Highlights

Techno-economic assessment of a hybrid PV-assisted biomass gasification CCHP plant for electrification of a rural area in the Savannah region of Ghana

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- A PV-assisted biomass gasification hybrid system is optimized for a real case study
- Peanut shells are used to drive the gasification plant with an electrical efficiency of 18.2%
- CCHP efficiency reaches 62.0%, with 27.5 kW of hot water and 26.3 kW of cooling capacity
- The hybrid system saves 93.8% of CO_2 emissions compared to a diesel-based scenario
- Economic viability is highly sensitive to low diesel price and rising biomass costs

Techno-economic assessment of a hybrid PV-assisted biomass gasification CCHP plant for electrification of a rural area in the Savannah region of Ghana

Daniel Sánchez-Lozano[a], Roque Aguado[a,*], Antonio Escámez[a], Augustine Awaafo[b,c], Francisco Jurado[a], David Vera[a]

[a] *Departamento de Ingeniería Eléctrica, Escuela Politécnica Superior de Linares, Universidad de Jaén, Avda. de la Universidad s/n, 23700 Linares, Spain*

[b] *Electrical and Computer Engineering Department, University of Energy and Natural Resources, P.O. Box 214, Sunyani, Ghana*

[c] *NASCO Feeding Minds, P.O. Box 13, Sawla, Ghana*

Abstract

In rural areas of sub-Saharan countries, there is great potential for solar and biomass resources to achieve a reliable electricity supply, reduce the dependence on fossil fuels, and mitigate greenhouse gas emissions, thereby tackling energy poverty and promoting sustainable development. This work aims to address the lack of reliable electricity access in rural communities of sub-Saharan countries through biomass gasification assisted by solar photovoltaic (PV) energy and a small back-up diesel engine–generator set. The biomass gasification plant is designed to convert locally available agricultural waste into producer gas, which can then be used to generate electricity. A detailed analysis of the system components, including the PV array, battery system, biomass gasifier with a combined cooling, heat and power generation unit (CCHP), is carried out to evaluate their performance and efficiency under different operating conditions. The results reveal a CCHP efficiency of 62% for the gasification CCHP unit, accompanied by a remarkable 93.8% reduction in CO_2 emissions considering the whole hybrid system. From an economic standpoint under conservative assumptions, the proposed facility can generate a cumulative profit of \$157,890 after 20 years, recovering the initial investment within a period of just under 7 years. This is reflected in a levelized cost of electricity (LCOE) of \$0.287/kWh, comparable to that of related studies. The outcomes demonstrate that the PV-assisted biomass gasification plant offers a sustainable technical, economical and environmentally friendly solution for electrification of rural communities in sub-Saharan countries.

Keywords: Downdraft gasifier, Producer gas, Load profile adjustment, Off-grid electrification, Trigeneration, Sensitivity analysis

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*Corresponding author

Email addresses: dslozano@ujaen.es (Daniel Sánchez-Lozano), ramolina@ujaen.es (Roque Aguado), aescamez@ujaen.es (Antonio Escámez), augustineawaafo@gmail.com (Augustine Awaafo), fjurado@ujaen.es (Francisco Jurado), dvera@ujaen.es (David Vera)

1. Introduction

Power generation from non-renewable energy sources, especially fossil fuels, has received an increasing trend over the years globally in the attempt to satisfy the increasing global energy demand. However, the negative economic and environmental impact of the use of fossils for energy generation, as a result of the high import bills, price volatility, and greenhouse gas (GHG) emissions associated with fossil fuels cannot be underestimated [1]. In this regard, using renewable energy sources such as biomass, solar, and wind for power generation is gaining much attention in recent times for addressing the hostile impact of non-renewable energy sources on the planet, people, and profit [2]. In Ghana, the use of renewable energy sources for power generation is central to the achievement of the nationally determined contributions (NDC) and other international protocols such as the Paris Agreement.

The electricity sector of Ghana is highly dependent on fossil fuels. Biomass and solar are noted to be the most abundant renewable energy sources, which when appropriately harvested have the ability to exceed the country's electricity demand [3, 4]. In 2020, the electricity generation mix of Ghana was made up of 29.9% hydro, 69% thermal (fossil fuels), and 1.1% other renewables [5]. In the same year, the total landmark cover of agricultural biomass in Ghana was about 15.7 million hectares (ha), with cocoa, maize, cassava, yam, and plantain constituting the dominant agricultural value chain, accounting for 68.5% of the total land cover [6], generating enough residues that have the ability to meet about 92% of the total electricity demand of the country [3]. The total consumption of biomass in the same year was estimated to be about 2,977 ktoe, with 2,567 ktoe residential, 279 ktoe industrial, and 131 ktoe services consumption [7], implying biomass use in Ghana is unsustainable since most consumption comes from the residential sector in the form of charcoal and firewood for cooking. This comes with a lot of environmental and health challenges, especially on women and children [8], thereby calling for the need to consider investing in appropriate biomass conversion technologies for the production of energy in a more sustainable and environmentally friendly manner in Ghana. Crop residues, which are classified as second-generation agricultural biomass, are considered to be the largest agricultural waste produced in Ghana [3]. First-generation biomass such as jatropha, sunflower, sugarcane, and oil palm can lead to land grabbing and the resulting effect of food shortage when its plantation is considered for energy generation. Therefore, second-generation agricultural biomass like the residues of cereals, legumes, vegetables, wood processing, etc. must be given high attention in terms of bioenergy production [9, 10]. Meanwhile, Ayamba et al. [11] found the use of second-generation feedstock for energy in Ghana to be more expensive than first-generation feedstock and call for appropriate intervention to avert the situation. In view of this, hybrid solar PV and biomass power generation constitutes one of the alternatives for mitigating the high cost of biomass power generation, since solar PV is found to be one of the cheapest renewable energy sources in recent times, receiving a price drop of up 90% between 2010 and 2019 [12].

Biomass gasification is considered one of the most common and preferred thermochemical conversion technologies for obtaining intermediate fuel (producer gas) from biomass feedstocks such as agricultural residues, which can be fed into a generator set to obtain electrical energy [13, 14]. Gasification technology is more suitable for rural power generation due to the relatively small energy needs of these sectors and the flexibility in the generation capacity of the technology. In this thermochemical process, biomass enters the top of the gasifier, accompanied by air as the gasifying agent. Different gasification systems exist, including fixed-bed gasifiers (downdraft, updraft, and crossdraft) and fluidized-bed gasifiers [13, 15, 16], with downdraft fixed-bed gasifiers typically being considered the preferred option for small-scale (<100 MW) biomass gasification for electricity generation [17]. In the reactor, carbonaceous substances are heated to a temperature of about 1000 °C under atmospheric conditions to produce a gaseous product referred to as producer gas, consisting of CO, H_2, CO_2, H_2O, hydrocarbons, tar, and char [15, 18, 19]. The charcoal discharged from the gasifier as a byproduct may be stored or certified as biochar for a variety of applications, including its agronomic use as soil amendment. The producer gas exiting the reactor is dirty and at a high temperature, requiring it to undergo cooling and cleaning.

Aside from the abundant nature of solar and biomass, which serve as enough motivation for their consideration for electricity generation, their use for power generation has the added advantage of local job creation, thereby reducing poverty [20] and bridging the gap between rural and urban development, since power generation is usually localized [21, 22]. They also serve as a better option for power generation in rural areas, due to the costly nature of grid extensions to these areas and the fact that solar and biomass can be used to generate power locally without relying on the central grid [23]. In this regard, it is noteworthy that approximately 37% of the Ghanaian population still resides in remote areas and isolated communities lacking access to electricity due to the high costs involved in extending the national grid to these communities [24]. The northern part of Ghana is predominantly rural, with agriculture being the main economic activity, yet access to electricity in the northern region of the country is significantly low [24]. Therefore, this current study performs a technical and economic feasibility assessment of a PV-assisted biomass gasification plant to be installed in the Sawla–Tuna–Kalba district in the Savannah Region of Ghana. This study aims at utilizing residues from the most important food crops planted in the district, together with PV panels for combined cooling, heat and power (CCHP) generation in a selected rural community.

Some studies have emphasized the urgent need for electrification in isolated areas of sub-Saharan Africa, particularly in Ghana, to promote sustainable development and improve access to electricity through integrated renewable energy systems. Afonaa-Mensah et al. [25] proposed a hybrid system for electrification of remote areas in Ghana, consisting of a photovoltaic system, a diesel generator, and a battery system. Their results reveal that integrating renewable energy in off-grid areas reduces electricity costs; however, achieving parity with the national grid requires further interventions and government policies to promote the adoption of sustainable energy in rural communities. Odoi-Yorke et al. [26] explored the potential of a hybrid energy system combining solar PV and biogas with battery storage to provide electricity to remote areas in Ghana. They used the HOMER® software to evaluate the technical, economic, and environmental aspects of this hybrid system. Findings indicate that the PV/biogas/battery system is more cost-effective and environmentally friendly compared to PV/diesel/battery and diesel-only systems, with significantly lower carbon emissions. The levelized cost of electricity (LCOE) for the hybrid system is approximately 0.256 USD/kWh, which is higher than the current grid tariffs in Ghana but shows promise for future development, particularly with investment support. Awopone et al. [27] presented a feasibility analysis of a hybrid PV, diesel generator and battery storage system for rural electrification in northern Ghana using HOMER® software for simulation. The PV/diesel/battery hybrid system was identified as the most feasible, with an LCOE of $0.399/kWh and a net present cost (NPC) of $296,552. This system has a renewable energy penetration of 40% and excess power generation of 10.6%, with no capacity shortfall. Comparatively, the diesel-only system has a LCOE of $0.782/kWh and an NPC of $580,170, and poor environmental performance. It is concluded that with adequate capital subsidies and reasonable tariffs, hybrid systems can be a viable solution for rural electrification in Ghana. Ansong et al. [28] conducted a technical and economic assessment of a hybrid electric power supply system for an off-grid mine in Ghana. The hybrid system generates 152.99 GWh annually, with solar PV providing 44%, the fuel cell 40%, and diesel 14%. The mine's load consumption is 127.75 GWh per year (87% of total production), and the remaining energy powers the electrolyzer for hydrogen production. With system costs and constraints considered, an LCOE equal to $0.212/kWh is reported, which is over 28% lower than the current approved tariff for mines in Ghana.

Only a limited number of studies have investigated hybrid systems incorporating biomass gasification technology in Ghana. Awafo et al. [24] underscored the importance of renewable systems to reduce agricultural waste in northern Ghana, highlighting biomass gasification as a solution. Tostado-Véliz et al. [29] presented a methodology for determining the optimal size of hybrid power plants integrating biomass gasifiers, diesel engine–generators, and PV arrays for electrifying isolated areas. Applied to an off-grid agricultural community in Ghana, their findings demonstrated that biomass gasification allows reducing project costs by over 90% and CO_2 emissions by 83% compared to using only diesel engine–generators. The gasification plant operates as base load generator, meeting a substantial part of the local demand. Finally, Arranz-Piera et al. [30] investigated the technical and financial feasibility of decentralized electrification based on agricultural waste gasification in five Ghanaian agricultural communities. They proposed installing a 17 kW biomass gasification CHP plant, along with a 90 kWh lead-acid battery system, 5 kVA bidirectional inverters, and a monitoring system. Their findings revealed that, like many biomass electricity projects, achieving profitability with 100% private funding is challenging. However, they found that a subsidy covering approximately 35% of the initial investment could yield a 15% internal rate of return (IRR) for private entrepreneurs, while a 60% subsidy could increase the IRR to 25%.

Despite the aforementioned efforts, research on hybrid systems for electrifying remote areas using local biomass resources through biomass gasification remains relatively scarce in literature. This work aims at presenting a significant advance, by conducting a comprehensive investigation into the electrification potential of a rural community in Ghana. It incorporates trigeneration as a key aspect, aiming to maximize energy efficiency and sustainability. Additionally, the study relies on the biomass gasification technology to leverage the agricultural waste produced locally, presenting an innovative approach to addressing energy challenges in remote off-grid areas. While previous studies have primarily considered hybrid systems combining photovoltaics, diesel generators and occasionally biomass gasifiers, this study explores the integration of CCHP systems to deliver electricity, heating and cooling simultaneously. Moreover, this original approach addresses the diverse energy needs of remote communities in sub-Saharan regions more effectively through technoeconomic and detailed sensitivity analysis of a CCHP system based on an internal combustion engine fueled with producer gas, a LiBr absorption chiller, and heat exchangers. By filling this literature gap, this study aims to provide a robust framework for sustainable energy solutions to improve the quality of life in rural sub-Saharan Africa.

