

Article

How Best to Use Forest Wood for Energy: Perspectives from Energy Efficiency and Environmental Considerations

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Abstract: This paper examines how best to use forest wood for energy application, considering that it is a limited natural resource. Eight systems are considered, including wood stoves, steam systems (boiler, power plant, and combined heat and power (CHP)), and gasification combined systems (gas turbine and combined cycle power plant, CHP, and Fischer–Tropsch). The methodology uses energy analysis and modelling and environmental/sustainability considerations to compare the energy systems. In terms of energy conversion efficiency, steam boilers and high-efficiency wood stoves for heating applications provide the highest efficiencies (~80 to 90%) and should be considered. Steam CHP systems provide lower overall energy conversion efficiencies (~75 to 80%) but do provide some electrical energy, and thus should be considered. The use of wood for the production of electricity on its own should not be considered due to low efficiencies (~20 to 30%). Particulate emissions hinder the application of high-efficiency stoves, especially in urban areas, whereas for industrial-scale steam boilers and CHP systems, particle separators can negate this problem. Gasification/Fischer–Tropsch systems have a lower energy efficiency (~30 to 50%); however, a sustainability argument could be made for liquid fuels that have few sustainable alternatives.

Keywords: sustainable energy; forest wood

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1. Introduction

It is estimated that around 2.3 billion people in developing countries rely primarily on wood energy for their everyday cooking and heating needs [1]. Furthermore, wood energy represents the leading source of renewable energy across a large number of developed countries. In the EU, wood energy is responsible for 45% of primary energy from renewable sources [2], and in the United States, wood energy accounts for a quarter of all renewable energy, second only to hydropower [3].

Some of these wood fuels are sourced directly from forests by harvesting trees to be used solely for fuel or indirectly as by-products from the wood processing and pulp industries. Additionally, wood fuels are also obtained through the recovery of processed wood products, mainly wood waste from construction, but also packaging and old furniture. The 2017 UNECE/FAO joint wood energy enquiry (JWEE) showed that 33.8% of wood for energy generation across the United Nations Economic Commission for Europe (UNECE) region came from direct sources, 50.9% from indirect sources, 5.3% from recovered wood products, and the remainder from unspecified sources [4]. Wood energy is consumed in roughly equal measure by industry (39.3%) and other final consumers (40.3%). Wood energy consumption in the power and heat sector accounted for 20.4%. In total, 88% of

industry usage is by the wood processing and pulp industries, and 89.3% of final consumer usage is by the residential sector.

Forest wood is used to provide energy in many different ways. It is used in wood processing plants, electric power generation plants, space-heating and steam-producing boilers in industry, combined heat and power (CHP) units in industry, boilers for district heating systems, boilers for hotels, and domestic boilers and wood-fired stoves for space heating [5]. Additionally, forest wood can be converted into syngas through the process of gasification [6], which can be used to run internal combustion engines and to fuel gas turbines for electricity generation. This syngas can also be processed into liquid biofuels using the Fischer–Tropsch (FT) process [7], which can be applied to produce diesel and aviation fuels in an environmentally sustainable way [8].

Energy from wood does have its problems. Wood combustion results in the release of both gaseous pollutants and particulate matter, including particles smaller than 2.5 μm ($\text{PM}_{2.5}$) [9,10]. Fitzpatrick [11] performed a life cycle assessment of supplying heat energy from forest wood, which showed that even though sustainably sourced forest wood is “greener” than heating oil from a climate change perspective, emissions of particulate matter during wood combustion are of major concern and contribute to the highest emissions impact from the life cycle. Particulate emissions from wood combustion can have a serious impact on human health and the natural environment if these are not separated from exhaust flue gases [12].

There are very few studies that compare alternative approaches to using wood energy, with a view to investigating which are the more effective approaches. Two studies [13,14] assessed the utilisation of wood energy for heat and electricity in Turkey. They compared the use of different wood feedstocks (wood chip vs. wood pellet and poplar vs. miscanthus) and used these wood sources in five alternative systems for generating heat and/or power (steam boiler, electric power plant, direct combustion CHP, gasification CHP, and co-firing with lignite). The studies made comparisons based on life cycle assessment and life cycle costing. In relation to the alternative systems, direct combustion CHP had the lowest environmental impacts and levelised costs.

Wood energy is not a “silver-bullet” sustainable energy solution, because it is very much a limited natural resource, which can contribute to the overall mix of approaches for supplying energy sustainably. For example, in Ireland, around 11% of the Irish land area is forested and around 31% of harvested forest wood is used for energy. A study by Fitzpatrick [11] showed that a steady-state sustainable supply of fuel wood energy from this area was estimated to contribute around 8.7% of the Irish heat primary energy demand in 2010. Thus, forest wood fuel is a limited resource even in a low-population country and can only sustainably supply a small fraction of demand. As forest wood fuel is a limited natural resource, it is important to use it wisely, and thus select those approaches to using wood energy that most effectively use it.

Considering the above, the objective or research question associated with this study is to explore the most effective approaches for using forest wood for energy applications, considering that forest wood is a niche and limited natural resource. Section 2 (Energy Analysis) starts by outlining the eight approaches or systems selected that utilise wood for energy. It then outlines the equations and parameter values used in the energy modelling of each of the systems. Section 3 is Results and Discussion. This section starts by presenting the results of the energy analysis for each of the eight systems. It presents the effects of key operational parameters, in particular wood water content and gasification efficiency. It then compares the energy efficiencies of the systems to elicit which systems are using energy more effectively and which are not. The final part of Section 3 focuses on important environmental and sustainability factors that may influence the choice of wood energy

systems used, such as particle emissions and the availability of alternative sustainable energy sources for an application. Finally, the major outcomes of the study are summarised in the Conclusions section. It is important to highlight that this study has limitations. These include the lack of economic comparison of the different systems and the study being limited to eight systems. There are a number of recent studies that explore advanced and novel approaches to using wood for energy, such as integrated processes to produce power, heat and hydrogen [15], advances in thermochemical conversion processes [16], integration of torrefaction [17], and advances in the synthesis of jet fuels [18].

2. Energy Analysis

2.1. Systems, Key Input Data, and Assumptions

The approaches or systems analysed in this work for utilising wood energy are listed below:

- (1) Wood-fired steam boiler (for heat application).
- (2) Wood-fired steam power plant (for generating electricity).
- (3) Wood-fired steam power plant CHP (for providing steam for heat application and generating electricity).
- (4) Gasification of wood + gas turbine power plant (for generating electricity).
- (5) Gasification of wood + combined cycle gas turbine power plant (for generating electricity).
- (6) Gasification of wood + gas turbine CHP (for providing steam for heat application and generating electricity).
- (7) Gasification of wood + Fischer–Tropsch (to produce liquid fuels).
- (8) Wood stoves (for heat application).

The selection of the eight approaches was based on a review of the literature presented in this paper, which represents approaches that are either commonly used or show potential for more common applications. Schematics and energy analysis of each of the systems are presented in this section. The feed mass flowrate of wood (m_f) is arbitrarily chosen as 10,000 kg h^{−1}. The wood has a lower heating value (LHV) of 14.75 MJ kg^{−1} (assuming a wood water content (w) of 0.2 or 20% wet basis) [19]. Ambient temperature (T_{amb}) is given a value of 20 °C. Any plant steam requirement for heat application is assumed to be 10 bar saturated steam with a latent heat of vaporisation (λ_v) of 2015 kJ kg^{−1}.

Industrial-scale electric generators for converting turbine work into electrical energy are usually very efficient at about 99% efficiency [20]; thus, the terms electrical and mechanical power are used interchangeably in this work. The analysis does not take into account incomplete combustion losses in boilers; however, a properly run industrial boiler with sufficient excess air should be able to achieve near-complete combustion. Casing losses (or heat transfer losses from the hot equipment to ambient) are also not considered in the analysis. There will be some casing losses, but this will be influenced by the thermal insulation of the equipment. Furthermore, the aim of this paper is a comparison of different approaches, and all of these approaches will have a certain amount of casing losses, which will result in lower energy efficiencies than those presented in this work.

2.2. Wood-Fired Steam Boiler

A schematic of the boiler system is presented in Figure 1. Boiler efficiency (η_B) is defined in Equation (1).

$$\eta_B = 100 \times \frac{m_s \lambda_v}{m_f LHV} \quad (1)$$

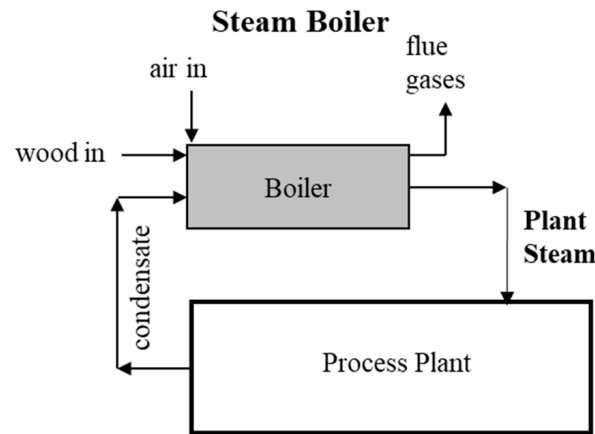


Figure 1. Schematic of steam boiler system for heating applications.

