrease in combustion temperature and loss of efficiency. Furthermore, increased humidity also harms the useful life of the system by forming deposits of undesirable chemical species [53].

3.1 Technical analysis

To analyze the production of electricity and evaluate the energy viability of the process, an energy balance was developed based on the principle of conservation of energy, the first law of thermodynamics. The energy balance can be written in simplified form as [54]:

$$\dot{Q} + \sum \dot{m}_{in} \times h_{in} = \dot{W} + \sum \dot{m}_{out} \times h_{out} \quad (1)$$

where, \dot{Q} is the thermal power, in kW; \dot{W} the electrical power, in kW; \dot{m}_{in} input mass flow, in kg/s; \dot{m}_{out} output mass flow, in kg/s; h_{in} the specific enthalpy of input (input), in kJ/kg; and h_{out} the specific enthalpy of output (output), in kJ/kg. The analysis will be applied to each component of the previously represented subsystems, delimited by the respective control volume.

3.1.1 Energy balance—biomass gasification

The energy balance for the gasification subsystem ICEG is based on the difference between the thermal powers at the entrance (from biomass and injected air) and the thermal powers at the exit (from syngas, ashes, and heat lost from the gasifier walls), as shown in Eq. (2) [54, 55].

$$\dot{E}_{bio} + \dot{Q}_{air} = \dot{E}_{syn} + \dot{E}_{ash} + \dot{E}_{loss} \quad (2)$$

To calculate the air flow that enters the gasifier, it is necessary to estimate the air/biomass equivalent ratio in the gasification process, it is known that this ratio is in the range of 0.19 to 0.43, for the present study it was adopted This is an equivalent ratio of 0.25, typical for a gasification process [56].

The fuel (eucalyptus biomass) energy input can be calculated considering the low heating value (LHV_{bio}) and mass flow rate (\dot{m}_{bio}) of the biomass, according to Eq. (3) [54].

$$\dot{E}_{bio} = \dot{m}_{bio} \times LHV_{bio} \quad (3)$$

The air power supplied to the gasifier (\dot{Q}_{air}) can be calculated considering the mass flow (\dot{m}_{air}) and the specific heat (Cp_{air}) of the air, and the difference between the heated air and the ambient temperature ($T - T_0$), as given by Eq. (4) [54].

$$\dot{Q}_{air} = \dot{m}_{air} \times Cp_{air} (T - T_0) \quad (4)$$

The syngas thermal power (\dot{E}_{syn}) can be calculated by using the mass flow (\dot{m}_{syn}) and the low heating value (LHV_{syn}) of the syngas, through Eq. (5) [54, 55].

$$\dot{E}_{syn} = \dot{m}_{syn} \times LHV_{syn} \quad (5)$$

The thermal power lost with the ashes (\dot{E}_{ash}) can be calculated considering the mass flow of the ashes (\dot{m}_{ash}) and the associated enthalpy (h_{ash}), considered equal to 538.28 kJ/kg [56] according to Eq. (6):

$$\dot{E}_{ash} = \dot{m}_{ash} \times h_{ash} \quad (6)$$

The cold efficiency of the downdraft gasifier is applied, since the gas is cooled during its conditioning, in which the output thermal power from the syngas is divided by the thermal input into the gasifier, from the biomass and injected air, as described in Eq. (7) [53, 54].

$$\dot{\eta}_{g-c} = \frac{\dot{E}_{syn}}{\dot{E}_{bio} + \dot{Q}_{air}} \quad (7)$$

Combustion engines have very low efficiency. According to [31], gasoline engines have an efficiency of approximately 20%. Of the losses, 10% are losses due to mechanical friction between engine components, and 65% are thermal losses, of which 30% are losses due to the interaction of gases with the combustion chamber wall, 35% are losses to the environment and approximately 5% of convection losses [57]. Therefore, the energy loss in the ICEG (\dot{Q}_{loss}) is calculated by Eq. (8) [54].

$$\dot{Q}_{loss} = \dot{E}_{syn} - \dot{W}_{ICEG} \quad (8)$$

The thermal efficiency of the ICEG (η_{ICEG}) is determined as the ratio between the output electrical power and the input syngas thermal power, as given by Eq. (9) [54].

$$\eta_{ICEG} = \frac{\dot{W}_{ICEG}}{\dot{E}_{syn}} \quad (9)$$

In the heat exchanger, the thermal power gained by the water (\dot{Q}_{H2O}) is equal to the thermal power lost by the syngas through convection. Thus, the thermal power lost from the syngas to the water in the heat exchanger can be calculated using Eq. (10) [54], and the Cp_{syn} considered is equal to 1.33 kJ/kgK according to [56]:

$$\dot{Q}_{H2O} = \dot{m}_{syn} \times Cp_{syn} (T - T_0) \quad (10)$$

3.1.2 Energy balance—photovoltaic solar panels

In the energy analysis calculation of the PV solar subsystem there is no mass flow involved, only energy. Therefore, all the energy that enters the system is equal to the energy that leaves in the form of electrical energy and losses associated with solar incidence. Equation (11) expresses the power delivered by the set of photovoltaic panels [55].

$$W_{pV} = \eta_i \times N_s \times A_s \times I \quad (11)$$

where W_{pV} represents the power delivered by the set of photovoltaic panels, η_i the efficiency of the photovoltaic set, N_s the number of photovoltaic modules (unit), A_s the area of a photovoltaic module (m^2) and I the global irradiation on an inclined plane (Wh/m^2).

