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ORIGINAL RESEARCH PAPER

Techno-economic analysis of direct combustion and gasification systems for off-grid energy supply: A case for organic rankine cycle and dual fluidized-bed

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Abstract

Biomass is one of the most versatile sustainable energy sources. This versatility allows utilization of different biomass feedstock using a verity of conversion techniques. Often, a biomass-to-bioenergy conversion method is selected depending on the application, end-use product, and the type of feedstock. In many applications such as residential energy supply, it is possible to select amongst various technologies. Although, there exist several challenges such as cost-effectiveness and sustainability that constrains bioenergy development. To this end, this research elaborates on the impacts of different conversion methods on techno-economic performance of bioenergy systems for residential energy supply. In this context, Organic Rankine Cycle based on direct combustion, and Dual Fluidized-Bed technology based on gasification were selected for that purpose. A techno-economic comparative analysis illustrates that the primary product of the system and fuel cost are the two most important factors in feasibility assessment. The negative impact of feedstock price was more severe on the Organic Rankine Cycle. For wood chips prices below 55$/t, Organic Rankine Cycle could be the better option due to lower capital and maintenance costs. In contrast, Dual Fluidized-Bed could better tolerate the variation of feedstock price; offering 8% lower cost of energy at 65$/t wood chips.

1 | INTRODUCTION

Over the past decade, global energy demand has been increasing at a fluctuating rate; experiencing 2.9% annual growth in 2018 which was the fastest rate seen since 2010. Various influencing parameters such as population growth, economic improvements, and weather-related effects have contributed to the increase of energy demand over the years. Weather-related effects are the direct consequence of climate change which has led to unforeseeable climate characteristics, and unexpected growth in energy demand for cooling and heating purposes. Rising energy demand is accompanied by greater challenges, concerning energy security and environmental impacts. Unfortunately, the growing energy consumption has resulted in excessive utilization of energy resources and accelerated carbon emissions. This is due to the fact that fossil fuels are still dominant in the energy sector, and they have established their dependency for power and heat generation. In the power sector, despite significant growth in renewable penetration, the fuel mix in the global power market remains relatively the same, as coal maintains its precedence over non-fossil fuel resources at 38% in 2018 [1]. Power generation is the single largest source of carbon emissions, and it should play the central role in the energy transition plan towards a low carbon society. Decarbonisation of the power sector, with regards to increasing the share of renewable resources in the fuel mix, highlights a crucial point that many institutions and researchers have emphasized recently. A sustainable and clean energy future will require a transformation in the way we generate, deliver, and consume electricity as well as other forms of energy. Diminishing fossil fuels intensity of the energy sector seeks for more versatile sustainable resources in order to replace fossil fuels not just for electricity generation, but also heating, cooling, and transportation as well. Among renewable resources, biomass is the one accompanied by greater prosperity in every country around the world.

Availability of forestry, agricultural residues, and all kinds of wastes in every country provided the opportunity for biomass resources to become the largest renewable source on the planet. In 2017, bioenergy was responsible for 70% of the renewable energy consumption, in which biomass dominated the third place on the most utilized RES for power generation, after hydropower and wind [2]. The versatility of biomass resources to be utilized in gaseous, liquid, and solid forms has featured bioenergy in all the energy future scenarios for addressing climate change and global warming. With regards to energy transition strategies for 2030 and 2050, biomass will become the most prominent source of energy accounting for 26% of the primary energy supply in 2050 [3]. Being the first source of energy to be realized by mankind, the utilization of biomass in today's world is primarily evolved around heat generation. In the heat market, biomass was responsible for 96% share of renewable heating production in 2017, while this was only 9% and 3% in the electricity and transportation sector, respectively [4]. This owes to the fact that the most common technique for utilization of biomass is the conventional burning of solid biofuels such as wood pellet. Although this method is associated with economic advantages due to commercial availability, it suffers from higher environmental consequences and limited type of feedstock to be utilized. In this regard, significant contributions have been made over the past decades to introduce other methods of utilization with the intention to improve conversion efficiency, lower environmental impacts, and broaden the classification of biomass for energy generation. This introduced various techniques, including, but not limited to Gasification, Pyrolysis, and Fermentation; each being suitable for different types of biomass feedstock.

HIGHLIGHTS

- Direct combustion and gasification are the two most-utilized technologies for biomass conversion
- Two bioenergy systems based on Organic Rankine Cycle and Dual Fluidized-Bed are developed
- The two systems are implemented in a case study for off-grid combined heat and power production
- Feedstock price and primary product are the two most important factors in technology selection

There is no doubt that renewable technologies have experienced significant progress driven by international policies, innovation, and financial investments. However, this development has not been progressive in all countries or sectors. The energy sector is primarily comprised of power, heat, and transportation, in which heat and transportation make up around 80% of the total global energy demand, while being the two most neglected sectors concerning renewable development and decarbonisation. In this context, energy systems integration which combines different energy carriers has been one of the most promising solutions to energy-related problems. This method makes for a very strong proposition given that it maximizes efficiency, lowers environmental impacts, improves economic aspects, and increases renewable share across all energy sectors. One of the first attempts towards energy systems integration was combined heat and power (CHP) production. In this method of energy generation, electrical and thermal energy are being produced simultaneously. Originally, the main idea was to recover and store the waste heat from power generation in order to be utilized during winter for residential applications [4]. Today, commercial CHP systems are being developed with different prime movers, sizes, and energy sequences to satisfy both electricity as well as process heat, space heating, or hot water demand. Combined heat and power is associated with several advantages over the conventional stand-alone generation, including fuel diversification, improved overall efficiency, and lower environmental impacts. Integration of renewable resources into CHP systems as fuel for generation, such as biomass, represents an alternative for the combination of an efficient energy technology and a sustainable fuel [5].

Worthwhile contributions have been made to design, optimize, and implement various types of biomass-fuelled CHP systems for domestic and industrial applications aiming at environmental protection and energy saving. Although, there are very limited contributions to justifying and comparing different biomass to bioenergy conversion techniques from technical, environmental, and economic aspects. In the subject of biomass gasification, several studies carried out thermo-economic assessment of gasification systems in integration with

TABLE 1 Summary of preliminary studies on biomass-fueled CHP systems

Reference	Research objective(s)	CHP system	Key findings
[19]	Conducting exergoeconomic analysis on an integrated system consisted of downdraft gasifier and Kalina cycle with carbon capture facility and district heating system.	ORC Gasification	Unit cost of product declines with the increment of ammonia concentration and temperature difference at air preheater terminal. Higher ammonia concentration lowers the exergy efficiency and net power output.
[20]	Integrating biomass gasification with solar thermal energy for power and steam generation. Optimizing the performance by modelling the heat exchanger network precisely.	Gasification Solar Thermal ORC	Oxygen/steam mixture gasification agent could yield the highest cold gas efficiency. Increasing the heat input from the solar thermal system to 15 MW_{th} could significantly increase the power production.
[21]	Conducting techno-economic analysis and environmental assessment of a biomass-based gasification system integrated with FC, gas turbine, and ORC.	ORC Gasification FC	Current density of the FC modules can influence the electrical specific biomass composition. The inlet temperature of the ORC expander has a strong impact on the power generation of the ORC system.
[10]	Investigating the possible integration of a steam injected micro gas turbine with ORC for improving environmental performance.	ORC Gasification	Despite increasing net power production, the electrical efficiency was penalized by adopting the wet cycle, however, thermal energy production could increase significantly.
[22]	Thermo-economic assessment of a bioenergy system that is based on the integration of a gasification system running on rice husk with an ORC.	ORC Gasification	Equivalent ratio of the gasifier had significant impacts on electricity and heat generation. This value should be set based on the primary energy product that is required.
[23]	Investigating the thermo-economic performance of an integrated solar-biomass energy system that is consisted of gasification, ORC, and concentrating solar power (CSP).	ORC Gasification CSP	Coupling CSP with the biomass-fueled system could increase the overall conversion efficiency at the cost of economic improvement. Net present value and internal rate of return influenced negatively by CSP operation.

other energy generation technologies such as Fuel Cell (FC) [6, 7], Stirling engines [8, 9], and micro-turbines [10, 11]. Often, optimizing the Levelised Cost of Energy (LCOE) and exergy efficiency, by performing sensitivity analyses on several thermodynamic parameters, was the main objective in these studies. Different studies utilized various biomass resources, however, woody biomass and animal manure were of interest to many researchers [11–13]. Availability of manure and wet waste in the majority of countries has made them an interesting source not just for power generation, but also for syngas and biomethane production using technologies such as anaerobic digestion (AD) [14, 15]. In an alternative approach, the implementation of biomass gasification CHP systems has also gained prominence in wastewater treatment plants (WWTP) for electricity and heating generation [16–18]. In such systems, heating demand was the priority since wet sludges had to be dried in order to be utilized for gasification and combustion purposes. Self-sufficiency in such systems was the main objective; producing enough energy from dried sludge to perform wastewater treatment process.

In recent studies, significant advantages of gasification and ORC integration have been emphasized numerously. Possible utilization of low-temperature thermal sources by ORC systems has made them a promising CHP source in biomass gasification systems. In gasification systems, the temperature of flue gas and raw syngas can drop as much as 70% after treatment and cleaning. ORC systems can utilize the remaining waste thermal energy for auxiliary power and heat generation. High overall efficiency of ORC systems gained prominence in District Heating (DH) applications as well as saturated steam production in the industry [4]. In general, the integration of gasification and ORC systems can be divided into two primary groups depending on the application. For domestic applications (district heating), gasification is the suitable choice for electricity generation, while ORC is more responsible for thermal energy production. This is due to gasification and ORC having higher conversion efficiency and overall efficiency, respectively. On the other hand, for industrial applications (e.g. drying or superheated steam production), the thermal content of syngas from gasification is utilized for thermal energy production, while ORC is mainly implemented for powering up the facility. Table 1 presents recent studies on integration of gasification with ORC systems for cogeneration applications.