The only unknown in this equation is the mass flowrate of steam generated (m_s), which is evaluated using the following equations.

The mass flowrate of air required depends on the air–fuel ratio (AF). For wood, the stoichiometric air–fuel ratio expressed in terms of mass of air per mass of dry solids in the wood (AF_{ds}) is typically in the range of 6 to 6.5 [21]. From this, the stoichiometric air–fuel ratio (AF_s = mass of air per mass of wood) is given in Equation (2).

$$AF_s = AF_{ds}(1 - w) \quad (2)$$

The excess air in wood combustion processes to achieve complete combustion is usually high, in the range of 50 to 100% [21]. This results in an excess air ratio (R_{ea}) of 1.5 to 2, giving the actual air–fuel ratio (AF) in Equation (3).

$$AF = (R_{ea})AF_s = (R_{ea})AF_{ds}(1 - w) \quad (3)$$

Considering the above, using $AF_{ds} = 6.25$ and $R_{ea} = 1.8$ results in $AF = 9$, which is the air–fuel ratio used in this work in the following wood combustion analysis.

The mass flowrate of air (m_a) is evaluated from Equation (4).

$$m_a = AF(m_f) \quad (4)$$

The mass flowrate of hot gases (m_g) is evaluated from Equation (5).

$$m_g = m_a + (m_f - m_m) \quad (5)$$

where m_m is the mass flowrate of ash, which depends on the wood ash content (4%).

The combustion temperature of the combustion gases (T_b) is estimated from Equation (6), which is an energy equation using the LHV value.

$$m_f LHV = m_g C_{pg}(T_b - T_{amb}) + m_m C_{pm}(T_b - T_{amb}) \quad (6)$$

where C_{pg} and C_{pm} are the specific heats of the combustion gases ($1.02 \text{ kJ kg}^{-1} \text{ }^\circ\text{C}^{-1}$) and ash ($1 \text{ kJ kg}^{-1} \text{ }^\circ\text{C}^{-1}$), respectively.

With this, the mass flowrate of the steam (m_s) generated is estimated from Equation (7).

$$m_g C_{pg}(T_b - T_{ge}) = m_s(\lambda_v) \quad (7)$$

T_{ge} is the temperature of the combustion gases leaving the boiler, and this is assumed to be 20 °C higher than the vaporisation temperature of the steam.

Flue or combustion gas losses are evaluated in Equation (8).

$$flue\ gas\ losses = 100 \times \frac{m_g C_{pg} (T_{ge} - T_{amb})}{m_f LHV} \quad (8)$$

2.3. Wood-Fired Steam Power Plant

A schematic of the steam power plant system is presented in Figure 2. The combustion analysis to evaluate m_g , T_b , and flue gas losses is the same as in Section 2.2, except that higher boiler pressures were considered in the range of 50 to 150 bar to produce higher energy superheated steam.

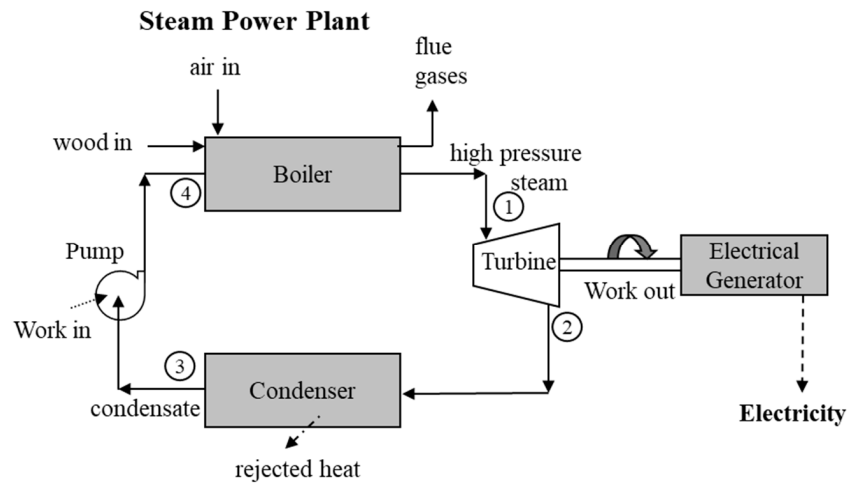


Figure 2. Schematic of steam power plant system.

The mass flowrate of the steam generated is estimated from Equation (9).

$$m_g C_{pg} (T_b - T_{ge}) = m_s (h_1 - h_4) \quad (9)$$

where h_1 and h_4 are the specific enthalpies of the superheated steam leaving and water entering the boiler, respectively.

The steam power plant cycle is modelled as a Rankine cycle with superheat, and relevant mathematical analysis [22] is applied to evaluate the electric power output, pump electric power input, and heat rejected in the condenser.

The following assumptions are applied:

- Turbine isentropic efficiency = 0.85
- Turbine exit pressure = 0.1 bar
- Superheated steam turbine inlet temperature is 600 °C, considering maximum steam temperatures entering steam turbines are around 620 °C [22].
- The dryness fraction of steam leaving the turbine is around 0.89.

Power efficiency is defined in Equation (10).

$$power\ efficiency = 100 \times \frac{m_s (h_1 - h_2) - m_s (h_4 - h_3)}{m_f LHV} \quad (10)$$

The heat rejection losses from the condenser are defined in Equation (11).

$$heat\ rejection\ losses = 100 \times \frac{m_s (h_2 - h_3)}{m_f LHV} \quad (11)$$

2.4. Wood-Fired Steam Power Plant CHP

A schematic of the steam power plant CHP system is presented in Figure 3. The mathematical analysis is the same as that in Section 2.3., except that the turbine exit condition is 10 bar saturated steam that is suitable for use as plant steam.

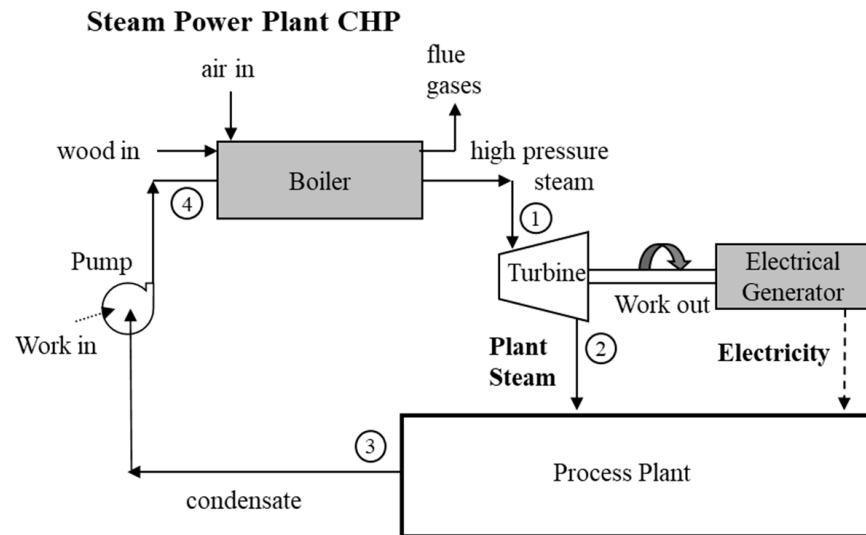


Figure 3. Schematic of steam power plant CHP.

The heat efficiency is presented in Equation (12) and is defined as the heat recovered from condensing the 10 bar steam divided by the heat generated from combusting the wood fuel.

$$\text{heat efficiency} = 100 \times \frac{m_s(h_2 - h_3)}{m_f \text{LHV}} \quad (12)$$

CHP efficiency is the sum of the power and heat efficiencies.

2.5. Gasification of Wood + Gas Turbine (GT) Power Plant

A schematic of the wood gasification and GT power plant system is presented in Figure 4. This section is broken up into two parts. The first part presents the analysis of the wood gasification process and the energy efficiency associated with gasifying wood into synthesis gas or syngas. The second part then presents an analysis of the GT power plant for generating electrical power from the combustion of the syngas.

