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Modelling Biomass Gasifiers in Hybrid Renewable Energy Microgrids; a complete procedure for enabling gasifiers simulation in HOMER

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Abstract

Off grid electrification is key to achieving universal electricity access. Despite the potential of biomass gasifiers as a clean technology to ensure reliable systems, they are not as well looked upon as their advantages suggest. In particular, the software HOMER, which researchers and technicians use the most to simulate and design Microgrids, does not include biomass gasification among its simulation technologies. Although some authors did simulate biomass gasifiers in HOMER, the necessary parameters and procedures to calculate and include them in the tool remain unclear, non-replicable, and leave open research questions as regards modelling. Using the inbuilt Biogas power plant modules in HOMER, this paper presents a set of steps to include the technical and economic parameters to simulate fuelling an electric generator through the syngas produced in a downdraft biomass gasification plant. Two case studies of isolated rural communities in Honduras and Zambia show the viability of the procedure. These case studies also confirm the technical and economic viability of islanded biomass-photovoltaic hybrid renewable energy microgrids. In both cases, the energy demand supplied and distributed by the microgrid had a Levelized Cost of Energy lower than the alternative of extending the electric grid to the communities.

Keywords— Hybrid Microgrids, Renewable Energy, Biomass Gasifier, HOMER

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1. Introduction

Access to modern electricity is one of the targets of the Sustainable Development Goal 7 (SDG7) and one of the United Nations' key priorities for humankind during the next decade [1]. Despite decades of effort, around 0.77 billion people still live without access to electricity [2]. Among them, 80% of the people without access to electricity live in rural areas that will achieve the SDG throughout the expansion of the grid, individual systems or microgrids [3]. According to the IEA, in their 100% electrification scenario, microgrids will provide almost 50% of the new access worldwide [4]. Moreover, if these microgrids need to be carbon neutral, they will rely on renewable energy sources (RES) combined in what is known as Hybrid Microgrid of Renewable Energy Sources (HRES) [5]. In this sense, the study of rural electrification with HRES is gaining increasing attention among scholars due to its potential to meet people's needs with sustainable solutions [6] and their potential to be designed with a holistic system perspective [7].

RES depends on natural resources that are by definition stochastic and variable. However, electricity systems require stability and equilibrium between generation and demand to ensure the security of supply. While Solar photovoltaic (PV) or Wind generation can provide generation at a competitive cost, they cannot always be dispatched when they are needed [8]. To overcome this, HRES planners install storage systems such as Battery Energy Storage Systems (BESS), include dispatchable technologies such as electric generators, or combine both to optimise the systems [9]–[12]. Communities, where electrification is required, tend to be isolated locations and sometimes without enough water resources. These contexts make it difficult to secure the supply with other dispatchable energy resources such as diesel, biomass anaerobic digestion, or mini-hydro schemes; the former due to high logistic costs, the latter two due to lack of water resources [5].

In contrast, dry biomass resources are common in most rural communities due to nearby forests and agricultural waste [13]. This availability leads to a growth of interest in small scale biomass gasification systems in developing countries [14], with India as one of the places with the most applications and significance [15]. Biomass gasifiers convert dry biomass into syngas that fuels an electric generator to dispatch electricity when needed. However, the amount of biomass to use in gasification or combustion needs to be properly managed to ensure correct forest management and avoid deforestation. This requires specific capacities, which are difficult to sustain in rural areas [16]. HRES with biomass gasification are promising since they allow renewable dispatchable generation and reduced consumption of biomass compared with systems that only rely on biomass [17], [18], [19]. Thus, carefully managed, biomass gasification stands as an alternative worth considering for the design and optimisation of HRES [5].

Nowadays, several options exist in the literature for evaluating, designing, sizing, and modelling HRES. Among mathematical software tools, HOMER is extensively used by researchers, academics, planners, and policy makers [20]. Furthermore, Kobayakaba and Kampal [21] justify that HOMER performs better compared with other modelling approaches and tools, which end up simplifying the HRES model for the simulation more. Indeed, Lal *et al.* consider it as one of the most useful tools for simulation and optimisation of both off-grid and grid-tied micro-grids [22]. In this regard, authors use HOMER for sizing and optimising HRES for rural electrification in several locations such as India [23], Iraq [24], Algeria [25], and Nigeria [26].

While there is a lot of work on modelling HRES in HOMER, there is little work on including biomass gasification as a potential technology in HRES. Table 1 summarizes the most recent work done by authors about the topic. The table classifies authors by type of technologies used in the simulation, biomass type, biomass characterization, syngas characterization, ratio syngas output to biomass input, type of gasifier, usage patterns, and economic parameters. This review shows how authors do not characterize nor explain how biomass gasification is simulated in HOMER. In this regard, most works do not consider or at least provide neither biomass type, syngas characteristics, parameters of the gasifier, usage patterns of the gasifier, economic parameters of both biomass and gasifier, nor the ratio syngas output to biomass input.

Table 1 Previous work modelling biomass gasifiers in HOMER

Energy Technologies	Biomass Type	Biomass characterization	Biogas characterization	Ratio syngas output to Biomass input	Type of gasifier	Usage patterns	Economic parameters	Ref.
Gasification + PV + Wind +Grid	Pine needles	Yes	No	No	Yes	No	Yes	[27]
Gasification + PV + Wind + Biogas + BESS + Fuel cell	Forest foliage	No	No	No	No	No	Incomplete, not justified	[28]
Gasification + PV + BESS + Grid	No	No	No	No	No	No	Yes	[29]
Gasification	Urban waste	No	Incomplete, not justified	No	No	Incomplete, not justified	Incomplete, not justified	[30]
Gasification + PV + Diesel + Grid	Rice straw, Rice husk, Agricultural waste, Forest feeds	No	No	No	Yes	No	Yes	[31]
Gasification +PV + Wind	Pine needles	No	No	No	No	No	Yes	[32]
Gasification + PV + BESS + Diesel	Rice husk	No	No	No	No	No	Yes	[33]
Gasification + BESS + CHP	Forestry feedstock and sawdust wood pellets	No	No	No	Yes	Incomplete, not justified	Incomplete, not justified	[34]
Gasification + PV + BESS + Fuel cell	No	No	No	No	No	No	No	[35]
Gasification+PV	No	No	No	No	Yes	Incomplete, not justified	Yes	[36]
Gasification + PV + Hydro	No	Incomplete, not justified	No	No	No	No	Incomplete, not justified	[37]
Gasification	Wood pellets	Incomplete, not justified	No	No	Yes	No	Incomplete, not justified	[38]
Gasification	Agro-industrial waste	Yes	No	No	Yes	No	No	[39]
Gasification + PV + Wind + BESS	Dung, Wood and Rice straw	No	No	No	No	Incomplete, not justified	Incomplete, not justified	[21]
Gasifier + PV + BESS	Dung, Wood and Rice straw	No	No	No	No	No	No	[40]
Gasification + PV + BESS + Fuel Cell	No	No	No	No	Incomplete	No	Incomplete	[41]
Gasification+ PV + Diesel	No	No	No	No	No	No	Incomplete, not justified	[42]
Gasification + PV + BESS + Grid	Wood pellets	Yes	Yes	No	Incomplete	Incomplete, not justified	Yes	[43]
Gasification + Grid	Rice straw and husks	No	No	No	No	No	No	[44]
Gasification + PV + Wind + Grid	Pine needles	Yes	No	No	Yes	No	Yes	[45]
Gasification + PV + BESS	No	No	No	No	No	No	Incomplete, not justified	[46]
Gasification + PV + Fuel cell	No	No	No	No	No	No	Incomplete, not justified	[47]
Gasification	Pine needles	No	No	No	No	No	No	[48]
Gasification +PV + Diesel + Grid	No	No	Incomplete	Yes, not justified	Yes	No	Yes	[49]

For instance, Kaur *et al.* model in HOMER an HRES for a rural community in India integrating biogas, PV, and batteries, but no specificities on how to include the biogas generator nor the biomass characteristics are included in their study [29]. Similarly, Suresh *et al.* [28] model in HOMER an HRES in India that includes PV, fuel cells, wind power, battery systems, biogas, and biomass, but without specifying the main economic or technical parameters, nor the sensitivity data used to include the biomass gasification in HOMER. Islam *et al.* analyse the potential of hybrid PV biomass gasification systems for electrifying the northern region of Bangladesh [33]. Chambon *et al.* provide an analysis of HRES that combine biomass gasification and PV panels by using HOMER [49]. However, how they include the biomass gasification properties in the software is generic, it does not show where the information comes from nor consider the operational hours of the biomass gasifier. Besides, the specific information about the biomass is not presented, making it impossible to replicate the complete characterisation of the biomass gasifier used in the research. Finally, Alfonso-Solar *et al.* model a hybrid PV-biomass system for higher education buildings in HOMER [43]. They include the main parameters but again no method is used to include the gasification in HOMER, especially regarding the usage patterns of the gasifier and the ratio syngas output to biomass input. To sum up, some authors pioneer the consideration of biomass gasifiers in HOMER, but no clear method on how to include them or where to find the specific information exists in the literature.

Therefore, gasification modelling in HOMER is still a self-made practice by specialists as the software does not include a direct way to model biomass gasifiers among their default generation options. This results in the incapability to easily model a viable and promising technology, or the common practice of leaving all the by default values, which compromises the results accuracy. In consequence, the gasifiers' potential is scarcely assessed with HOMER, and even less so for HRES in dry rural areas.

To overcome this gap, this paper provides a procedure to model biomass gasifiers in HOMER considering and naming the main parameters needed to include them in the software, and where to obtain the required data. The paper also points out the critical elements for modelling gasifiers for rural areas. The proposed steps pay special attention to the main variables of this technology, fuel type, resource and technology costs, and operational availability under rural conditions. The method details the possible paths to obtain this information and how to process it for the correct coupling with the software. To prove the viability of the process, we apply it to two real projects on isolated rural communities in Honduras and Zambia, with populations of around a thousand people. Then, the paper discusses the critical information needed to model this technology and provides valuable findings and tips to model gasifiers based on the authors' real experience.