2. Methodology

This work follows a methodological approach that can be divided into several sections. Initially, the case study is introduced, followed by an estimation of the biomass potential of crops planted in the district, and the physicochemical characterization of the biomass residues that serve as the feedstock for the gasification CCHP plant. Afterward, the solar potential of the study location is also introduced. Subsequently, the measurement procedure for determining the load profile of a rural community in Ghana is included. Finally, the process simulation approach and the description of the governing equations used for evaluating the performance of the biomass gasification CCHP plant are presented.

2.1. Case study

The Tuna community, in the Sawla–Tuna–Kalba (STK) district of the Savannah Region of Ghana, is selected as a case study location for this study. Tuna is a highly populated community and the second most populous in the STK District. As shown is Fig. 1, Tuna is geographically positioned approximately 26 km north of Sawla, the district capital, at a latitude of 9°29'18.28" N and a longitude of 2°25'51.02" W, just west of the N12 highway.

Data from the 2020 Ghana Population and housing census (PHC) indicates that the total land area of the district is estimated to be about 4,173 km^2 with a population of 112,664 [31]. The district is agricultural-dominated, with about 97.1% of the population engaged in crop farming and 64.4% engaged in animal farming as their major source of income. Over 58% of all crop production in the Savannah region comes from the STK district, making it the major food supplier in the district [32]. In terms of energy access, the energy statistics by the Energy Commission of Ghana indicate that the Savannah region has the lowest electricity access rate in Ghana, with regard to population and household electricity access rates which is 60.1% and 59.5% for population and household access respectively [7]. Also, the STK district is noted to be the district with the lowest electricity access rate in the Savannah region, which is pegged at 31% residential access rate [33].

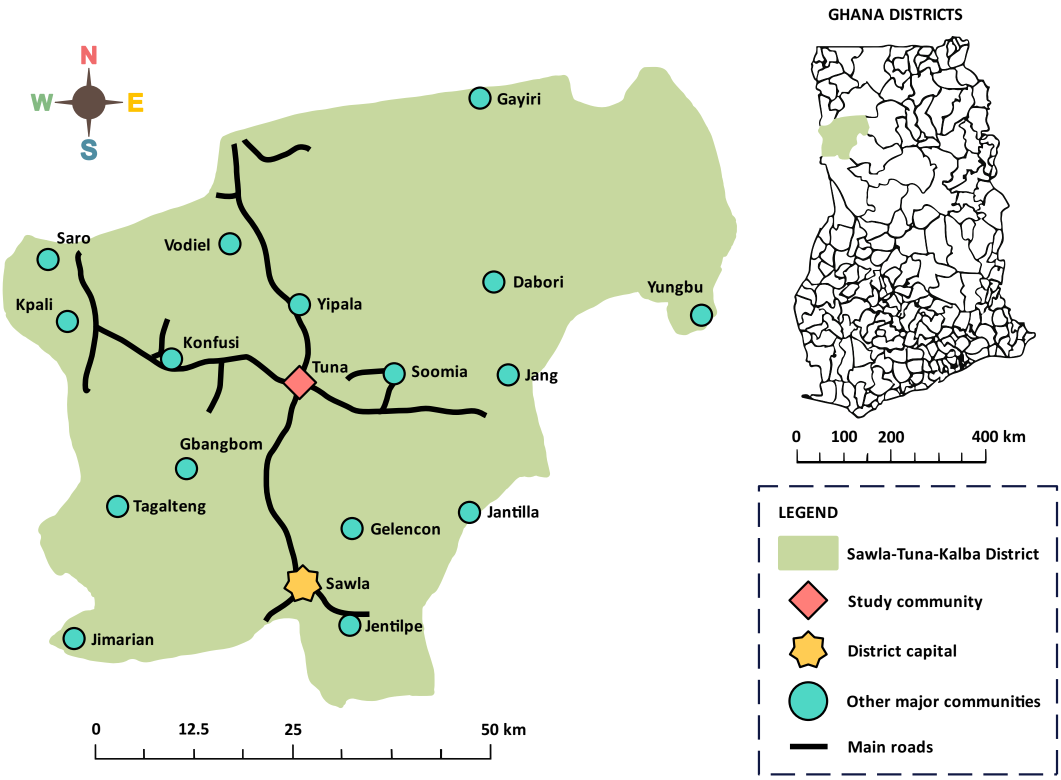

Figure 1: Administrative map of STK district, where the Tuna community is located.

In terms of energy supply, the Tuna community currently faces two major challenges, which are power supply insecurity and high energy bills. Aside from the challenges faced by this community in terms of energy supply, the district report of STK states that the major challenge faced by the agricultural sector of the district is the decreasing crop yield due to soil nutrients depletion, which is caused by overuse of agrochemicals, tree felling for fuel wood or charcoal, overgrazing, and bush burning [24].

To address the challenges faced by the agriculture and energy sector of the STK district, a biomass gasification plant supported by a solar PV system is proposed as a solution for CCHP generation using locally produced biomass wastes as a fuel source. Subsequently, the hybrid PV-assisted gasification plant is economically and technically demonstrated through a case study at Tuna.

2.2. *Biomass feedstock assessment*

In Ghana, various types of agricultural waste can be viable options as potential feedstock for the gasification process, including cassava, sorghum, yam, and peanut [34]. This paper focuses on peanut shell as feedstock to the gasification plant due to their highly advantageous properties for utilization in thermochemical processes.

The peanut industry constitutes a significant contributor to waste within the agri-food sector [35]. In many African nations, the common waste management practices following peanut crop harvesting involve incineration, land disposal, or incorporation into soil. Despite its prevalence, incineration notably exacerbates air pollution concerns [36]. Residues from peanuts, including the leaves, straw, and shells have no commercial value in Ghana, hence farmers usually leave the leaves and straw in the field [37]. The leaves and straws of peanuts are sometimes also used as feed for cattle, goats, and sheep. However, when it comes to peanut shells, there is no identified use for them. Farmers usually send their peanuts with the shells to the crushing machines to remove the peanuts from the shells. The shells then become unwanted waste at the machine site, which is usually disposed of and burned. Moreover, small-scale farmers often face low profitability and yield during harvests [38]. Therefore, there is a pressing need to reconsider the value of peanut by-products, such as the shell, which possess favorable physicochemical properties suitable for thermochemical conversion applications. These initiatives could foster a market for peanut shells, thereby enhancing the financial viability of small agricultural communities.

Although relatively smaller in size compared to other African countries, Ghana has a significant annual peanut production. According to the latest data from the Food and Agriculture Organization of the United Nations (FAO) in 2022, Ghana's annual production value (excluding the shell) reaches 611,000 tonnes, positioning Ghana as the fifteenth largest peanut producer worldwide [39].

The annual production of shelled peanuts allows for the estimation of the annual residue production from this crop using a parameter known as the residue-product ratio (RPR). This parameter represents the relationship between the mass of a specific type of residue generated by the crop and the useful part or the actual product of the crop. This parameter can be used for determining the residue yield of a particular crop [40]. Mawusi et al. [34] reported an RPR of 2.08 for groundnut production, which includes shells, husk and straw. By contrast, Kemausuor et al. [40] and Ayamga et al. [11] reported a lower RPR value of 0.35, focusing solely on peanut shells. Therefore, it is estimated that on average, between 2018 and 2022, Ghana produced approximately 193,342 tonnes of peanut shells. The Savannah is the major peanut producing agro-ecological zone in Ghana. It accounts for 94% of the total peanut production in the country. Indeed, peanut shell production is concentrated in the former Northern region of Ghana (including the current Northern, Savannah and North East regions), with 20.1 kt (dry weight) per year available for bioenergy [3]. This quantity of crop residue is projected to double by 2050 [34].

Table 1 includes the proximate analysis, ultimate analysis and heating values of peanut shells, as characterized by Perea Moreno et al. [35], with highly advantageous properties for utilization as feedstock in thermochemical processes. This is attributed to their relatively high heating value, comparable to that of other biomass fuels such as olive pits [35].

Table 1: Physicochemical properties of peanut shells [35].

Proximate analysis (wt.%)	
Moisture content (wet basis)	5.79
Ash content (dry basis)	4.16
Volatile matter (dry basis)	82.44
Fixed carbon (dry basis)	13.40
Ultimate analysis (wt.%, dry basis)	
Carbon	46.42
Hydrogen	6.61
Nitrogen	0.50
Sulfur	0.54
Oxygen	41.77
Heating values (MJ/kg, dry basis)	
Lower heating value (LHV)	17.101
Higher heating value (HHV)	18.547

2.3. Solar resource assessment

In Ghana, the average solar radiation is estimated to be around 4.5 to 6.0 kWh·m^{-2}·day^{-1}, with the highest annual and daily sunshine hours of 3000 h and 7.7 h respectively being recorded in the northern belt of the country in areas such as Bawku, Navrongo, Bolga, Wa, Sawla, etc., which is mostly dry and sunny and the minimum annual and daily sun hours of 1800 and 5.3 h respectively recorded at the southern and middle belts of the country like Kumasi, Accra, Sunyani, Cape Coast, etc, which is mostly cloudy [33, 41].

The daily global horizontal irradiance (GHI) for the typical meteorological year (TMY) obtained from the National Renewable Energy Laboratory (NREL) [42], specifically from the National Solar Radiation Database (NSRDB) [43], is presented in Fig. 2. This bar graph indicates that the STK district receives a high GHI rate, ranging from 4.9 to 6.2 kWh·m^{-2}·day^{-1}. These high values make the Tuna community favorable for PV power generation. As evidenced in Fig. 2, the period from February to May presents the greatest potential for photovoltaic production capacity in the Tuna community, whereas July demonstrates the lowest potential, as it coincides with the rainy season in the Savannah region of Ghana [26].

Another important aspect highlighted in Fig. 2 is the clearness index (K_t), a variable that indicates atmospheric conditions and changes in global radiation caused by various factors [44, 45]. The expression for calculating the monthly value of the K_t is shown in Eq. (1) [46].

$$K_t = \frac{G_T}{G_0} \tag{1}$$

where G_T is the monthly average global horizontal radiation and G_0 the extraterrestrial horizontal radiation, meaning the radiation on a horizontal surface at the top of the earth's atmosphere, both expressed in (kWh·m^{-2}·day^{-1}).

From this expression, it is evident that a high K_t indicates clear skies and high atmospheric transparency, resulting in a greater amount of solar radiation reaching the Earth's surface. For the

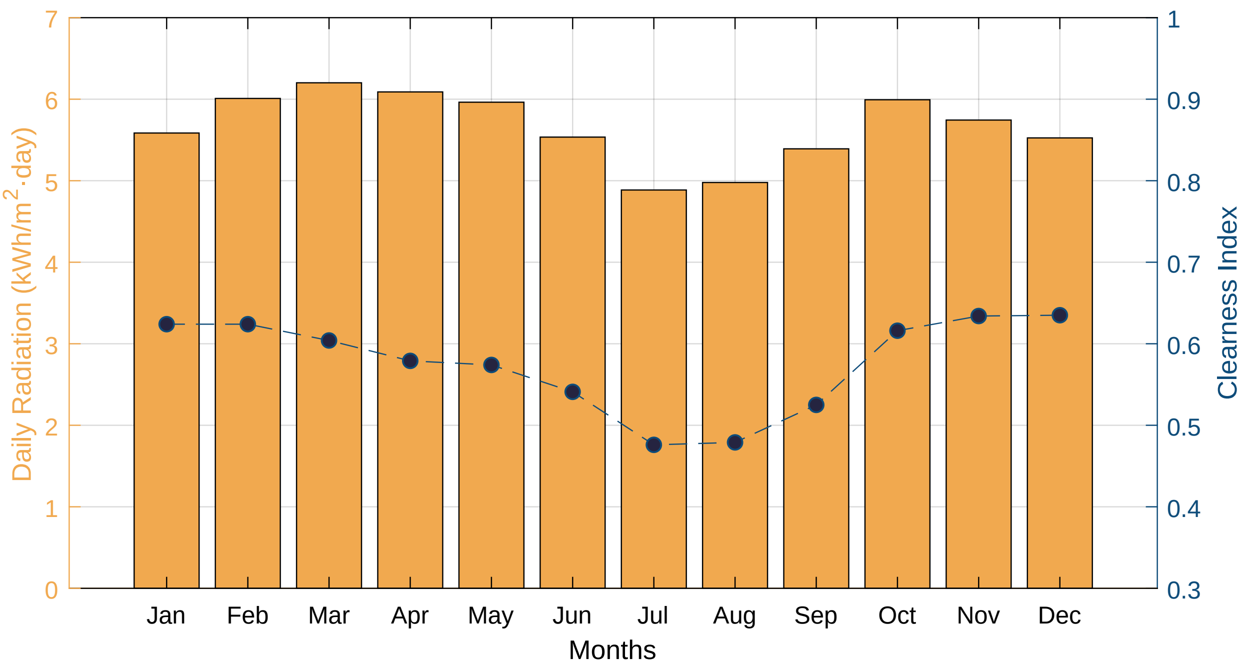

Figure 2: Daily GHI of Tuna community according to NREL databases [43].