There is no deniability on the advantages of biomass resources over fossil fuels. Lowering environmental impacts and providing energy security are the primary reasons that attracted a great deal of attention towards bioenergy systems. Despite its renewability, biomass sustainability is constrained by influencing factors concerning practical, environmental, and economic feasibility. With various conversion techniques and possible utilization in different states of matter, cost-effectiveness and sustainability are the current challenges that any biofuelled energy system is faced today. Several factors such as resource availability, transportation costs, size of the plant, and type of feedstock should be taken into consideration while implementing a biomass-fuelled energy system. These parameters along with influencing factors of CHP systems can cause complexity and discouragement for further developments of biofuelled-CHP systems. The costly nature of such configurations, lack of information on renewable development, and absence of comprehensive research on economic and environmental perspectives of biofuelled-CHP systems, particularly for mini-grid applications, have had more severe impacts on remote locations. In this regard, the current research elaborates on the integration of biomass resources for combined heat and power production in off-grid locations using two well-known conversion technologies, namely, Direct Combustion and Gasification. Although the two methods are different in the principle of operation and fundamental characteristics, each one of these techniques has its own merits. Thus, it is of utmost importance to address the economic and environmental challenges of adopting these technologies for domestic applications. To this end, different energy scenarios are implemented, in which biomass-to-energy conversion is carried out using Direct Combustion or Gasification. These two configurations are presented to investigate the effect of biomass energy conversion on both technical and economic aspects. Further, the practical viability of each system is being analysed when biomass is consumed for cogeneration applications in mini-grids. For that purpose, a case study is presented in which the suggested structures are responsible for satisfying the energy demands of Masset village located in Haida Gwaii, Canada. The primary contributions of this research can be summarized as follow:

- Realizing the two most well-known biomass conversion techniques for satisfying residential energy demands in remote locations.
- Developing a direct combustion system based on the Organic Rankine Cycle (ORC), and a gasification system based on Dual Fluidized Bed (DFB).
- Conducting a comparative analysis to evaluating the performance of each system concerning technical and economic aspects.
- Implementing the energy systems in a case study with realistic data in terms of energy profile, capital cost, and economic incentives.

In this study, Section 1 was focused on previous research works and introduced the objectives of this study. Given that there are very limited research works in the relevant literature, which performed such precise comparative analysis between direct combustion and gasification for this particular application, the literature review was primarily fixated on model development and optimization of gasification and ORC systems. The most recent designs are realized and analysed thoroughly. Section 2 looks into the model description and the methods that are utilized to carry out the current research. This section presents a comprehensive description of ORC and gasification systems and lays out the suggested energy scenarios. In Section 3, the case study properties are discussed in terms of technical and economic aspects. Section 4 presents the simulation results, in which the two configurations are being compared technically and economically. Section 5 concludes this research by emphasizing the key findings and the results.

2 | METHODS AND MATERIALS

Developing biomass-to-bioenergy systems requires careful consideration of upstream as well as downstream supply chain. This is done to account for all the influencing factors involving the supply of biomass and generating energy. These factors include technical, environmental, and economic parameters which may vary depending on the conversion technology that is being implemented. In this section, the choice of biomass feedstock, the conversion technologies, economic indices, and environmental incentives are discussed thoroughly.

2.1 | Biomass feedstock

The physical and chemical characteristics of biomass resources have strong impacts on the method of utilization and the required end-use product. Influencing parameters such as particle size, ash content, and moisture level may vary from one type of biomass to another, or even within a feedstock lot. Often, small-scale energy systems require feedstock quality control, as opposed to large-scale systems [24]. To this end, high-quality briquettes or pellets were the first options for energy generation. One of the key parameters in the selection of feedstock was the moisture content (MC). This parameter can affect syngas content and gasification time or increase burn-out time in combustion. Provided that both methods of energy conversion require a limited level of moisture, it was intended to select a type of feedstock with limited MC. Another important factor in the selection of proper feedstock was the calorific value which expressed the energy content of the biomass feedstock. Considering the upstream biomass supply chain, several parameters including cost and ease of transportation, bulk density, storage capacity, and availability of feedstock in that particular location were taken into consideration. In accordance with Table 2, dried wood chips were the best option as fuel for generation in both conversion technologies. The limited MC, high calorific value, low ash content, and high availability were the primary reasons that made this type of feedstock suitable for the application in this study. In general, the lower ash and MC would be advantageous for utilization in the gasification and combustion process, respectively. Another important fact that made wood chips a better option over other resources such as Pine Wood and Sawdust Pellet was availability and lower cost on a dry basis. Wood chips material is the first choice for large-scale CHP gasification systems.

Transporting energy resources and its associated costs is an influencing factor in any energy system, particularly for biomass due to the lower energy density compared to that of fossil fuels. In this study, similar quantification analysis that was conducted in ref. [25] was employed in order to determine the true cost of wood chips for power and heat generation. Evaluating the influence of transportation cost on the overall price of feedstock requires an understanding of two cost components, namely, distance variable cost (DVC) and distance fixed cost (DFC). While DVC depends directly on the distance and mode of transportation, DFC is an independent component to distance which is

TABLE 2 Characteristics of common woody biomass feedstock (wt%) [27]

Type	MC (%)	Ash Content (%)	C (%)	H (%)	N (%)	LHV (MJ kg^{-1})	Bulk Density (kg/m^3)
Pine wood	9.5	0.7	49.7	6.5	0.2	18.9	750
Sawdust pellet	10.0	0.8	49.8	6.4	0.3	17.4	650
Wood chips [28]	23.0	0.8	46.6	5.5	0.27	19.0	250
Birch Wwood	7.4	2.6	48.3	8.3	0.1	19.3	600
Fire wood	7.7	5.8	48.6	6.5	0.2	18.9	700-800

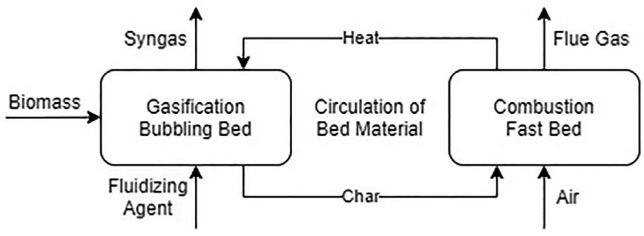


FIGURE 1 Block diagram representation of dual fluidized-bed gasification process [39]

mainly relied on the type of biomass feedstock [26]. DVC was the parameter that was considered in this study because such evaluation considers the mode of transportation as well as feedstock characteristics. The value of DVC for wood chips was recorded at 0.07, 0.017, and 0.01 \$/tonnes-km by means of truck, rail, and ship transportation, respectively.

2.2 | Biomass gasification

The suggested gasification system in this study was based on a dual fluidized-bed (DFB) gasifier coupled with internal combustion engines (ICEs). For the application considered, a fluidized-bed gasifier was the best option since the possibility of up-scaling within a wide power range is provided [29]. In comparison with the fixed-bed technology, changes in fuel characteristics are more tolerable since the ratio of biomass to oxygen can be varied independently to maintain the temperature uniform throughout the bed [30]. The major drawback of such a compact and economic arrangement is the contamination of syngas with nitrogen, tars, and particles which drastically reduces the heating value of gaseous fuel. This is due to the fact that conventional fluidized-bed gasifiers involve bed materials and biomass in a single reactor. Dual fluidized-bed gasifier can overcome this issue by employing two physically separated reaction zones (reactors), namely, gasifier and combustor, with a possible circulation of bed material (Figure 1) [31]. The implemented DFB gasification system (Figure 2) was based on an operational biomass CHP plant in Güssing, Austria [32], including the improvements that were carried out in ref. [33]. In this system, a controlled feeder transfers biomass feedstock to the gasifier, which is operated in bubbling bed regime and fluidized with a portion of recycled syngas. Thermal decomposing of woody feedstock into char and gas takes place in this reactor at 760 °C. Further, the char is transferred to the combustion reactor through the circulation of fluidized bed material. The combustion process is carried out in the presence of air and a portion of cleaned syngas at 980 °C. This process leads to the formation of hot flue gas and ashes, in which the flue gas is utilized for maintaining the temperature of the catalytic tar reformer at 900 °C. After combustion, the heated sand bed is circulated back to the top of the gasifier reactor, providing the required heat for the endothermic gasification reaction (950 °C) through heat transfer between descending sand particles and ascending pyrolysis gas.

The produced raw syngas contains nitrogen, tar, and solid particles which should be removed for its utilization in ICEs. To this end, a gas cleaning facility based on tar cracking and Venturi Scrubber was considered for this purpose. There are numerous catalysts that could be utilized for tar reforming application, amongst which, a natural mineral (olivine) was considered in this study. After tar reduction, the syngas should be cooled down to a temperature level below 150 °C in order to meet the temperature requirement for Venturi Scrubber. This process was carried out using a radiant cooler, in which the recovered heat was utilized for district heating application (80/105 °C). Clean syngas for combustion in ICEs could be extracted after the Venturi Scrubber at 40 °C temperature with 13.6 MJ kg^{-1} lower heating value (LHV).