3.1.3 HRES global energy efficiency

To calculate the energy efficiency of the system, the concept of the Eq. (12) [54] is applied.

$$\eta_T = \frac{\sum E_{out}}{\sum E_{in}} \quad (12)$$

The energy efficiency of the system in case 1 (HRES without considering combined energy and heat—CHP) is calculated through Eq. (13) [58].

$$\eta_{HRES} = \frac{\dot{W}_{ICEG} + \dot{W}_{PV}}{\dot{E}_{bio} + I_t} \quad (13)$$

were I_t represents the global irradiation on an inclined plane over the total area of the plates (W). On the other hand, the energy efficiency of the system in case 2 (HRES considering CHP and the sale of surplus energy) can be calculated applying Eq. (14) [54].

$$\eta_{HRES} = \frac{\dot{W}_{ICEG} + \dot{W}_{PV} + \dot{E}_{rec}}{\dot{E}_{bio} + I_t} \quad (14)$$

According to [59], the heat recovery system of an ICE is the subject of extensive research. This organic cycle is around 7 to 10% efficient, which leads to approximately 10% fuel savings when implementing this technology. For this study, the case of lower waste heat recovery efficiency was considered, with 7%, as shown in Eq. (15).

$$\dot{E}_{rec} = E_{gex} \times 0,07 \quad (15)$$

3.2 Economic analysis

Through economic analysis, it is possible to assess the feasibility of implementing a project for decision making. Several indicators can be used for this feasibility analysis, the most common are net present value, profitability index, internal rate of return, energy cost and initial capital cost of the system [55].

To make an economic comparison between the system proposed in this work and others in the literature, the LCOE generated by each system is estimated. LCOE is the most used indicator to assess the feasibility of any power plant and to compare different power generation technologies. It can be calculated as shown in Eq. (16) [21].

$$LCOE = \frac{CRF \cdot CI + C_{O\&M}}{PG_{liq_{yearly}}} \quad (16)$$

where CI represents the total investment cost of the system (US\$), $C_{O\&M}$ represents the annual cost of maintenance and operation, $PG_{liq_{yearly}}$ denotes the annual net power generation of the system; CRF is the capital recovery factor, which in turn can be calculated through Eq. (17) [21].

$$CRF = \frac{i_r \cdot (1 + i_r)^n}{(1 + i_r)^n - 1} \quad (17)$$

where i_r is the interest rate and n is the number of years the plant has been operating. The interest rate in this work is assigned as 12%, where 5% refers to Business Risk [60], 5% referring to Liquidity [61], and 2% referring to the opportunity cost SELIC rate (Special Settlement and Custody System) [62]. The number of years of operation in this work is assumed to be 10 years, according to the useful life cycle of the plant equipment [63].

The CI is related to the acquisition of all equipment for the gasification system—ICEG (gasifier, motor/generator, filter, and heat exchanger) and equipment for generating electricity from solar energy (solar panels and inverter). The correction factor of 1.23 refers to 23% refers to the cost of land preparation (5%), design and engineering costs (10%), contingency costs (5%) and permission (3%), adding up to 23% in relation to acquisition costs, as shown in Eq. (18) [64]:

$$CI = 1,23 (INV_g + INV_{PV}) \quad (18)$$

where INV_g refers to the capital investment cost of the gasification system—ICEG and INV_{PV} to the photovoltaic solar panel system.

The CO&M (Eq. 18) is determined as 4% of the IC, referring to the expenses required to operate and maintain the installation including costs for labor, materials, equipment, replacement, and repair of permanent equipment [65] as shown in Eq. (19).

$$C_{O\&M} = 0,04 \times CI \quad (19)$$

The expected annual revenue equations for the economic feasibility analysis with the commercialization of bio-electricity produced by the system are expressed in Eqs. (20, 21, 22) [66].

$$R_g = E_g \times H_g (C_{el} - C_{el_g}) \quad (20)$$

$$R_{PV} = E_{PV} \times H_{PV} (C_{el} - C_{el_{PV}}) \quad (21)$$

$$R_T = R_g + R_{PV} \quad (22)$$

E represents the energy produced (kWh) and H represents the total operating hours of each subsystem, with the subscript g for the gasification subsystem—ICEG and PV for the solar subsystem – PV. C_{el} is the the average value of tariffs for electricity trading companies in the studied region (US\$/kWh), and the subscripts g and PV correspond to the value of the cost of electricity produced in the gasification subsystem—ICEG and the solar subsystem—PV, respectively Finally, R is the annual revenue generated (US\$/year) from the HRES, and the subscripts g , PV and T correspond to the revenues of the gasification subsystem—ICEG (US\$/year), solar subsystem—PV (US\$/year), and total revenue of HRES, respectively.

According to the tax sector, depreciation (D_t) is a cost to be considered in revenue. For this, investment costs (CI) must be divided by the useful life (n) in years of the system, multiplied by the depreciation rate (R), as can be seen in Eq. (23) [67].

$$D_t = \frac{CI - R}{n} \quad (23)$$

The useful life and depreciation rate data are presented in Table 4, in accordance with Normative Instruction of the Federal Revenue of Brazil n° 1700 [63].

The MAT (minimum alternate tax) is the minimum return required for an enterprise. Its definition is of great importance in the decision making of investors [68]. For this study, a MAT of 12% per year was adopted, obtained at the rate of the Brazilian Special Settlement and Custody System (SELIC), in the year 2022 [69, 70]. Net present value (NPV) is an indicator of the present value of future payments discounted at an appropriate interest rate minus the initial cash flow [71]. The calculation of the NPV was based on Eq. (24).

$$NPV = \sum_{t=1}^n \frac{CF_t}{(1+i)^t} - CF_0 \quad (24)$$

NPV values provide an indication of the project's viability according to pre-defined parameters. When they present values greater than zero, they indicate a viable system, indicating the coverage of implementation and maintenance costs of the production system in question. When they present values less than zero, they indicate an unviable system, where there was a possible loss and decapitalization, not covering the costs involved in implementing the production system. In its calculation, CF is considered, which refers to the flow of cash value raised and spent by the project (US\$) during period t , defined as 1 year, in which the money will be invested (from the period in which the first cash flow occurs), n represents the number of periods, defined as 10 years, and i the average discount rate considered per year. [68].