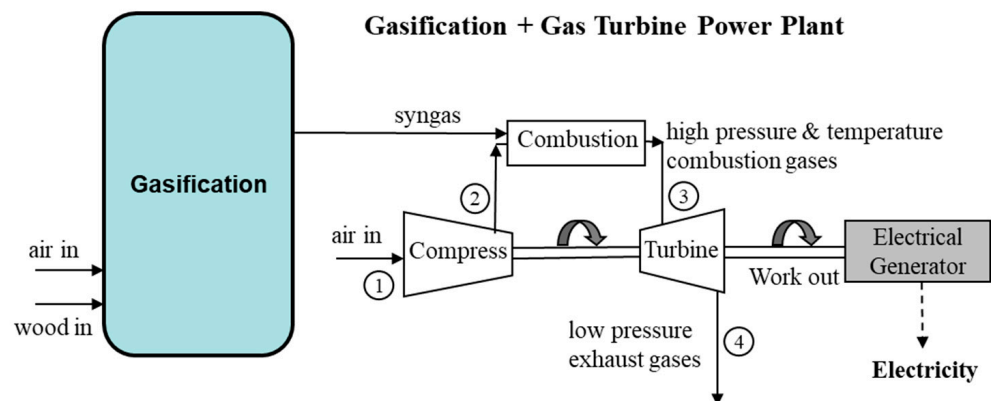


Figure 4. Schematic of the gasification and gas turbine plant system.

2.5.1. Gasification of Wood

The gasification efficiency (η_G) is defined in Equation (13).

$$\eta_G = 100 \times \frac{E_{syngas}}{m_f LHV} \quad (13)$$

where E_{syngas} is the combustion energy in the syngas and is given in Equation (14).

$$E_{syngas} = m_{sg} LHV_{sg} \quad (14)$$

where m_{sg} is the mass flowrate of syngas produced and LHV_{sg} is its lower heating value.

Two key parameters that influence the gasification efficiency and LHV_{sg} are the equivalence ratio and the water content of the wood. The equivalence ratio (ER) is defined as the ratio of actual air used in gasification to the stoichiometric air required for complete combustion. The reason this ratio is of such importance in the gasification process is because in gasification, the aim is to produce CO and H₂ and not CO₂ and H₂O. Managing this ratio is key to ensuring that the former and not the latter are produced. In practice, the optimum ER value tends to be in the range of 0.25 to 0.3 [6].

From the data presented by Kirsanovs [6] on the gasification of wood chips, a gasification efficiency of around 63% and a LHV_{sg} value of around 5 MJ kg⁻¹ can be achieved with a wood chip water content of 12%. Mustafa et al. [7] highlighted that LHV_{sg} values for syngas obtained from biomass are typically in the range of 4 to 5.6 MJ Nm⁻³. Le-stander et al. [23] investigated the effect of individual tree components (such as stem wood, branches, etc.) on gasification, including gasification efficiency. The gasification efficiencies obtained were around 60% for stem wood and branches that had been dried to 10% water content. Morita et al. [24] presented a much higher wood gasification efficiency value of 72% at a 15% water content. Francois et al. [25] presented results from a detailed process modelling study, where they provided a gasification efficiency of 84%. van der Meijden et al. [26] presented gasification efficiencies of 54%, 58%, and 67% for three different wood gasification systems. Sher et al. [27] presented a review of cutting-edge biomass gasification technologies for energy generation with gasification efficiencies ranging from 34 to 80% for biomass-only systems.

Considering the values above and being conservative, a 60% gasification efficiency and a LHV_{sg} value of 5 MJ kg⁻¹ are used in this work. With these values, m_{sg} can now be evaluated from Equation (13). The analysis also shows that the hot syngas leaving the gasifier is used to heat up ambient air in a heat exchanger, which is used to dry the feed wood from 20% to 10% water content. Mathematical modelling of the air drying showed that this is feasible.

The 60% gasification efficiency value is particularly important, as this will significantly impact the energy performance of the following systems that utilise gasification. Gasification of wood is a complex process, and there are many factors that may affect the gasification efficiency. Consequently, sensitivity analysis is performed to investigate how varying gasification efficiency influences the energy performance of these systems. In relation to wood water content, this has a significant negative impact on gasification efficiency, which is considered further in Section 3.

2.5.2. GT Power Plant

A schematic of the GT power plant system is shown in Figure 4. The GT power plant is modelled using the Brayton cycle, coupled with isentropic efficiencies for the compressor and turbine. The inlet temperature of the compressor (T_1) is set at an ambient temperature of 20 °C. As the syngas also needs compression, this assumes that the syngas has been

ambiently cooled to this temperature, as the compressor power requirement is influenced by temperature. Gas turbines have a temperature limitation; thus, the inlet temperature to the gas turbine (T_3) is limited to 1200 °C. The pressure ratio (r_p) is defined in Equation (15) and is given a value of 10.

$$r_p = \left(\frac{P_2}{P_1} \right) \quad (15)$$

In the Brayton cycle, the compression process is modelled as the isentropic compression of an ideal gas, and the temperature of the gas exiting the ideal compressor (T_{2s}) is evaluated in Equation (16).

$$\frac{T_{2s}}{T_1} = (r_p)^{(k-1)/k} \quad (16)$$

where k is the specific heat ratio of the gas = 1.4.

With this, the ideal compressor-specific work input (w_{comp_s}) is evaluated from Equation (17).

$$w_{comp_s} = C_{pa}(T_{2s} - T_1) \quad (17)$$

where C_{pa} is the specific heat of air. The real compressor-specific work input (w_{comp}) is evaluated in Equation (18) using a compressor isentropic efficiency (η_{comp}) of 0.87.

$$w_{comp} = \frac{w_{comp_s}}{\eta_{comp}} \quad (18)$$

Now, the real exit temperature from the compressor (T_2) can be evaluated from Equation (19).

$$w_{comp} = C_{pa}(T_2 - T_1) \quad (19)$$

In the Brayton cycle, the turbine process is also modelled as an isentropic process, and the temperature of the air exiting the ideal turbine (T_{4s}) is evaluated in Equation (20).

$$\frac{T_3}{T_{4s}} = (r_p)^{(k-1)/k} \quad (20)$$

With this, the ideal turbine-specific work output (w_{turb_s}) is evaluated from Equation (21).

$$w_{turb_s} = C_{pa}(T_3 - T_{4s}) \quad (21)$$

The real turbine-specific work output (w_{turb}) is evaluated in Equation (22) using a turbine isentropic efficiency (η_{turb}) of 0.85.

$$w_{turb} = \eta_{turb} w_{turb_s} \quad (22)$$

Now, the real T_4 is evaluated from Equation (23).

$$w_{turb} = C_{pa}(T_3 - T_4) \quad (23)$$

The net specific work output (w_{net}) is evaluated from Equation (24).

$$w_{net} = w_{turb} - w_{comp} \quad (24)$$

To evaluate the net power output, the mass flowrate of gas (m_g) in the cycle is required. This is evaluated in Equation (25).

$$m_g = \frac{E_{syngas}}{q_{23}} \quad (25)$$

E_{syngas} is the heat energy generated by syngas combustion and is evaluated in Equation (14). q_{23} is the specific heat energy input in the combustion process, and is given by

$$q_{23} = C_{pa}(T_3 - T_2)$$

(At this stage, it should be noted that the turbine inlet temperature (T_3) is limited to 1200 °C, which is less than the adiabatic flame temperature for combusting the syngas [28,29]. Consequently, the limiting turbine inlet temperature of 1200 °C determines the evaluation of m_g as opposed to the air–syngas fuel ratio for complete combustion).

From the above, m_g is evaluated from Equation (25), and the net power output ($Power_{net}$) is evaluated from Equation (26).

$$Power_{net} = m_g w_{net} \quad (26)$$

The power efficiency of the GT plant is defined in Equation (27).

$$power\ efficiency = 100 \times \frac{Power_{net}}{m_f LHV} \quad (27)$$

The power cycle efficiency is defined in Equation (28) as the net power output obtained from the combustion energy in the syngas.

$$power\ cycle\ efficiency = 100 \times \frac{Power_{net}}{E_{syngas}} \quad (28)$$

The flue gas losses associated with combustion gas losses leaving the gas turbine are evaluated in Equation (29).

$$flue\ gas\ losses = 100 \times \frac{m_g C_{pa}(T_4 - T_{amb})}{m_f LHV} \quad (29)$$

2.5.3. GT Power Plant with Regeneration

A schematic of the GT power plant with regeneration is presented in Figure 5. This is commonly used to improve the power efficiency by transferring some of the heat energy in the flue gases into the gas leaving the gas compressor. This heats the gas up from temperature T_2 to an intermediate temperature (T_5). The effectiveness of the regenerator (ϵ) is used to evaluate T_5 and is defined in Equation (30). The effectiveness is typically around 0.8 [22].

$$\epsilon = \frac{T_5 - T_2}{T_4 - T_2} \quad (30)$$

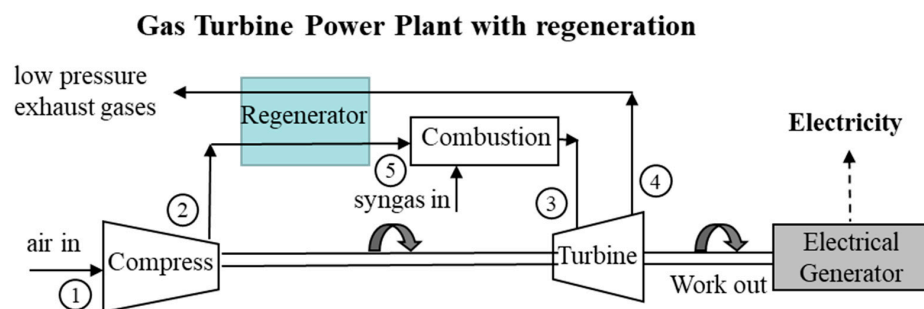


Figure 5. Schematic of a gas turbine power plant with regeneration.