Electrical energy could be generated by means of any natural gas engine. The selection of the JMS 620 Jenbacher gas engine was considered in this study since such ICE was capable of generating 3,044 kW power (running on biogas) with 43% electrical efficiency, and 2,982 kW heat with 42.1% thermal efficiency. Gasifier efficiency is often described in terms of cold gas efficiency which presents the ratio between energy contained in the syngas and the energy contained in the biomass feedstock [34]. This can be calculated using Equation (1), in which $\dot{m}_{gas}$ and $\dot{m}_{bio}$ are the mass flow rate of syngas and biomass feedstock, respectively. The LHV of the syngas can be determined using Equation (2) based on the molar fraction (Y_z) and LHV of the different gas constituents [35]. The net electric and thermal efficiencies of CHP system can be calculated based on Equations (3), (4) and (5). The syngas consumption of biogas engine (f_{syngas}) can be determined using Equation (6), in which f_{engine}, $LHV_{natural\ gas}$, and LHV_{syngas} indicate natural gas consumption of engine, LHV of natural gas, and LHV of syngas, respectively.

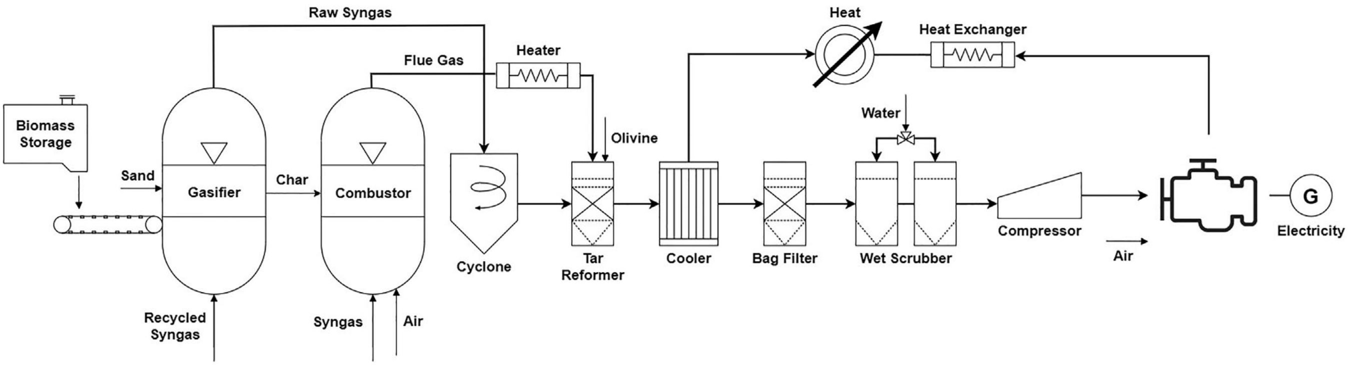


FIGURE 2 Schematic representation of the suggested CHP system based on gasification

TABLE 3 Technical properties of the CHP system based on gasification (100% rated)

Properties	Unit	Value
Clean syngas temperature	°C	40.0
Clean syngas LHV [36]	MJ/kg	13.6
Cold gas efficiency [37]	%	75.0
Temperature of the gasifier bed	°C	760
Temperature of the combustion	°C	980
Temperature of the raw syngas	°C	960
Recycled syngas to gasifier	[vol%]	14.0
Clean syngas to combustor	[vol%]	12.6
Electrical output of JMS 620 engine	kW	3,044
Thermal output of JMS 620 engine	kW	2,982
Electrical efficiency of JMS 620 Engine	%	43
Thermal efficiency of JMS 620 engine	%	42.1
Fuel consumption of JMS 620 engine (Fuel LHV: 44 MJ kg^{-1})	kg/h	615
Fuel consumption of JMS 620 engine (Fuel LHV: 13.6 MJ kg^{-1})	kg/h	1,986
Hot water flow rate of JMS 620 engine	m^3/h	89.9
Overall electric efficiency [33]	%	27%
Overall heat efficiency [38]	%	53%

Table 3 provides technical specifications of the gasification CHP system. Rated values of biogas engine are given at full-load condition.

$$\eta_{\text{gasifier}} = \frac{\dot{m}_{\text{gas}} \cdot \text{LHV}_{\text{gas}}}{\dot{m}_{\text{bio}} \cdot \text{LHV}_{\text{bio}}} \tag{1}$$

$$\text{LHV}_{\text{gas}} = \sum \text{Y}_z \cdot \text{LHZ}_z \ \ (z = \text{CO},\ \text{CH}_4, \text{H}_2) \tag{2}$$

$$\eta_{\text{e}} = \frac{\dot{W}_{\text{engine}} - \dot{W}_{\text{input}}}{\text{LHV}_{\text{bio}} \times \dot{m}_{\text{bio}}} \tag{3}$$

$$\eta_{\text{th}} = \frac{\dot{Q}_{\text{DH}} - \dot{Q}_{\text{input}}}{\text{LHV}_{\text{bio}} \times \dot{m}_{\text{bio}}} \tag{4}$$

$$\eta_{\text{CHP}} = \eta_{\text{e}} + \eta_{\text{th}} \tag{5}$$

$$\text{f}_{\text{syngas}} = \frac{\text{f}_{\text{engine}} \times \text{LHV}_{\text{natural gas}}}{\text{LHV}_{\text{syngas}}} \tag{6}$$

2.3 | Biomass combustion

Extracted heat in the direct combustion of biomass is often utilized in circulation loops such as Rankine Cycles to convert the heat into mechanical energy for power generation. In this study, the use of Organic Rankine Cycle was suggested to take advantage of the thermodynamic properties of organic working fluids. The developed model was comprised of grate biomass boiler, ORC system, MEA-based carbon capture facility, and a number of pumps and inter-connected pipelines for thermal oil circulation (Figure 3). The principle of operation in the ORC-based CHP system is much simpler than the gasification process. The thermal efficiency of the boiler was in the range of 85–90%, and the combustion would take place once the boiler's temperature would reach as high as 850 °C. The heat produced during combustion of biomass in the boiler was transferred to the pressurized thermal oil (Therminol 66) that circulated between the boiler and the evaporator. The organic working fluid (octamethyltrisiloxane) would then absorb the heat from the pressurized thermal oil in the evaporator in order to flow into the expander and generate power.

Thermal energy production for domestic use would take place in the condenser and economizer. The inlet water to the DH system was at 50 °C and it was split between the economizer and condenser. In the economizer, hot water for DH application (above 80 °C) was produced by recovering the thermal energy of flue gas before entering the carbon capture facility. In the condenser, heat recovery would take place between the working fluid and water during condensation. In this system, the flue gas exiting out of the boiler was at 950 °C temperature. Its thermal energy was utilized for preheating the air entering the boiler, while flowing into the economizer at 170 °C. The flue gas would then continue into the carbon capture facility based on monoethanolamine (MEA) in order to limit CO_2 emissions as much as possible. Given the maturity and simplicity of this technology, MEA was the best option for this application, even

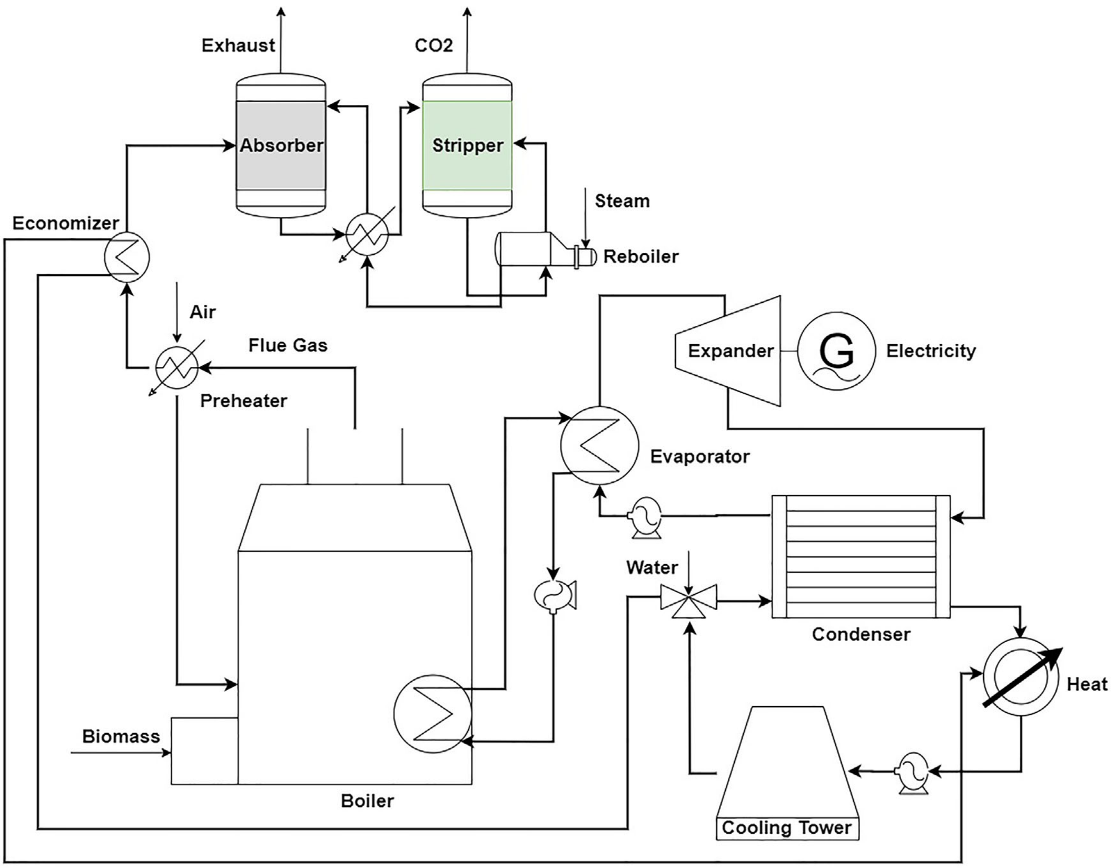


FIGURE 3 Schematic representation of the suggested CHP system based on ORC

though, it required thermal energy to regenerate MEA. The input heat to the ORC system ($\dot{Q}_{in}$) can be described based on the total input heat rate to the boiler ($\dot{Q}_{bio}$) and the boiler's efficiency (η_{boiler}) using Equation 7. $\dot{Q}_{in}$ can also be expressed in terms of the average specific heat capacity of boiler thermal oil (c_{oil}), its mass flow rate ($\dot{m}_{oil}$), and the temperature difference of the pressurized thermal oil when entering and exiting out of the boiler [40]. The following Equations (7)–(14) indicate heat transfer and the work done by evaporator ($\dot{Q}_{ev}$), expander ($\dot{W}_{exp}$), condenser ($\dot{Q}_{con}$), and pumps ($\dot{W}_{pump}$).