Table 4 Useful life and depreciation rate of equipment

Equipment	Useful life	Depreciation rate %
Gasifier	10	10
Generator-engine	10	10
Heat exchanger	10	10
Solar Equipment	12,5	8
Battery	10	10

Source: Adapted from (INSTRU; RFB; MAR 2021) [63]

The internal rate of return (IRR) represents a hypothetical discount rate when applied to a cash flow, making the values of expenses, brought to present value, equal to the values of investment returns, also brought to present value, calculated by Eq. (25). The calculated IRR must be equal to or greater than the MAR for the viability of the project [72].

$$0 = \sum_{t=1}^n \frac{CF_t}{(1 + IRR)^t} \quad (25)$$

Payback (Eq. 26) is the time required for the recovery of an investment, which is used as a measure of attractiveness for investors [73].

$$\text{Payback} = \frac{\text{Initial Investment}}{\text{Gain in the period}} \quad (26)$$

For this economic feasibility study, the HRES bioelectricity sold to the local grid at a price of 0.1014 US\$/kWh, according to the Average Tariffs by Class of Consumption, from the Residential Consumption of the Statistical Yearbook of Electric Energy 2021 [48]. The plant's useful life was estimated at 10 years [49], and cash flows were projected considering bio-energy production per hours of operation and selling price. In addition, 18% of taxes on gross revenue were considered, including PIS (Social Integration Program); COFINS (Contribution for Social Security Financing), CSLL (Social Contribution on Net Profit), and ICMS (Tax Relating to the Circulation of Goods) [74], along with Income Tax (IT) of 34% on gross profit, which is the maximum amount allowed by law to be charged from any company in Brazil [63].

For the economic analysis, Table 5 presents the main financial data, such as investment costs, operation and maintenance costs, electricity cost, rates, and other financial assumptions. To ensure uniformity, all costs have been converted into dollars (US\$).

In this study, cost catalogs for the implementation of the gasification system and solar PV panels were used as the basis for investment cost budgets, so that this analysis can be closer to a real scenario.

3.3 Ecological analysis

3.3.1 Simulation of the combustion using GASEQ

A syngas presents the following molecular composition on a dry basis: $H_2=0.2489$, $CO=0.1967$, $CO_2=0.1014$, $CH_4=0.0094$, $N_2=0.4436$. Table 6 relates the initial conditions of reagents in the syngas combustion process in an ICEG at standard temperature pressure [80].

Through the simulation using GASEQ software, it was possible to evaluate the combustion reaction of syngas (Eq. (27)), with a molecular weight of 29.11 kg/kmol.

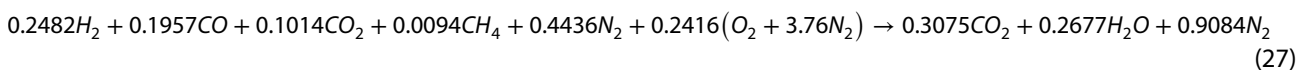


Table 5 Data considered in the economic analysis

Item	Value	Remarks	Refs.
INV_g (US\$/kW)	1159	Costs related to the acquisition of the downdraft biomass gasifier, heat exchanger, cyclone filter, internal combustion engine and generator	[75]
INV_{pv} (US\$/kW)	1000	Costs related to the acquisition of photovoltaic panels, controller, inverter, and battery	[76, 77]
C_{el} (US\$/kWh)	0.12	Electricity sales price for the state of Minas Gerais	[49]
$C_{O\&M}$ (%)	4	Operation and maintenance (O and M) costs are related to labor, material, equipment, supplies and spare parts, etc. and correspond to 4% of the total investment	[78]
i (%)	12	Average discount rate considered per year	[79]
Taxation (%)	18	Taxes on gross revenue, referring to: PIS; COFINS; CSLL and ICMS	[74]
IT (%)	34%	Income Tax on gross profit	[63]

Source: Prepared by the author

Table 6 Reagents in the combustion process in an ICEG

Syngas composition in dry basis	
H_2 (mol)	0.2489
CO (mol)	0.1967
CO_2 (mol)	0.1014
CH_4 (mol)	0.0094
N_2 (mol)	0.4436
MP (g/Nm ³)	10, 20, 30, 40
LHV (MJ/kg)	5.50
Air	
O_2 (mol)	0.2416
N_2 (mol)	0.9085
ICEG synthesis gas intake temperature (K)	300
Combustion temperature (K)	1952
ICEG Air intake temperature (K)	298

Source: Prepared by the author

3.3.2 Ecological Efficiency

Ecological efficiency (ε) allows you to evaluate the potential for air pollution, in accordance with existing air quality standards, taking into account the efficiency of converting fuel into energy, demonstrated by the Eq. (28) [81, 82].

$$\varepsilon = \left[c \frac{\eta}{(\eta + \Pi_p)} \ln(K - \Pi_p) \right]^n \quad (28)$$

where ε is the ecological efficiency of the HRES biomass-solar PV, when the number is equal to 1, the efficiency is maximum, and when it is equal to zero, it is considered inefficient; η represents the overall energy efficiency of the HRES biomass-solar PV; Π_p is the pollution indicator, in kg CO₂eq/MJ. For the constants c , K and n the values 0.204, 135 and 0.5 were considered, respectively referring to electricity production, in accordance with the literature [81, 82].