The rest of the paper's structure is as follows. Section 2 presents the method and material used, including a description of HOMER and the way of modelling biomass gasifiers. Section 3 provides the information on the case studies, the biomass used, and how it was modelled. Section 4 discusses the results and section 5 presents the conclusions.

2. Material and methods

This section describes the general procedure to perform feasibility analysis of HRES using HOMER simulation software [50], which, as previously stated, is widely used for economic and environmental feasibility analysis of case studies and policies [38], [43], [51], [52]. A detailed description of how to introduce performance characteristics of a biomass gasifier for electricity generation including the typical ranges of the key performance parameters has been included.

2.1 General procedure to define simulation inputs

Before running the simulation, it is necessary to predefine the system, i.e. energy sources must be selected, together with the storage systems and the energy demand. Figure 1 shows a scheme of the chosen sources and devices. Either an AC or a DC bus could be chosen to integrate the sources, the utility grid (if available), the primary load (electricity load curve of the site), and, additionally, a converter (inverter-charger) that connects both buses.

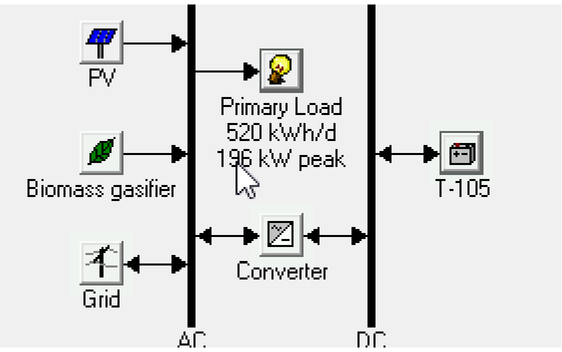


Figure 1 **Scheme of the components once the inputs have been introduced in HOMER.**

Figure 2 shows the required inputs for the setup and the outputs given after the simulation process in the HOMER software that should be considered in any HRES simulation.

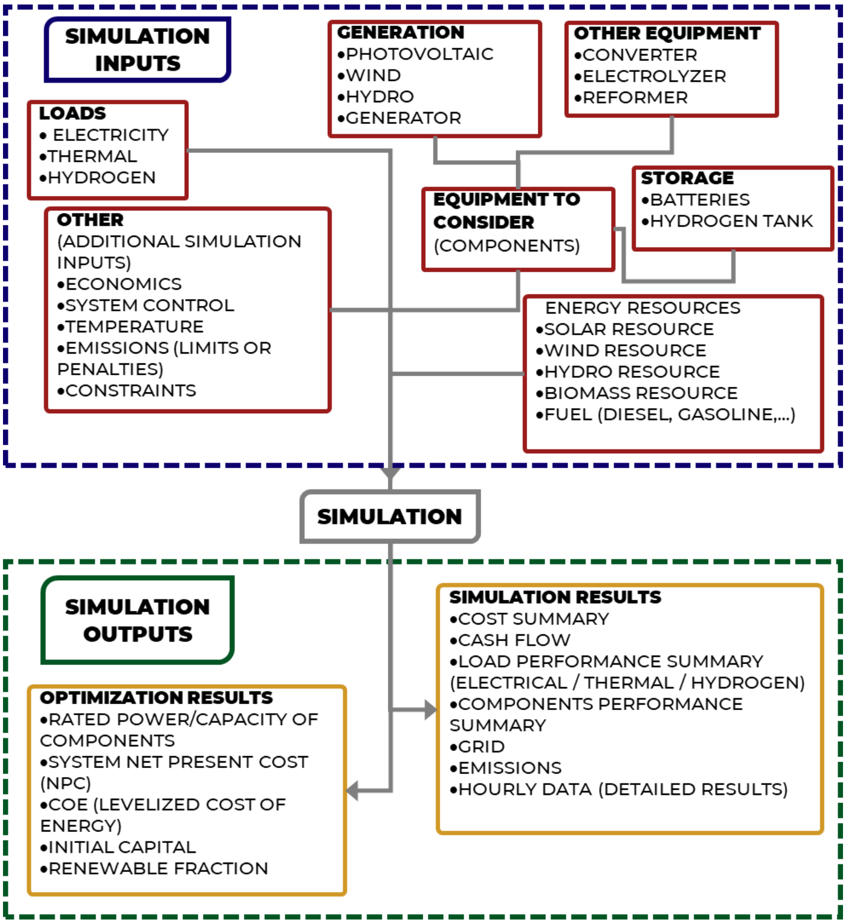
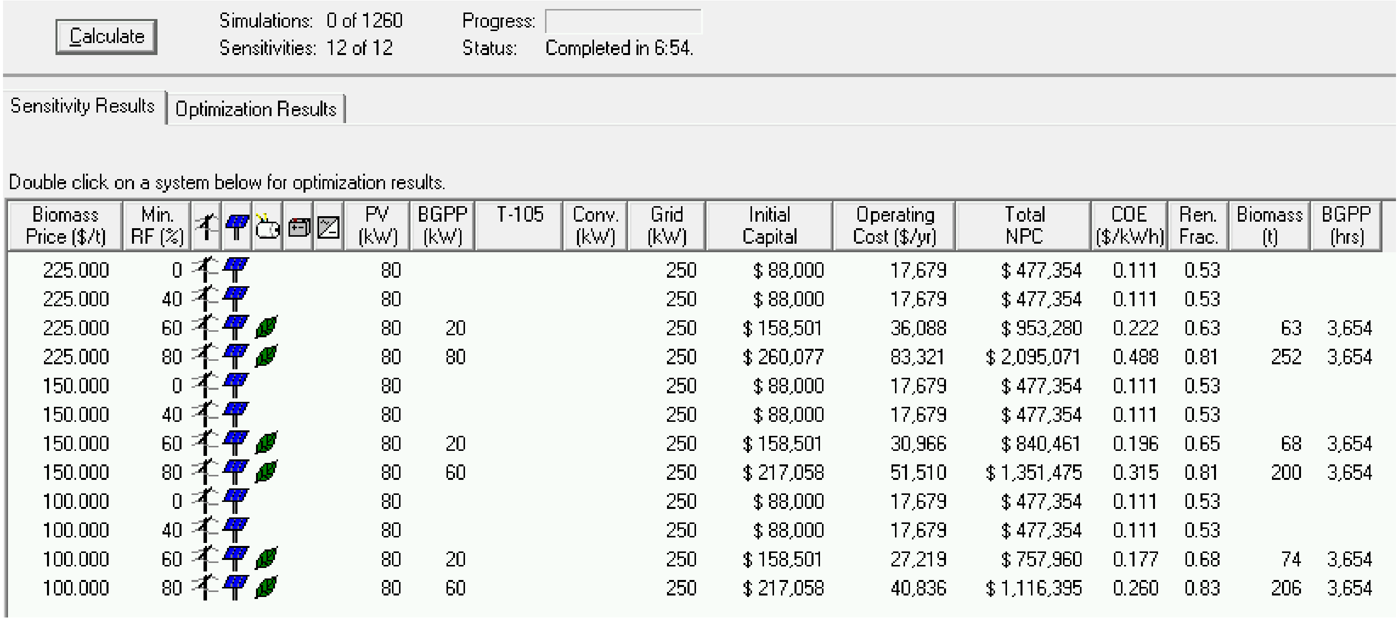


Figure 2 **Schematic overview of inputs and outputs of HOMER Software**

The system uses these inputs to make hourly energy balances for a year. For each hour, generation and storage components cover the electricity demand, the software calculates the flows of energy from/to each component (generation, storage, or other energy conversion system). Feasible configurations are only those combinations that cover the demand for the whole year with a set parameter of the non-covered load.

Then HOMER orders the feasible configurations according to the lowest Net Present Cost (NPC) [50]. For the studied project's lifespan, NPC takes into account initial investment, component replacement cost within the project lifetime, Operation and Maintenance (O&M) cost, fuel cost and cost of energy purchased from the grid, if available [53], [54]. As a result, a sensitivity analysis is obtained, giving information about the size of each component, the energy transacted with the grid, the renewable energy fraction, and the costs and the emissions produced for each scenario (Figure 3).



Simulations: 0 of 1260
Sensitivities: 12 of 12
Progress:
Status: Completed in 6:54.

Double click on a system below for optimization results.

Biomass Price ($/t)	Min. RF (%)	PV (kW)	BGPP (kW)	T-105	Conv. (kW)	Grid (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Biomass (t)	BGPP (hrs)
225.000	0	80				250	$ 88,000	17,679	$ 477,354	0.111	0.53		
225.000	40	80				250	$ 88,000	17,679	$ 477,354	0.111	0.53		
225.000	60	80	20			250	$ 158,501	36,088	$ 953,280	0.222	0.63	63	3,654
225.000	80	80	80			250	$ 260,077	83,321	$ 2,095,071	0.488	0.81	252	3,654
150.000	0	80				250	$ 88,000	17,679	$ 477,354	0.111	0.53		
150.000	40	80				250	$ 88,000	17,679	$ 477,354	0.111	0.53		
150.000	60	80	20			250	$ 158,501	30,966	$ 840,461	0.196	0.65	68	3,654
150.000	80	80	60			250	$ 217,058	51,510	$ 1,351,475	0.315	0.81	200	3,654
100.000	0	80				250	$ 88,000	17,679	$ 477,354	0.111	0.53		
100.000	40	80				250	$ 88,000	17,679	$ 477,354	0.111	0.53		
100.000	60	80	20			250	$ 158,501	27,219	$ 757,960	0.177	0.68	74	3,654
100.000	80	80	60			250	$ 217,058	40,836	$ 1,116,395	0.260	0.83	206	3,654

Figure 3 **Example of sensitive results given by HOMER.**

2.3 Simulation in HOMER of gasification technology

The issue when designing an HRES integrating a Biomass Gasification Plant (BGP) emerges when the simulation program, such as the case of HOMER, does not have a predefined energy technology associated with it, usually resulting in the need to accommodate it with the existing elements. To integrate a BGP in HOMER, the first step needed is to understand the necessary parameters to include both the desired generator and the fuel (biomass in this case). Secondly, the method requires the performing of a literature review and the problem formulation. The aim is to identify the key features that describe how to define a BGP and the fuel by the software, according to the requested parameters [19], [53]. Finally, the software runs the simulations with the gasifier correctly modelled if all data are correctly entered. Figure 4 illustrates the process.