$$\dot{Q}_{bio} = \dot{m}_{bio} \cdot LHV_{bio} \tag{7}$$

$$\dot{Q}_{in} = \dot{Q}_{bio} \cdot \eta_{boiler} \tag{8}$$

$$\dot{Q}_{in} = c_{oil} \cdot \dot{m}_{oil} \cdot (T_{out} - T_{in}) \tag{9}$$

$$\dot{Q}_{ev} = c_{ORC} \cdot \dot{m}_{ORC} \cdot (T_{out} - T_{in}) \tag{10}$$

$$\dot{W}_{exp} = c_{ORC} \cdot \dot{m}_{ORC} \cdot (T_{out} - T_{in}) \cdot \eta_{turbine} \tag{11}$$

$$\dot{Q}_{con} = c_{ORC} \cdot \dot{m}_{ORC} \cdot (T_{out} - T_{in}) \tag{12}$$

$$\dot{W}_{pump} = c_{ORC} \cdot \dot{m}_{ORC} \cdot (T_{out} - T_{in}) \cdot \eta_{pump} \tag{13}$$

$$\dot{W}_{pump} = c_{water} \cdot \dot{m}_{water} \cdot (T_{out} - T_{in}) \cdot \eta_{pump} \tag{14}$$

The overall efficiency of the ORC system can be calculated using Equations (15) and (16). Table 4 provides the technical properties of the CHP system based on direct combustion.

$$\eta_{el} = \frac{\dot{W}_{exp} - 3 \times \dot{W}_{pump}}{\dot{Q}_{bio}} \tag{15}$$

$$\eta_{th} = \frac{\left(\dot{W}_{exp} - 3 \times \dot{W}_{pump}\right) + \dot{Q}_{DH}}{\dot{Q}_{bio}} \tag{16}$$

2.4 | Economic incentives and environmental policies

Economic indices concern all financial factors that impact the operation of the system over the project lifetime. Economic parameters include financial availability, expenses, and government incentives that influence the cost of energy. Environmental incentives can also affect the economic feasibility of an energy system. Sustainability and carbon emissions are the

TABLE 4 Technical properties of the CHP system based on direct combustion (100% rated)

Parameter	Unit	Value
Turbine isentropic efficiency	%	80
PumpeEfficiency	%	75
Grate boiler efficiency	%	85
Thermal oil fluid	–	Therminol 66
Working fluid	–	Octamethyltrisiloxane $C_8H_{24}Si_3O_2$
Flue gas outlet temperature	°C	950
Thermal oil loop temperature (inlet/outlet)	°C	320/250
Evaporation temperature	°C	<300
Condensation temperature	°C	90
Domestic hot water temperature (inlet/outlet)	°C	50/80
Electrical efficiency	%	18
Thermal efficiency	%	68

two most important factors that are associated with significant penalties if domestic and international limitations are not met. In this context, both economic and environmental perspectives are tied, therefore, it is of utmost importance to consider both aspects when implementing such biofuel energy systems. Although, economic indices and environmental incentives might vary depending on the domestic and international policies in different countries. The majority of developed countries have firm regulations to limit GHG emissions as well as encourage the energy sectors to adopt more sustainable methods of generation. Carbon tax and federal tax return were the two government incentives that were considered in this study.

Economic analysis was performed taking into consideration all the stages of the biomass-to-energy supply chain. All the economic parameters fell into four main categories, namely, investment cost, operating and maintenance cost, development cost, and fuel cost. In accordance with the net present cost (NPC) and levelised cost of energy (LCOE), system attractiveness and feasibility could be compared between the two configurations. Given that practical viability was one of the primary objectives, cost allocation for gasification and ORC systems was based on operational plants or the existing units in the market. In this context, the Gothenburg Biogas Gasification project located in Sweden [41], and the Scharnhauser Park ORC project located in Germany [42] were considered as the reference systems for unit cost allocation (investment, operating, and maintenance), development cost calculation, and fuel price estimation for the two proposed configurations; this was carried out using Equations (17)–(30).

Investment cost (C_i) allocation for the primary units (i) in each system was performed using Equation (17); knowing the reference plant investment cost (C_r), its capacity (S_r), incidence factor (m), and the capacity required (S). The sum of investment costs for the primary units would result in the total investment cost of the system (C_{total}), which then would be used for specific capital cost calculation related to the depreciation (c_{dep}) and the interest from the investment (c_{int}). These two costs are the function of project lifetime (LT), interest factor (θ_{int}), and full-load hours (FLH) operation.

$$C_i = C_{r,i} \cdot \left(\frac{S}{S_r}\right)^{m,i} \tag{17}$$

$$C_{total} = \sum_i C_i \tag{18}$$

$$c_{dep} = \frac{C_{total}}{(S \cdot LT \cdot FLH)} \tag{19}$$

$$c_{int} = \frac{C_{total} \cdot \theta_{int}}{(S \cdot LT \cdot FLH)} \tag{20}$$

$$\theta_{int} = \frac{LT \cdot int}{1-(1+int)^{-LT}} - 1 \tag{21}$$

$$c_{dev} = \frac{C_{total} \cdot \theta_{dev}}{(S \cdot LT \cdot FLH)} \tag{22}$$

The same cost allocation method was used in Equations (23)–(25) for operating and maintenance cost calculation. Specific fuel cost (c_{fuel}) and the specific cost of production ($c_{production}$) were determined using Equations (26) and (27), respectively. The LCOE and NPC could be represented based on the specific cost of production, the total electrical energy produced ($W_{produced}$), boiler marginal cost (c_{boiler}), total thermal load served (Q_{served}), total electrical load served (W_{served}), interest rate (i_r), and inflation rate (i_f).

$$C_{opm,i} = C_{opm\_r,i} \cdot \left(\frac{S}{S_r}\right)^{m,i} \tag{23}$$

$$c_{opm,i} = \frac{C_{opm,i}}{(S \cdot FLH)} \tag{24}$$

$$C_{opm\_total} = \sum_i c_{opm,i} \tag{25}$$

$$c_{fuel} = C_{fuel} \cdot \left(1 - \frac{MC_{bio}}{1 - MC_{bio}} \cdot \frac{2.4}{LHV_{bio}}\right) \cdot \frac{1}{\eta_{conv}} \quad (26)$$

$$c_{production} = c_{dep} + c_{int} + c_{dev} + c_{opm} + c_{fuel} \quad (27)$$

$$LCOE = \frac{c_{production} \cdot W_{produced} - c_{boiler} \cdot Q_{served}}{W_{served}} \quad (28)$$

$$c_{boiler} = \frac{3.6 \cdot (C_{fuel} + C_{boiler,emission})}{\eta_{boiler} \cdot LHV_{bio}} \quad (29)$$

$$NPC = \sum_{t=1}^{N} \frac{c_{production} \cdot W_{produced\_year} \cdot (1 + i_f)^N}{(1 + i_r)^N} + C_{total} \quad (30)$$

3 | CASE STUDY

Comparative analysis, in terms of technical viability and economic attractiveness, between the DFB and ORC system is carried out in a case study under similar operating circumstances. In this case study, both systems were implemented for off-grid electrification in a mini-grid scaled power system. The two configurations are subjected to similar energy profile, governmental incentives, and environmental policies. In this section, information concerning the location, energy demand, renewable energy subsidy, and carbon emission tax are provided.

3.1 | Location

Masset is an Aboriginal Canadian village located on the northern Pacific coast of Canada in Haida Gwaii Island, British Columbia province. The Masset population was recorded at 793 in 2016, however, the village provides amenities and services to a larger rural area with a population nearing 2,300, including the unincorporated area of Tow Hill. The current population reside in approximately 400 private dwellings that were constructed in the 1970′s. Agriculture and forestry are the primary contributors to the economic activities of the island. Thus, residues associated with these two industries can be the primary source of energy in the near future. Selecting this location for the case study is due to the fact that this village is heavily relied on diesel fuel for energy generation. The carbon dioxide equivalent emission was 6,784 tonnes in 2009, in which residential energy generation was responsible for almost 15% of that amount. The GHG emissions per person was 30 times more than any location within the British Columbia province.

3.2 | Energy profile

Over the past decades, the electrical energy demand of Haida Gwaii Island has been supplied by BC Hydro Company via two unconnected distribution systems located in the northern and southern parts of the island. The northern power system includes Masset Village and the surrounding areas. In 2014, the northern power grid was comprised of five diesel generators with a combined capacity of 10.445 MW. Three stationary diesel-fuelled generators with an individual rated power of 2.865 MW were the primary units, while the two road-mobile generators rated at 1.00 and 0.85 MW were considered as an operating reserve. Electricity load profile of the northern grid is only provided for the period of 2001 to 2011. In this 10-year interval, electricity demand witnessed an uptrend fluctuation, increasing moderately at 0.98% in the first 4 years, following by a 4.3% growth in the next 6 years (Figure 4).