The pollution indicator, Π , is the sum of Π_{HT} and Π_{GW} , as in Eq. (34), given in $kg_{eq\ pollutant} / MJ_{fuel}$.

$$\Pi = 0.742\Pi_{HT} + 0.258\Pi_{GW} \quad (29)$$

Through this method, it is possible to estimate the human toxicity and the global warming indicators, as shown in Eqs. (30) and (31).

$$\Pi_{GW} = \frac{f_{CO_2eq}}{LHV_{fuel}} \quad (30)$$

$$\Pi_{HT} = \frac{f_{1,4DCBeq}}{LHV_{fuel}} \quad (31)$$

where Π_{GW} quantifies the emissivity of gases that contribute to global warming, [$kg_{eq\ pollutant} / MJ_{fuel}$] and Π_{HT} quantifies the emissivity of gases that contribute to human toxicity [$kg\ 1,4DCB_{eq} / kg_{fuel}$] [81, 82]. The equivalent emission factors for carbon dioxide (f_{CO_2eq}) and 1,4-dicholobenzene ($f_{1,4DCBeq}$) can be calculated through Eqs. (32) and (33).

$$f_{CO_2eq} = f_{CO_2} + 28f_{CH_4} + 265f_{N_2O} \quad (32)$$

$$f_{1,4DCBeq} = 4.54f_{SO_2} + 56.71f_{NO_x} + 38.75f_{PM} \quad (33)$$

The specie emission factor (f_{specie}) represents the emission factor of each species rising from the combustion of the air–fuel mixture, in kg_{specie} / MJ_{fuel} , determined by Eq. (34).

$$f_{specie} = \frac{n_{specie} \times W_{specie}}{n_{fuel} \times W_{fuel}} \quad (34)$$

where n_{specie} and n_{fuel} correspond to the number of moles of the species and fuel, respectively; and W_{specie} and W_{fuel} correspond to the molecular weight of each species and fuel, respectively.

3.3.3 Eco-efficiency calculation

The eco-efficiency indicator (EE) is an internationally used tool with a standard established in accordance with ISO14045:2012, being defined as the relationship between the value of the product/service offered and the proportional environmental impact. The definitions of both terms are established according to the applied context [84]. In this work, the NPV of the LCOE was used as a parameter for the product/service offered, which presented the total value for the two cases investigated. While for the proportional environmental impact parameter, the ecological efficiency studied was also used for cases 1 and 2 presented. Thus, the equation for eco-efficiency is defined as:

$$EE = \frac{f_{CO_2eq}}{NPV} \quad (35)$$

In order to compare the different cases investigated so that they are on the same scale, it is necessary to normalize the data, where the results are presented on a scale of values between 0 and 1, with 0 for the least favorable case and 1 for the most favorable case [85]. To obtain standardized results, the values obtained for eco-efficiency in Eq. (36) are applied.

$$EE_{normalized} = \frac{x_i - Min(x)}{Max(x) - Min(x)} \quad (36)$$

where $EE_{normalized}$ is normalized value of eco-efficiency; x_i is the eco-efficiency value calculated by Eq. (35) that we wish to compare; $Min(x)$ is the smallest value obtained from x (according to the other calculated); $Max(x)$ is the highest value obtained x (according to the other calculated).

The eco-efficiency helps to reveal the behavior between added value in the product/service provided and the respective environmental impacts of HRES biomass-solar configurations while it operates. According to the sustainability perspective, the objective of achieving the optimum state is the mitigation of environmental impacts and a considerable increase in economic value (complete decoupling between environment and economy) [83].

4 Results and discussions

In this study, the mass flow rate of syngas was calculated, and the energy efficiency and energy life cycle costs of HRES biomass-solar operating modes were determined. The CO_2 emission factor was calculated to obtain the ecological efficiency of the system and to determine the eco-efficiency indicator. According to the preset power required by the 20 kW photovoltaic panels, the dimensioning of the photovoltaic panel system was obtained with the number of modules equal to 48.

4.1 Technical analysis

The energy analysis was conducted using the first law of thermodynamics to analyze the distribution of energy fluxes in the gasification ICEG subsystem. The chemical and physical properties of the biomass, together with the biomass consumption in the gasifier, the volume flow of the heat exchanger, and the efficiency of the generator engine, were crucial for conducting the analysis. This allowed for the examination of the air flow and the syngas mass in the gasification process, as well as the combustion in the generator engine, and the mass flow of the exhaust gasses from the generator engine. The result of the energy balance with the respective mass fluxes of the analyzed components are presented in Table 7.

The power provided by the calculated biomass was calculated by multiplying its mass flow rate by the LHV of the eucalyptus with 592.6 kW of power, obtaining 646.47 kW of energy at the gasifier inlet, considering the air input for the combustion reaction in the gasifier. The power supplied by the calculated synthesis gas is equal to 442.67 kW, considering

Table 7 Main results of energy analysis

Gasification-ICEG Subsystem				
Pts	\dot{m} (kg/h)	P (kPa)	T (°C)	E (kW)
1	120.00	101.30	25	646.67
2	117.54	101.30	25	–
3	161.00	101.30	400	483.06
4	2.99	101.30	400	–
5	–	–	–	163.61
6	717.84	101.30	20	21.7
7	162.70	101.30	25	–
8	–	–	–	80.00
9	323.70	101.30	450	396.41

Source: Prepared by the author

a production given by the Pulita New Energy Technology Co., Ltd. catalog [33] of $0.1107 \text{ m}^3/\text{s}$ and a synthesis gas LHV of 4000 kJ/m^3 . As a result, the cold efficiency of the gasifier was calculated at 78%, considering the energy produced by the synthesis gas and the power provided by the biomass and air at the gasifier inlet, applying Eq. (7). The efficiency value calculated for the gasifier is in agreement with the values found in the literature of 75 to 80% efficiency [55], showing that the power provided by biomass and the energy produced by synthesis gas are at optimal values. In the heat exchanger there is a loss of thermal power calculated at 21.72 kW, due to convective heat transfer in the concentric tubes, absorbed by the cooling water. This loss value is considered necessary, since the syngas needs to lose energy to be at the ideal temperature of 40°C when feeding the internal combustion engine. Therefore, the power of the syngas at the input to the generator engine is 421.06 kW. Finally, the electricity delivered to ICEG is 80 kW, considering 10% losses due to mechanical friction, 30% losses due to exhaust gases, 35% losses to the environment and 5% losses due to convection. These calculations were performed with the application of the energy balance based on the first law of thermodynamics. The power provided by solar radiation is 106 kW according to area of 2.21 m^2 48 photovoltaic panels, and local solar radiation of 4800 W, with an efficiency of 19.9%, the power delivered by photovoltaic panels is 20 kW.