Tuna community, the values of clearness index range between 0.48–0.64. As shown in Fig. 2, the clarity index is lower during the summer months, attributed to increased cloud cover.

2.4. Load profile estimation

A thorough analysis of the energy consumption patterns by considering the operating hours, power consumption, and peak power demand of the various appliances and equipment is essential for understanding the energy requirements and optimizing the energy distribution in a system. The power demand was determined by conducting a comprehensive inventory of all electrical energy-consuming devices. Additionally, discussions with the local population helped estimate the usage hours for each individual appliance. Fig. 3 shows the relative distribution of power demand by type in the Tuna community.

2.5. System description and process modeling

Currently, electricity generation at the Tuna community is carried out using an 80 kVA (64 kW) diesel generator, resulting in significant environmental pollution and greenhouse gas emissions, as well as high costs associated with fuel procurement. In order to address these concerns, an integrated hybrid power system is proposed (see Fig. 4), which consists of a CCHP gasification plant fueled by peanut shells, a PV system, a battery storage system, and a small-size back-up diesel engine–generator set (genset) for peak demand supplementation. This setup aims to reduce pollution and greenhouse gas emissions by generating electricity in a more sustainable manner.

Peanut shells fuel a downdraft gasifier to produce a lean fuel gas termed producer gas, which is subsequently cooled and cleaned downstream in a conditioning unit. The conditioned producer gas is then used to drive the genset, where electricity is produced, and high-temperature exhaust gases are released through the engine exhaust. These exhaust gases are directed to an absorption chiller for production of cooled water at 7 °C. Furthermore, the jacket cooling system of the generator set is used for production of sanitary hot water (SHW) at 60 °C. The biomass gasification CCHP plant serves as the primary power generation unit of the hybrid system. Secondly, to leverage the available solar resources in the area, PV panels are considered to cover consumption during peak

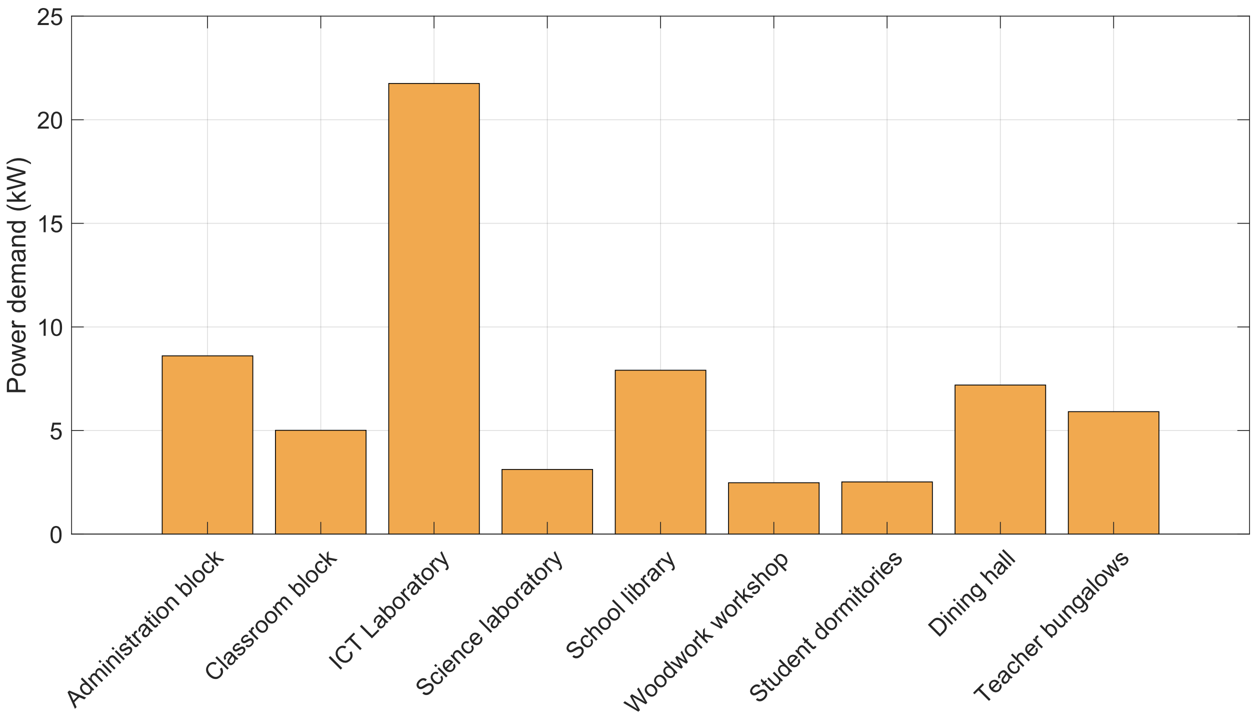

Figure 3: Detailed power consumption analysis of the Tuna community.

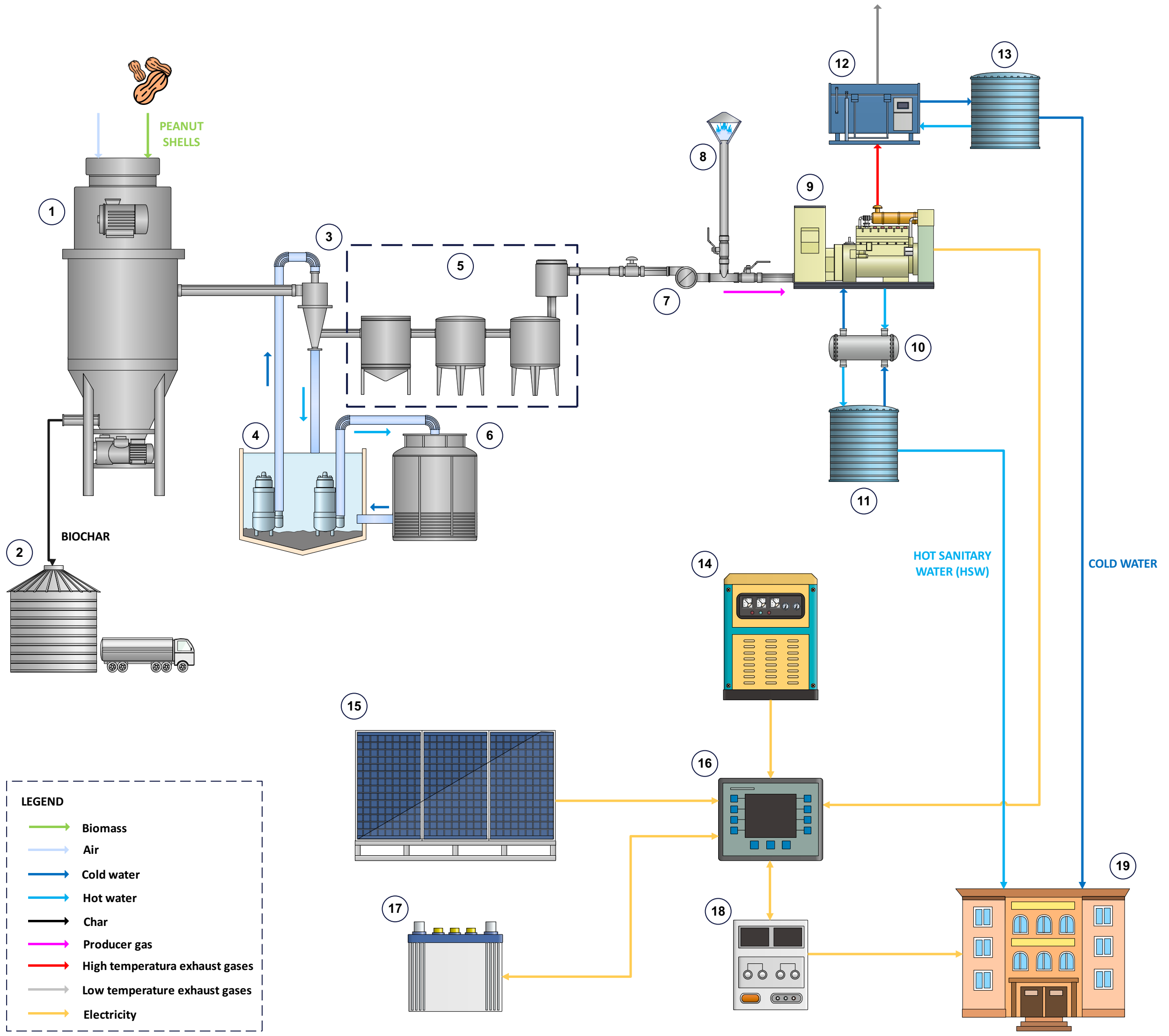

Figure 4: Design process flow diagram of the PV-assisted gasification CCHP plant: ① Reactor, ② Charcoal storage tank, ③ Scrubber, ④ Water tank, ⑤ Cleaning unit, ⑥ Cooling tower, ⑦ Blower, ⑧ Flare, ⑨ Power generator unit, ⑩ Heat exchanger, ⑪ Sanitary hot water tank, ⑫ Absorption chiller, ⑬ Low-temperature water tank, ⑭ Diesel generator, ⑮ PV system, ⑯ Charge controller, ⑰ Batteries, ⑱ Converter, ⑲ Tuna Community.

demand hours. A Li-ion battery system accumulates energy during periods of production surplus and provides additional energy at times when the photovoltaic system does not reach the required power production to meet demand. A diesel genset is used to supplement peak power demand during specific moments of the day.

2.5.1. *Biomass gasification CCHP system*

For simulation of the biomass gasification CCHP system, Thermoflex®, an advanced software developed by Thermoflow Inc. (Jacksonville, FL, USA), was used [47]. This software provides a comprehensive suite of simulation and modeling tools designed to cover a wide range of power plants, from conventional steam cycles and combined cycles to repowering projects, as well as various renewable energy systems [48–51]. The standout feature that motivated this choice lies in its extensive library of commercial products, including easily adaptable gensets.