With this, the mass flowrate of gas is evaluated in Equation (31).

$$m_g = \frac{E_{syngas}}{q_{53}} \quad (31)$$

where q_{53} is now the specific heat energy input in the combustion process and is given by

$$q_{53} = C_{pa}(T_3 - T_5)$$

The net power output, power efficiency, and flue gas losses are evaluated as in Section 2.5.2.

2.6. Gasification of Wood + Combined Cycle Gas Turbine (CCGT) Power Plant

A schematic of the wood gasification and CCGT power plant system is presented in Figure 6. The mathematical analysis for the GT power plant (Section 2.5.2) is used, except that the gases leaving the turbine are sent to a steam power plant cycle to generate some additional power from the hot gases. The boiler in the steam power plant is operated at 20 bar pressure. The steam power plant analysis (Section 2.3) is applied to evaluate the power efficiency of the steam plant and the heat rejection losses. The power efficiency of the CCGT plant is the sum of the power efficiencies for the GT and steam power plants.

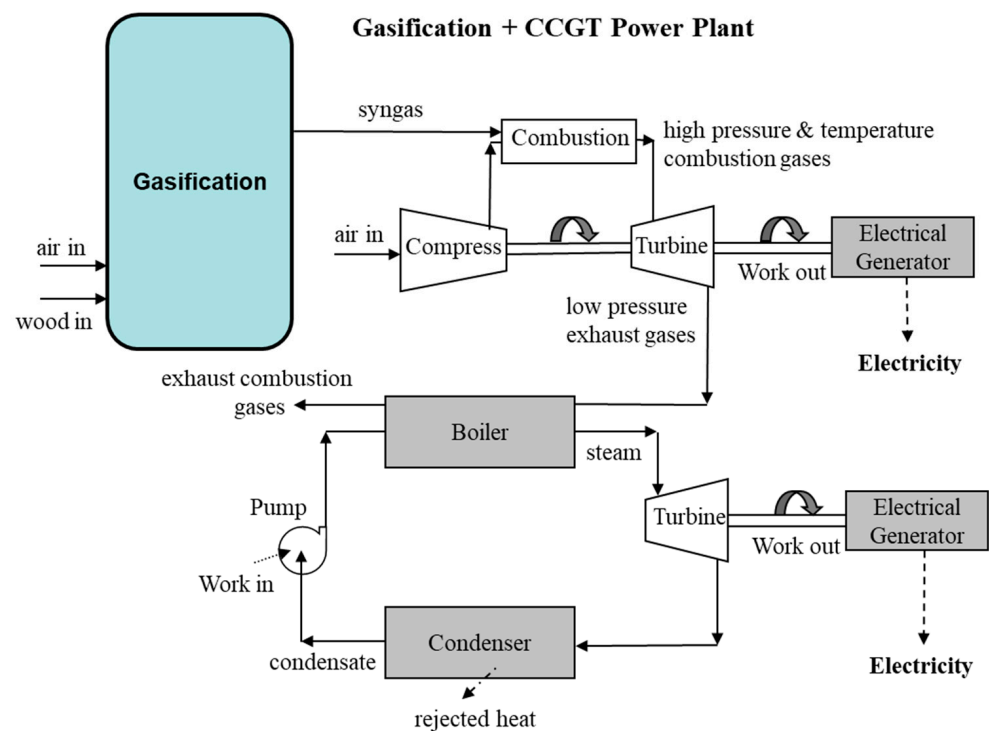


Figure 6. Schematic of the gasification and CCGT power plant system.

2.7. Gasification of Wood + Gas Turbine CHP

A schematic of the wood gasification and the gas turbine CHP system is presented in Figure 7. The mathematical analysis for the GT power plant (Section 2.5.2) is used, except that the gases leaving the turbine are sent to the boiler to generate 10 bar saturated steam that is suitable for use as plant steam for heat application. The heat efficiency is presented

in Equation (32) and is defined as the heat recovered from the combustion gases to generate steam divided by the heat generated from combusting the wood fuel.

$$\text{heat efficiency} = 100 \times \frac{m_a C_{pa} (T_4 - T_{ge})}{m_f \text{LHV}} \quad (32)$$

where T_{ge} is the temperature of the gases leaving the boiler, which is 199.9 °C (or 20 °C greater than the boiling temperature at 10 bar pressure).

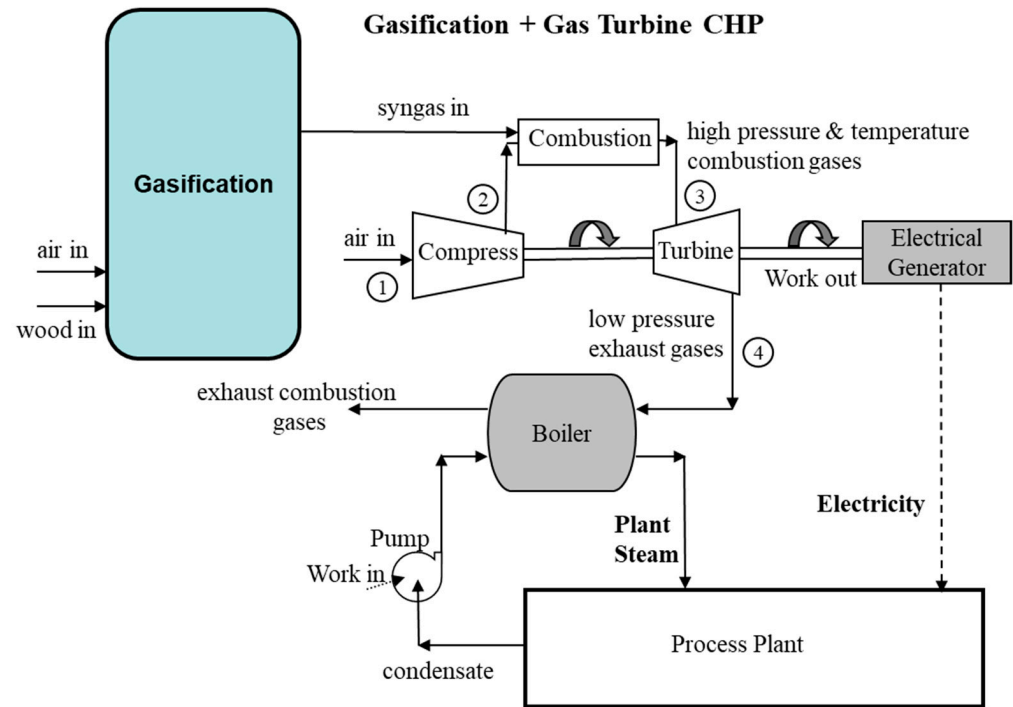


Figure 7. Schematic of the gasification and gas turbine CHP system.

The CHP efficiency is the sum of the power and heat efficiencies.

The CHP cycle efficiency is defined in Equation (33).

$$\text{CHP cycle efficiency} = 100 \times \frac{\text{Power}_{\text{net}} + \text{Heat recovered}}{E_{\text{syngas}}} \quad (33)$$

The flue gas losses associated with combustion gas losses leaving the boiler are evaluated in Equation (34).

$$\text{flue gas losses} = 100 \times \frac{m_a C_{pa} (T_{ge} - T_{amb})}{m_f \text{LHV}} \quad (34)$$

2.8. Gasification of Wood + Fischer–Tropsch

A schematic of the wood gasification and Fischer–Tropsch (FT) process is presented in Figure 8. In the FT reactor, cleaned syngas, containing mainly CO and H₂, is converted into hydrocarbons of various molecular weights. The syngas must first undergo preparation processes prior to the FT reaction, as illustrated in Figure 8. This includes gas cleaning to remove contaminating components, including organic components (such as tars), inorganic components (such as nitrogen and sulphur compounds), and particulates [8,30,31]. A water gas shift (WGS) reaction may be required to give the desired H₂–CO ratio, but this will depend on the FT catalyst used. Syngas compression to about 20–40 bar is required for the

FT reaction at a temperature typically in the range of 150–350 °C [7,32]. These preparation processes do require significant energy, in particular gas compression.