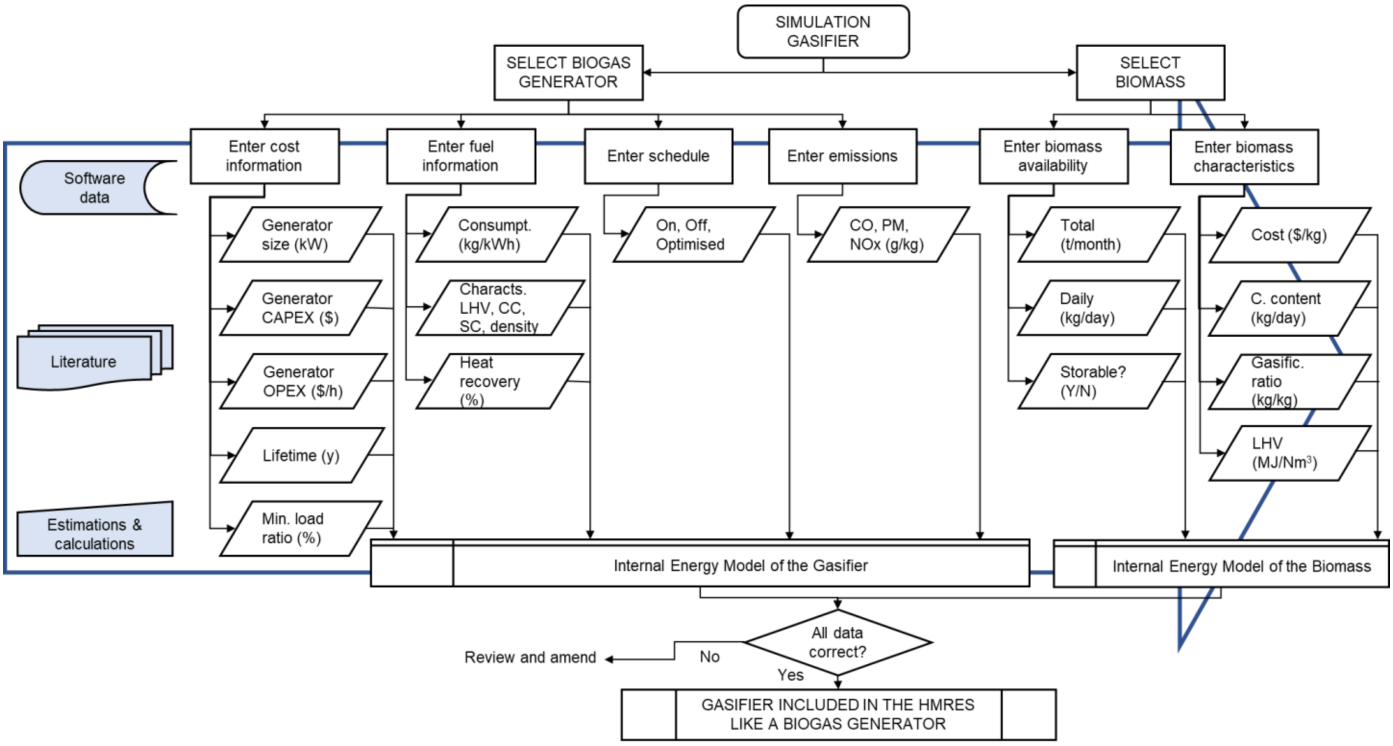


Figure 4 **Methodology to add a BGP in HOMER**

The information required to set up the biomass gasification generator in the subsection “Equipment to consider” is “Cost”, “Fuel”, “Schedule”, and “Emissions". First, the software requires adding a generator in the section ‘components’ and introducing economic information about the gasifier such as the size and cost of at least one gasifier (the one intended to be installed). The cost of the gasification plant for small scale applications is in the range of 2.0-3.5 USD/W [53], [55]. To this value, shipping cost and taxes must be added. Both of them depend on the final location of the plant. Replacement and Operation and Maintenance (O&M) costs are also needed, and both strongly depend on the gasifier’s location. According to [55], [56], the fixed cost of O&M (without considering fuel cost) for a gasification plant ranges from 2 to 6 % of CAPEX/year [53]. HOMER requires the O&M cost in USD per hour of operation (if all the values are in another currency, HOMER will give all the results in that currency) so users must consider an estimated annual operation time of the gasification plant to calculate this cost. If the O&M cost information is available in terms of USD per produced kWh of electricity, typically 0.05 to 0.2 USD/kWh [55]), users must consider an average operational power of the gasification plant, usually 50- 100% of rated installed power, to define the value in USD per hour.

In subsection “Schedule” it is possible to set up the gasification plant’s operation schedule (hour by hour). For every month, what time the gasifier will be ON, OFF, or OPTIMIZED, can be set up. If the OPTIMIZED option is selected the generator will be ON or OFF according to each possibilities' higher economic feasibility.

By default, the program decides for each time step whether or not to operate the generator based on the electrical demand and the generator's economics compared to other power sources. However, it is possible to force using or not using the generator during the planning time [57]. The operational schedule is especially useful when the manufacturer advises using the gasifier no more than a certain number of hours per day to avoid damage or the reduction of the gasifier's lifespan. In this case, it is necessary to analyse and set the most convenient schedule for the gasifier's operation when simulating. HOMER will decide, within the selected range, how long the BGP must operate. Moreover, to improve social acceptability of a BGP in HRES of "Prosumers", usage hours should be optimised in an hour range that is compatible with living patterns.

In subsection "Fuel", information about fuel consumption as a function of the output power must be provided to HOMER. The aim is to calculate the efficiency at different loads. Fuel can be a fossil or renewable fuel (gasoline, natural gas, biogas…), or stored hydrogen. For the simulation, the fuel properties needed are: Lower Heating Value (LHV), Carbon content (CC), Sulphur content (SC), and density. For this method, biogas is selected as fuel, therefore, to introduce information about biomass resources will be necessary. For this, HOMER requires the setting up of biomass availability and properties.

Biomass availability represents the average biomass feedstock availability. Available biomass is the sustainably available biomass per month (tonnes/month) or, if necessary, kilograms for each hour of the year. Then, for simulation purposes, the available biomass feedstock (tonnes/day) is required. If all the biomass is not used in a given time step, the user must set if the biomass can be used in future time steps [50].

Biomass properties include four parameters. The biomass cost depends on the plant's location. The carbon content depends on the biomass used, typically in the range 45-55% on the dry mass basis [58]. The Lower Heating Value (LHV) of the obtained biogas, which in the method refers to the syngas obtained from the biomass gasification process. And finally, the gasification ratio, which is the mass ratio of produced syngas (biogas for HOMER) to biomass consumed by the reactor. This ratio allows us to calculate the amount of biomass resource used or purchased if the price of the biomass is assigned. One of the limitations is that the program assumes the gasification ratio value is constant in time, but in reality, it depends on the biomass characteristics, the efficiency of the gasification process, and the power ratio of the plant. If one or more of these values are modified, the gasification will change. Even during the operation of a BGP, the efficiency could change as a load function. In this case, an average or a weighted value must be used as an input. A typical gasification ratio usually ranges from 2 to 3 Nm^3 of syngas per kg of biomass [59]–[62]. However, HOMER requires this parameter in kg gas/kg biomass. The syngas density is around 0.9 – 1.1 kg/Nm^3. For instance, at 20°C and 1 atmosphere, and assuming a composition of 21% CO, 17% H_2, 48% N_2, 13% CO_2, 1% CH_4, the syngas density would be equal to 0.95 kg/m^3 [63]. Thus, the value to use as input would range from 1.8 to 3.3 kg of syngas per kg of biomass.

The LHV values range from 4.5 to 6 MJ/Nm^3. The gasifier uses biomass as primary fuel and air as a gasifying agent. These values of LHV are within the range of that obtained by [18], [19], [53], [58]–[60], [64], [65]. Users must check that the efficiency of the gasification process (ratio syngas flow to biomass flow, both expressed in terms of energy) is consistent with literature values, i.e. it ranges from 60 to 88% [18], [59], [65] or make the required experiments in the laboratory to measure biomass' properties.

Finally, in subsection "Emissions" the definition of the expected generator emission factors is provided. The program estimates the generator's absolute total emissions per year, of Carbon Dioxide (CO_2), Carbon Monoxide (CO), Unburned Hydrocarbons (UHC), Particulate Matter (PM), Sulphur Dioxide (SO_2) and Nitrogen Oxides (NO_x). HOMER requires four of the six mentioned pollutants (in grams per kg of fuel) to carry out the estimation. The emission factor is required for CO, UHC, PM, and NO_x. Additionally, the user must indicate which proportion of fuel sulphur the fuel emits as PM (so the rest will be emitted as SO_2). The quantity of the pollutant produced by the generator depends on the fuel, engine design, and operating conditions, including the load of the generator. For simplicity's sake, the program assumes the emission factors are constant values [57].

3. Case Studies

The proposed process has been implemented in two case studies: the rural community of El Santuario, in the Honduran Dry Corridor; and Mumbeji, located in the North-Western province of Zambia. The communities have been selected given their similarity in terms of socio-economic, environmental, and energy context. This allows us to assess the feasibility of implementation and replication potential of the model for the gasification introduction in HOMER. Also, the benefits of incorporating gasifiers to HRES when there is enough available dry biomass.