In accordance with the population growth, the number of households, and industrial activities, similar growth rate is subjected for the period of 2011 to 2019 in order to estimate the electricity supply in 2019. Similar approach was taken for the monthly generation data (Figure 5), projecting the total electricity generation for every month based on available monthly generation data between 2001 to 2011. Gross daily generation illustrates a significant difference in daily demand for months with higher electricity consumption such as January, while on the other hand, this variation is limited for months with lower demand such as June (Figure 5). In accordance to the energy profile, the suggested bioenergy systems were sized based on the electrical peak demand with 15% margin of safety, resulting in a combined capacity of 6.088 MW.

The thermal energy profile of this island is mainly comprised of space heating and hot water consumption for residential usage, and the drying process for the sawmill facility in the industrial sector. The residential power and heat demand in a typical day in mid-January is presented in Figure 6. Unlike electrical energy demand, there is no annual or monthly generation data available for heating consumption. Although, a logical demand profile can be structured for the residential sector based on the number of households on the island, average property area, and climate characteristics. In accordance with a preliminary study conducted in British Columbia [43], the average energy demand in the residential sector is 213 kWh/m^2.year; in which 37% is used for space heating purposes.

Provided that there are 464 private dwellings with an average area of 200 m^2, the annual heating consumption can reach up to 7,313.5 MWh (Figure 7(a)). Concerning the industrial heating demand, the island has two sawmill facilities that each are capable of processing 40,000 m^3 timber per year [44]. Based on energy flowcharts in typical sawmill facilities, a thermal energy demand of 350 kWh/m^3 at 75 °C is expected for drying purposes [45]. To this end, the sawmill facility in Masset village can consume approximately 28,000 MWh thermal energy in a year (Figure 7(b)) [46].

3.3 | Economic incentives and cost analysis

Evaluating the economic performance of any energy system relies on numerous influencing factors that may vary depending on the domestic and regional policies or conditions. For the case of Masset Village, British Columbia offers various

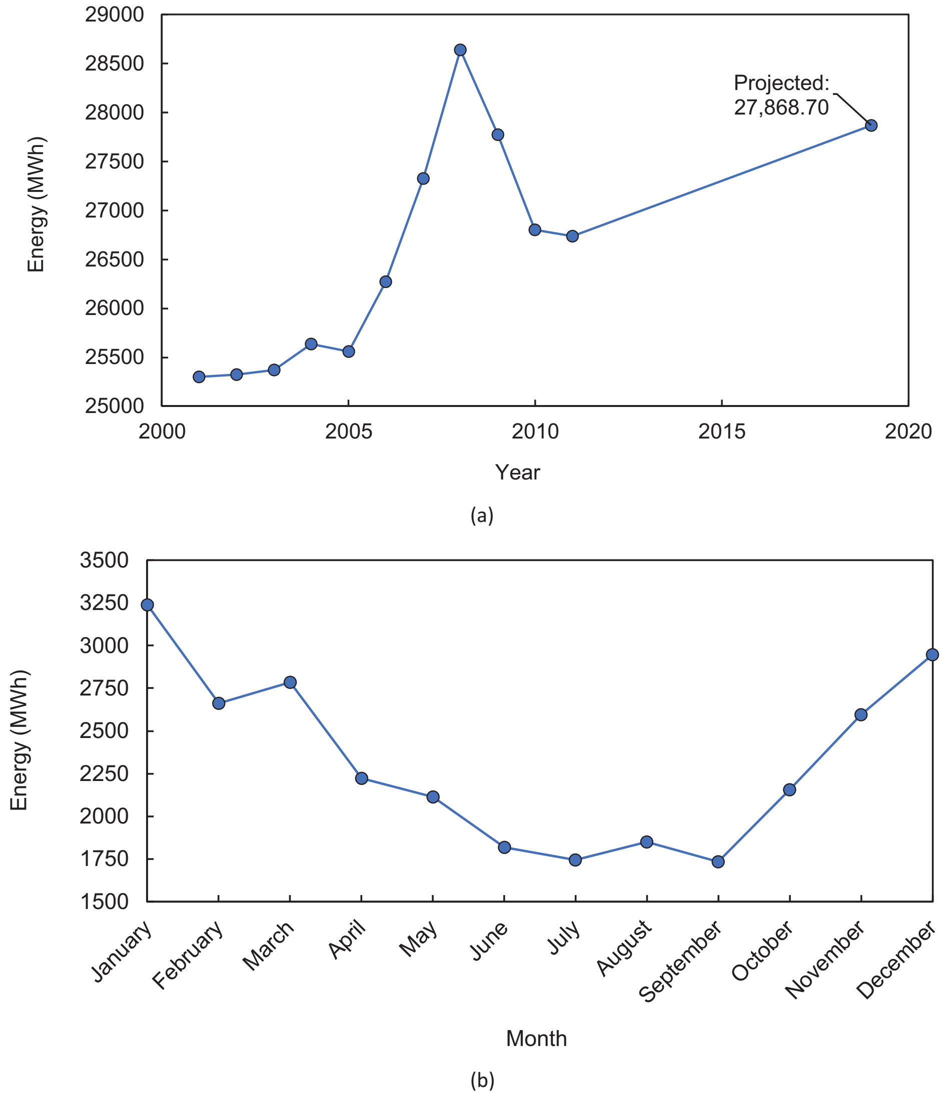


FIGURE 4 (a) Annual and (b) monthly electricity generation in 2019

forms of subsidy to support energy planning, energy efficiency, and clean energy generation projects. There exist several funding opportunities for the Haida Gwaii that support sustainable development in different forms. One of the available programs that target energy generation is Renewable Energy for Remote Communities (RERC), which aims to reduce diesel fuel dependency for energy generation in Haida Gwaii. This strategy was designed for large-scale capital intensive projects, in which the responsible councils are bound to deliver up to $16.5 million to remote communities for electricity generation using sustainable resources [47]. Other economic influencing parameters such as inflation rate, nominal discount rate, and carbon tax were defined at a more domestic level; these values were recorded at 2%, 5%, and 30 $/tonne, respectively [48, 49].

Table 5 presents the economic and technical parameters that were subjected to both systems over the project lifetime. Electricity is considered as the main product of the bioenergy systems, while heat is only a byproduct. In this context, full load hour represents the amount of time that the system would theoretically have to be operated at full output in order to achieve its annual energy yield. This value was then used in the calculation of development, operating, and maintenance costs for each system. In both configurations, similar battery storage technology as well as bidirectional power converter units were implemented in order to improve flexibility and ramp rate depending on the technology utilized. A model optimizer was used with the intension to determine the best number of storage units for each bioenergy system, considering the ramp rate of each technology. The energy storage units were based on sodium–sulfur (NaS) technology, in which a single unit was rated at 1200 kWh with 85% round-trip efficiency [50]. The project finance scheme indicates that 30% of the capital cost for each system should be financed by the owner (cash), while the remaining 70% can be paid over the project lifetime at a 4% interest rate.

Energy systems cost analysis often include all the associated costs with the site preparation, construction, installation, operation, and maintenance. In this case study, site preparation and construction were not considered since such assessments

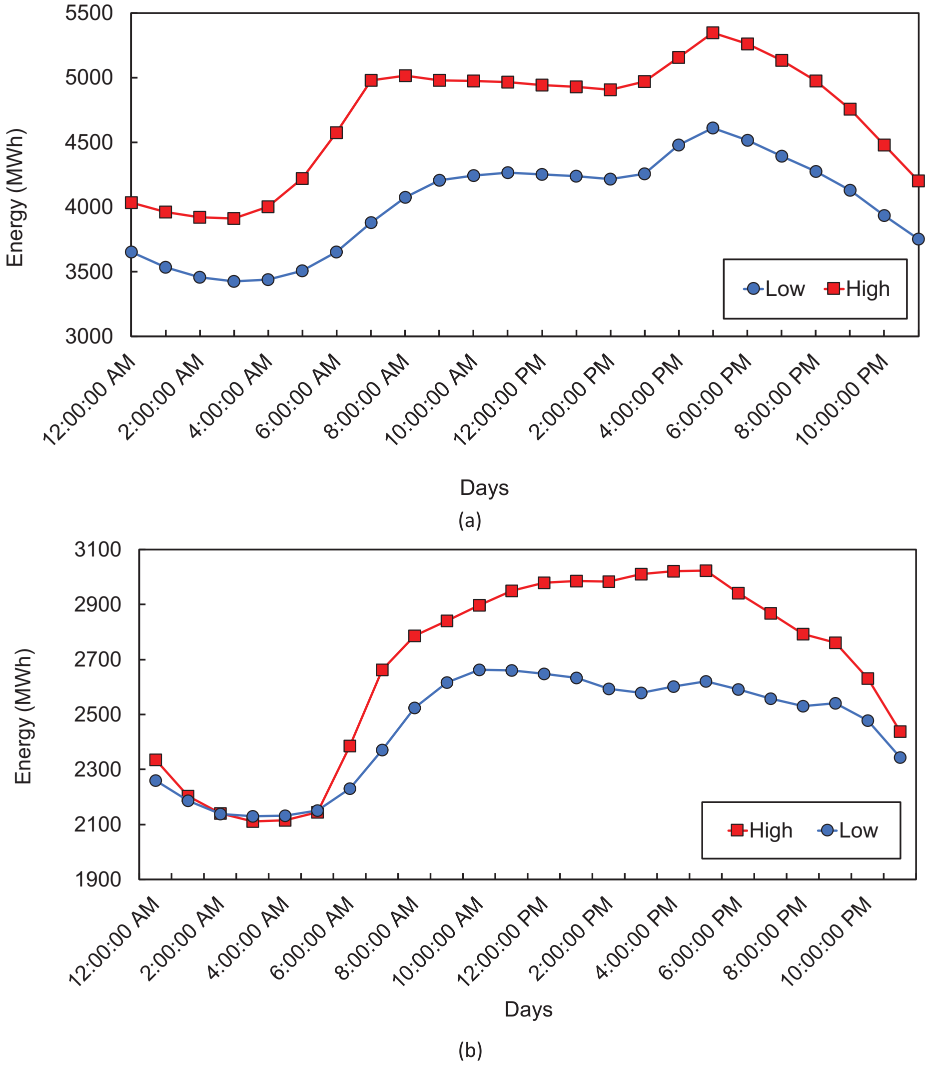


FIGURE 5 Gross electricity generation of a typical day in (a) January and (b) June

depend on various regional regulations entailing safety precautions and hazardous limitations. Assuming that both bioenergy systems can be developed in the same construction area by the same number of workers taking the same amount of time, cost analysis for each system can be carried out with regards to the reference plants mentioned in Section 0. Tables 6 and 7 provide comprehensive details on economic conditions of the CHP-gasification and CHP-ORC systems, respectively. The key points are:

- Specific investment cost is in accordance with the latest information provided by the International Renewable Energy Agency (IREA)
- Specific investment cost is related to the net electrical output
- Specific cost of fuel is related to the conversion efficiency (not electricity generation efficiency)
- Development, operating, and maintenance costs are related to the annual electricity generation
- Similar fuel feeding system was considered for both configurations

4 | RESULTS

The model development and simulation of the characteristics of each bioenergy system was carried out using HOMER PRO Software, which is focused on technical, environmental, and economic aspects of energy systems. In this context, the two suggested configurations were sized at 6.088 MW electrical output power and simulated under similar economic circumstances. The comparative analysis between the two plants is conducted in terms of energy generation, energy storage performance, fuel consumption, and economic feasibility.

4.1 | Energy generation

In this study, the suggested systems were prioritized for electricity generation, and the electrical output of the system was fixated on the electrical load to avoid any power shortages or excess electricity generation. Despite the limited efficiency of ORC-CHP configuration at full-load electrical generation,

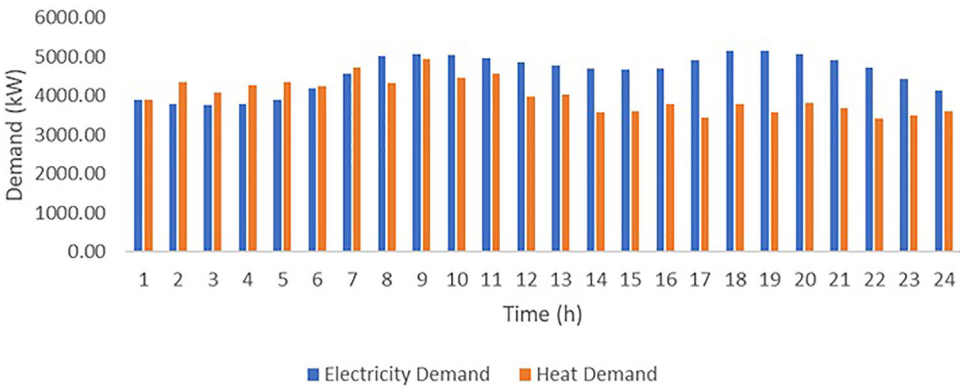


FIGURE 6 Residential power and heat demand in a typical day in mid-January

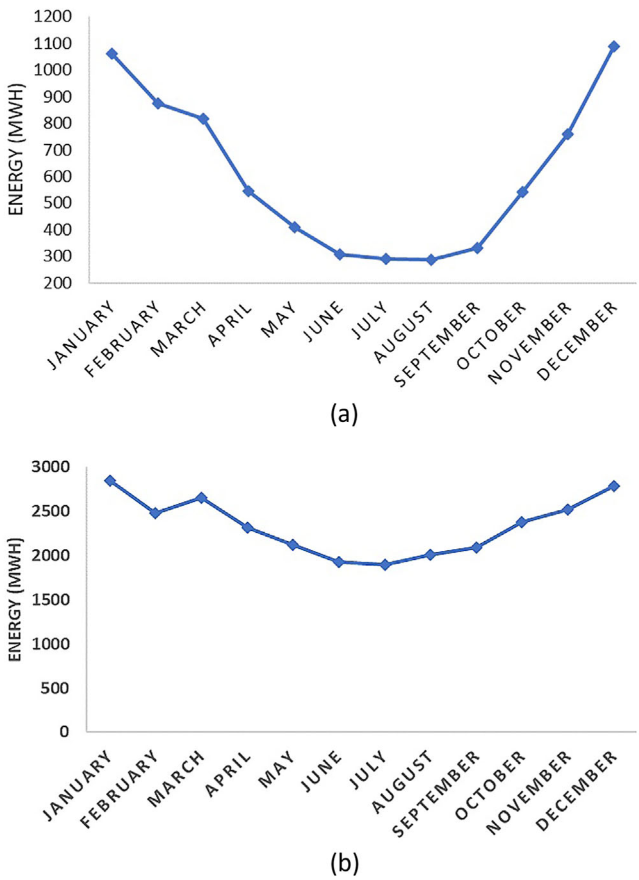


FIGURE 7 Monthly heating demand profile in (a) residential and (b) industrial sector

TABLE 5 Economic parameters over the project lifetime

Parameter	Unit	Amount
Full load hour	h	4578
Project lifetime	years	20
Commercial loan payback period	years	10
Battery storage unit capacity	kWh	1200
Battery storage unit cost	M$	1.20
Power converter rated capacity	kW	250
Power converter cost	M$	0.125
Cost of Water	$\$/m^3$	0.61
Environmental Cost	$/GJ	0.089
Carbon tax	$/t	30
Cost of Feedstock (incl. 200 km transportation) [28]	$/ton	65
Discount rate	%	5
Inflation rate	%	2
Interest rate	%	4
Insurance	[%] Investment	0.5

thermal energy production in this system was associated with significant excess output, roughly 3 times that of the gasification system (Figure 8(a)). The high thermal efficiency in both systems, allowed excess thermal energy production during low power demand periods, providing the possibility of thermal storage and supplying the thermal loads during higher demands. The simulation results illustrate the fact that the ORC system can be the best possible choice for locations with thermal energy intensity (high heat-to-power ratio). This type of system can provide the possibility for implementation of long-term thermal energy storage (TES) and heat pumps, which can result in significant flexibility improvements of the system. Considering the total output (power and heat) of both systems with respect to the total demand, average excess heat production was higher during low power demand, particularly from May to September (Figure 8(b)). This is due to the inverse proportionality between thermal and power efficiency, and the constrained minimum load ratio (MLR). One of the most important factors in technical operation and economic feasibility is the minimum generation level. While ICE units can take advantage of lower MLR (10–20%), steam turbines are subjected to higher ratios (25–60%). Technical constrained in heat-recovery steam generators (HRSGs) poses a challenge for steam turbines to lower the MLR, in which multi-pressure level steam turbines can be a solution. Although such method can lower the minimum load level, but it negatively affects the economics of system in such small-sized plants. In this study, the minimum load level for ICE units in the gasification system was set at 20%, whereas, the

TABLE 6 Cost analysis of the CHP-gasification system

Parameter	Unit	Scale Factor	Reference plant [41]	Suggested plant
Rated biomass power	MW	–	32.00	22.55
Specific investment cost [51, 52]	$\$/kW_{prod}$	–	8093.5	8000
Specific Cost of Fuel	$/ton	–	215.49	83.40
Fuel feeding	M$	0.65	9.87	6.82
Gasifier	M$	0.80	13.16	9.17
Cooling and treatment	M$	0.80	5.38	3.75
Flue gas cleaning	M$	0.60	9.87	6.81
Syngas compressor	M$	0.60	16.27	11.21
Development	$\$/MWh_{prod}$	0.40	5.06	8.74
Operating and Maintenance	$\$/MWh_{prod}$	0.70	50.38	179.72
Combustion engines [53]	$\$/kW_{prod}$	–	–	1156

TABLE 7 Cost analysis of the CHP-ORC system

Parameter	Unit	Scale factor	Reference plant [42, 54]	Suggested plant
Rated biomass power	MW	–	6	33.82
Specific investment cost [51]	$\$/kW_{prod}$	–	6000	5080
Specific Cost of Fuel	$/ton	–	50	73.58
Evaporator	M$	0.8	0.57	1.51
Condenser	M$	0.8	1.15	3.07
ORC module	M$	0.8	1.93	5.13
Thermal oil circuit	M$	0.8	0.79	1.24
Pumps and heat exchangers	M$	0.6	0.66	1.24
Development	$\$/MWh_{prod}$	0.4	8.22	10.26
Operating and maintenance	$\$/MWh_{prod}$	0.7	32.90	47.08
MEA-based gas cleaning [55]	M$	0.8	–	13.92
Gas cleaning maintenance [55]	M$/year	0.6	–	2.36
Fuel feeding	M$	–	–	6.82

expander in the ORC system was subjected to 40%. It is evident from the results that the gasification system could affectively respond to low power demand periods. On the contrary, the ORC system was fixated on a minimum of 40% of the rated power. Higher thermal efficiency and constrained MLR were the primary reasons for higher excess generation. High thermal excess generation can pose economic disadvantages if suitable storage or application is not considered. To this end, the electrical efficiency of the ORC system should be improved (results in lower thermal efficiency), and the MLR should be lowered to its minimum practical value.