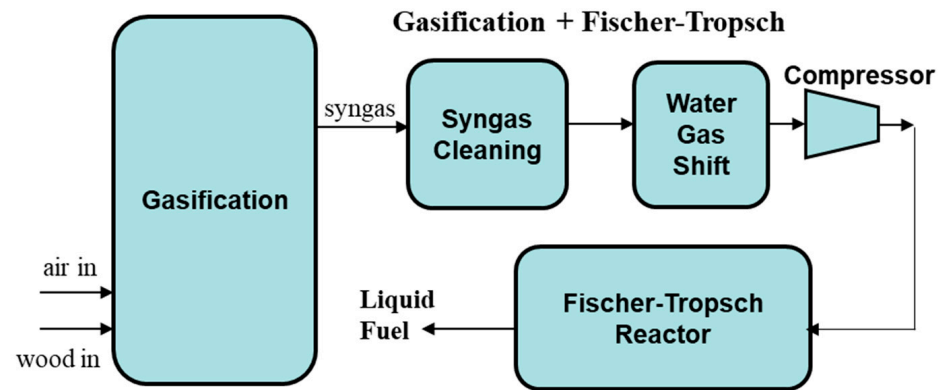


Figure 8. Schematic of the gasification and Fischer–Tropsch process to produce liquid fuel.

For Fischer–Tropsch reactions, a very important parameter is the carbon conversion%, i.e., the percentage of carbon in the syngas that is converted into hydrocarbons. This is because this directly influences the energy conversion efficiency of the FT process. Depending on the syngas composition, typical carbon conversions vary from 60 to 75% [32]. In this work, estimation of the Fischer–Tropsch or FT efficiency (η_{FT}) is very important and is defined in Equation (35).

$$\eta_{FT} = 100 \times \frac{E_{liquid-fuel} - E_{inputs}}{E_{syngas}} \quad (35)$$

where $E_{liquid-fuel}$ is the combustion energy in the liquid fuel (i.e., the mass flowrate of the liquid fuel produced multiplied by its lower heating value) and E_{inputs} is the energy associated with the energy inputs, in particular syngas compression. This is included in the energy analysis because gas compression is typically not negligible. Estimation of the energy requirement associated with syngas compression is undertaken using the gas compression analysis in Equations (15)–(19). This is estimated for typical FT reaction pressures in the range of 20 to 40 bar with an inlet compression gas temperature of 60 °C. It also assumes that there is effective syngas cleaning that removes the syngas impurities, in particular the nitrogen, which greatly reduces the mass of the syngas to be compressed. This analysis shows that the electrical energy required by the syngas compression represents around 3.3 to 4.6% of the combustion energy in the syngas leaving the gasifier (E_{syngas}). As an approximation in this study, it is assumed that E_{inputs} represents 5% of E_{syngas} .

Recently, van den Oever et al. [33] systematically reviewed studies on the energy efficiency of biomass-based Fischer–Tropsch (FT) plants. They reported biomass-to-liquid-fuel energy efficiencies for 24 studies, with the bulk of them being in the 25 to 45% range, with a mean value being above the mid-range at about 37%. These efficiency values were harmonised based on LHVs for biomass and liquid fuels. This biomass-to-liquid-fuel energy efficiency (η_{BL}) is defined in Equation (36).

$$\eta_{BL} = 100 \times \frac{E_{liquid-fuel}}{m_f LHV} \quad (36)$$

$E_{liquid-fuel}$ is evaluated from Equation (36) considering a biomass-to-liquid-fuel energy efficiency of 37%. With these calculated values of $E_{liquid-fuel}$ and E_{inputs} , the FT efficiency is estimated from Equation (35). For a gasification efficiency of 60% considered in Section 2.5.1,

this results in an FT efficiency of 56.7%. This value is used as an indicative mid-range value of the FT efficiency in this work.

The liquid-fuel efficiency is defined in this work in Equation (37) as the product of the gasification and FT efficiencies.

$$\text{liquid} - \text{fuel efficiency} = \eta_G(\eta_{FT})/100 \quad (37)$$

The FT losses for the FT system (Figure 8) are defined in Equation (38).

$$FT \text{ losses} = \frac{E_{\text{syngas}} - E_{\text{liquid-fuel}} + E_{\text{inputs}}}{m_f LHV} \quad (38)$$

2.9. Wood Stoves

The energy losses that reduce wood stove energy efficiency are due to flue gas losses and incomplete combustion losses. Consequently, the overall efficiency for a stove (η_{Stove}) is defined in Equation (39).

$$\eta_{\text{Stove}} = 100 - (\text{flue gas losses} + \text{incomplete combustion losses}) \quad (39)$$

where the flue gas losses are evaluated in Equation (40). T_{se} is the temperature of the combustion gases leaving the stove pipe.

$$\text{flue gas losses} = 100 \times \frac{m_g C_{pg}(T_{se} - T_{amb})}{m_f LHV} \quad (40)$$

2.10. Power–Heat Equivalent Energy Efficiency of a System

The steam and GT systems deliver power or heat, or a combination of both. The resultant power and heat efficiencies cannot be directly compared because power is a higher grade of energy and is thermodynamically of a greater energy value than heat. Consequently, when comparing power and heat, the power should be multiplied by a power–heat factor whose value is greater than 1. This leads to the concept of the power–heat equivalent energy efficiency of a system (η_{PHE}), which is defined in Equation (41).

$$\eta_{PHE} = \text{heat efficiency} + F_{PH}(\text{power efficiency}) \quad (41)$$

where F_{PH} is the power–heat factor. This can be used for comparing the energy efficiencies of different systems that produce heat and/or power. This requires the estimation of F_{PH} . One approach to estimating F_{PH} is to consider a unit mass of a fuel, e.g., methane, and evaluate the amount of heat output (in the form of 10 bar steam) generated in an efficient boiler and also the amount of electric power output from an efficient electric power cycle, such as a CCGT system. Dividing the heat output by the power output gives a value for F_{PH} of roughly 1.8.

3. Results and Discussion

This section presents and discusses the energy performance results for each of the alternative systems individually. It considers some of the parameters that influence performance, such as gasification efficiency and wood water content. It compares the energy efficiencies of the systems and considers environmental and sustainability factors and how they may influence the choice of which system to use for wood energy.

3.1. Energy Efficiency

3.1.1. Steam Boiler, Steam Power Plant, and Steam CHP

Key energy performance data for the steam boiler, steam power plant, and steam CHP are presented in Table 1. The steam boiler produces 10 bar saturated steam. The heat efficiency or boiler efficiency is around 87.5%, which is similar to the values reported in the literature [34,35]. As highlighted earlier, complete combustion is assumed, and casing losses are not considered. Overall, a boiler efficiency of around 87.5% highlights that using wood energy to produce steam for heating is a very effective means of using wood energy, as most of the wood energy is effectively utilised.

Table 1. Steam boiler, steam power plant, and steam CHP plant energy performance values (%).

Energy Performance Parameter	Boiler	Steam Power		Steam CHP	
		50 bar	150 bar	50 bar	150 bar
CHP efficiency	-	-	-	81.7	76.3
power efficiency	-	25.6	27.9	10.5	16.0
heat efficiency	87.5	-	-	71.2	60.3
flue gas losses	12.5	18.3	23.6	18.3	23.7
heat rejection losses	-	56.1	48.5	-	-

The energy performance data for the steam power plant (Table 1) are for operating the power plant at boiler pressures of 50 and 150 bar. The values were obtained for steam leaving the turbine at 0.1 bar pressure and a dryness fraction greater than 0.89, and for a turbine inlet superheat steam temperature of 600 °C. The operating boiler pressure in the range of 50 to 150 bar had a significant effect on increasing flue gas losses on the one hand but reducing heat rejection losses on the other (Table 2). The net effect is an increase in power efficiency ranging from 25.6% at 50 bar to 27.9% at 150 bar, which is similar to the values reported in the literature [36]. A power efficiency of 27.9% is a low value; thus, most of the wood energy is lost. This suggests that the steam power plant is an ineffective way of utilising the energy in wood. Now, it must be considered that the mechanical work/electrical energy produced by the steam power plant is a higher grade of energy thermodynamically than heat energy and that second law of thermodynamics considerations mean that heat combustion energy cannot be all converted into work energy. However, 27.9% power efficiency is still a very low value in comparison to the efficiency of the boiler for heat application, and thus represents poor use of wood energy. This is reinforced by the fact that wood is a limited resource and should be used as effectively as possible.

Table 2. Gasification + GT power plant/GT CHP energy performance values (%).