Both communities are characterized by being isolated and non-electrified. Currently, population densities are respectively around 500 in 76 households in the Honduran community and around 1,000 inhabitants in the Zambian located in 100 households. Solar and dry biomass are the main available renewable resources, due to climate and geographic conditions. The predominance of agroforestry and farming activities provides biomass resources in the form of crop and timber waste. Wind power and micro-hydraulics were discarded due to their unreliable supply.

Energy demand was estimated according to the detected needs in the fieldwork, surveys [66], and the literature regarding similar rural electrification projects [16], [67], [68]. Similar results were obtained for both communities. The annual energy demand is estimated at 2-3 kWh per day and household, aligned with the global data on basic energy needs for ensuring human well-being [69]. The load profile has two typical peak loads: one during the early morning and one more prominent in the evening, at dusk after the working hours, reaching a maximum value of 18 kW (6:00 pm) in the case of Honduras and 30.5 kW (9:00 pm) in the case of Zambia.

The gasification plant is integrated into an HRES that combines a PV system, gasification, and a battery bank. Gasifier integration was simulated following the following proposed procedure. Syngas generation technologies have been techno-economically assessed to model a potentially replicable system. Nevertheless, biomass availability and characteristics will differ in different locations and must be independently evaluated.

3.1 Biomass generator selection

Downdraft technology is recommended as proven on small scale projects with good performance results [70]. It is less costly and easier to operate than other syngas generation technologies, which makes it suitable for small rural communities [71]. Besides, the tar content ratio is below 1 g/Nm^3, almost 100 times lower if compared to updraft gasification technologies [72].

Among more than 20 models and manufacturers, the *PP30* gasifier from *All Power Labs* [73] was assessed as the most proven, efficient, and cost-effective technology. The installed power is 30 kW, with a maximum electrical power output of 27 kW at 60 Hz frequency. The investment cost of the gasification plant is 2 USD/W of equipment [73]. The total cost is 60,000 USD, including shipping and installing. Replacement costs of the whole system were set to 10% less of the investment costs (1.8 USD/W). Maintenance costs are considered 2% of the investment costs (0.04 USD/W), equivalent to 0.072 USD/hour considering that the gasifier lifetime is calculated as 15,000 operating hours.

The minimum syngas flow rate for the gasification system is 2.2 Nm^3/h, equivalent to approximately 3 kW of electrical power output. The gasifier load ratio is recommended to be above 10% to avoid operational failures. Two different scenarios have been assessed regarding the minimal load ratio in the syngas gasifier output. In the case study of Honduras, the minimum load ratio is set to 50%, whereas in Zambia's case there is no load restriction, provided that output does not go below the minimum set by the manufacturer, 3 kW.

Gasifier biomass electrical generation efficiency is 23% based on the manufacturer's data. Manufacturer tests show a typical composition from syngas obtained of 21% CO, 19% H_2, 3% CH_4, 11% CO_2, 44% N_2, and

Sulphur content almost negligible. Biogas fuel properties (LHV, CC, SC, and density) will be defined according to the biomass characteristics. The gasification plant allows us to recover heat from the engine, in a proportion of 1.5-2 kWth/kWe. Heat recovery efficiency reaches close to 42%. This thermal energy will be available to serve future thermal needs in the community, although it is not considered as part of the simulation outputs.

In the proposed model, the gasifier is expected to operate mainly as a back-up system to the HRES to avoid biomass over-consumption. Therefore, the gasifier is expected to generate enough energy to cover the demand when the solar resource is not enough, or the batteries reach a State of Charge (SoC) of 30%. To implement that in the simulation, the usage schedule is set to follow “Optimized” operation. In addition, the operation of the gasifier is further improved by forcing it to stop during the central hours of the day and resting hours at night. In the simulations no emission limits and penalties have been considered, syngas being a renewable gas within a closed biomass carbon cycle [49].

3.2 Biomass selection and characterization.

Biomass availability and characteristics will vary according to the location. When possible, biomass properties should be determined in specific physicochemical laboratory tests. As an alternative, research was performed in order to define wood biomass characteristics. The results showed similar characteristics in both case studies.

In the Honduran Dry Corridor, forest biomass in the form of branches predominates due to forestry activities. In contrast, the North-Western province of Zambia is an area of farmland, Cassava being the most predominant and suitable crop in the region [74]. In the Honduras case study, the inhabitants noted a dry biomass consumption ratio of 17 kg/day and household, mainly for cooking and lighting activities. But biomass availability for the community is up to 2 tonnes/day [75].

Forestry biomass properties in Honduras were estimated based on literature [61], [76] ICF’s data (Honduran Forestry Conservation Institute), and a similar stand-alone HRES consuming wood biomass [19]. According to the references, the syngas generation per kg biomass was set to 2.1 Nm^3/kg. The density of syngas is about 0.72 kg/m^3, then the gasification ratio is calculated at 1.85 kg gas/kg biomass. The LHV input was 5.5 MJ/Nm^3 (1.53 kWh/Nm^3). Knowing that conversion gas-electricity using the syngas generator is 23%, the electrical generation per kg of biomass is calculated at 0.9 kWh/kg.

The rural community of Mumbeji in Zambia currently cultivates 23 ha of Cassava with a crop yield of 5.8 tonnes/ha/year. Cassava production is calculated in 0.365 tonnes per day. The final dry biomass potential is estimated at 0.13 tonnes/day based on literature data regarding the ratio waste-useful crop (36 %) [74], [77].

Cassava waste properties had to be sought from existing literature [61], [74], [76], [78], [79] considering its physicochemical properties comparable to wood biomass ones [77]. LHV of syngas is set at the minimum suggested 4.5 MJ/Nm³ (1,25 kWh/Nm³) and the carbon content to 44%. Gasification ratio wood-syngas is set at 2.08 Nm3/kg to be conservative, and following the proposal by [61], while the gasification ratio is calculated at 1.24 kg gas/kg biomass. Applying 23% electrical generation efficiency, the gasifier produces 0.83 kWh/kg biomass.

Although available biomass is considered as a waste, a certain biomass acquisition price is recommended to be included in the cost structure. This will allow us to cover the future expenditure of maintenance and replacements, as well as to avoid deforestation by raising awareness of the cost of renewable electricity generation.

According to an IRENA report [80], biomass for power generation costs ranges between 44 and 94 USD per tonne. The commercialisation price of dry biomass in Latin-America is about 300 USD/tonne [75], whereas the sale price of fresh cassava roots in 2013 was around 20 USD/tonne [81]. To avoid the risk of under or overestimation of the price, it is fixed at 100 USD/tonne in the case of Honduras and 50 USD/tonne in the case of Zambia.

3.3 Simulation results

Once the BGP and the biomass have been modelled, data was introduced in HOMER and the gasification plant was simulated. The results allow us to study the energy model and the integration of the gasifier in the HRES.

Figure 5 and Figure 6 show gasifier power output throughout the year for the 24 hours in a day in the case studies of Honduras and Zambia, respectively. In both cases, the gasifier starting schedule is in intervals from 6 am to 12 pm and from 6 pm to 12 am. Therefore, the gasifier's role as a backup system is confirmed when solar power is low, demand high and storage SoC decreases to 30%.

However, the number of starts during the year differ according to the location, with 8.5 times more in the case of Zambia. This is based mainly on the free minimum load ratio, the higher maximum load peak, and the lower biomass cost. It does influence as well that the wet season in the Honduran Dry Corridor (May to September) is drier than the one in the North-Western region of Zambia (November to February). Hence, it turns out that, in the case of Zambia, the gasifier operates more as complementary power than as a back-up system to the HRES.

Also, in the case of Zambia, the gasifier works at 30% of its rated capacity, which means that it still has the potential to generate energy if the needs of the community increase in the future. The same applies to the Honduras's case, in which the capacity factor is around 3%. This value is consistent with the role of the gasifier as backup system. In addition, non-fixing of a minimum load ratio in the Zambian case, gave a biomass consumption of 5.37 tonnes per day, 37% lower than in the 50% minimum load ratio case (8.5 tonnes/day). Hence it is more efficient in biomass but much less efficient in equipment usage, as will be discussed in the next section. Anyhow, both outcomes are below the current biomass availability identified in the community.

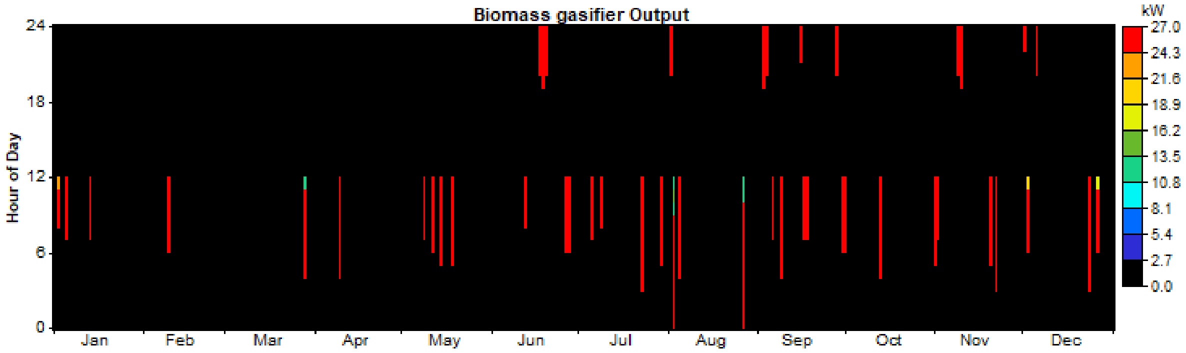


Figure 5 **Output of the gasifier during a typical year for the case in Honduras.**