4.2 | Energy storage performance

Storage capacity depends on several factors in which generating unit ramp rate, start-up time, and MLR are important factors. To this end, an optimizer was implemented in order to determine the best storage capacity. In this study, ICE units could take advantage of 100% P_{rated}/min ramp rate, maximum 5 min start-up time, and minimum load level of 20%. On the other hand, ORC system ramp rate was set on 8% P_{rated}/min, minimum start-up time of 2 hours, and minimum load level of 40%. The optimizer suggested four storage units (NaS technology in Section 0) for the gasification system, whereas, no units for the ORC system. The possibility of dispatching generating units in the gasification system allowed economic implementation of battery units for low power demand periods throughout a day. In contrast, the ORC system could achieve the best economic performance when the system could take advantage of 24 h operation. One of the main reasons for continuous operation of ORC was the lower marginal generation cost at 0.146 $/kWh, in comparison to the ICEs at 0.165 $/kWh. The average energy cost of battery units (0.205 $/kWh) could compete with the marginal generation cost of ICE units at a given time interval (low power demand periods), however, it could not reach as low as that of the ORC system. To this end, no storage system was suggested for the ORC system; even with three minor and two

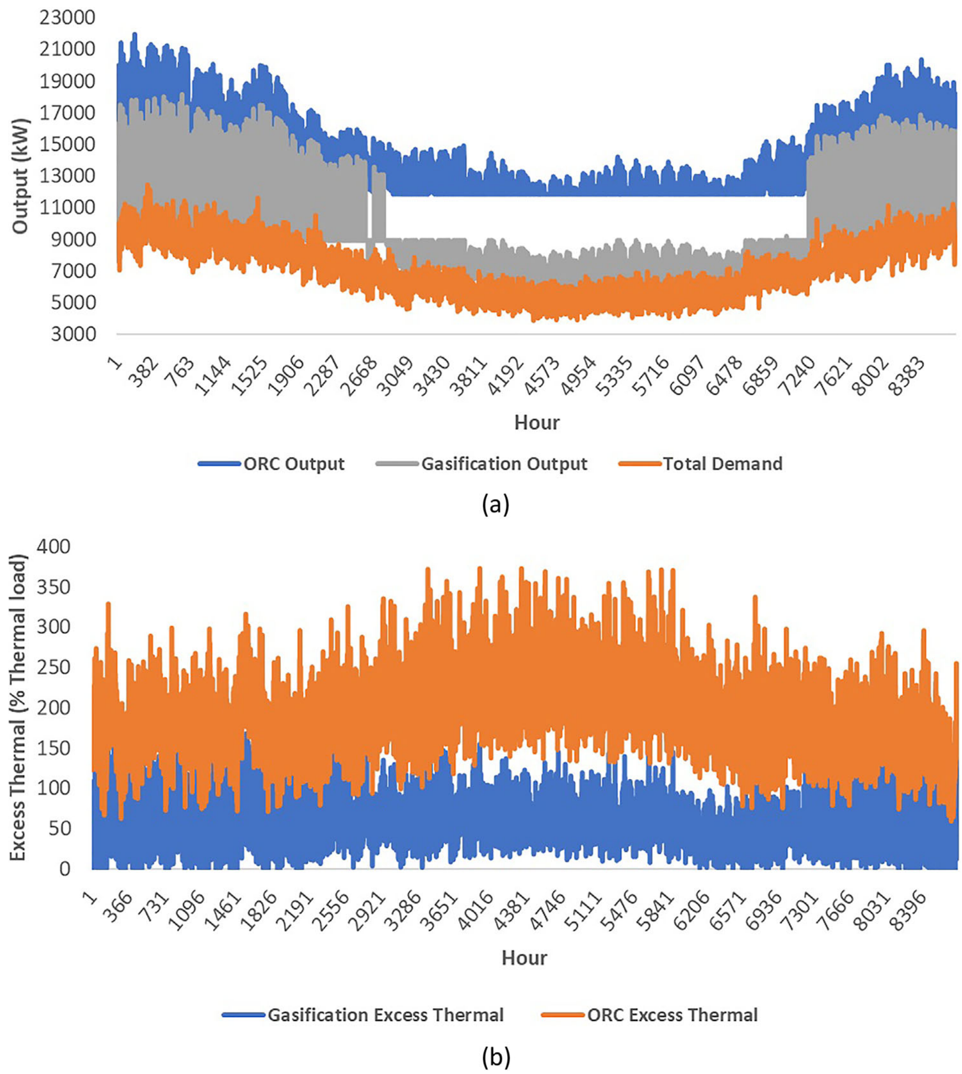


FIGURE 8 (a) Energy generation and (b) thermal excess production of gasification and ORC systems

major maintenance tasks the system could generate excess electricity at minimum marginal generation cost to cover the entire maintenance plan over the project lifetime. Although, an important factor that can result in implementation of battery units is higher MLR. This value is not only constrained by technical properties of the equipment, but also can be limited due to environmental impacts of the system. The MLR can be a trade-off between environmental impacts and the financial investments on improving environmental performance of a system. In this study, a carbon capture facility with 90% efficiency was designed for the ORC system. Lowering carbon capture ratio can result in higher economic benefits, while the MLR should be increased to meet the emission regulations. In this particular case, the ORC system required storage units if the MLR was increased above 75%. With MLR value at 80%, the system required 12 battery units, in which case the LCOE would increase by 32.7%, compared to the default MLR at 40%. The battery input power illustrates the energy transfer in the storage system throughout a year (Figure 9). The difference in time of utilization between the gasification and ORC system is mainly arise from the battery energy cost and minimum generation level. It is more economic for the ORC system to operate continuously during high power demand, while the generation throughout May to September is constrained by the MLR. On the other hand, gasification system could dispatch generating units (ICEs) based on the electric load profile. This allowed the gasification system to take advantage of battery storage units for improving the flexibility and economic of the system. In this regard, the storage units were mostly utilized during winter for periods with low power demand, particularly between hour 0 to 7 every day. The sodium-sulphur technology provided the possibility of long discharge as much as 6 h in a day.

4.3 | Fuel consumption

Fuel consumption in any energy system is the primary factor in economic and environmental feasibility. In this case study, gasification could take advantage of lower fuel consumption due to its higher power efficiency. Given the fact that exergy

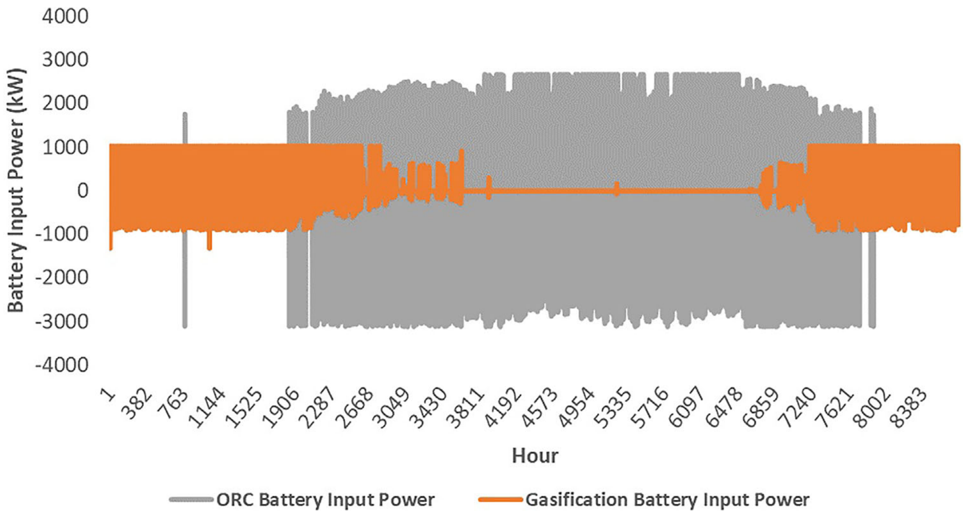


FIGURE 9 Battery unit input power in connection to gasification and ORC system

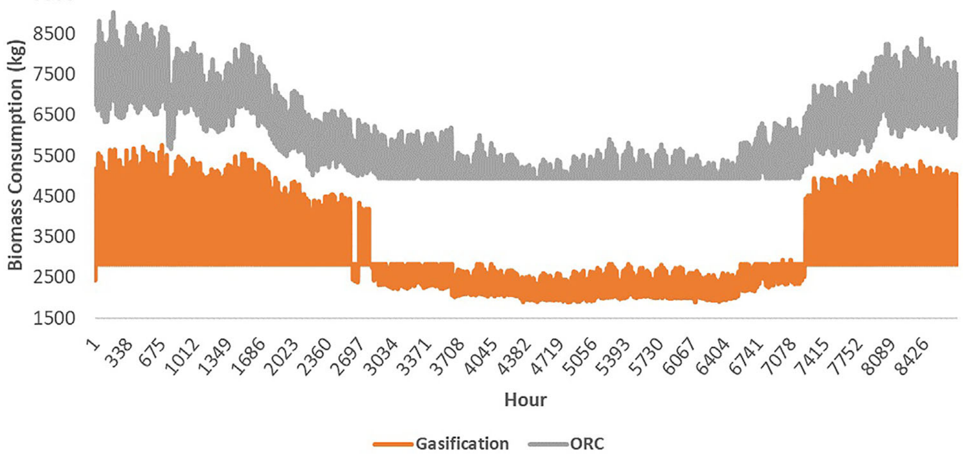
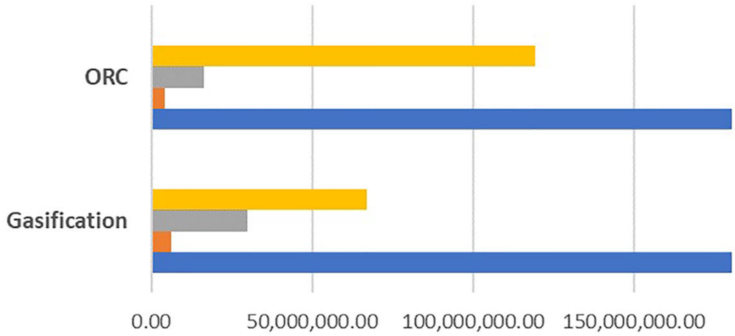


FIGURE 10 Annual biomass feedstock consumption

destruction is lower in such system compared to the ORC, fuel consumption was half of the direct combustion method. In Figure 10, the fuel consumption is presented based on the delivered feedstock at 23% moisture content. The main contributor to the higher fuel consumption of the ORC system was the power efficiency since electricity was the primary product of the system. The huge power efficiency difference between the two systems could increase the fuel consumption of ORC by two times that of the gasification one. The destructive result of such characteristic can be observed in the economic performance and energy cost. Another important factor that lowered the fuel consumption of gasification system was the integration of battery storage units. The storage units provided flexibility and lowered the operating hours of the generating units, while resulted in lower fuel consumption by 4%. The fuel consumption in both systems follows the same pattern as the monthly energy demand, having the lowest consumption during summer.