Energy Performance Parameter	Gasification + GT Power Plant		Gasification + GT CHP	
	Without Regenerator	with Regenerator	Without Regenerator	with Regenerator
power cycle efficiency	33.5	44.2	-	-
CHP cycle efficiency	-	-	79.2	72.6
CHP efficiency	-	-	47.6	43.5
power efficiency	20.1	26.5	20.1	26.5
heat efficiency	-	-	27.5	17.0
flue gas losses	39.9	33.5	12.4	16.5
gasification losses	40	40	40	40

The energy performance data for the steam CHP plant (Table 1) are also for operating the power plant at boiler pressures of 50 and 150 bar. The values were obtained for 10 bar saturated steam leaving the turbine that can be used for heating applications. Boiler pressure had a significant effect on energy performance. The power efficiency increased with higher pressure and was much more pronounced than in the steam power plant. The reason for this was that higher turbine superheated steam inlet temperatures were required at higher inlet pressures to produce 10 bar saturated steam leaving the turbine. These higher inlet superheated steam temperatures resulted in higher power efficiencies, with the highest being 16% at 150 bar. Higher boiler pressure also influenced the heat efficiencies, with higher pressures correspondingly leading to lower heat efficiencies. Combining these efficiencies together showed that higher boiler pressures resulted in lower CHP efficiencies. This is due to higher flue gas losses associated with higher flue gas temperatures, leaving the boiler at higher boiler pressures. Furthermore, even though higher boiler pressures result in lower CHP efficiencies, they do result in higher mechanical work energy, which is a higher grade of energy than heat. Overall, the CHP efficiencies were in the range of 76.3% at 150 bar pressure up to 81.7% at 50 bar pressure, which is similar to the values reported in the literature [35]. These values are high, showing that much of the wood energy is being converted into useful heat and power, which demonstrates that this is a useful means of utilising wood energy. The CHP efficiency is lower than the boiler efficiency of 87.5%; however, the steam CHP plant is producing a certain amount of mechanical work/electrical energy, which is a higher grade of energy, and thus the CHP system is considered to be on par with the boiler in regard to effective utilisation of wood energy.

3.1.2. Gasification of Wood + Gas Turbine (GT) Power Plant/GT CHP

Key energy performance data of the gasification + GT power plant and gasification + GT CHP are presented in Table 2. Regeneration has a significant impact on the results, and its impact is also included in Table 2. For the gasification + GT power plant, regeneration increases the power cycle efficiency from 33.5% to 44.2%, and reduces the flue gas losses from 39.9% to 33.5%. A power cycle efficiency of 44.2% is promising; however, the 60% gasification efficiency (or 40% gasification losses) negates this by giving a power efficiency of 26.5%. This is lower than that of the steam power plant efficiency, at 27.9%. Consequently, like the steam power plant, a 26.5% power efficiency represents poor utilisation of the energy in the wood.

The energy performance data for gasification + GT CHP are presented in Table 2. As already presented for the GT power plant, the power efficiency with regeneration is higher at 26.5% than without regeneration at 20.1%. This corresponds to less heat being generated, a lower heat efficiency of 17% with regeneration, and a much higher value of 27.5% without regeneration. The sum of the power and heat efficiencies results in a higher CHP efficiency of 47.6% without regeneration and 43.5% with regeneration. Consequently, the CHP efficiency without regeneration is significantly higher than with regeneration, and flue gas losses are correspondingly lower. However, it must be considered that significantly more work/electrical energy is generated with regeneration, which is a higher grade of energy. Comparing the GT CHP efficiency (in the 43 to 48% range) with that obtained by the steam CHP system (76 to 82% range) shows that the steam CHP is utilising the wood energy more effectively. This is once again due to the 40% gasification losses. The CHP cycle efficiency of the GT CHP is comparable to the steam CHP, and the GT CHP produces much more power. Consequently, improving the gasification efficiency improves the potential effectiveness of the GT CHP and is explored further in Section 3.2.

3.1.3. Gasification of Wood + Combined Cycle (CCGT) Power Plant

Key energy performance data for the gasification and CCGT power plants are presented in Table 3. The combined cycle improves the power cycle efficiency to 44.8% without regeneration and to an impressive 50.1% efficiency with regeneration. There is also a corresponding improvement of the power efficiency to 26.4% without regeneration and 29.9% with regeneration. The additional contribution of the steam turbine to power efficiency is 6.3% without regeneration and 3.4% with regeneration. Overall, the power efficiencies are still relatively low and represent a poor utilisation of the energy in the wood due mainly to the 40% gasification losses.

Table 3. Gasification + CCGT power plant energy performance values (%).

Energy Performance Parameter	Without Regenerator	with Regenerator
power cycle efficiency	44.8	50.1
power efficiency	26.4	29.9
power efficiency—gas turbine	20.1	26.5
power efficiency—steam turbine	6.3	3.4
flue gas losses	14.3	19.1
heat rejection losses	19.5	11.0
gasification losses	40	40

3.1.4. Gasification of Wood + Fischer–Tropsch

Considering the analysis and values presented in Section 2.8, the key energy performance data for the production of liquid fuel using the gasification and FT process are presented in Table 4 and illustrated in Figure 9. The energy efficiency for the FT process itself, or the FT efficiency, is 56.7%. Factoring in a gasification efficiency of 60% results in a liquid-fuel efficiency of 34% (Equation (37)). Figure 9 shows that 37% of the energy in the wood is converted into combustible energy in the liquid fuel, and this is higher than the liquid-fuel efficiency. This is because there are energy inputs into the FT process equivalent to 5% of the syngas energy, which is considered in the FT efficiency (Equation (35)).

Table 4. Energy performance values (%) for the production of liquid fuel with an FT efficiency of 56.7% (for gasification efficiencies of 60% and 80%).

Energy Performance Parameter	$\eta_G = 60\%$	$\eta_G = 80\%$
liquid-fuel efficiency	34	45.3
FT losses	26	34.7
gasification losses	40	20

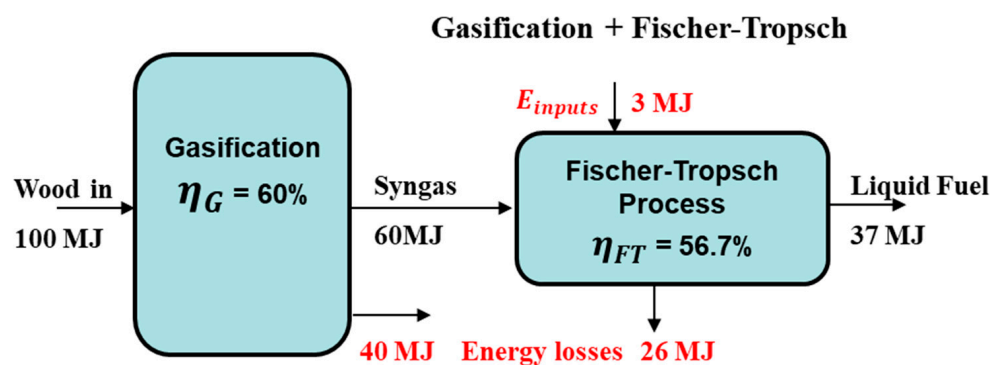


Figure 9. Illustration of the energy flows for the gasification and Fischer–Tropsch process considering wood input with energy of 100 MJ on a lower heating value basis.

The liquid-fuel efficiency of 34% is a relatively low energy efficiency; however, it does depend on the gasification efficiency. Increasing the gasification efficiency to 80% increases the liquid-fuel efficiency to just over 45%. These values are still much lower than the energy efficiencies obtained by steam boiler and steam CHP systems. Furthermore, the efficiency of converting liquid-fuel energy into mechanical energy needs to be factored in, which is around 40% for a diesel engine [37]; however, it must also be considered that mechanical energy is a high grade of energy.

3.1.5. Wood Stoves

A standard fireplace is only about 30% efficient in terms of heating [38]. This means that 70% of the potential energy that could be utilised to heat a home is lost mainly by flue gas losses up the chimney and by incomplete combustion losses, mainly through the generation of smoke. Wood Stoves provide a more efficient method of heating a home than a standard fireplace. There are 3 popular options for household wood stoves. These are non-catalytic, catalytic, and gasification stoves. A non-catalytic stove uses air tubes and oxygen heated by the stove to generate a secondary burn of the gases and particles generated from wood burning. This reduction of incomplete combustion losses alongside the convection heating of the stove results in a much greater efficiency of about 75%, with flue gas exhaust temperature of about 280 °C [39]. Catalytic stoves undergo an additional burning step; after the secondary burning similar to non-catalytic stoves, the remaining gases and particulates go through a catalyst, leading to a third round of burning [40]. This tends to offer increased overall efficiency to about 81% and lowers flue gas exhaust temperature to between 200 and 250 °C. Gasification Stoves represent the cutting edge of household stove designs. They can achieve an overall efficiency of around 90% and an exhaust temperature of under 170 °C [41]. Data from the US EPA wood stove database [42] showed that non-catalytic stoves obtain overall efficiencies in the range of about 60 to 80%, and catalytic stoves were in the range of 68 to 81%. Overall, higher overall efficiencies are obtained by reducing both incomplete combustion losses and flue gas losses.

There is a significant amount of variability in terms of the overall efficiency obtained in practice. This depends on the excess air used, which can be as high as 300% and is under the control of the user. Too high an excess air leads to higher flue gas losses, and consequentially lower overall efficiency. For example, calculations performed in this study show that increasing the excess air from 50% to 300% can increase flue gas losses by about 12%. Furthermore, the water content of the wood should be kept at around 20%, as high wood water content leads to poor combustion and more incomplete combustion losses. It also results in the formation of more smoke and greater particulate emissions.