Figure 6 presents the Sankey diagram for the energy flow results, with Fig. 6a for the solar—PV subsystem and 6b for the gasification—ICEG subsystem.

The generated power rates of each subsystem vary according to the renewable energy source used and their corresponding process losses. The solar subsystem—PV consists of 48 monocrystalline silicon photovoltaic modules with an installed capacity of 20 kW. The conversion efficiency of photovoltaic modules depends on some factors, such as the type of photovoltaic material and the conversion efficiency of the cells ($\eta = 17\text{--}26\%$) [45], which is 19.9% in the present study, as shown in Fig. 6a. According to Comello et al. [44], photovoltaic panel technologies tend to become more attractive in the future due to the development of new technologies with better cost and performance.

The HBF-300 W downdraft gasifier is fed with 120 kg/h of biomass, with an estimated syngas generation of $398 \text{ m}^3/\text{h}$ [34]. The thermochemical conversion that takes place in the gasifier transforms the energy contained in the biomass into physical and chemical energy. The largest energy losses in this phase of the subsystem are due to solid residues (ash, tar, and others) and heat losses in the gasifier wall, accounting for about 25.3% of the total energy (Fig. 6b). The largest losses of this subsystem are the losses of the exhaust gases to the syngas burned in the ICEG, which account for 61.3%.

Fig. 6 Sankey diagram of the **a** solar-PV subsystem and **b** gasification-ICEG subsystem. Source: Prepared by the author

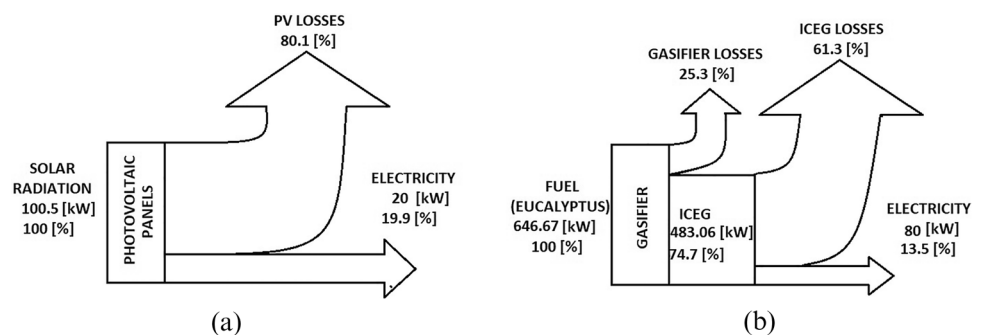


Fig. 7 Overall efficiency for the two considered cases. Source: Prepared by the author

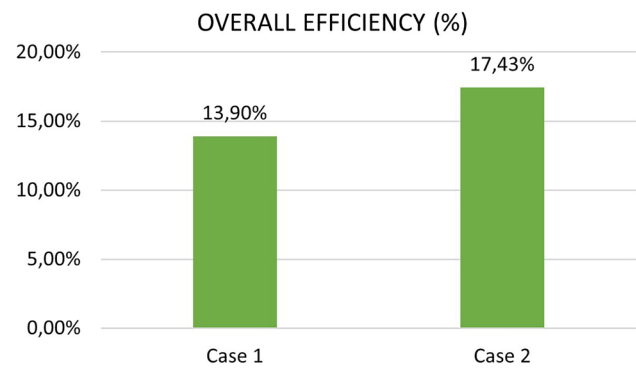


Table 8 Levelized Cost of Electricity calculated for each subsystem and for the HRES biomass-solar PV

$LCOE_g$	0.039 [US\$/kWh]
$LCOE_{PV}$	0.136 [US\$/kWh]
$LCOE_{HRES-case1}$	0.045 [US\$/kWh]
$LCOE_{HRES-case2}$	0.034 [US\$/kWh]

Source: Prepared by the author

The general efficiency of the system found of 13.5% can be considered an acceptable value, since this is close to the values found in the literature, which are around 14% [14, 30].

The calculations proved that it is possible to generate electricity from the conversion of eucalyptus biomass with a downdraft gasifier fed with syngas. However, due to the low LHV value of syngas, which is about 10 times lower compared to conventional fuels, there are power losses in the ICEG, which can range from 20 to 55% [56, 86]. A possible way to reduce losses is the implementation of a waste heat recovery system, increasing the total efficiency of the system, as proposed in case 2. Fig. 7 shows the global efficiencies for case 1 and case 2.

The overall efficiency of the HRES biomass-solar PV in case 1 was approximately 13.90%, being in the range of the lowest values reported in the literature review in the introduction of 11.35% [26], addressed in the introduction. For case 2, in which there is a recovery of 7% of the power of the exhaustion and the thermal power of water vaporization in the heat exchanger, obtaining an increase of 27.34% in relation to the general efficiency for case 1, having a final value of general efficiency of 17.43%, a value higher than that found in the literature by some authors of 16.70% [23].