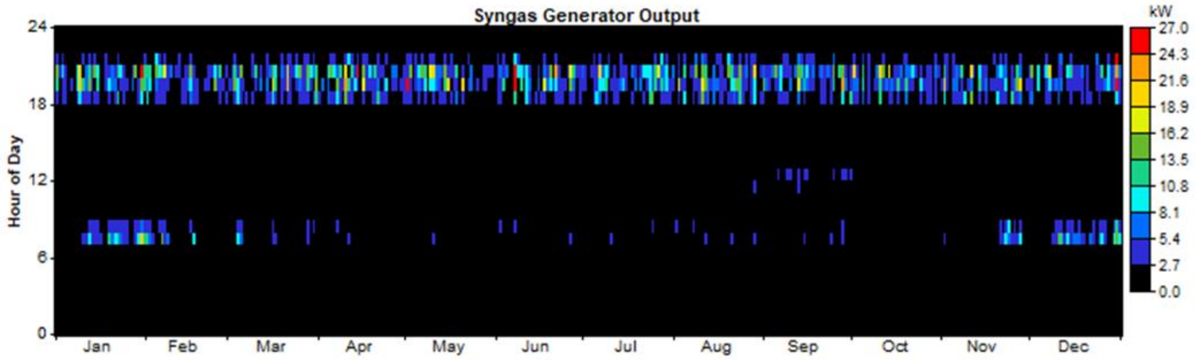


Figure 6 **Output of the gasifier during a typical year for the case in Zambia.**

The simulations provide an overview of the operation of the gasifier as part of the HRES. Figure 7 shows the example for a typical week of June when solar irradiation was limited due to the rainy season in Honduras. Therefore, the PV power is limited, and the batteries must be used. When the batteries' SoC is close to the minimum value of 30% the gasifier is activated, thus covering the demand of the community while charging the batteries.

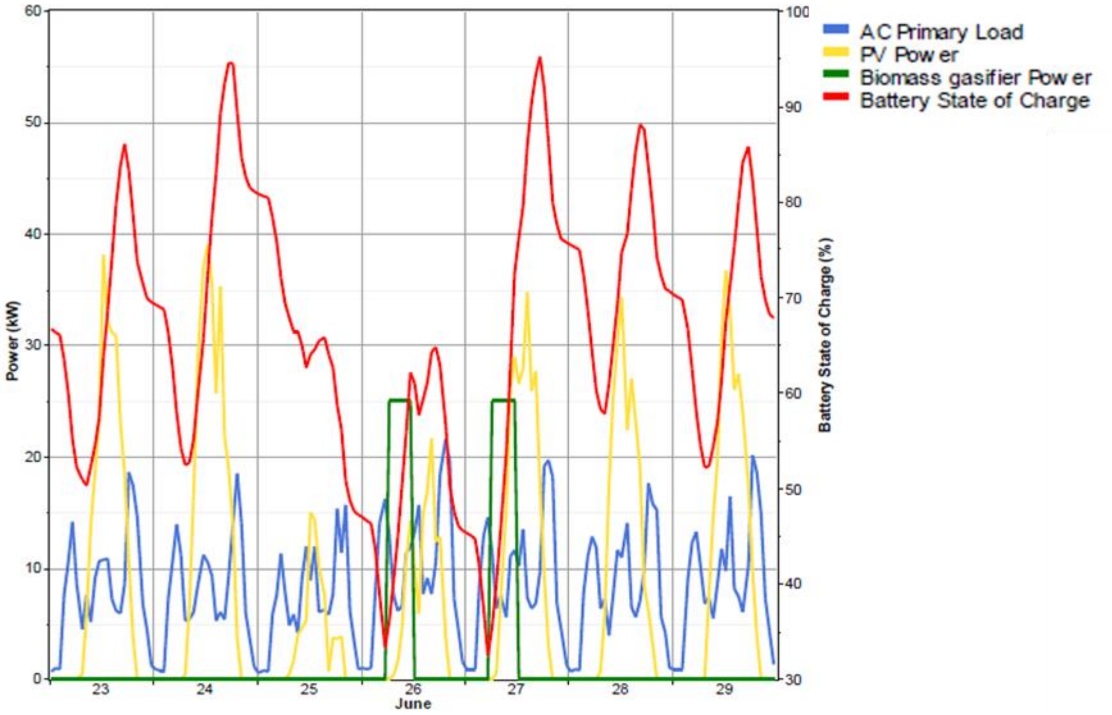


Figure 7. **Hourly operation according to HOMER for a typical week of June. Case of Honduras.**

A different scenario occurs in the case of Zambia (Figure 8) during November. On the 7th and 9th of November the gasifier starts to operate even though the PV power generation is high, but it is not enough to cover the demand. In this case, the batteries do not reach a SoC below 45%.

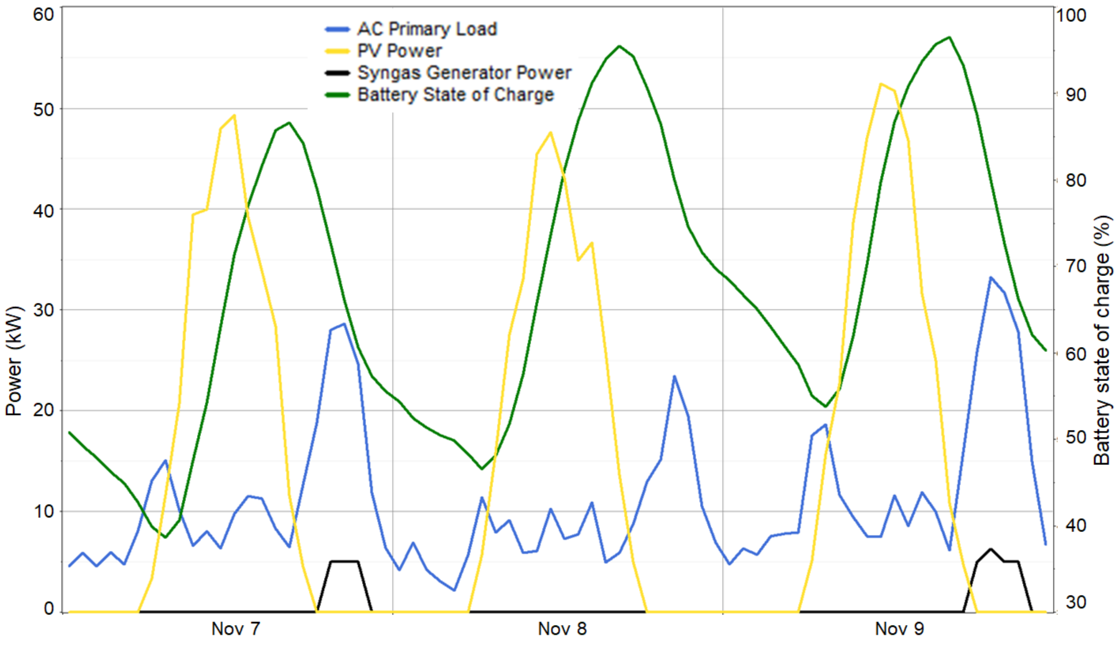


Figure 8. **Hourly operation according to HOMER for a typical week of November. Case of Zambia.**

Finally, Table 1 summarises the main economic and socio-technical features of the simulated HRES. The gasifier allows us to ensure the reliability and continuity of the energy supply, in El Santuario only 1.26 kWh/yr out of a demanded 73,000 kWh/yr will not be met (0.002%). In Mumbeji, the yearly electricity production is 155,693 kWh, and the unmet load 1,537 kWh/yr (0.99%).

Table 1. **Main economic and socio-technical features of the simulated HRES.**

Case Study	Unmet Load (kWh/yr)	Initial Capital (USD)	Total NPC (USD)	LCoE (USD/kWh)
El Santuario (Honduras)	1.26	181,733	256,133	0.06
Mumbeji (Zambia)	1,537	429,400	564,697	0.48

The Levelized Cost of Energy (LCoE) could be assessed as the price the community would have had to pay back on the investment. However, in the case of a donation, the community would only have to cover the costs of dry biomass, other O&M costs, and future replacements.

The LCoE for the HRES in the rural community of El Santuario amounts to around 0.06 USD/kWh, clearly below the typical price of Honduran residential electricity: 0.12 to 1.14 USD/kWh [82]. The obtained value is higher for the case of Mumbeji (around 0.48 USD/kWh). The difference is mainly due to the higher usage of the gasifier increasing the O&M costs, the lower LHV of Cassava, and the higher investment costs considered for the installation (4.45 USD/kWh), which were based on African mini-grids literature [83].

Finally, the breakeven grid extension distance for Mumbeji was also evaluated, obtaining a value of 70.2 km. Calculation is based on [19], [74], [84], using a capital cost of 5,000 USD/km, an O&M cost of 160 USD/km/y and a grid power price of 0.02USD/kWh. As the nearest electricity transport line is more than 150 km away, the HRES results in a cost-effective solution for the electrification of the community.

4. Discussion

The simulation proposal resulting from this research has enabled the simulation of the performance of a gasifier in two HRES case studies combining PV, biomass gasifier, and batteries; one in Honduras and the other in Zambia. For this purpose, the already in-built model of a biogas electricity generator has been used.

The results obtained are fully consistent with the scarce literature found on the HOMER simulation of HRES combining the same RES. See Introduction. Of this literature, only the paper by Chambon *et al.* and Alfonso-Solar *et al.* can be considered detailed on the modelling of the gasifier in HOMER [43], [49]. However, Chambon *et al.* does not explain the LHV of the biogas, the *electric* generation ratio, nor the mode of operation in the schedule (only downtime of 48 to 120 hours every 1,500 to 2,000 hours of operation). In that paper, the minimum load ratio is set at 30%, as in the HRES of Islam *et al*. [33] while in the rest of the sources there is no data. Regarding the paper from Alfonso-Solar *et al.,* while they include the biomass and syngas characteristics, they do not provide the syngas output to biomass input nor the justification of the usage patterns of the gasifier. No other paper has been found to explain how to set the schedule of the gasifier.