3.2. Effect of Gasification Efficiency and Wood Water Content on Energy Performance

3.2.1. Effect of Gasification Efficiency

The value for gasification efficiency is very important, as it influences the energy performance of the gas turbine systems and the FT process. For GT systems, the effect of gasification efficiency on power and CHP efficiencies is presented in Figure 10. At 40% gasification efficiency, the efficiencies are very low, even for the CHP system at 31.7%, and are thus not an effective utilisation of wood energy. However, at 80% gasification efficiency, the power efficiencies of the GT and CCGT systems increase to 35.4% and 40.4%, respectively. The CHP efficiency increases to 63.4%, which makes it somewhat comparable to the steam CHP system, considering that it has a 26.8% power efficiency, and that of the steam CHP is much lower at around 10.5 to 16%. This is comparable to the results obtained from a detailed simulation study [25] that presented CHP and power efficiencies of 66% and 27%, respectively, after obtaining a gasification efficiency of 84%.

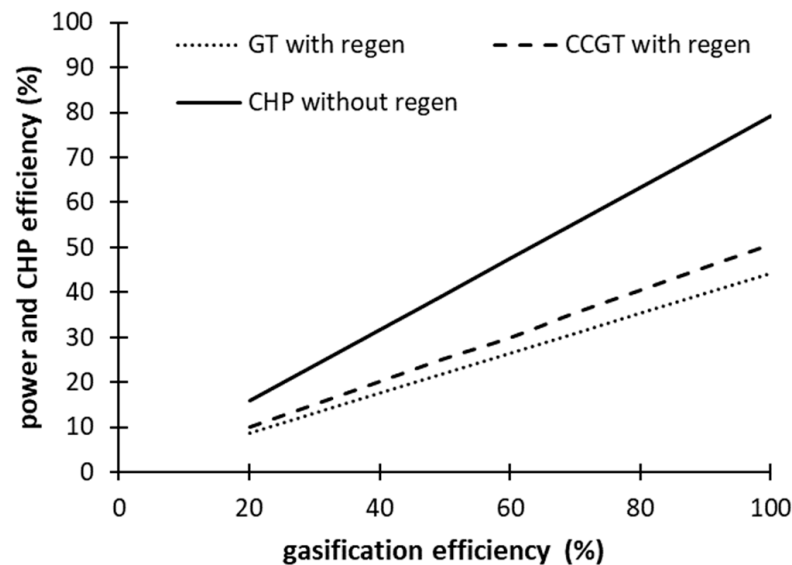


Figure 10. Effect of gasification efficiency on the power and CHP efficiency of gas turbine systems.

3.2.2. Effect of Wood Water Content

The water content of forest wood can vary quite considerably. At harvest, the wood water content can be around 60%. Ambient drying over time can reduce this to around 20%, depending on ambient air conditions. In the analysis so far, the wood water content is given a value of 20%. Further analysis is performed to evaluate the effect of water content on boiler efficiency. In this analysis, it is assumed that the mass flowrate of dry solids within the feed wood remains constant and that water content varies by varying the amount of water in the wood. This mimics the reality where wood is harvested with a high water content of 60%, and the water content gradually reduces over time due to ambient drying. Incorporating the effect of water content into the boiler efficiency calculations shows that increasing wood water content does significantly affect boiler efficiency. For example, the boiler efficiency decreases by about 16% when the wood water content increases from a water content of 20% to 60% water content. This is mainly due to the energy required to vaporise the additional water, and due to a small increase in flue gas losses associated with the additional water vapour. Furthermore, as highlighted earlier in relation to wood stoves, higher water content can lead to poorer combustion, leading to higher incomplete combustion losses, resulting in even lower efficiency, as well as higher particle emissions.

Wood water content has a significant impact on gasification. The results presented by Kirsanovs [6] indicate that wood chip water content increasing from 12% to 21% reduces the gasification process efficiency by around 12%, while Morita et al. [24] show around a 5% reduction in gasification efficiency of woody biomass for a similar water content reduction. Consequently, higher wood water content causes a significant reduction in gasification efficiency, which will have a knock-on effect on the efficiencies of the systems that require gasification. Considering this, hot syngas from the gasifier can be used to dry the feed wood to the gasifier. The temperature of hot syngas leaving the gasifier is often around 500–700 °C. A heat exchanger can be used to transfer energy from hot syngas into ambient air. This heated air can then be used in a dryer to reduce the water content of the feed wood to the gasifier to increase the gasification efficiency. For example, wood at 30% water content can be dried to about 10% water content using hot syngas at 550 °C to heat drying air.

3.3. Comparing the Energy Efficiencies of Systems Delivering Heat and/or Power

A comparison of the energy efficiencies of the seven systems producing heat and/or power is illustrated in Figure 11. These data are obtained from the tables presented above.

Figure 10 illustrates that wood stoves, steam power and steam CHP systems are much superior from a purely energy efficiency perspective.

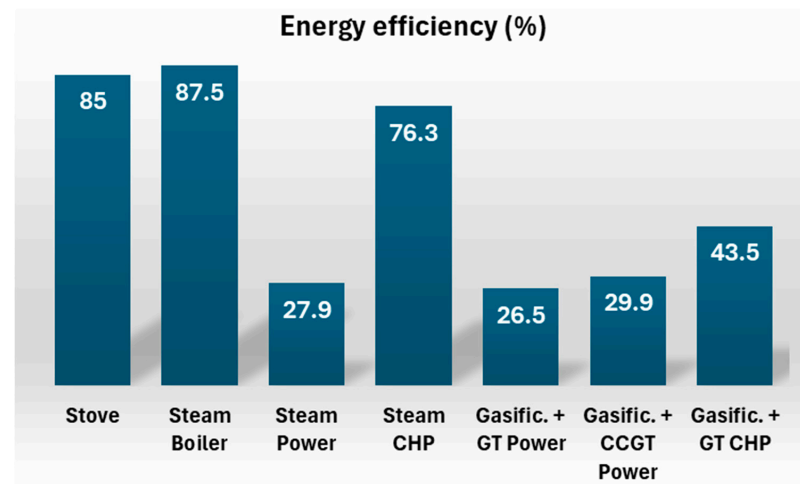


Figure 11. Comparison of system energy efficiencies (heat efficiency for heat systems; power efficiency for power systems; CHP efficiency for CHP systems. GT systems with regeneration; steam power/CHP systems at 150 bar).

However, as highlighted in Section 2.10, the steam and GT systems deliver power or heat or a combination of both; thus, their efficiencies cannot be directly compared because power is a higher grade of energy than heat. The power–heat equivalent energy efficiency (η_{PHE} in Equation (41)) is used in this study for comparing the energy efficiencies of different systems that produce heat and/or power. Applying a F_{PH} value of 1.8 to the power efficiency values in the tables above is used to generate the η_{PHE} data presented in Table 5. Some of these data are also presented in Figure 12 to provide a graphical comparison of the power–heat equivalent energy efficiencies. These data highlight that high-efficiency wood stoves, steam boiler and steam CHP systems provide the best η_{PHE} values. Consequently, they remain the superior approaches from an energy effectiveness perspective. These data highlight that the production of electric power alone is a less effective use of wood energy, especially for steam power plants and GT power systems with 60% gasification efficiency. Table 5 highlights that improving the gasification efficiency to 80% can enable the GT CHP system to achieve η_{PHE} values somewhat comparable to the steam boiler and steam CHP systems.

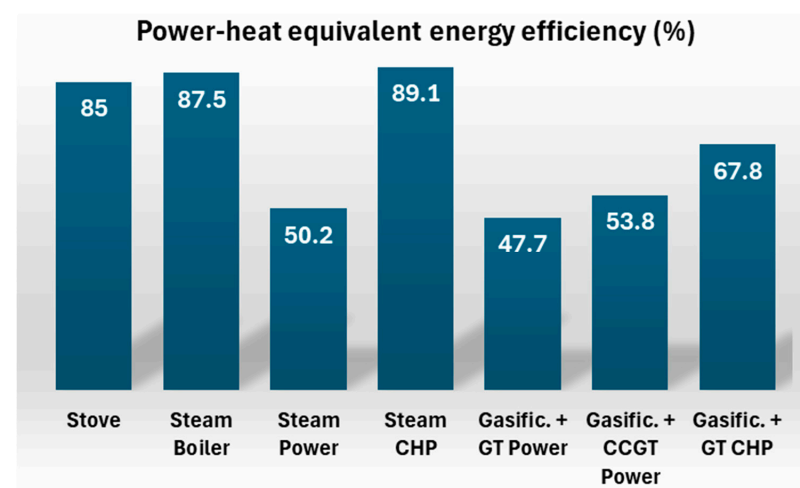


Figure 12. Comparison of system power–heat equivalent energy efficiencies (GT systems with regeneration; steam power/CHP systems at 150 bar).