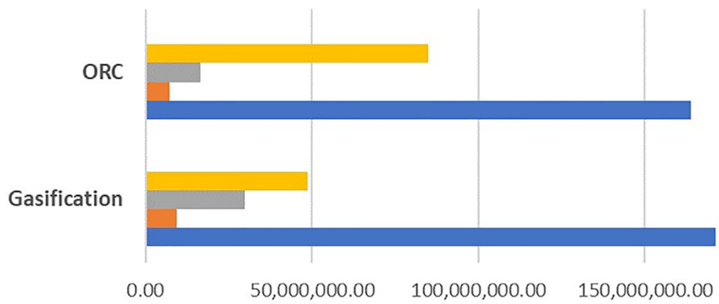
4.4 | Economic performance

Economic analysis was carried out as a comparative assessment between the two systems in terms of capital cost, initial capital, operating cost, fuel expenses, and total net present cost (NPC). This analysis was performed with regards to two different biomass feedstock prices. The prices that were presented in Tables 6 and 7 correspond to specific cost of fuel including 200 km transportation. As established in the last section, fuel consumption for the case of ORC is noticeably higher, which resulted in 78% higher fuel expenses than gasification system (Figure 11). This effect could overcome the lower cost of operating and maintenance of the system (32% compared to gasification) and result in higher total NPC than the gasification system by approximately 5%. To this end, the energy cost was 7.5% higher than the cost of energy production by means of gasification.



	Gasification	ORC
Levelized Cost of Energy ($/kWh)	0.2907	0.3118
Fuel Expenditure Cost ($)	67,099,174.00	119,313,124.00
Capital Cost ($)	29,947,730.00	16,430,000.00
Operating Cost ($/yr)	6,115,795.00	4,172,279.00
Net Present Cost ($)	189,345,300.00	198,155,100.00

(a)



	Gasification	ORC
Levelized Cost of Energy ($/kWh)	0.2469	0.2256
Fuel Expenditure Cost ($)	48,835,081.00	84,870,382.00
Capital Cost ($)	29,947,730.00	16,430,000.00
Operating Cost ($/yr)	9,433,704.00	7,351,201.00
Net Present Cost ($)	171,063,800.00	163,791,300.00

(b)

FIGURE 11 Economic performance of CHP-ORC and CHP-gasification with (a) high and (b) low feedstock price

If the transportation cost is to be halved, the economic performance with regards to the cost of energy can result in interesting outcomes. Decreasing the cost of feedstock by roughly 28% could reverse the economic profitability situation, meaning that the ORC could be associated with lower energy production cost than its gasification counterpart. The influence of biomass feedstock price did not affect both systems in a similar manner. Its impact on economic viability of the ORC system was more severe since such system was linked with higher fuel consumption (Figure 12(a)). For any feedstock value above 55 $/t, the practical implementation of the ORC could be questioned, and its development could only be feasible for communities with presence of thermal demand intensive industries (Figure 12(b)). The high thermal efficiency of ORC would allow production of huge thermal energy that could provide high revenue and financial benefits, whereas, this was limited in gasification system. In contracts, if the fuel price is not a limitation, ORC development for community energy supply with presence of thermal intensive industries can in fact be financially viable. Subjecting the two systems to 35,313 MWh thermal demand and considering the lower feedstock base price (47.32 $/t), would result in 0.2256 $/kWh LCOE by means of CHP-ORC, and 0.2469 $/kWh by means of CHP-gasification system, which are in compliance with the global values for woody bioenergy

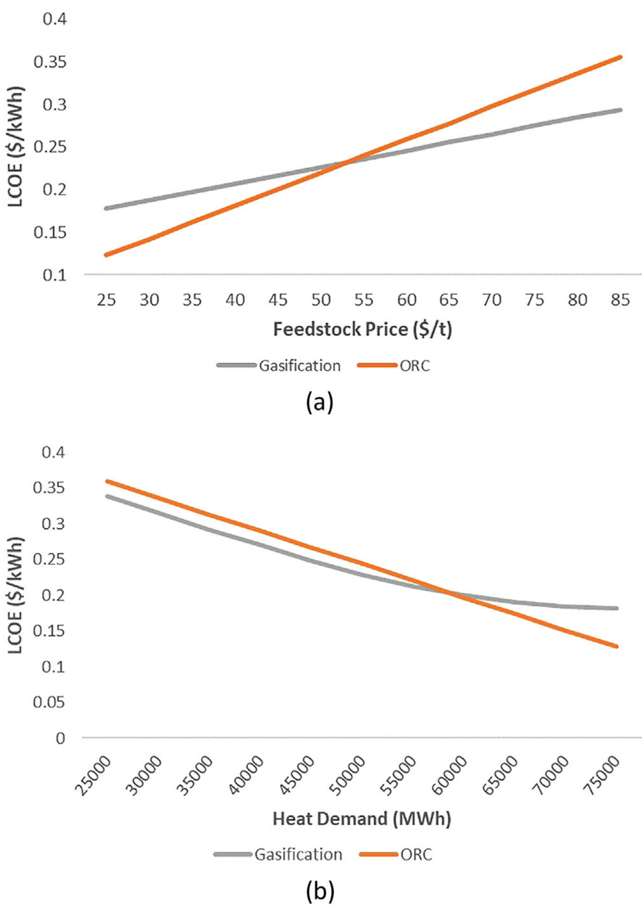


FIGURE 12 (a) Variation of LCOE versus feedstock price and (b) annual heat demand

systems [56, 57]. The recorded LCOE prices are slightly higher than the global weighted average for bioenergy in North America. This is because the considered specific investment cost for each conversion technology was at the higher-end values.

Abbreviations

$\bar{L}_{primary}$	Average primary load (kWh)
$\dot{C}$	Cost flow
c_{dep}	Cost of development ($/MWh)
c_{fuel}	Specific cost of fuel ($/t)
C_i	Capital cost for unit i ($)
c_{int}	Capital Interest ($/MWh)
$C_{opm,i}$	Operating cost for unit i ($)
C_{total}	Total capital cost
L_{res}	Operating Reserve (W)
$\dot{m}$	Mass flow rate (kg/s)
$\dot{Q}$	Rate of input heat (kJ/s)
η_{CHP}	CHP efficiency (%)
η_{el}	Electrical efficiency (%)
η_{ex}	Heat exchanger efficiency (%)
$\eta_{gasifier}$	Gasifier efficiency (%)
θ_{dev}	Development factor
θ_{int}	Interest factor
CCHP	Combined Cooling Heating and Power
CHP	Combined Heat and Power
Cp	Specific heat capacity (kJ/kg K)
CRF	Capital Recovery Factor
DH	District Heating
FC	Fuel Cell
GHG	Greenhouse Gases
HHV	Higher Heating Value
ICE	Internal Combustion Engine
IES	Integrated Energy System
LCOE	Levelized Cost of Electricity
LHV	Lower Heating Value
NPV	Net Present Value
OPH	Operating Hours
ORC	Organic Rankine Cycle
PBP	Payback Period
PEC	Primary Energy Consumption
RES	Renewable Energy Sources
T	Temperature (K)

Variables

W	Output power (kJ/s)

5 | CONCLUSION

Utilizing biomass resources for energy generation can be done using different methods, and the end-use product can take different forms depending on the demand or application. Direct combustion and gasification are the two widely used techniques for biomass to bioenergy conversion. The lower capital and maintenance cost make direct combustion a favourable choice for larger implementation, while gasification is selected for its higher conversion efficiency and lower environmental consequences. There exist several influencing factors such as feedstock type, plant size, cost of biomass, and primary energy form that can determine the viability of each conversion technique for residential energy supply. In this research, Organic Rankine Cycle was selected as the suitable technique for direct combustion, while Dual Fluidized-Bed for that of gasification. Each system was developed with technical operating conditions based on reference operational plants around the world. The results suggested that the feedstock price is the primary factor in realizing the economic feasibility. The financial outcomes illustrated that each system could be advantageous under different operating conditions. For thermal demand intensive locations (communities), ORC can be present higher economic advantageous than gasification. Although the system is associated with lower capital and maintenance cost, but the limited electrical efficiency can result in significantly higher fuel consumption, approximately two times than the gasification system. For the case of Masset Village this resulted in 8% higher LCOE price when utilizing biomass feedstock with 65.0 $/t base value. Moreover, direct combustion can result in 190,549 kg/year CO_2 emissions which is approximately twice the gasification system. In contrast, the gasification system based on DFB could take advantage of higher conversion efficiency (27%) and better environmental performance (92,529 kg/year equivalent CO_2). Despite its higher capital cost (50% higher than ORC), the system can be advantageous when electricity is the primary product of the system or providing biomass resources is costly. Given that the impact of feedstock price on such system is not as severe as the ORC, such method of bioenergy conversion can result in higher financial prosperity, particularly for smaller applications.

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