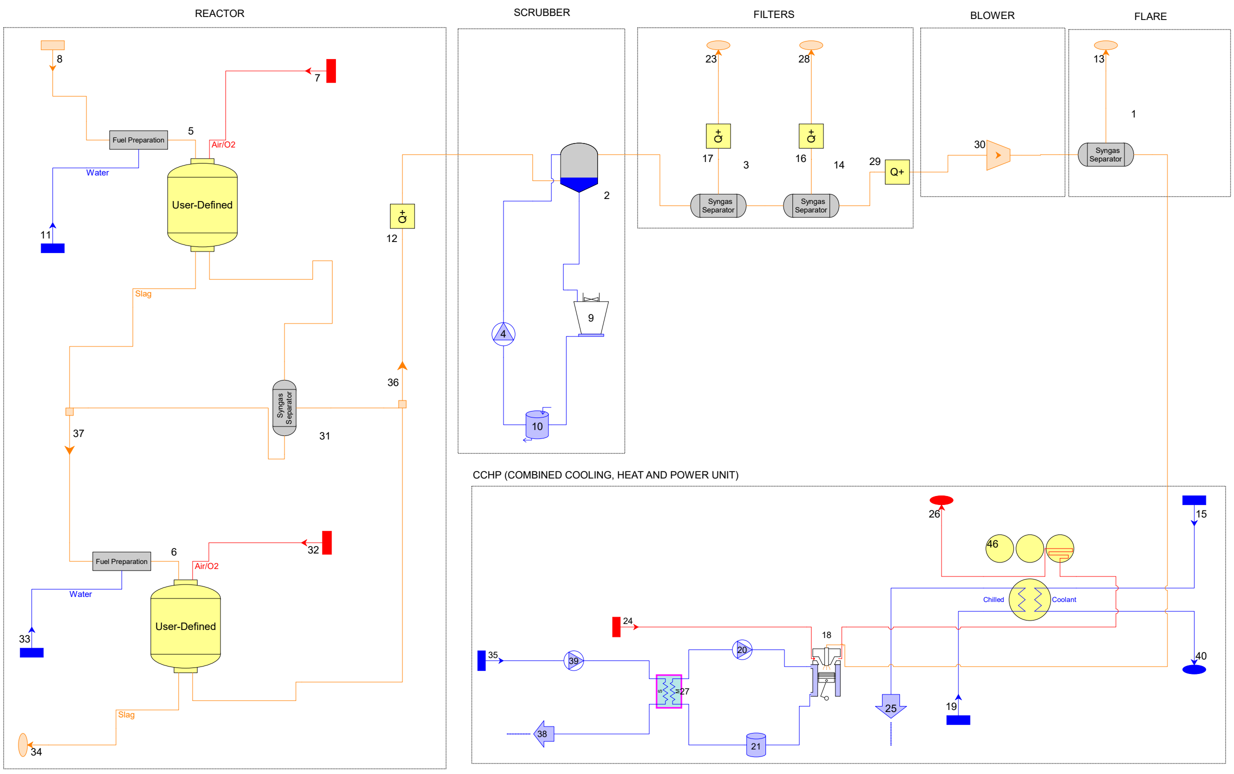

Figure 5: Process flow diagram of the biomass gasification CCHP plant in the Thermoflex® simulation environment.

Fig. 5 illustrates the process flow diagram of a gasification CCHP plant that produces electricity, sanitary hot water, and chilled water from biomass in the Thermoflex® simulation environment. This system design comprises five distinct subsystems: biomass gasification, producer gas conditioning, electric power generation using an engine–generator set, production of sanitary hot water, and production of chilled water using an absorption chiller. Detailed descriptions of the specific features of each of these subsystems, along with their respective modeling approaches, are reported below.

- The gasifying agent consists of humid atmospheric air under standard ambient conditions, with the following molar distribution: 20.75% oxygen, 77.29% nitrogen, 0.92% argon, 0.03% carbon dioxide and 1.01% water. The relative humidity of the environment is 60%.
- An acceptable estimate for the typical temperature of the available water resources at the plant site is 25 °C [52].
- Perfect mixing with uniform pressure and temperature distribution is assumed within the gasification reactor [53].
- The residence time of the reactants is assumed to be prolonged enough to reach chemical equilibrium [51, 53].
- The oxidizing agent is able to convert most of the carbon content in the biomass feedstock into producer gas. Only a small fraction of this carbon is removed from the gasifier system together with ash, representing the typical charcoal formation in biomass gasification processes. Based on extensive experience with downdraft gasifiers, it has been observed that some unconverted carbon always remains. In fact, several experimental studies have reported biochar yields (including ash) of around 10–15% by weight of the input biomass feedstock (as received) [54, 55]. In many simulations of downdraft gasifiers fueled with biomass, a carbon conversion efficiency of approximately 95% is assumed [56]. In other words, approximately 5% of the carbon content is not converted during the operation of the gasifier [17, 53]. Therefore, assuming a carbon conversion efficiency of 95% is both reasonable and consistent with observed data.
- During the gasification process, ashes are separated and discharged from the bottom of the gasifier together with the unconverted carbon, thus becoming part of a carbonaceous solid residue known as biochar [54, 55]. This solid byproduct is extracted from the bottom of block number 34 in Fig. 5, constituting the stream designated as “slag”.

- A downdraft reactor configuration is considered for the gasifier. These reactors are generally limited to a relatively low thermal input (< 1 MW_{th}) and small-scale electricity generation [57].
- Thermoflex® software simulations rely on thermodynamic equilibrium models [47], and it is important to note that under these conditions, methane formation does not occur at temperatures above 800 °C [53]. However, it is widely established that the product gas does not attain complete equilibrium composition in downdraft gasifiers, as indicated by the presence of a relatively small fraction of methane [53]. To address this limitation, the proposed simulation model consists of two reactors. In the first reactor, the pyrolysis process is carried out at a temperature of 560 °C, while in the second reactor, the gasification process is simulated at a thermodynamic equilibrium temperature of 1000 °C. Since the concentration of methane in the product gas is expected to be very close to zero after the second reactor, a fraction of the methane from the first process is bypassed to the gasifier outlet [53]. The experimental results obtained by Jayah et al. [58] were used to validate the modified thermodynamic equilibrium model. Once the gas exits the gasifier, it enters a cooling and cleaning system consisting of a wet scrubber and a series of filters for impurity removal, represented in Fig. 5 by the "Syngas Separator" block. Finally, the clean producer gas is pressurized by a compressor unit simulating a blower before being fueled to the genset for electricity production.
- The air–fuel equivalence ratio (λ) is a crucial operating parameter in biomass gasification processes. This ratio expresses the actual proportion of oxidizer-to-fuel supplied to the downdraft gasifier compared to the oxidizer-to-fuel ratio required for stoichiometric combustion [51, 53, 55, 59, 60]. The air–fuel equivalence ratio is adjusted to values within the typical range in downdraft gasifiers (λ = 0.20–0.45) [56, 61, 62]. The following expression has been used for calculation of this parameter [55].

$$\lambda = \frac{(\dot{m}_{O_2})_{actual}}{(\dot{m}_{O_2})_{stoich}} = \frac{(\dot{n}_{O_2})_{actual}}{(\dot{n}_{O_2})_{stoich}} = \frac{y_{O_2,air}\,\dfrac{\dot{m}_{air}}{M_{air}}}{\dot{m}_f\left(\dfrac{x_{C,f}}{M_C} + \dfrac{x_{H,f}}{4\,M_H} - \dfrac{x_{O,f}}{2\,M_O}\right)} \tag{2}$$

where $\dot{m}_{air}$ represents the mass flow rate of the gasifying agent introduced into the gasification reactor, M_{air} is the weighted molar mass of air, $y_{O_2,air}$ is the mole fraction of oxygen in atmospheric air, $\dot{m}_f$ is the mass flow rate of biomass introduced, $x_{C,f}$, $x_{H,f}$, $x_{O,f}$ are the mass fractions of carbon, hydrogen, and oxygen from the final feedstock analysis and M_C, M_H, M_O are the atomic masses of carbon, hydrogen, and oxygen, respectively.

- Tar production is not a byproduct of thermodynamic equilibrium; therefore, it is not directly accounted for in the thermodynamic equilibrium model of biomass gasification. However, it is well-established that downdraft gasifiers typically yield producer gas with tar concentrations below 3 mg/Nm^3 [57]. Moreover, the temperature inside the downdraft gasifier reaches 1000 °C, which is high enough for thermal cracking most of the tar [63]. This assumption is grounded in reality, as per manufacturers' specifications, gasification plants using downdraft gasifiers effectively reduce the tar content in the gas to approximately 5–15 mg/Nm^3, significantly below permitted limits for fuel use in internal combustion engines, which typically range from 50 to 100 mg/Nm^3 [55].
- In order to evaluate the conversion efficiency of the biomass feedstock into producer gas, the cold gas efficiency (η_{cg}) is calculated [48, 53, 55–57, 64].

$$\eta_{cg} = \frac{\dot{v}_{cg}\,\mathrm{LHV}_{cg}}{\dot{m}_f\,\mathrm{LHV}_f} \tag{3}$$

where $\dot{v}_{cg}$ and $\dot{m}_f$ represent the volume flow rate of conditioned producer gas and the biomass consumption, respectively. Accordingly, the LHV of the conditioned producer gas is expressed in terms of heat per unit volume, while the LHV of the biomass feedstock is expressed in terms of heat per unit mass.

- For calculation of the electrical efficiencies and CCHP efficiencies, referred to both the genset alone (*genset*) and biomass gasification plant as a whole (*plant*), the following expressions are used [48, 64].

$$\eta_{e,genset} = \frac{P_e}{\dot{v}_{cg}\,\mathrm{LHV}_{cg}} \tag{4}$$

$$\eta_{\mathrm{CCHP},genset} = \frac{P_e + P_{heat} + P_{cool}}{\dot{v}_{cg}\,\mathrm{LHV}_{cg}} \tag{5}$$

$$\eta_{e,plant} = \eta_{cg}\,\eta_{e,genset} = \frac{P_e}{\dot{m}_f\,\mathrm{LHV}_f} \tag{6}$$

$$\eta_{\mathrm{CCHP},plant} = \eta_{cg}\,\eta_{\mathrm{CCHP},genset} = \frac{P_e + P_{heat} + P_{cool}}{\dot{m}_f\,\mathrm{LHV}_f} \tag{7}$$

where P_e is the gross electric power generated by the genset, P_{heat} is the heat flow rate necessary to raise the water temperature in the heat exchange process from 25 °C to 60 °C. Additionally, P_{cool} denotes the cooling requirement to produce chilled water at 7 °C. Finally, $\dot{v}_{cg}$ and LHV_{cg} stand for the volumetric flow rate and lower heating value of the cold producer gas, respectively.

- The coefficient of performance (COP) of the two-stage lithium bromide absorption chiller is assumed at 1.35 [65], with a water outlet temperature of 7 °C. The exhaust gas outlet temperature of the absorption chiller to the atmosphere is set at 130 °C.
- Sanitary hot water (SHW) production at 60 °C is accomplished through a heat exchanger with a relative heat loss of 15% to the surrounding environment and 2% pressure drop [48]. The engine cooling water circuit is assumed to operate within the temperature range of 70 to 90 °C [55]. With a heat exchanger pinch point temperature difference of 30 °C, corresponding to a heat transfer effectiveness of 60%, and a *UA* value of 1.753 kW/K, a costly

heat exchanger is not required for this application.

2.5.2. Integrated hybrid system

For optimization of the proposed hybrid PV-assisted gasification CCHP system, HOMER Pro® software was used [46]. HOMER is widely recognized as the industry standard for microgrid design and has been extensively utilized worldwide [25–28, 30, 66–70]. One of the remarkable advantages of HOMER Pro® lies in its ability to determine the optimal system configuration of hybrid systems integrating multiple energy sources such as solar, wind, biomass, and conventional fossil fuels, among others, with a reasonably high degree of customization [66–68].

HOMER Pro® models a particular hybrid system configuration by performing an hourly time series simulation of its operation over one year. The algorithm steps through the year one hour at a time, calculating the available renewable power, comparing it to the electric load, and deciding what to do with surplus renewable power in times of excess, or how best to generate additional non-renewable power in times of deficit [71]. The primary goal is to minimize the total cost of the system while meeting energy demand and reliability criteria. HOMER Pro® generates potential configurations ranked in ascending order based on their net present cost (NPC), also known as the life-cycle cost [27]. The objective function considers capital costs, operating expenses, and component replacements over time. The energy balance equation ensures that the energy generated by the system matches the energy consumed by the load and system losses. For further details on the optimization problem, readers can refer to Lambert et al. [71].

Fig. 6 displays the configuration adopted in HOMER Pro® software for sizing the proposed hybrid off-grid system. The main design premises are outlined below:

- The gasification plant is sized for a nominal power capacity of 30 kW_e. It is designed to operate continuously under three different loads of the genset, corresponding to ⅓ (10 kW_e), ⅔ (20 kW_e), and 3/3 (30 kW_e) of the nominal operating conditions. A constant parasitic load of 3 kW_e is assumed, representing 30%, 20% and 10% of the power generation for ⅓, ⅔, and 3/3 loads. A comparable share of parasitic loads has been reported for a similar biomass gasification plant [55]. Additionally, maintenance activities require the plant to be shut down for 7 hours at night for every 648 hours of uninterrupted operation.