In the following proposed models, a CAPEX of 2 USD/kW has been set based on the manufacturer and in the literature, which was found between 1.1 USD/kW [33] and 3.64 USD/kW [49]. Replacement costs vary between 1,000 USD/kW and 20,000 hours of operation in [33] and 2,909 USD/kW in [49], who consider 150,000 hours of a gasifier's lifespan without distinguishing between operating and idle hours. Moreover, an O&M cost of between 0.03 USD/h [49] and 0.10 USD/h [85] has been found, and in this paper is 0.072 USD/h. The LCoEs found ranges between 0.16 USD/kWh from Suresh *et al.* [28] and 0.21 from Chambon *et al*.[49], which leaves the LCOE of the Zambian case very high. However, it should be noted that in the case of Chambon *et al.* when they lower the blackout allowance from 4% to 0%, the LCoE rises rapidly to 0.8 USD/kWh, while in the Zambian case 2% is allowed.

Furthermore, although it is a critical parameter for the simulation, only Chambon *et al.* give the gasification ratio: 2.5 kg gas/kg biomass [49], which is within the range from 1.8 to 3.3 estimated in this study. In the case studies 1.9 kg/kg are considered for Honduras and Zambia, which is on the safe side. While the literature on gasifiers proposes an LHV for the biomass of between 12.5 and 19.0 MJ/kg [76], only Suresh *et al.* [28] give the figure: 18.81 MJ/kg for forest foliage. In the presented case studies, the LHV considered is 15.55 MJ/kg for wood in Honduras and 9.36 MJ/kg for cassava in Zambia. On the contrary, biomass prices do occur and vary between 0.3 USD/ton of Suresh *et al.* [28] and 58 USD/ton of Chambon *et al*. [49].

In contrast, it is worth arguing that there are social variables that must also be considered in the simulation. As the difference in operation between the Honduran and Zambian cases shows, if no minimum load ratio is set, the optimum performance is reached with the gasifier in continuous operation. But this is not desirable because of the need for constant attention by a community member (mainly feeding it), and the higher O&M costs for too much operation and too little generation. Thus, unless the gasification technology is used as a base one and not as backup, setting a minimum load ratio improves the gasifier's operation. Indeed, in Honduras's case (Figure 5) the gasifier operates mainly at its maximum capacity (mean power output 24.7 kW), whereas in the case of Zambia (Figure 6) there is a mean electrical power output of 7.22 kW. In that regard, the biomass storing and the periodicity in the feeding of the gasifier should be controlled to avoid operational failures. Therefore, the minimum load ratio and the schedule must be set in a coordinated way for a socially acceptable operation of the equipment.

The authors find that the social acceptability of a project is key to ensure the success of a rural electrification project [5], [86]. Usage hours of the gasifier should be compatible with living patterns in the community. In this regard, modelling the operation hours of the gasifier remains crucial to ensure that the optimised hours are not only ideal from a technological perspective but also from a social acceptance one. Another concern arises regarding the payments needed to sustain the resource flow to the gasifier and its operation. Specific payments regarding obtaining the resource and the hours of management may generate problems among the community. This results in the need to understand that variable costs of the gasifier may vary or not be used as designed if the opinion of the community is not considered in a first design. Nevertheless, producers and consumers' communities of energy, energy "Prosumers" communities, are in a better position to move from energy poverty to the understanding of the technicalities and externalities of the supply, to manage, and maintain the power system and to include all participants of the energy community in its benefits [87].

Finally, the simulation results prove biomass gasifiers are a dispatchable energy source that enables valorising biomass resources or biomass waste to generate electricity in key moments. The inclusion of this technology allows HOMER to optimise the HRES performance and achieve lower LCoE of the system without compromising its reliability.

Hence, gasification serves three main purposes and benefits in an HRES: first, it delivers capacity during peak demand hours and ensures a flexible resource for future demand increases as can be seen in Figures 5 and 6. Second, it ensures the security of supply of the HRES during adverse weather events such as consecutive days of low solar irradiation, avoiding in this way designing a system with over-generation and storage capacity as seen in Figures 7 and 8. Besides, the operation of batteries is improved by not allowing them to go below certain SoC levels by being switched on to supply electricity to the community and charge the battery bank as shown in Figures 7 and 8. Third, gasifiers contribute to optimising the initial capital costs to solve the energy poverty of isolated and rural areas without access to electricity without compromising the SDG7. Their dispatchability helps HRES to compete in reliability and cost with the alternative to electrifying rural areas, the grid extension.

5. Conclusion

This study proposes a complete procedure to model a biomass gasifier in HOMER. For this, the biogas pre-set energy source in HOMER is taken due to the absence of gasifiers as a generation technology. To prove the feasibility of the simulation proposal two case studies were carried out. On the one hand, the models of the gasifiers were included in HOMER. On the other hand, the viability of gasifiers as dispatchable renewable energy is confirmed if the biomass resource is available, as well as its benefits for the beneficiaries of the

HRMES. This paper advances ongoing research and, particularly, one of the hybrid power plants of the case studies is currently being executed.

To model a gasifier in HOMER numerous parameters must be set up, such as fuel consumption, operation hours, and output power, among others. This fact presents the disadvantage of needing to determine not only the biomass properties but also the syngas, assimilable to biogas produced in HOMER, and the performance of the generator when converting biomass into syngas. However, those are data that gasifier technology suppliers and the literature provide for a reliable model of gasifier performance. The availability of biomass resources, in turn, is normally more readily available than other data on renewable resources, as biomass plays a key role in energy for poor, isolated rural communities.

The proposal enables us to completely model biomass gasifiers in HOMER with realistic results. All the HOMER parameters that too often are left “by default”, or where left unexplained (and thus not-replicable) could be estimated following this process: the biomass characteristics, the ratio of biomass input to syngas output, the characteristics of the syngas, the performance of the gasifier, etc. This will help designers and researchers to reliably include this technology in their analysis of biomass gasifiers’ potential for all types of applications in HOMER. Of particular interest is the participation of gasifiers as power systems (backup or not) in off-grid HRES for energy-poor isolated communities, provided there is a sufficient supply of dry biomass. These HRES help to mitigate climate change and help the energy-poor communities to better adapt to it, to align their development with national, and international sustainable development strategies, particularly SDG7.

Moreover, should the grid reach the community over time, the power plant will still help to reduce the energy costs, keep the greenhouse gas emissions low, and preserve the reliance of the community against blackouts, prices increase, or even fuel poverty, understood as the incapability to pay the price of the energy they have access to.

Furthermore, based on the results of the case studies in El Santuario and Mumbeji, an HMRES including a gasifier as a backup system achieves competitive LCoE of electricity: in El Santuario around 0.06 USD/kWh, below the typical Honduran residential electricity price of 0.12 to 1.14 USD/kWh. The obtained value is higher for the case of Mumbeji: 0.48 USD/kWh. However, it is still lower than extending the electric grid to the community. Besides, the simulation shows the importance of correctly setting the free minimum load ratio, the higher maximum load peak, and the lower biomass cost. The continuous operation in Mumbeji’s case is less convenient than the in El Santuario’s. The simulation forced the gasifier to act as a backup system, but in both cases the gasifiers have a wide margin to increase their energy generation (if there is enough biomass) as they are delivering less than 30% of their peak power. The gasifier is activated when the batteries' SoC is close to 30%, thus covering the demand of the community while charging the batteries. This arrangement will prolong the life of batteries, around 40% of the CAPEX in both HMRES. This way, the gasifier ensures the reliability and continuity of the energy supply in El Santuario, with only 1.26 kWh/yr that will not be met (0.002%). In Mumbeji, the unmet load is 1,537 kWh/yr (0.99%).

Nevertheless, in contrast with its potential, modelling biomass gasifiers in HOMER may not be considered as essential elements of their daily operation, maintenance, costs, and necessities, which are relevant, and which designers ought to consider. Gasification has a potential environmental impact such as overharvesting, deforestation, and waste mismanagement. Social implications arise from the community usage times of the gasifier and the cost structure and payment of its management. Finally, physical-chemical characteristics and the energy transformation process of the biomass must be carefully considered so as not overestimate the potential of the technology and resource.

Other issues to be concerned with are that dry biomass and agricultural waste are the main energy sources of most rural areas without access to electricity. Biomass is used for cooking lighting and heating in these areas with a common rules-based management that prevents deforestation. The usage of dry biomass to generate electricity is a sensitive issue and may lead to deforestation patterns following the Jevons paradox. Consequently, when modelling gasifiers these concerns must be considered in the total biomass resource of the model and transferred to the community to ensure the proper management of the common resources. Moreover, if agricultural waste is used to power gasifiers, the community requires seasonal storage systems that need to be counted in the cost structure of the system. The storage needs to be managed properly in order to minimise property loss due to anaerobic degradation, ensure proper humidity conditions, and avoid spontaneous ignition. Thus, since the cost structure, biomass resource use and usage patterns vary according to the project country, local data must be considered in order to project the economic balance of the system and introduce the above-mentioned design components of HOMER.

Finally, and also as discussed, the social acceptability of a project is key to ensuring the success of a rural electrification project. Using hours of the gasifier, payments of the fuel, etc. should be compatible with living patterns in the community. Nevertheless, communities of energy prosumers are more competent and resilient to all these challenges.

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References

[1] UN, “Sustainable Development Goals ,” 2019. [Online]. Available: https://sustainabledevelopment.un.org/?menu=1300. [Accessed: 01-Dec-2019].

[2] IEA, “ SDG7: Data and Projections,” Paris, 2020.

[3] I. - International Energy Agency, “WEO-2017 Special Report: Energy Access Outlook,” 2017.

[4] IEA, “Energy Access Outlook,” 2017.

[5] D. Ribó-Pérez, P. Bastida-Molina, T. Gómez-Navarro, and E. Hurtado-Pérez, “Hybrid assessment for a hybrid microgrid: A novel methodology to critically analyse generation technologies for hybrid microgrids,” *Renew. Energy*, vol. 157, pp. 874–887, Sep. 2020.