4.2 Economic analysis

The economic analysis conducted in this feasibility study converts the cash flows and revenues generated from the production of electricity by the HRES biomass-solar into economic indicators. This enables to assess the feasibility of implementing the system based on the obtained results. The total investment cost of the plant (CI), including an additional 23% for equipment installation, was equal to US\$ 138,645.60, equivalent to 0.00227 US\$/kWh of total cost of maintenance and operation of the plant during operating hours, this value is within the range of the value calculated in the literature 0.00125 US\$/kWh–0.005 US\$/kWh, of a deal with [56]. The gasification subsystem—ICEG was responsible for most of the investment, representing approximately 66.88% of the total. However, the cost of producing electricity for this subsystem is lower compared to the solar-PV plant (Table 8).

This fact can be explained by the fact that the cost of producing electricity in a system is related not only to the investment value, but also to the hours of operation of the plant. The intermittent nature of the solar-PV system raises the cost of electricity production, while the subsystem powered by biomass gasification operates continuously and can deliver electricity at a more affordable cost. However, as both technologies were associated in an HRES, the final electricity production cost is compensated and reaches a satisfactory value.

Studies presented by Agyenim et al. [87] point out that the cost of producing electricity in a hybrid system (C_{el_HRES}) must be less than 0.16 US\$/kWh for it to be considered viable. While the works cited in the introduction shows that a HRES biomass-solar PV finds an electricity production cost between 0.042 US\$/kWh to 0.247 US\$/kWh. The values found in this work of 0.045 US\$/kWh and 0.034 US\$/kWh are relatively lower than those found in the literature and below that reported by IRENA 2020 (0.066 US\$/kWh). This is due to the use of eucalyptus residues as a source of biomass and raw

material to produce syngas, since the system is located in João Pinheiro, a region highlighted for being the largest in eucalyptus production in Brazil, providing a lower related cost. transport and acquisition of waste.

From this comparison and from an economic point of view, it can be said that the HRES biomass—solar PV proposal is feasible. In case 2, with the production of thermal energy and the marketing of the surplus energy, the LCOE value presented was even lower compared to case 1, proving that it is a viable alternative for access to clean energy in rural communities.

Economic viability was calculated based on cash flow and revenue calculation, according to Eq. (20, 21, 22). Table 9 shows the results of the NPV calculation, representing the net profit of the HRES during the 10 years of the project's useful life for cases 1 and 2. The results for IRR and Payback for cases 1 and 2 are also presented.

The results obtained meet the requirements of the literature [63], obtaining an NPV > 0 and IRR > MAR (24.07% > 12% and 33.96 > 12%). The results demonstrate that the NPV over the useful life of the HRES (10 years) is estimated at US\$ 74,578.30 for case 1 and US\$ 142,478.72 for case 2. This difference from case 1 to case 2 is related to the 27.34% increase in global efficiency, from case 1 to case 2, which means that, due to the greater amount of electrical energy generated, the annual gross revenue of case 2 is greater than that of case 1, and consequently, increasing the net present value of the plant. Furthermore, the proposed HRES IRR value is 24.07% for case 1 and 33.96% for case 2. Although the IRR value for case 1 was more than double the MAR, case 2 presented almost triple the MAR, which guarantees a better result. The payback time for case 1 and 2 were respectively: 5 years and 2 months and 3 years and 8 months. The Payback for case 1 is more than half of the useful life, while for case 2 it presented a value of approximately 1/3 of the useful life, obtaining a faster return on investment. Therefore, the values obtained from NPV, IRR and payback clearly show that the proposed HRES investment is economically viable for energy recovery from eucalyptus and consequent hybrid generation of bio-energy, an important alternative for access to clean energy in remote communities in Brazil.

4.3 Ecological analysis

The syngas was analyzed through the simulation of instruction 30 in the GASEQ software to evaluate the gas control indicators. Table 10 shows the simulation reagents and product specifications and product emission factors related to the global warming and human toxicity indicators that were determined through Eq. (29). Table 11 presents the ecological efficiency results, considering the variations in the values of particulate matter emissions presented. From this, the values of f_{CO_2eq} and $f_{1,4DCBeq}$ were determined by applying the Eqs. (32) and (33).

As can be seen, the f_{CO_2eq} values found are practically equal to the f_{CO_2} factor due to the number of moles of CO₂ resulting from its combustion, with negligible CH₄ and N₂O values. On the other hand, the $f_{1,4DCBeq}$ values found are relatively low. It is because of the null value of f_{S_2O} produced by the synthesis gas combustion and the low factor value of f_{N_2O} produced and low value of f_{MP} considered.

Finally, a comparison was made between the ecological efficiency obtained by Coronado et al. [88] of ecological efficiencies in internal combustion engines powered by different fuels (biodiesel B100 biodiesel in pure form and biodiesel B20- blended with diesel fuel, gasoline, natural gas, diesel) and the results obtained by Madeira et al. [89] for hydrogen and Lu et al. [90] for biogas and syngas fed into the ICEG of this work, which can be seen in Table 12.

The result showed that burning syngas presented results of 4.54% for case 1 and 0.29% for case 2 higher than those of Biodiesel B20, and 6.53% for case 1 and 2.17% for case 2 superior to diesel.