- The whole gasification unit is incorporated in the HOMER Pro® model as a engine–generator set fueled with producer gas. This modeling approach is based on the assumptions and parameters established in the Thermoflex® model, ensuring consistency and accuracy across both simulations.
- A daily variation of 5% is accounted for in the power demand profile shown in Fig. 7.
- The hybrid system is optimized to meet the power demand by both reducing CO_2 emissions and seeking maximum reduction in capital costs, as well as operation and maintenance (O&M) costs.
- For sizing of the solar PV system, data from the National Solar Radiation Database (NSRDB) [43] were used. In addition, the effect of temperature on the PV system was considered equal to −0.35%/°C, as well as a nominal operating cell temperature (NOCT) of 45 °C and an efficiency of 21.5% under Standard Test Conditions (STC). These assumptions are in accordance with the technical specifications of a benchmark PV module A-450M GS (Atersa, Spain).
- The current diesel generator set is downscaled from 64 kW to 10 kW, reserved solely for addressing peak power demands.
- The batteries utilize Li-ion technology and have a maximum depth of discharge of 80%, meaning they maintain a minimum state of charge of 20% [70].

Two dispatch strategies are available in HOMER Pro® for simulation of the hybrid system, either “cycle charging” (CC) or “load following” (LF) [69, 72]. Both dispatch strategies follow a structured set of rules to manage the operation of diesel generators and batteries during periods when renewable energy sources like solar and biomass are insufficient to meet the load requirements [72, 73]. In CC strategy, the generator works at its utmost limit whenever it is required, and

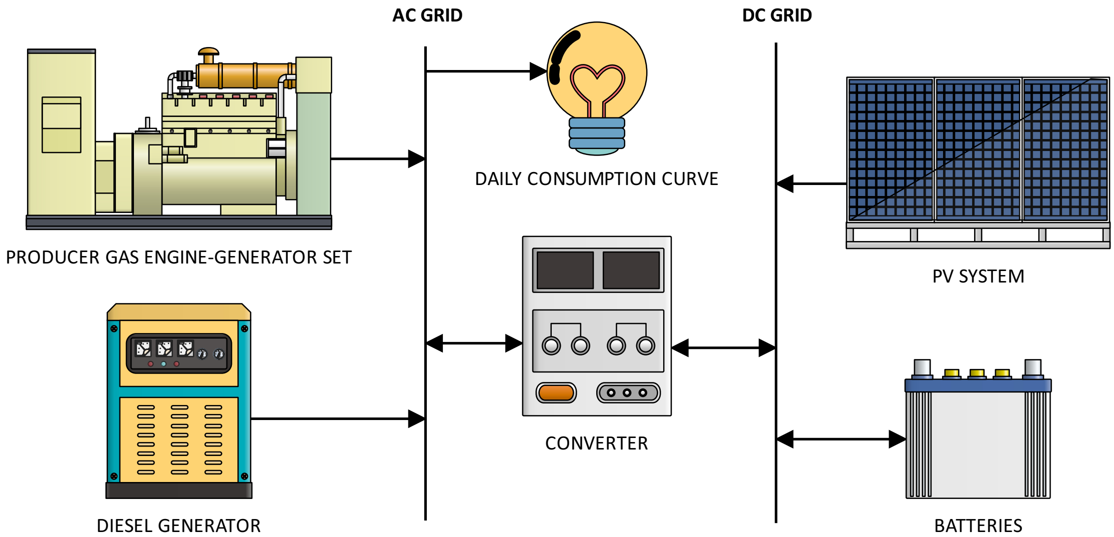

Figure 6: The proposed simulation framework for implementation of the hybrid PV-assisted gasification CCHP system using HOMER Pro® software.

the excess power is used to charge the batteries [72]. However, under the LF strategy, when available alternative energy falls short of meeting the power demand, the diesel generators primarily supply electricity to the load instead of recharging the batteries. The LF strategy has been opted for in this work, because it effectively reduces both electricity costs and CO_2 emissions compared to other techniques offered by the software, such as CC [72]. For a detailed explanation of the adopted hybrid system dispatch strategy, readers are encouraged to refer to Barley and Winn's work [73].

2.6. Economic feasibility assessment

An economic feasibility assessment of the hybrid PV-assisted biomass gasification CCHP plant was conducted using standard financial appraisal methods. These methods include the net present value, internal rate of return, profitability index, payback period, and levelized cost of electricity [74].

The Net Present Value (NPV) is the difference between the present value of the project's future cash flows and the initial investment. This parameter reflects the earnings after paying back the initial capital investment (INV). Consequently, NPV > 0 represents a profit, while NPV < 0 indicates a loss.

$$\mathrm{NPV} = \sum_{t=1}^{n} \frac{\mathrm{NCF}_t}{(1 + \mathrm{WACC})^t} - \mathrm{INV} \tag{8}$$

where NCF is the net cash flow during period t, WACC is the weighted average capital cost as discount rate, INV is the initial capital investment, and n is the project lifetime (in years).

The Internal Rate of Return (IRR) is the discount rate that makes the Net Present Value (NPV) of the project equal to zero. This parameter represents the highest discount rate at which the investment remains at break-even [74].

$$\mathrm{NPV} = \sum_{t=1}^{n} \frac{\mathrm{NCF}_t}{(1 + \mathrm{IRR})^t} - \mathrm{INV} = 0 \tag{9}$$

The Profitability Index (PI) is the ratio of the net present value to the initial investment [75]. A value of the PI greater than 1 indicates that the project is profitable.

$$\mathrm{PI} = \frac{\mathrm{NPV}}{\mathrm{INV}} \tag{10}$$

The Discounted Payback Period (DPB) is the time required to recover the initial investment, accounting for the annual rate of discount. The DPB can be determined using the following equation, which assumes equal cash flows and is thus applicable only for constant cash flows. As a result, an average annual cash flow has been used for calculation of this parameter.

$$\mathrm{DPB} = \frac{\log\left(\dfrac{1}{1 - \dfrac{\mathrm{INV} \times \mathrm{WACC}}{\frac{\sum_{t=1}^{n} \mathbf{NCF}_t}{n}}}\right)}{\log(1 + \mathrm{WACC})} \tag{11}$$

The Levelized Cost of Electricity (LCOE) is the average cost per unit of electricity generated, considering the total life cycle costs (C_t) and total electricity produced.

$$\mathrm{LCOE} = \frac{\mathrm{INV} + \sum_{t=1}^{n} C_t\,(1+\mathrm{WACC})^{-n}}{\sum_{t=1}^{n} E_t\,(1+\mathrm{WACC})^{-n}} \quad \text{where } C_t = I_t + O_t + F_t \tag{12}$$

where I_t represents investment costs, O_t denotes operation and maintenance costs, F_t stands for fuel costs, and E_t is the electricity generated, all in year t.

3. Results and discussion

This section presents the load profile estimation for the Tuna community, in addition to the results of the biomass gasification CCHP plant simulation using Thermoflex® and the outcomes of the hybrid generation system optimization using HOMER Pro®.

3.1. Load profile

The load profile shows the aggregate power consumption across all the appliances combined at each time interval. The curve provides insights into the overall energy usage pattern and facilitates the identification of peak energy consumption periods. The resulting hourly-averaged demand profile is depicted in Fig. 7.

Based on the information gathered from surveys of the local population, two main consumption periods can be identified in Fig. 7. The first one occurs in the interval from 8 to 11 in the morning. This consumption is primarily driven by the ICT Laboratory, which includes all the computers where students engage in learning activities. The second peak in consumption is observed during the midday hours. This consumption is attributed to the dining hall, administration block, and school library.

In addition to the power demand of the Tuna community, a constant consumption of 3 kW of electricity is assumed due to parasitic power usage by the ancillary equipment of the gasification plant. This includes the electric motors of the char removal pump, scrubber pump, cooling pump, cooling tower fan and gas blower, as well as other components [55]. The assumed value for the

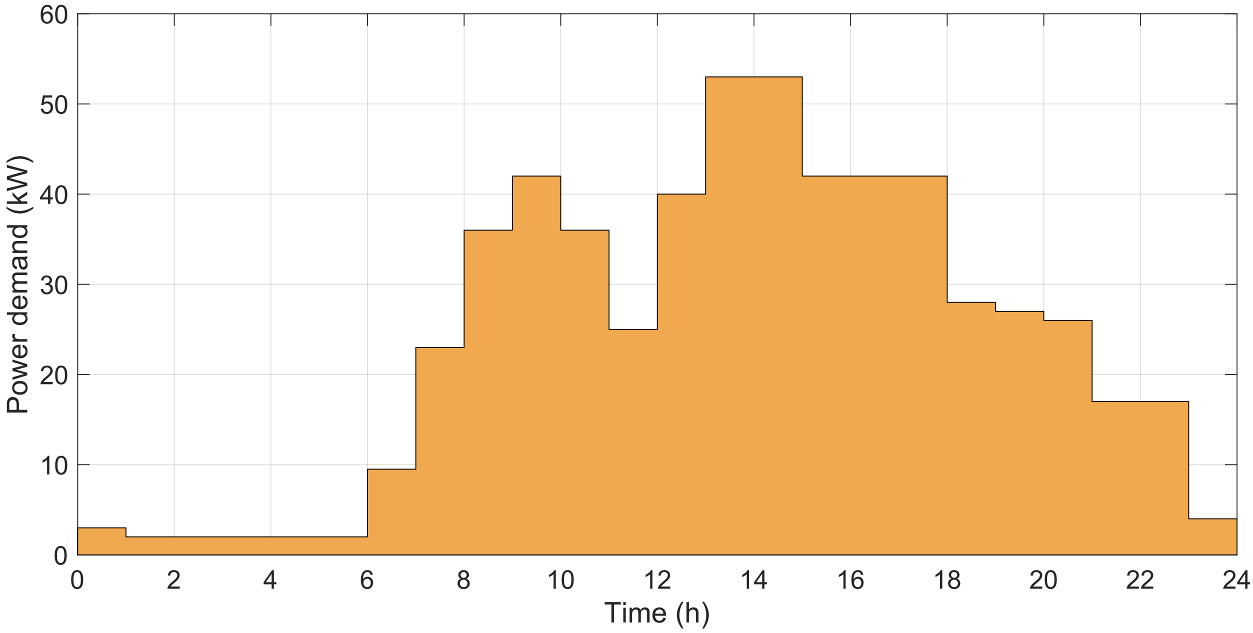

Figure 7: Example of a typical daily power demand profile at Tuna community, averaged over hourly intervals.

electrical self-consumption by the ancillary equipment is in agreement with the typical share of parasitic power consumption in small-scale downdraft gasifiers [55].

3.2. Biomass gasification CCHP system

The biomass gasification model was validated by comparing its predictions with the experimental results obtained by Jayah et al. [58]. Fig. 8 illustrates the remarkable resemblance between the gas composition derived from experimental data and the model predictions, revealing minimal disparities and a close alignment with the air–fuel equivalence ratio of the gasification reactor. Additionally, the validation process facilitated the adjustment of the methane bypass amount in the initial reactor. Upon successful validation of the gasification model, the system was simulated under the specified nominal operating conditions of 30 kW_e using peanut shells as biomass feedstock.