[6] P. A. Østergaard, N. Duic, Y. Noorollahi, and S. Kalogirou, “Latest progress in Sustainable Development using renewable energy technology,” *Renew. Energy*, vol. 162, pp. 1554–1562, Dec. 2020.

[7] P. A. Østergaard, N. Duic, Y. Noorollahi, H. Mikulcic, and S. Kalogirou, “Sustainable development using renewable energy technology,” *Renewable Energy*, vol. 146. Elsevier Ltd, pp. 2430–2437, 01-Feb-2020.

[8] P. D. Lund, J. Lindgren, J. Mikkola, and J. Salpakari, “Review of energy system flexibility measures to enable high levels of variable renewable electricity,” *Renewable and Sustainable Energy Reviews*, vol. 45. Elsevier Ltd, pp. 785–807, 01-May-2015.

[9] O. D. T. Odou, R. Bhandari, and R. Adamou, “Hybrid off-grid renewable power system for sustainable rural electrification in Benin,” *Renew. Energy*, vol. 145, pp. 1266–1279, Jan. 2020.

[10] E. Ayodele, S. Misra, R. Damasevicius, and R. Maskeliunas, “Hybrid microgrid for microfinance

institutions in rural areas – A field demonstration in West Africa," *Sustain. Energy Technol. Assessments*, vol. 35, pp. 89–97, Oct. 2019.

[11] B. K. Das and F. Zaman, "Performance analysis of a PV/Diesel hybrid system for a remote area in Bangladesh: Effects of dispatch strategies, batteries, and generator selection," *Energy*, vol. 169, pp. 263–276, Feb. 2019.

[12] A. C. Brent and D. E. Rogers, "Renewable rural electrification: Sustainability assessment of mini-hybrid off-grid technological systems in the African context," *Renew. Energy*, vol. 35, no. 1, pp. 257–265, Jan. 2010.

[13] S. Mazzola, M. Astolfi, and E. Macchi, "The potential role of solid biomass for rural electrification: A techno economic analysis for a hybrid microgrid in India," *Appl. Energy*, vol. 169, pp. 370–383, May 2016.

[14] Y. A. Situmorang, Z. Zhao, A. Yoshida, A. Abudula, and G. Guan, "Small-scale biomass gasification systems for power generation (<200 kW class): A review," *Renew. Sustain. Energy Rev.*, vol. 117, p. 109486, Jan. 2020.

[15] S. Das, D. Kashyap, P. Kalita, V. Kulkarni, and Y. Itaya, "Clean gaseous fuel application in diesel engine: A sustainable option for rural electrification in India," *Renewable and Sustainable Energy Reviews*, vol. 117. Elsevier Ltd, p. 109485, 01-Jan-2020.

[16] S. Mandelli, J. Barbieri, R. Mereu, and E. Colombo, "Off-grid systems for rural electrification in developing countries: Definitions, classification and a comprehensive literature review," *Renew. Sustain. Energy Rev.*, vol. 58, pp. 1621–1646, May 2016.

[17] A. S. Bisht and N. S. Thakur, "Small scale biomass gasification plants for electricity generation in India: Resources, installation, technical aspects, sustainability criteria & policy," *Renew. Energy Focus*, vol. 28, pp. 112–126, Mar. 2019.

[18] A. Pérez-Navarro *et al.*, "Experimental verification of hybrid renewable systems as feasible energy sources," *Renew. Energy*, vol. 86, pp. 384–391, Feb. 2016.

[19] E. Hurtado, E. Peñalvo-López, Á. Pérez-Navarro, C. Vargas, and D. Alfonso, "Optimization of a hybrid renewable system for high feasibility application in non-connected zones," *Appl. Energy*, vol. 155, pp. 308–314, Oct. 2015.

[20] S. Farahat, M. A. Y. Jahromi, and S. M. Barakati, “Modeling and Sizing Optimization of Stand- alone Hybrid Renewable Energy Systems,” *Int. Conf. Mech. Nanotechnol. Cryog. Eng.*, pp. 212–217, 2012.

[21] T. Kobayakawa and T. C. Kandpal, “Optimal resource integration in a decentralized renewable energy system: Assessment of the existing system and simulation for its expansion,” *Energy Sustain. Dev.*, vol. 34, pp. 20–29, Oct. 2016.

[22] D. K. Lal, B. B. Dash, and A. K. Akella, “Optimization of PV / Wind / Micro-Hydro / Diesel Hybrid Power System in HOMER for the Study Area,” *Int. J. Electr. Eng. Informatics*, vol. 3, no. 3, pp. 307–325, 2011.

[23] O. Krishan and S. Suhag, “Techno-economic analysis of a hybrid renewable energy system for an energy poor rural community,” *J. Energy Storage*, vol. 23, pp. 305–319, Jun. 2019.

[24] A. S. Aziz, M. F. N. Tajuddin, M. R. Adzman, A. Azmi, and M. A. M. Ramli, “Optimization and sensitivity analysis of standalone hybrid energy systems for rural electrification: A case study of Iraq,” *Renew. Energy*, vol. 138, pp. 775–792, Aug. 2019.

[25] F. Fodhil, A. Hamidat, and O. Nadjemi, “Potential, optimization and sensitivity analysis of photovoltaic-diesel-battery hybrid energy system for rural electrification in Algeria,” *Energy*, vol. 169, pp. 613–624, Feb. 2019.

[26] A. B. Esan, A. F. Agbetuyi, O. Oghorada, K. Ogbeide, A. A. Awelewa, and A. E. Afolabi, “Reliability assessments of an islanded hybrid PV-diesel-battery system for a typical rural community in Nigeria,” *Heliyon*, vol. 5, no. 5, p. e01632, May 2019.

[27] P. Malik, M. Awasthi, and S. Sinha, “Study of grid integrated biomass-based hybrid renewable energy systems for Himalayan territory,” *Int. J. Sustain. Energy Plan. Manag.*, vol. 28, pp. 71–88, Jan. 2020.

[28] V. Suresh, M. Muralidhar, and R. Kiranmayi, “Modelling and optimization of an off-grid hybrid renewable energy system for electrification in a rural areas,” *Energy Reports*, vol. 6, pp. 594–604, Nov. 2020.

[29] M. Kaur, S. Dhundhara, Y. P. Verma, and S. Chauhan, “Techno-economic analysis of photovoltaic-biomass-based microgrid system for reliable rural electrification,” *Int. Trans. Electr. Energy Syst.*, vol. 30, no. 5, p. e12347, May 2020.

[30] O. M. Anssari, E. A. Alkaldy, N. Almudhaffar, A. N. AlTaee, and N. S. Ali, “A feasibility study of electrical

energy generation from municipal solid waste in Iraq: Najaf case study," *Int. J. Electr. Comput. Eng.*, vol. 10, no. 4, pp. 3403–3411, Aug. 2020.

[31] M. Wegener, A. Isalgué, A. Malmquist, and A. Martin, "3E-Analysis of a Bio-Solar CCHP System for the Andaman Islands, India—A Case Study," *Energies*, vol. 12, no. 6, p. 1113, Mar. 2019.

[32] P. Malik, M. Awasthi, and S. Sinha, "Analysis of sensitive parameters influencing a SPV/WT/Biomass/Battery based hybrid system," in *2019 8th International Conference on Power Systems: Transition towards Sustainable, Smart and Flexible Grids, ICPS 2019*, 2019.

[33] M. S. Islam, R. Akhter, and M. A. Rahman, "A thorough investigation on hybrid application of biomass gasifier and PV resources to meet energy needs for a northern rural off-grid region of Bangladesh: A potential solution to replicate in rural off-grid areas or not?," *Energy*, vol. 145, pp. 338–355, Feb. 2018.

[34] M. Ali Bagherian, K. Mehranzamir, J. Ahmed, M. Nafea, H. Nabipour-Afrouzi, and C. Wooi, "Development of Biomass-fueled Cogeneration Systems for Off-grid Electrification," in *2nd International Conference on Smart Power & Internet Energy Systems*, 2020.

[35] A. Singh, P. Baredar, and B. Gupta, "Computational Simulation & Optimization of a Solar, Fuel Cell and Biomass Hybrid Energy System Using HOMER Pro Software," in *Procedia Engineering*, 2015, vol. 127, pp. 743–750.

[36] N. Ramchandran, R. Pai, and A. K. S. Parihar, "Feasibility assessment of Anchor-Business-Community model for off-grid rural electrification in India," *Renew. Energy*, vol. 97, pp. 197–209, Nov. 2016.

[37] M. Younas, R. Kamal, M. S. Khalid, and A. Qamar, "Economic Planning for Remote Community Microgrid Containing Solar PV, Biomass Gasifier and Microhydro," in *Clemson University Power Systems Conference, PSC 2018*, 2019.

[38] L. Montuori, M. Alcázar-Ortega, C. Álvarez-Bel, and A. Domijan, "Integration of renewable energy in microgrids coordinated with demand response resources: Economic evaluation of a biomass gasification plant by Homer Simulator," *Appl. Energy*, vol. 132, pp. 15–22, Nov. 2014.

[39] A. M. Rosso Cerón, S. Weingärtner, and V. Kafarov, "Generation of Electricity by Plant Biomass in Villages of the Colombian Provinces: Chocó, Meta and Putumayo," in *CHEMICAL ENGINEERING TRANSACTIONS*, 2015, vol. 43.

[40] M. Singh and P. Balachandra, “Microhybrid Electricity System for Energy Access, Livelihoods, and Empowerment,” *Proc. IEEE*, vol. 107, no. 9, pp. 1995–2007, Sep. 2019.

[41] A. Singh and P. Baredar, “Power sharing and cost optimization of hybrid renewable energy system for academic research building,” *J. Electr. Eng. Technol.*, vol. 12, no. 4, pp. 1511–1518, 2017.

[42] R. Rajbongshi, D. Borgohain, and S. Mahapatra, “Optimization of PV-biomass-diesel and grid base hybrid energy systems for rural electrification by using HOMER,” *Energy*, vol. 126, pp. 461–474, May 2017.