Diesel contains carbon dioxide, sulfur oxides and particulate matter as its main pollutants when burned. B20 biodiesel generally has the same or similar properties as conventional diesel oil, since 80% of its composition is pure diesel oil, with a slightly lower pollution rate than diesel [88]. Furthermore, Brazilian diesel oil, compared to American and European ones, has a high sulfur content, which raises a great concern when using it [88]. In this way, with

Table 9 Main results of the economic analysis

NPV_{case1} (10 years)	74,578.30 [US\$]
NPV_{case2} (10 years)	142,478.72 [US\$]
IRR_{case1} (10 years)	24.07%
IRR_{case2} (10 years)	33.96%
$Payback_{case1}$	5.14 [Years]
$Payback_{case2}$	3.61 [Years]

Source: Prepared by the author

Table 10 Reactants and products, and specie emission factors of the syngas combustion

Reactants	No. moles	Mol. weight	
CH_4	0.0094	16	
CO	0.1967	28	
CO_2	0.1014	44	
H_2	0.2489	2	
O_2	1.3520	32	
N_2	0.2416	28	
Products	No. moles	Mol. weight	f_{specie}
CO_2	0.3004	44	1.2449
CH_4	$1.193e^{-18}$	16	$1.7878e^{-18}$
N_2O	$5.861e^{-08}$	44	$2.4288e^{-07}$
SO_2	0	64	0
NO_x	0.0012	30	0.0034
MP	–	12	–

Source: Prepared by the author

Table 11 Results referred to the calculations of ecological efficiency, emission factors and pollution indicators

	$MP(kg/kg_{syngas})$			
	0.000010	0.000020	0.000030	0.000040
$f_{MP} (kg/kg_{syngas})$	$1.1302e^{-05}$	$2.2604e^{-05}$	$3.3906e^{-05}$	$4.5208e^{-05}$
$f_{CO2eq} (kg_{CO2 eq}/kg_{fuel})$	1.2449	1.2449	1.2449	1.2449
$f_{1.4DCB eq} (kg_{1.4DCB eq}/kg_{fuel})$	0.1927	0.1932	0.1936	0.1940
$\Pi_{GW} (kg_{CO2 eq}/MJ)$	0.2264	0.2264	0.2264	0.2264
$\Pi_{HT} (kg_{1.4DCB eq}/MJ)$	0.0350	0.0351	0.0352	0.0353
$\Pi (kg_{CO2}/MJ)$	0.0844	0.0845	0.0845	0.0846
$\epsilon_{case1} (\%)$	79.0782	79.0078	78.9974	78.9869
$\epsilon_{case1} (\%)$	82.3953	82.3860	82.3768	82.3675

Source: Prepared by the author

Table 12 Ecological efficiency variation in function of biogas, hydrogen, biodiesel B20 and biodiesel B100, gasoline, natural gas, diesel, and syngas

Fuel	Ecological Efficiency %	Refs.
Biodiesel B100	86.75	[88]
Biodiesel B20	78.79	[88]
Gasoline	82.52	[88]
Natural gas	91.95	[88]
Diesel	77.34	[88]
Hydrogen	93.73	[89]
Biogas	92.80	[90]
Syngas–case 1	82.39	–
Syngas–case 2	79.02	–

Source: Prepared by the authors

syngas surpassing the ecological efficiency of these fuels, it indicates that the proposal of this study is an alternative to reduce negative impacts on the environment and human health. Furthermore, syngas produced from eucalyptus biomass has a percentage of atmospheric CO_2 fixed during plant growth, which returns to the atmosphere after consumption, resulting in lower impacts on the environment.

Table 13 The eco-efficiency of cases 1 and 2 for the HRES biomass-solar PV and the normalized eco-efficiency result

	Case 1	Case 2
$EE(kg_{CO2_eq}/US\$)$	$1.77e^{-04}$	$0.93e^{-04}$
$EE_{normalized}$	0	1

Source: Prepared by the author

Table 13 shows the relationship between the calculated eco-efficiency resources that can be used to identify the best-case scenario.

When normalized, an eco-efficiency value close to 1 should be considered efficient from both an environmental and economic perspective. That is, the closer the eco-efficiency value is to 1, the better the performance. Case 2 achieved the best value in the calculation of the eco-efficiency index because the highest net present value offsets the CO₂ emission value. It is common to present the results in normalized form, and for this reason it is difficult to compare them with data from the literature.

4.4 Sensetive analysis results

An increase in the consumption of eucalyptus biomass in the gasifier increases the power in the generator engine. On the other hand, this increase in consumption directly influences the entire cost of the project and the gas emissions emitted during the combustion of syngas. To find out how the Power parameters in the generator engine, Global Efficiency, LCOE, NPV, Ecological Efficiency and Eco-efficiency behave, a test was carried out increasing the consumption from 120 kg/h to 150 kg/h of eucalyptus in the gasifier. Figs 8, 9 show the results for cases 1 and 2, respectively.

As can be seen, for both cases, with an increase in biomass consumption of 30 kg/h, they obtained an increase in generator engine power of 25%, with 100 kW of electrical power generated. However, there was a drop in the overall efficiency of 17.55%, with 11.46% for case 1 and 14.37% for case 2. NPV and Ecological Efficiency also suffered a drop

Fig. 8 Effect of biomass consumption on technical, economic, ecological and eco-efficiency analysis parameters for case 1. Source: Prepared by the authors