The results from the simulation performed in Thermoflex® provide an insightful assessment about the performance of the biomass gasification CCHP system. The simulation was carried out under three load conditions, namely ⅓, ⅔ and 3⁄3 of the nominal operating conditions. The

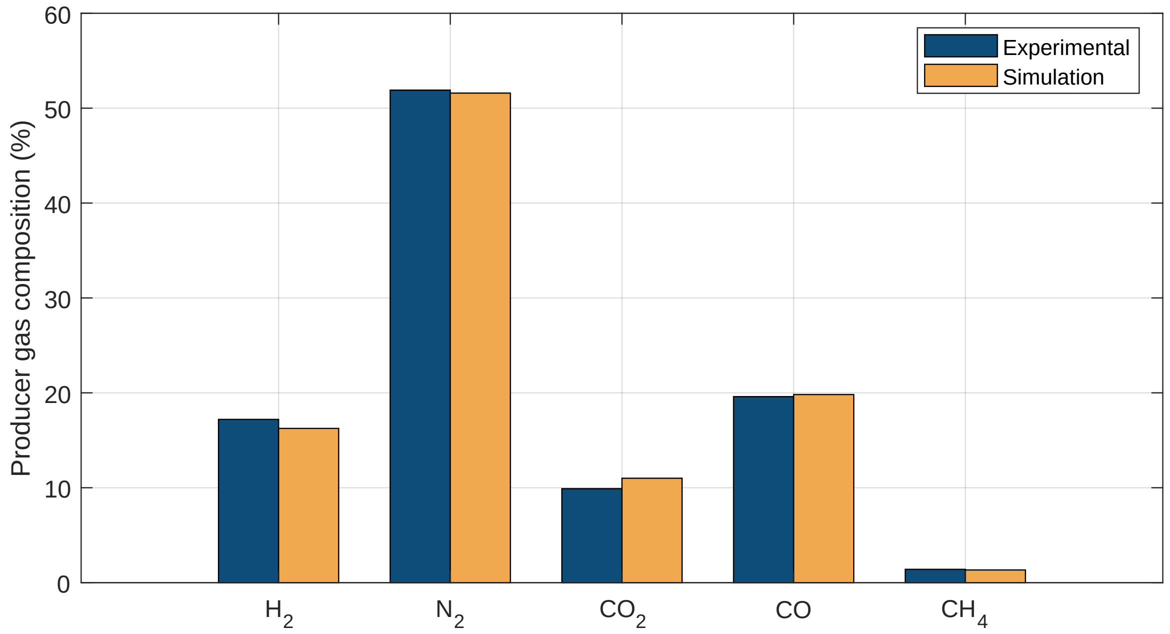

Figure 8: Validation of the modified thermodynamic equilibrium model with the experimental results of Jayah et al. [58].

average volumetric composition of the conditioned producer gas, achieved with a value of air–fuel equivalence ratio (λ) equal to 0.373, is distributed as follows: 21.1% CO, 16.84% H_2, 0.12% CH_4, 10.19% CO_2, and 51.74% N_2. This composition results in a lower heating value (LHV) of 4.04 MJ/kg (4.83 MJ/Nm^3) for the producer gas. The remaining plant performance parameters are presented in Table 2. Under nominal load operation (3/3), the volume flow rate of producer gas is 82.4 Nm^3/h, considering that the gasifier is fed with peanut shell biomass at a consistent rate of 32.8 kg/h. The simulation results under nominal operating conditions revealed substantial outputs in cold water production at 7 °C and sanitary hot water at 60 °C, with rates of 1563 kg/h and 853 kg/h, respectively. A 67.9% cold gas efficiency is obtained, which is virtually constant regardless of the load of the power generation unit. Under nominal operating conditions, a 19.2% electrical efficiency, and a 69.1% CCHP system efficiency are attained. The different conversion efficiencies for all examined loads of the gasification plant are also reported in Table 2.

Table 2: Performance parameters and conversion efficiencies of the biomass gasification CCHP system for different loads of the engine–generator set.

Load fraction	$\dot{m}_b$ (kg/h)	c_b (kg/kWh)	$\dot{V}_{cg}$ (Nm^3/h)	$\dot{m}_{cw}$ (kg/h)	$\dot{m}_{shw}$ (kg/h)	$\eta_{e,plant}$ (%)	$\eta_{\mathrm{CCHP},plant}$ (%)	$\eta_{e,genset}$ (%)	$\eta_{\mathrm{CCHP},genset}$ (%)
⅓ (10 kW)	15	1.50	37.9	719	393	14.0	57.5	21.0	85.7
⅔ (20 kW)	24.9	1.24	62.1	1,178	642	16.9	59.8	25.5	89.9
3⁄3 (30 kW)	32.8	1.09	82.4	1563	853	19.2	62.1	30.0	93.1

3.3. Integrated hybrid system

The results from simulation of the hybrid system using HOMER Pro® indicate that the optimal alternative to meet the power demand involves the installation of a 30 kW gasification plant, connected in parallel with a 10 kW diesel generator and a 16.2 kW$_p$ photovoltaic system. All this equipment is integrated with a battery system with a capacity of 56 kWh. A bidirectional converter (inverter and rectifier) with a minimum capacity of 16.1 kW must also be incorporated.

Fig. 9 shows various performance parameters of the hybrid system simulated in HOMER Pro®. Initially, adjustments equivalent to 5% of the daily average power demanded by the off-grid community were introduced (see the example power demand demand profile in Fig. 7). These variations provide a more realistic representation of the power demand, as consumption varies from day to day and is not consistently identical. A decrease in the output power of the photovoltaic modules during the summer months is observed, coinciding with the decrease in solar irradiance during the rainy season (Fig. 2). This effect is also reflected in the battery system, with deeper discharges occurring during these months. It is noteworthy that the battery system remains within states of charge of 80–100% most of the time at night, except during scheduled maintenance works. Additionally, Fig. 9 illustrates the power output of the diesel genset, which operates for 1428 hours per year, mostly at nominal power, to meet peak power demands, generating a total of 13,416 kWh of electricity.

As previously reported in Table 2, the biomass gasification unit is operated at three distinct electric power loads. Fig. 9 shows that, from 0 am to 7 am, the genset runs at a partial load of 10 kW, i.e., ⅓ of the nominal load. Subsequently, there is a gradual load increase during the following

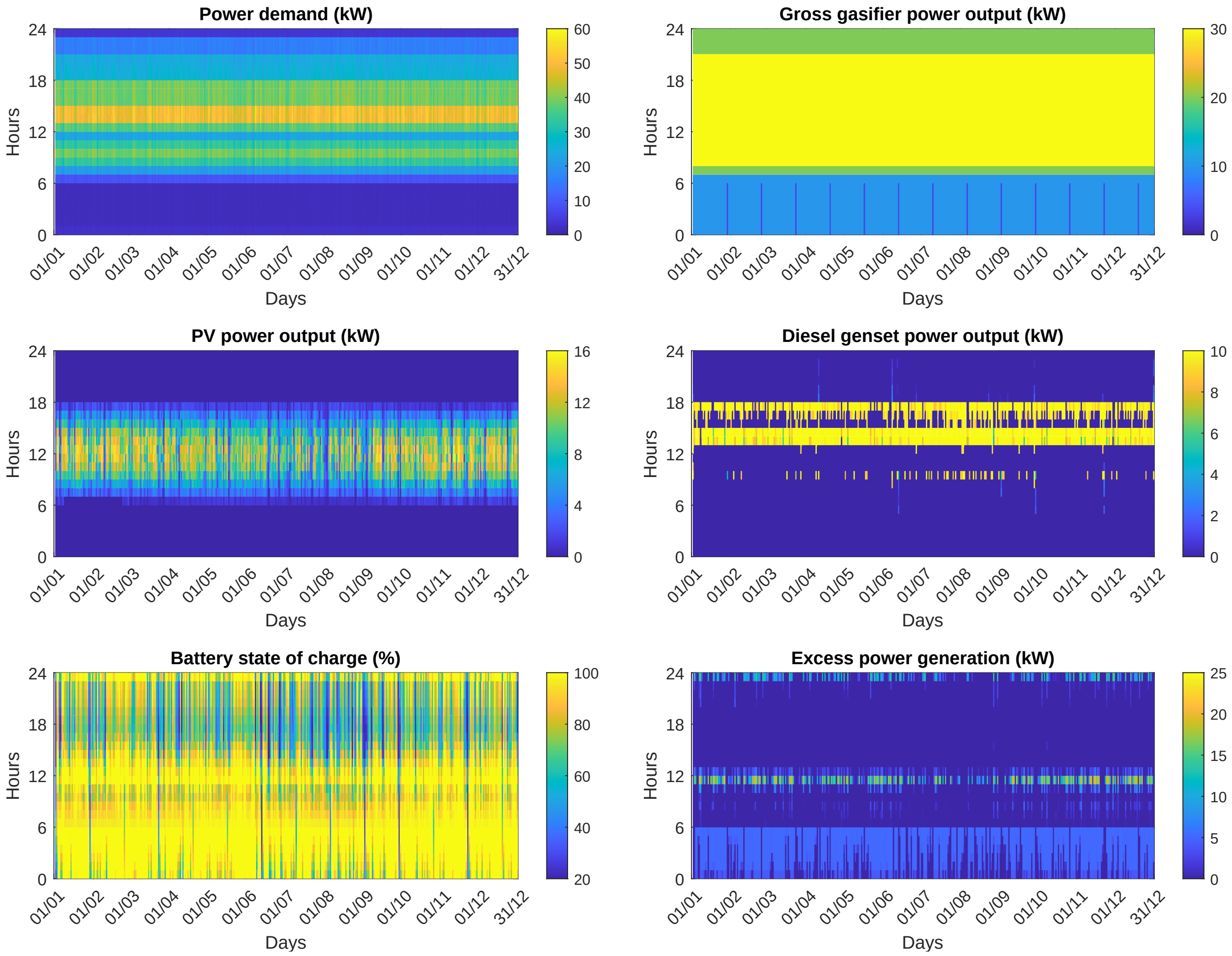

Figure 9: Power demand, gross gasifier power ouput, PV power output, diesel genset power output, battery state of charge and excess power generation of the proposed PV-assisted biomass gasification CCHP plant.

hour, reaching 20 kW. This progressive load increment is attributed to the high thermal inertia within the gasification system [55]. Following this, the gasification plant maintains a nominal load of 3/3 until 9 pm, after which it transitions back to a partial load of 2/3. Finally, the cycle repeats with a 1/3 load at 0 am. Throughout this operational sequence, the biomass gasification unit generates 196 MWh of gross electricity (170 MWh of net electricity production after deducting parasitic losses), 11,187 tonnes of chilled water and 6,105 tonnes of SHW. For example, in a typical day of operation, a total of 16.7 tonnes of sanitary hot water and 30.5 tonnes of chilled water are produced. At present, the Tuna community has a basic SHW production system by recovering waste heat from the cooling jacket water system of the existing 64 kW diesel engine-generator. However, this production exceeded demand. In addition, the absence of cooling facilities resulted in an unknown and unsatisfied demand for this service. However, the integrated hybrid system aims to address this shortfall by introducing cooling capacities into the community, despite the lack of immediate knowledge of demand. It is considered essential that the community has access to these services for their overall well-being. This system not only meets the current needs of the community by matching SHW production to demand, but also adds additional value by introducing the possibility of obtaining chilled water. The introduction of chilled water production would significantly benefit the community in various ways. It would enhance food preservation capabilities, facilitating the transportation of perishable goods to areas distant from production fields. Furthermore, it will provide comfort on hot days, improving the quality of life of the residents.

A total of 229 tonnes of peanut shells are required to sustain the gasifier operation yearly. Accordingly, the average specific biomass consumption of the gasification unit is 1.16 kg/kWh of electricity. This figure closely aligns with the specific feedstock consumption of 1.2 kg/kWh experimentally determined for a comparable biomass gasification plant, which operated on cotton residues as its fuel source [76]. The gasification plant operates during 6533 equivalent hours at nominal load (4745 h at nominal load, 1460 h at ⅔ load and 2477 h at ⅓ load), which corresponds to a capacity factor of 0.746. It is noted that maintenance shutdowns, lasting for 7 hours, are conducted after every 648 hours of operation. These maintenance activities are preferably scheduled during nighttime hours to mitigate disruption at times of peak power consumption. The integrated system generates 212,250 kWh annually, with an excess electricity production of 13,882 kWh per year, which represents 6.54% of the total electricity generation. The hybrid system effectively meets the energy demand of the STK community, with an unmet electricity of approximately 170 kW per year, which constitutes only 0.1% of the total annual demand.

As previously mentioned in Section 2.5, the Tuna community currently uses an 80 kVA diesel genset to meet their electricity demand, consuming 73933 L of diesel fuel and generating 193.4 tonnes of CO_2 emissions into the atmosphere yearly. However, with the proposed integrated system, emissions would be reduced by 93.8%, resulting in annual emissions of 11.8 tonnes of CO_2 with a consumption of 4522 L of diesel fuel. The implementation of the hybrid PV-assisted gasification CCHP plant would greatly reduce emissions into the atmosphere, providing a more robust and sustainable self-consumption system for the Tuna community.

It is noteworthy that the biogenic CO_2 emissions from the genset belonging to the biomass gasification plant have been disregarded, since biomass is considered carbon-neutral [77]. Moreover, setting aside the carbon-neutral aspect of biomass, the amount of CO_2 released per unit energy production is considerably lower compared to fossil fuels due to biomass being a low C/H ratio fuel [57].