[43] D. Alfonso-Solar, C. Vargas-Salgado, C. Sánchez-Díaz, and E. Hurtado-Pérez, “Small-Scale Hybrid Photovoltaic-Biomass Systems Feasibility Analysis for Higher Education Buildings,” *Sustainability*, vol. 12, no. 21, p. 9300, Nov. 2020.

[44] M. Ahmed, M. S. Parvez, M. M. Hossain, and M. M. Rahman, “Simulation of standalone 80kW biomass fueled power plant in Sailchapra, Bangladesh,” in *2015 International Conference on Green Energy and Technology, ICGET 2015*, 2015.

[45] P. Malik, M. Awasthi, Sinha, and S 2, “Study on an Existing PV/Wind Hybrid System Using Biomass Gasifier for Energy Generation,” *Pollution*, vol. 6, no. 2, pp. 325–336, 2020.

[46] I. Eziyi and A. Krothapalli, “Sustainable rural development: Solar/Biomass hybrid renewable energy system,” in *Energy Procedia*, 2014, vol. 57, pp. 1492–1501.

[47] A. Singh and P. Baredar, “Techno-economic assessment of a solar PV, fuel cell, and biomass gasifier hybrid energy system,” *Energy Reports*, vol. 2, pp. 254–260, Nov. 2016.

[48] P. Malik, M. Awasthi, and S. Sinha, “Techno-economic analysis of decentralized biomass energy system and CO2 reduction in the Himalayan region,” *Int. J. Energy Environ. Eng.*, pp. 1–11, Jan. 2021.

[49] C. L. Chambon, T. Karia, P. Sandwell, and J. P. Hallett, “Techno-economic assessment of biomass gasification-based mini-grids for productive energy applications: The case of rural India,” *Renew. Energy*, vol. 154, pp. 432–444, Jul. 2020.

[50] NREL, “HOMER ENERGY,” 2020. [Online]. Available: www.homerenergy.com. [Accessed: 08-Feb-2020].

[51] M. Hailu Kebede and G. Bekele Beyene, “Feasibility Study of PV-Wind-Fuel Cell Hybrid Power System

for Electrification of a Rural Village in Ethiopia," *J. Electr. Comput. Eng.*, vol. 2018, 2018.

[52] O. Hafez and K. Bhattacharya, "Optimal planning and design of a renewable energy based supply system for microgrids," *Renew. Energy*, vol. 45, pp. 7–15, Sep. 2012.

[53] D. Alfonso-solar, C. V. C. Sánchez-díaz, and E. Hurtado-pérez, "Small-scale hybrid photovoltaic-biomass systems feasibility analysis for higher education buildings," pp. 1–11, 2020.

[54] S. Bahramara, M. P. Moghaddam, and M. R. Haghifam, "Optimal planning of hybrid renewable energy systems using HOMER: A review," *Renew. Sustain. Energy Rev.*, vol. 62, pp. 609–620, Sep. 2016.

[55] N. Indrawan, B. Simkins, A. Kumar, and R. L. Huhnke, "Economics of distributed power generation via gasification of biomass and municipal solid waste," *Energies*, vol. 13, no. 14, pp. 1–18, 2020.

[56] IRENA International Renewable Energy Agency, *Renewable Power Generation Costs in 2018*. 2018.

[57] Homer Energy, "HOMER Pro 3.14 User Manual." 2020.

[58] A. Porcu, S. Sollai, D. Marotto, M. Mureddu, F. Ferrara, and A. Pettinau, "Techno-economic analysis of a small-scale biomass-to-energy BFB gasification-based system," *Energies*, vol. 12, no. 3, 2019.

[59] B. Prabir, *Biomass Gasification and Pyrolysis. Practical Design and Theory*, First Edit. © 2010 Elsevier Inc., 2010.

[60] J. R. Copa *et al.*, "Techno-economic assessment of the use of syngas generated from biomass to feed an internal combustion engine," *Energies*, vol. 13, no. 12, p. 3097, 2020.

[61] J. D. Martínez, K. Mahkamov, R. V. Andrade, and E. E. Silva Lora, "Syngas production in downdraft biomass gasifiers and its application using internal combustion engines," *Renewable Energy*, vol. 38, no. 1. Pergamon, pp. 1–9, 01-Feb-2012.

[62] L. Montuori, C. Vargas-Salgado, and M. Alcázar-Ortega, "Impact of the throat sizing on the operating parameters in an experimental fixed bed gasifier: Analysis, evaluation and testing," *Renew. Energy*, vol. 83, pp. 615–625, Nov. 2015.

[63] A. Mustafa, R. K. Calay, and M. Y. Mustafa, "A Techno-economic Study of a Biomass Gasification Plant for the Production of Transport Biofuel for Small Communities," *Energy Procedia*, vol. 112, no. October, pp. 529–536, 2017.

[64] C. Vargas-Salgado, J. Aguila-Leon, C. Chiñas-Palacios, and E. Hurtado-Perez, “Low-cost web-based Supervisory Control and Data Acquisition system for a microgrid testbed: A case study in design and implementation for academic and research applications,” *Heliyon*, vol. 5, no. 9, Sep. 2019.

[65] C. Vargas-Salgado, E. Hurtado-Pérez, D. Alfonso-Solar, and A. Malmquist, “Empirical Design , Construction , and Experimental Test of a Small - Scale Bubbling Fluidized Bed Reactor,” *Sustain.*, vol. 13, no. 3, pp. 1–23, 2021.

[66] GIZ, “What size shall it be? A guide to mini-grid sizing and demand forecasting,” 2016.

[67] C. Muhoza and O. W. Johnson, “Exploring household energy transitions in rural Zambia from the user perspective,” *Energy Policy*, vol. 121, no. January, pp. 25–34, 2018.

[68] G. J. Prinsloo, “Scoping exercise to determine load profile archetype reference shapes for solar co-generation models in isolated off-grid rural African villages,” *J. Energy South. Africa*, vol. 27, no. 3, p. 11, 2016.

[69] X. . He and D. Reiner, “Electricity Demand and Basic Needs: Empirical Evidence from China’s Households.,” *Cambridge Work. Pap. Econ.*, 2014.

[70] T. B. Reed and A. Das, “Handbook of Biomass Downdraft Gasifier Engine Systems,” Golden, 1988.

[71] L. Waldheim, *Gasification of waste for energy carriers A review Gasification of waste for energy carriers A review Content*. IEA Bioenergy, 2018.

[72] S. De, A. Kumar Agarwal, V. S. Moholkar, and B. Thallada, *Coal and Biomass Gasification: Recent Advances and Future Challenges - Google Libros*. Springer, 2018.

[73] All Power Labs, “Affordable portable on-demand carbon-negative energy from biomass-powered gensets.”

[74] V. Okudoh, C. Trois, T. Workneh, and S. Schmidt, “The potential of cassava biomass and applicable technologies for sustainable biogas production in South Africa: A review,” *Renew. Sustain. Energy Rev.*, vol. 39, pp. 1035–1052, Nov. 2014.

[75] FAO-Mesoamerican subregional Office, “Oferta, demanda, barreras y plan para incrementar el uso de madera legal. Mercado de los productos forestales en Honduras,” Tegucigalpa, 2018.

[76] A. Molino, S. Chianese, and D. Musmarra, “Biomass gasification technology: The state of the art overview,” *J. Energy Chem.*, vol. 25, no. 1, pp. 10–25, Jan. 2016.

[77] J. P. S. Veiga, T. L. Valle, J. C. Feltran, and W. A. Bizzo, “Characterization and productivity of cassava waste and its use as an energy source,” *Renew. Energy*, vol. 93, pp. 691–699, 2016.

[78] A. Pattiya, “Thermochemical characterization of agricultural wastes from thai cassava plantations,” *Energy Sources, Part A Recover. Util. Environ. Eff.*, vol. 33, no. 8, pp. 691–701, 2011.

[79] M. K. Commeh, F. Kemausuor, E. N. Badger, and I. Osei, “Experimental study of ferrocement downdraft gasifier engine system using different biomass feedstocks in Ghana,” *Sustain. Energy Technol. Assessments*, vol. 31, no. October 2018, pp. 124–131, 2019.

[80] IRENA, “Zambia Renewables Readiness Assessment 2013,” 2013.

[81] Lusaka Voice, “Cassava commercialisation good for agro sector | Lusaka Voice,” 2013.

[82] CEPAL, “Estadísticas del subsector eléctrico de los países del Sistema de la Integración Centroamericana (SICA), 2017,” 2018.

[83] M. Moner-Girona *et al.*, “Adaptation of Feed-in Tariff for remote mini-grids: Tanzania as an illustrative case,” *Renew. Sustain. Energy Rev.*, vol. 53, pp. 306–318, Jan. 2016.

[84] M. H. Jahangir, S. Fakouriyan, M. A. Vaziri Rad, and H. Dehghan, “Feasibility study of on/off grid large-scale PV/WT/WEC hybrid energy system in coastal cities: A case-based research,” *Renew. Energy*, vol. 162, pp. 2075–2095, 2020.

[85] A. Islam, R. S. Hasib, and S. M. Isalm, “Journal of Power Technologies 93 (4) (2013) 185-193 Short Term Electricity Demand Forecasting for an Isolated Area using Two Different Approaches,” vol. 93, no. 4, pp. 185–193, 2013.

[86] P. Lillo, L. Ferrer-Martí, A. Boni, and Á. Fernández-Baldor, “Assessing management models for off-grid renewable energy electrification projects using the Human Development approach: Case study in Peru,” *Energy Sustain. Dev.*, vol. 25, pp. 17–26, 2015.

[87] T. Morstyn, N. Farrell, S. J. Darby, and M. D. McCulloch, “Using peer-to-peer energy-trading platforms to incentivize prosumers to form federated power plants,” *Nat. Energy*, vol. 3, no. 2, pp. 94–101, 2018.