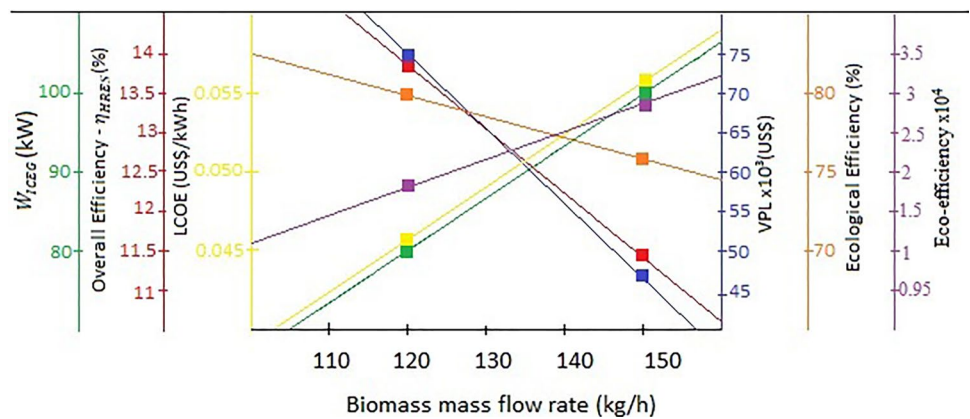
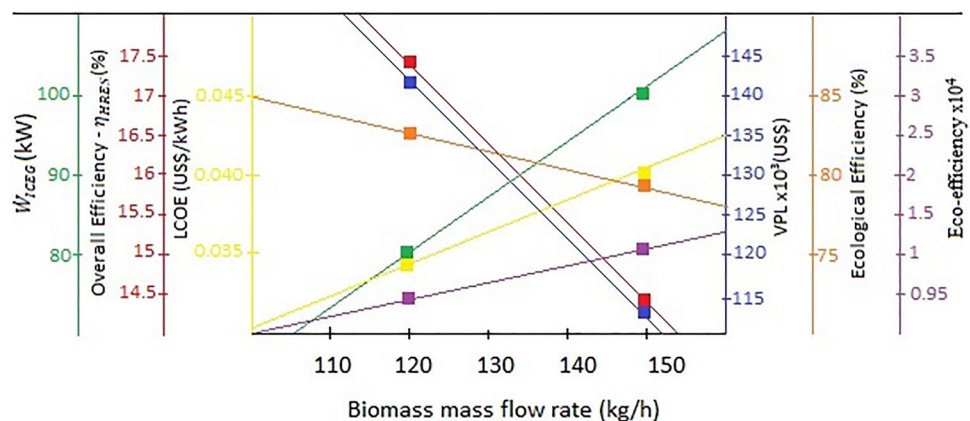


Fig. 9 Effect of biomass consumption on technical, economic, ecological and eco-efficiency analysis parameters for case 2. Source: Prepared by the authors



in their values, with US\$ 46,592.03 for case 1, with NPV results at US\$ 114,492.46 for case 2, a drop of 37.52% for case 1 and 19.64% for case 2. Ecological Efficiency demonstrated a drop in efficiency of 3.92% for case 1 and 3.63% for case 2.

The LCOE and Eco-efficiency results increased, which is not favorable. The LCOE increased generation costs from 0.045 to 0.054 US\$/kWh in case 1 and from 0.034 to 0.041 US\$/kWh for case 2, although being below IRENA data, as they suffer an increase, they may reduce the margin of competitiveness and attractiveness of the price of installing the generation plant. For eco-efficiency values, it is worth highlighting that the lower the environmental impact and the greater the economic return, the lower the eco-efficiency indicator. If the eco-efficiency indicator increases (as in the case of this sensitive analysis), it indicates a greater environmental impact and a lower economic return, which also compromises the viability and implementation of the electricity generation plant.

However, there is an attractive scalability of the generation plant to meet changes in demand and use with an increase in production capacity, because even if there is a decrease in global efficiency, the results for cases 1 and 2 are still within the values expected results found in the literature. Likewise, the increase in LCOE did not exceed IRENA data, which is still acceptable. And also the ecological efficiency, with 79.40% for case 2, still surpassing diesel and B20 biodiesel. This way, there is a guarantee that the system will be able to handle a greater number of users and transactions on demand.

5 Conclusions

The rapid expansion of Hybrid Renewable Energy Systems (HRES) globally has made bioenergy generation a promising solution for isolated rural communities. This study explores opportunities for adopting HRES biomass-solar technologies, considering energy, economic, and ecological factors. A techno-economic analysis was conducted to identify the most profitable and sustainable configuration. The theoretical system was implemented in João Pinheiro—Minas Gerais, Brazil, leveraging its significant eucalyptus production to reduce biomass waste processing costs.

The techno-economic analysis determined the most suitable energy efficiency and economic decision for the HRES biomass-solar technology, comparing Case 1 (without considering thermal energy) and Case 2 (considering thermal energy recovery).

The economic analysis revealed competitive and satisfactory costs, especially due to the association of solar PV energy with the biomass plant, which lowered electricity production costs. The calculated LCOE presented values of 0.045 US\$/kWh for case 1 and 0.034 US\$/kWh for case 2, both below the value given by IRENA and data presented in the literature, becoming economically attractive.

The ecological analysis compared ecological efficiency between burning syngas and burning fossil fuels in the ICEG. Syngas combustion showed better ecological efficiency (79% for Case 1 and 82% for Case 2) than burning fuels like diesel, and biodiesel B20, minimizing sulfur levels in the atmosphere with its replacement.

The eco-efficiency indicator provided a comprehensive view of environmental and economic performance, favoring Case 2 with the lowest value at 0.93×10^{-4} , since the lower eco-efficiency indicator indicates a lower environmental impact and a greater economic return, and thus affirms the viability and implementation of the electricity production plant.

In conclusion, the proposed HRES biomass-solar is a viable and efficient technology that meets the region's energy demands through locally available renewable resources. This innovative approach holds significant potential for sustainable energy solutions in isolated rural communities.

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Author contributions Below it is a description of the authors' contributions: First author: Camila Fonseca Chaves: responsible for the idea and elaboration of all stages of construction of the manuscript, including the project and Techno-Economic Feasibility Analysis and Eco-efficiency of the HRES plant for bioenergy generation. Second author: Vanessa Aparecida de Sá Machado: contributed to the revision of the manuscript in the calculation stage of economical viability. Third author: Ronney Arismel Mancebo Boly: advisor responsible to the theme of the manuscript, and for guiding and correcting all steps taken by the 1st author.

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Data availability The authors can confirm that all data generated and analyzed during this systematic review study are included in this article and cited in the references. All data collected and/or analyzed during this investigation have been reported in this article.

Cody availability Not applicable.

Declarations

Ethical approval and consent to participate. Not applicable.

Competing interests The authors declare no competing interests.

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