Finally, to provide an overview of the energy flows, losses and efficiencies over the course of one year under varying loads, an energy balance was conducted for the CCHP gasification plant. Fig. 10 conveniently illustrates the overall energy balance of the proposed CCHP system in the form of a Sankey diagram. As observed, 67% of the chemical energy input in the raw material for the downdraft gasifier is converted into producer gas. Subsequently, this producer gas is utilized to generate electrical energy ($\eta_{e,plant}$ = 18.2%), useful heat from the cooling circuit for sanitary hot water production ($\eta_{shw,plant}$ = 22.4%), and for cold water production in an absorption chiller with a COP of 1.3 ($\eta_{cw,plant}$ = 21.3%). Together, these provide an overall CCHP efficiency ($\eta_{CCHP,plant}$) of 62.0% for the facility. The majority of system losses occur in the form of waste heat release to the environment through various units of the integrated gasification plant. The major energy losses occur in the gasifier and producer gas conditioning, constituting 33% of the input energy flow. Other minor energy losses include heat losses in the power generation unit (3.5%), power conversion losses in the generator (1.5%), heat losses in the heat exchanger (1.2%), and unutilized energy from exhaust gases (3.8%).

3.4. *Economic feasibility assessment*

In this section, an economic feasibility assessment and sensitivity analysis of the proposed hybrid PV-assisted gasification CCHP plant is performed. The economic evaluation of the proposed

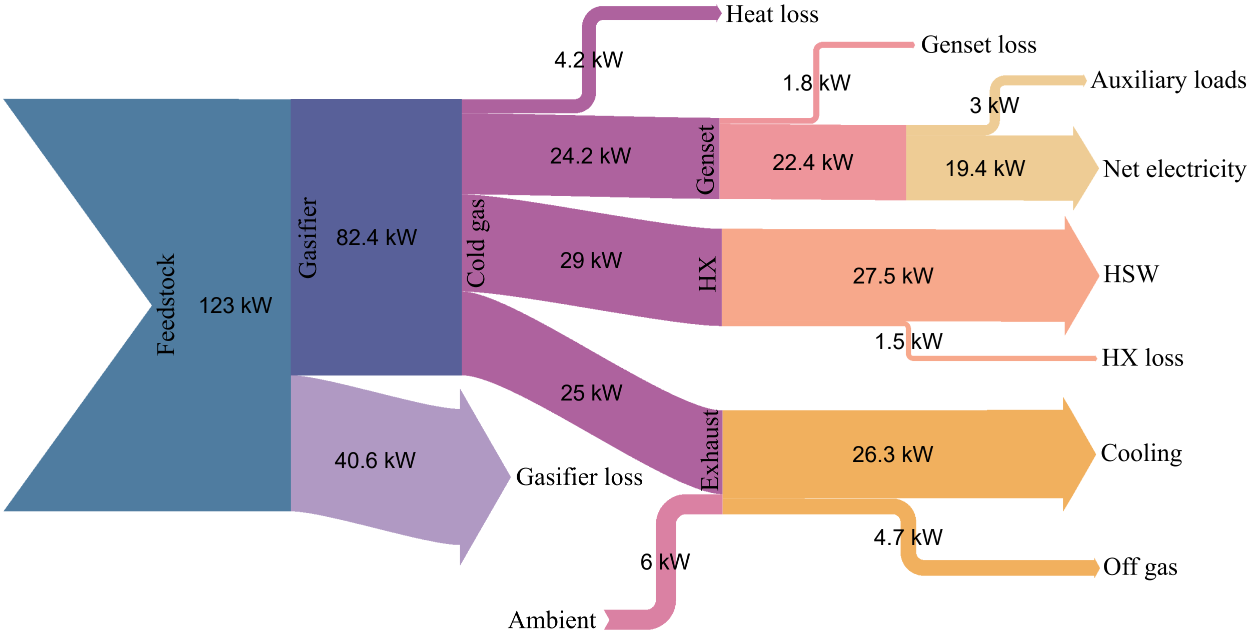

Figure 10: Sankey diagram of the CCHP gasification plant over the course of one year under varying loads.

hybrid system was conducted using the current scenario as the benchmark for comparison.

3.4.1. Baseline assessment

The Tuna community operates independently from the main power grid, relying on an 80 kVA diesel generator to meet their energy needs. Since the generator is fully amortized, its capital cost is not considered. The main expenses for the community are diesel fuel consumption and O&M costs.

As mentioned above, the proposed scenario involves the implementation of an integrated hybrid system that relies on renewable energy sources, particularly solar PV (16.2 kW_p), and a biomass gasification plant (30 kW), producing SHW through a heat exchanger and cool water through a LiBr absorption chiller. This hybrid system is supported by a Li-ion battery bank (56 kWh) and a small back-up diesel genset (10 kW) to address peak-hour demands. The nominal installation capacity of each element, as well as references for capital cost, operation and maintenance costs, replacement cost and useful life of the equipment are shown in Table 3.

Below are all the considerations and assumptions taken into account for the economic feasibility assessment of the alternative scenario:

- The projected operational lifespan considered for the economic feasibility assessment of the hybrid PV-assisted gasification CCHP plant is estimated to be 20 years [48, 78].
- The discount rate (interest rate) is set at 10% [74].
- As of early 2024, the average price of diesel fuel in Ghana is around \$1.1/L [25, 79].
- The estimated cost of gasification technology for combined heat and power (CHP) at a distributed scale is approximately \$3000 per kilowatt of electrical power (kW_e) on a commercial scale [48, 80]. This valuation comprises the expenses associated with the gasifier, producer gas conditioning unit, and the genset, including the heat exchanger. For instance, for the 30 kW_e CHP gasification plant of the present study, the capital cost would amount to a total of \$90,000. A value of \$0.05/kWh for O&M cost was assumed [78].
- Although gasification produces a high value-added by-product called biochar [57], which offers a wide variety of benefits, including significant potential as a soil enhancer [54, 55], this by-product is not considered in the economic feasibility assessment because Ghana does not yet have a consolidated biochar market.
- The batteries are deemed to have a useful life of 5 years [81], thereby requiring replacement during the 5^{th}, 10^{th} and 15^{th} year. A realistic value for the specific storage cost of batteries in Ghana is reported at \$310/kWh [25].
- The cost of the PV system, excluding the bidirectional converter, is assumed to be \$1100/kW based on a similar rural off-grid system in Ghana [25]. Additionally, an O&M cost of \$0.03/kW·year and a lifespan of 25 years are considered [82].
- The converter is expected to last for 20 years and has a capital cost of \$300/kW [83]. An O&M cost of \$6/kW is considered [25, 84].
- The specific cost of the LiBr absorption chiller is \$942 per kilowatt of cooling, with operating and maintenance costs of \$0.00085/kWh [65]. A 20-year lifespan is assumed for this equipment [85].

- The purchase cost of the diesel group was fixed at \$300/kW. For example, Li et al. [84] considered a cost of \$200/kW. Other studies have considered a slightly higher specific investment cost of \$220/kW [82, 83]. By contrast, Iqbal et al. [70] and Afonaa-Mensah et al. [25] reported higher specific costs of \$500/kW and \$525/kW, respectively. Therefore, a specific capital cost of \$300/kW seems a reasonable assumption for the present case study. A value of \$0.03/kWh for O\$M cost is considered [70, 82]. The lifespan of the diesel unit is assumed to be 43,800 h. On the one hand, Li et al. [84] and Kumar et al.[86] consider a useful life of 20,000 h value similar to the one provided by Bacha et al. [87] considering a useful life of 24,000 h. On the other hand, Montuori et al. [88] expected a useful life of 108,000 h. Hence, adopting the estimated value of 43,800 h seems a reasonable assumption.
- Local sources estimate that the installation of the equipment as well as the civil works represent a cost overrun of 25% of the capital cost of acquiring the equipment. Sánchez-Lozano et al. [48] estimated fixed and installation costs of the gasification plant (civil works, electrical and mechanical assemblies) as 10% of the total investment. Clausen et al. [89] considered the cost of the civil works to be higher, which would represent a third of the capital invested in the purchase of the equipment. Zang et al. [90] proposed direct costs of installation, civil works and adaptation of the devices of 17.5% of the total investment. However, considering that the hybrid CCHP system of the present work includes diverse equipment and is comparatively smaller in terms of nominal power output, an additional cost of 25% seems a reasonable assumption.
- The operation and maintenance of the gasification plant requires the creation of a permanent technical job [56, 91]. The personal costs are estimated at 5 times the minimum wage in Ghana [74, 92]. In addition, an annual personnel cost overrun of 30% is assumed due to recruitment costs.

The total capital expenditure in the turnkey project of the PV-assisted CCHP gasification plant is expected to amount to \$213,010. Any form of subsidy from the Government of Ghana is disregarded for the baseline case of the economic study.

Table 3: Nominal capacity and typical economic parameters of the main equipment included in the proposed PV-assisted biomass gasification CCHP plant.

System	Nominal capacity	Capital cost	O&M cost	Replacement cost	Lifespan
Biomass gasification plant	30 kW_e	\$2580/kW_e [74] \$2443–\$3636/kW_e [80] €3000/kW_e [48]	\$0.03–\$0.07/kWh·year [78] \$76/kW·year [80]	Not applicable	15 years [74] 20 years [48, 78]
LiBr absorption chiller	9.3 TR (32.7 kW)	\$3300/TR (\$942/kW) [65]	\$0.3/TRh (\$0.00085/kWh) [65]	Not applicable	20 years [85]
Diesel engine–generator set	12.5 kVA/10 kW	\$200/kW [84] \$220/kW [82, 83] \$362/kW [93] \$500 [70] \$525/kW [25]	\$0.03/kWh·year [70, 82]	\$200/kW [82–84] \$509/kW [25]	15,000 h [82, 83] 20,000 h [84, 86] 24,000 h [87] 108,000 h [88]
PV plant	16.2 kW_p	\$1100/kW_p [25] \$1300/kW_p [83]	\$10/kW·year [25]	Not applicable	25 years [82, 83, 86, 94, 95]
Li-ion batteries	56 kWh	\$350/kWh [28] \$310/kWh [25] \$270/kWh [70]	\$1–\$3.75/kWh·year [94] \$3/kWh·year [84] \$7/kWh·year [25]	\$253/kWh [25]	5 years [25] 6–7 years [95] 10 years [81]
Bidirectional converter	16.1 kW	\$300/kW [83] \$648/kW [82]	\$10/kW·year [83] \$6/kW·year [25, 84]	Not applicable	15 years [83, 84, 95] 25 years [70]

Note: All costs are expressed in US dollars. A ton of refrigeration (TR) is equivalent to 3.51685 kW.

For the baseline values, with a weighted average cost of capital (WACC) of 0.1, the investment is estimated to be recovered in 6.8 years based on the discounted payback (DPB) method. The project's net present value (NPV) is $157,890 with an internal rate of return (IRR) of 0.20. Additionally, a profitability index (PI) of 74% is obtained, with a levelized cost of electricity (LCOE) of $0.2870/kWh. This LCOE is comparable to values reported in similar studies on PV-diesel-gasification installations in remote areas. For instance, Chambon et al. [80] concluded that a PV-gasification hybrid system in India would yield LCOE values of $0.17/kWh. Likewise, Aditya and Simaremare [96] calculated LCOE values between $0.163/kWh and $0.292/kWh for several hybrid renewable energy systems composed of PV, batteries, biomass gasifiers, and diesel generators in Indonesia. By contrast, Kumar et al. [95] reported a value of $0.36/kWh for a biomass gasification system in rural India. Additionally, Kumar et al. [86] analyzed a PV/gasification/battery/diesel hybrid system in remote Indian areas and found an LCOE of $0.222/kWh. Moreover, Odoi-Yorke et al. [26] indicated an LCOE of $0.256/kWh for a PV/biogas/battery system, while Awopone et al. [27] obtained an LCOE of $0.399/kWh for a PV/diesel/battery hybrid system in remote areas of Ghana. Finally, Li et al. [84] analyzed a PV/biogas/diesel/battery system in off-grid areas of China and provided an LCOE value of $0.24/kWh. As observed, the LCOE value of $0.287/kWh achieved in the present work falls within the range of other similar studies conducted in remote areas.

In general, the results of this economic feasibility assessment compare well with other related works in the scientific literature. For example, Kumar et al. [86] reported a PI of 45.5%, an IRR of 49.4%, and a DPB of 2.25 years for a hybrid biomass gasification system assisted by photovoltaic energy, which also includes batteries and a diesel generator. On the other hand, Seo et al. [97] documented an IRR of 17.95% and a DPB of 14 years for a hybrid biomass gasification system assisted by solar energy, considering the sale of carbon credits. As evidenced, the DPB of 6.8 years, PI of 74%, and IRR of 20% obtained in this study fall within the ranges reported for similar hybrid systems.

3.4.2. Sensitivity analysis

A sensitivity analysis of the NPV for various values of the WACC ranging from 0 to 0.20 is represented in Fig. 11. Related studies by Aziz et al. [82], Kumar et al. [95], and Zang et al. [90] considered discount rates of 4%, 5.88%, and 8%, which for our present study would result in NPV values of $376,990, $290,110, and $214,000, respectively. In contrast, Salisu et al. [74] reported a higher value of 10%. Accordingly, adopting a value for the WACC equal to 10% for the baseline case seems a conservative assumption.

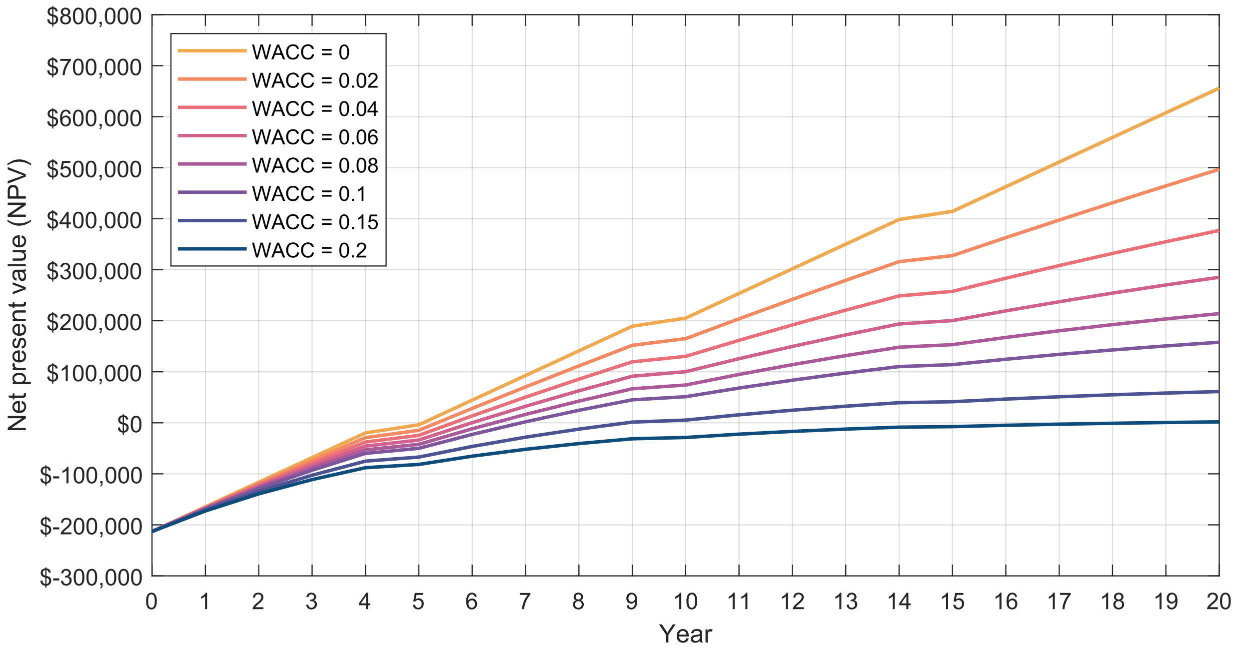

Figure 11: Sensitivity analysis for different values of the WACC.

Fig. 12 examines the impact of variations in the price of diesel, the purchase cost of biomass, as well as the percentage of subsidy from the government of Ghana on the initial investment. The diesel price is a crucial variable significantly affecting the project's viability, as it is a rather uncertain parameter due to market price fluctuations. If the diesel price were to reach $1.6/L, the project's investment would be recovered in just 3.3 years, reaching a PI of 212%. Conversely, if it decreases to a value of 0.9, the investment would be recovered in 12.4 years with a PI of 19%. Considering the low variability of prices in Ghana over the past few years [79], a significant decrease in the price of \$1.1/L set for the study is not expected. By contrast, and based on the trend, the price is expected to remain stable or slightly increase. Regarding the cost of biomass, the LCOE shows high variability with modifications to this parameter, ranging from \$0.2223/kWh to \$0.3734/kWh as variations in cost occur in the range of \$0–140/t. The acquisition cost of biomass has a negligible effect on the investment payback period. For instance, in scenarios where biomass is freely available at no cost, the payback period remains slightly under 5 years. However, the return on investment increases more markedly as biomass costs rise, reaching approximately 20 years at a biomass cost of \$140/t. Finally, focusing on the percentage of subsidy, strong impacts are observed, with IRR values increasing from 0.20 to 0.32 as the subsidy increases from 0% to 35%. The payback period can also be reduced from around 6.8 years to just under 4 years, while the profitability index (PI) can be doubled by increasing subsidy rates from 0% to 35%.

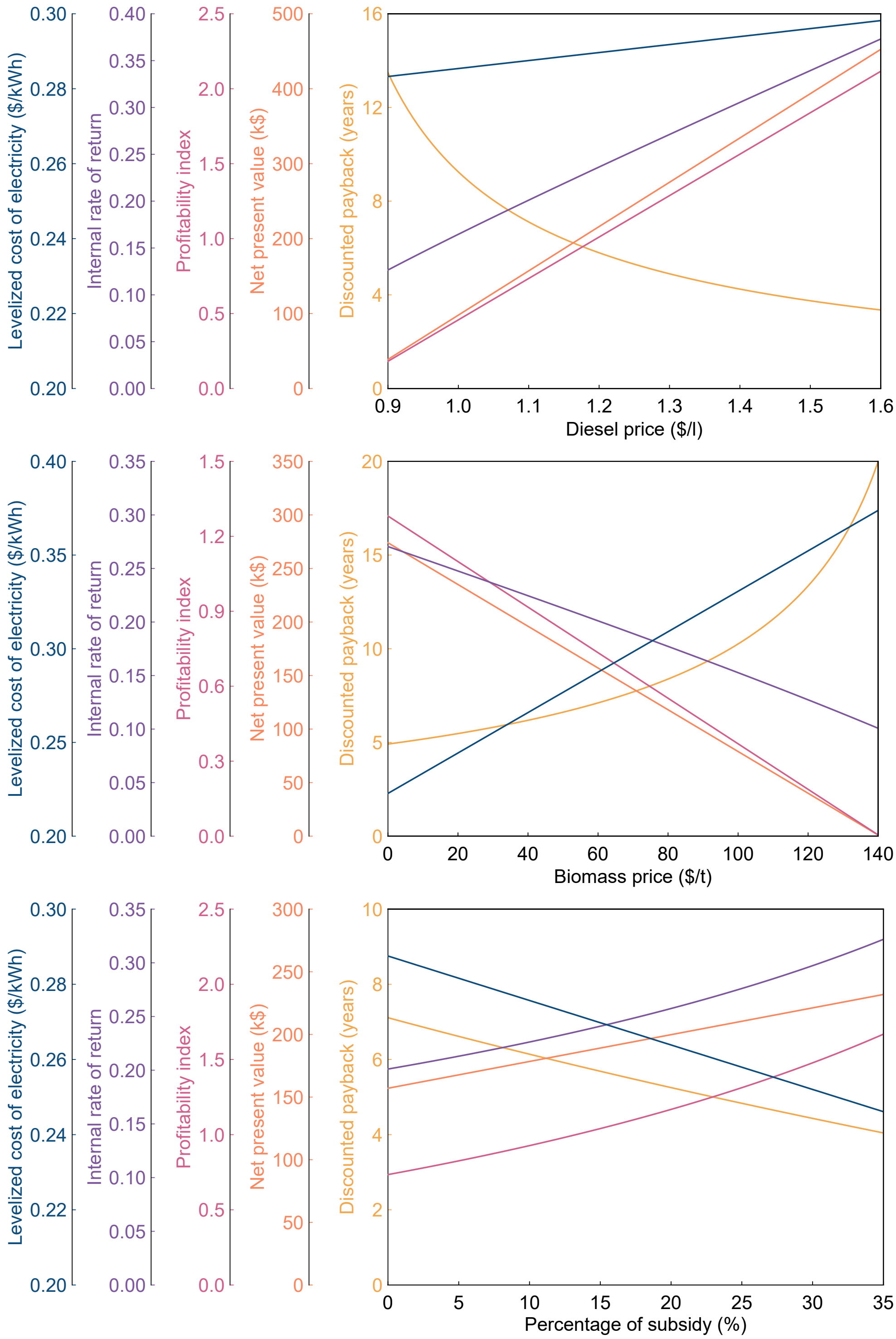

Figure 12: Sensitivity assessment of the different economic parameters as a function of the diesel price (*top*), biomass price (*center*) and percentage of subsidy (*bottom*).

4. Conclusions

This study has demonstrated the techno-economic viability of installing a hybrid PV-assisted biomass gasification CCHP plant for electrification of a rural community in the Savannah region of Ghana. The plant exhibits an electrical efficiency of 18.2%, with an overall CCHP efficiency of 62%. This system provides additional value to the rural areas of the Savannah region of Ghana by introducing a LiBr absorption chiller for cold water production, thereby addressing the cooling needs in the rural community. The gasification system contributes to enhancing energy sustainability by converting local biomass waste into valuable products and by-products. Furthermore, the advantageous solar irradiance conditions in the region are harnessed by a PV system, which helps meeting peak-hour demand, while a battery backup system ensures reliability during periods of maintenance or in case of energy production shortfalls, enhancing energy security for the rural community. The integrated approach leads to a 93.8% reduction in CO_2 emissions compared to a baseline case that relies solely on traditional fossil-based energy sources.

The profitability assessment of the PV-assisted hybrid biomass gasification CCHP system with respect to the baseline scenario shows that the proposed system can generate an accumulated profit margin of 74% based on the capital investment, with a payback period of just under 6.8 years. The calculated LCOE of $0.287/kWh aligns with scientific literature and supports the system's economic viability, making it a competitive option for rural electrification. These findings suggest that the proposed hybrid plant is not only an environmentally friendly solution, but also a potentially economically viable option for electrifying off-grid areas in Ghana and other isolated rural communities of sub-Saharan Africa. Future research could focus on optimization strategies for further improving the efficiency and economic viability of these hybrid systems, integration of additional renewable energy sources, as well as investigate the scalability and potential for replication in other rural regions globally. Additionally, further studies could explore the long-term operational performance of such systems, particularly in varying climatic conditions, and assess the socio-economic impacts on local communities over time.

Nomenclature

Symbols

$\dot{m}$	Mass flow rate [kg/h]
$\dot{n}$	Mole flow rate [kmol/h]
$\dot{v}$	Volume flow rate [m^3/h]
A	Area [m^2]
G_0	Extraterrestial horizontal irradiation [kW·m^{-2}]
G_T	Global horizontal irradiation [kW·m^{-2}]
K_t	Clearness index
M	Molar mass [kg/kmol]
P	Power [kW]
U	Global heat transfer coefficient [kW·m^{-2}·K^{-1}]
y	Mole fraction

Greek letters

η	Efficiency
λ	Air–fuel equivalence ratio

Subscripts

cw	Chilled water
e	Electricity
f	Fuel
$genset$	Engine–generator set
hsw	Hot sanitary water
pg	Producer gas
$plant$	Biomass gasification plant

Abbreviations

CCHP	Combined cooling, heat and power
CHP	Combined heat and power
FAO	Food and agriculture organization of the united nations
GHG	Greenhouse gas
GHI	Global horizontal irradiance
LHV	Lower heating value
NDC	National determined contributions
PHC	Ghana population and housing census
PV	Photovoltaic
SOA	Soil organic amendments
STK	Sawla-Tuna-Kalba
TMY	Typical meteorological year
TUSEC	Tuna senior high and technical school

CRediT authorship contribution statement

D. Sánchez-Lozano: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing - Original Draft, Writing - Review & Editing. **R. Aguado:** Conceptualization, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing - Original Draft, Writing - Review & Editing. **A. Escámez:** Conceptualization, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing - Review & Editing. **A. Awaafo:** Investigation, Methodology, Visualization, Writing - Original Draft, Writing - Review & Editing. **F. Jurado:** Funding acquisition, Resources, Supervision. **D. Vera:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Validation.

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