Table 5. Comparing the power–heat equivalent energy efficiency (%) for the systems delivering heat and/or power (regen is regenerator).

System	Power–Heat Equivalent Energy Efficiency (%)	
High-efficiency wood stoves	80–90	
Steam boiler	87.5	
Steam power and CHP	50 bar	150 bar
Steam power plant	46.1	50.2
Steam CHP	90.1	89.1
GT systems ($\eta_G = 60\%$)	no regen	regen
GT power plant	36.2	47.7
CCGT power plant	47.5	53.8
GT CHP	58.1	67.8
GT systems ($\eta_G = 80\%$)	no regen	regen
CCGT power plant	48.2	63.7
CCGT power plant	64.4	72.7
GT CHP	84.8	86.4

3.4. Environmental and Sustainability Considerations

A simplified illustration of the life cycle of forest wood for energy application is presented in Figure 13. Other researchers have presented life cycle assessments of the life cycle [11,13,14,43]. In this section, the focus is on wood energy applications and on a number of environmental and sustainability considerations that may influence the choice of wood energy applications.

**Figure 13.** Schematic of the life cycle of forest wood for wood energy applications.

3.4.1. Sustainably Sourced Forest Wood

From an environmental sustainability perspective, it is very important to highlight that wood used for energy is being sourced from a sustainable source of wood. For example, forest wood should be sourced from a forest that is being managed sustainably [11]. The forest land should be reforested after clear-felling at the end of a forest rotation so that the forest can regenerate itself and continue to sustainably provide wood for energy into the future. Consequently, applications that use wood from sustainable sources should only be considered.

3.4.2. Environmental Emissions—Wood Stoves

Poor air quality in urban areas can be caused by wood stoves [44]. Furthermore, indoor pollution from wood-burning residential stoves is also a health concern [45]. Emissions of particulate matter (PM) are a serious cause of concern due to the PM_{2.5} particles emitted, which can bypass the lung wall and affect human health [46,47]. This problem is only exacerbated by using wet wood with a water content greater than 30%. A study conducted in New Zealand [48] found that these emissions can vary widely depending on the household. This variation is due to variations in stove operating conditions, such as ignition methods, fuel loads, and air supply settings, and wood-related factors, such as wood water content and wood type, many of which are under the control of and depend on the user of the stove [47].

Overall, wood burning stoves can achieve high overall efficiencies in the range of 70 to 90%, which makes them an effective way of utilising wood energy. However, particle emissions are of concern to human health, especially in urban areas, which may limit their application. Higher efficiency stoves greatly reduce particle emissions [40,41], but they are still present, and there is the potential for much variability due to stove operation and maintenance depending on who uses the stove. This is of particular concern in urban locations.

3.4.3. Environmental Emissions—Large-Scale Wood Combustion Processes

Large-scale wood combustion processes, such as industrial-scale steam boilers and steam power and CHP plants, can greatly reduce emissions to the environment through two broad approaches. The first is through effective control of the combustion process [49], by ensuring more complete combustion and better control of wood water content entering the boiler [50]. The second approach is through the application of particle separation technologies, such as cyclones, bag filters, and electrostatic precipitators [9,49], which can be used to remove particles from the flue gases leaving the boiler, thus reducing their concentrations to low levels.

3.4.4. Applications with Little or No Sustainable Energy Sources

Even though the energy efficiencies may be considered low for the production of liquid fuels using gasification and the FT process, there may be some justification for considering this approach for applications that have little or no alternative approaches for supplying energy sustainably. An example of this is aviation fuels, where there are very few sustainable sources (although it could be argued that aviation fuel is a poor choice of application and should not be considered because much of the current air travel is non-essential from a human well-being perspective).

Another interesting and more essential application is the production of biodiesel for agriculture. The high productivity obtained by modern agriculture is partly obtained by the use of mechanisation that is mainly fuelled by diesel. Production of biodiesel by the wood gasification and FT process could be applied to sustainably supply some of this diesel energy without using up valuable agricultural land that is used in food production. For example, in Ireland, around 470 million litres of diesel is used in agriculture annually [51,52]. Diesel has a lower heating value of 42.6 MJ kg^{-1} , and thus this results in around 20 PJ of diesel energy used in Irish agriculture annually. As highlighted earlier, around 11% of the Irish land area is forested, and around 31% of harvested forest wood is used for energy. This land area has the potential to provide a sustainable steady-state supply of about 19 PJ of wood combustion energy [11]. If this wood were to be converted to biodiesel using gasification and the FT process outlined earlier, with a liquid-fuel efficiency of 34%, then this could potentially supply 6.44 PJ of liquid-fuel energy per year. This represents around 32%, or nearly a third, of the diesel energy used in Irish agriculture. This is a significant contribution of sustainable energy for agriculture but highlights the point that forest wood energy is a limited resource. One other interesting advantage of using forest wood to produce liquid fuel is that a central processing plant could be built to process all the wood that is available from which the resulting liquid fuel, such as biodiesel, could be conveniently stored and distributed. Thus, this would benefit from economies of scale and the existing fuel storage and distribution network.

3.4.5. Application in Associated Forest Wood Industries

As highlighted in the Introduction, some wood fuels are sourced indirectly as by-products from the wood processing and pulp industries, and the majority of industry usage of these wood fuels is within the wood processing and pulp industries. This could be

considered an appropriate application of wood energy, as these industries have significant heat and power requirements and are at an industrial scale that can use the energy efficiently and can effectively control emissions from wood combustion. It also greatly reduces fuel transportation.

3.4.6. Non-Use

A final environmental/sustainability consideration in an era of a major climate change crisis is that the best application for forest wood might be to not use it for energy. Instead, forestry has great potential for naturally sequestering large amounts of carbon dioxide [53,54]. Kreysa [53] presented an initial feasibility study that showed that sustainable forestry and the geostorage of wood from it in the environment represent an ecologically sensible and economical means of carbon removal from the atmosphere. However, this only makes sense for the case where the wood for energy is being substituted by other sources of renewable or low carbon energy. Otherwise, fossil fuels will most likely substitute wood energy, and this could potentially counter or offset the carbon sequestered by wood geostorage.

4. Conclusions

The focus of this paper is on assessing the most effective approaches for utilising wood for energy application, considering that it is a limited resource, and conversely, identifying the least effective ones. From the results of the energy analysis presented above, wood-burning steam boilers for heat application along with steam CHP systems for supplying both heat and power are the most energy-efficient approaches, with efficiencies in the range of around 76% to 87%. Wood stoves are also similarly efficient. Particulate emissions are a major environmental concern associated with the combustion of solid wood fuels, such as in steam boiler, steam CHP, and wood stove systems. However, reliable particle separation technologies are economically available on a large scale for steam boiler and CHP systems to satisfactorily alleviate this problem. Consequently, the energy efficiencies of steam boilers and steam CHP systems coupled with adequate particulate emissions control make them a very effective way of utilising wood energy. The potential for gasification followed by GT CHP depends on the gasification efficiency. If this is at 60%, the corresponding CHP efficiencies (40–50%) are typically much lower than steam CHP systems, and are thus not recommended. However, high gasification efficiencies in excess of 80% can make them comparable to steam CHP systems and are recommended. Application of wood energy to produce electric power only provides low energy efficiencies at around 30%. Consequently, electrical power generation on its own is not an effective way of utilising the energy in wood and is thus not recommended. There are other more effective approaches that are more suited to producing renewable electrical power, such as hydro, wind, and solar.

Particulate emissions remain a major environmental problem for wood stoves, which limits their application in urban areas due to their impact on air quality and human health. However, it may still be possible to use high-efficiency wood stoves in lower population density rural areas where there is sufficient ambient air dilution to counter any potential reduction in air quality due to particle emissions. A significant amount of wood energy is used by the wood processing and pulp industries, which is around 35% in the UNECE countries. This is used to supply heat and some CHP. Considering the high energy efficiencies highlighted earlier, this represents an effective utilisation of this wood energy, provided that the energy generated is not wasted and is used effectively. Production of liquid fuels using the wood gasification and FT process might be considered an effective approach to utilising wood energy. Even though the liquid-fuel efficiency is a lot lower in comparison to efficiencies obtained by steam boilers and steam CHP systems, there may

exist applications with little or no alternative supplies of sustainable fuels that may justify the production of liquid fuels from limited wood resources, such as agricultural diesel replacements and aviation fuels that are considered essential for human well-being. On a final note, the work presented in the paper represents a contribution to the literature on how best to use wood for sustainable energy applications. It would be of interest to compare this work to that of other wood energy systems and to assess the impact of economic analysis.

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Nomenclature

AF	air–fuel ratio
AF_{ds}	mass of air per mass of dry solids in the wood
AF_s	stoichiometric air–fuel ratio
C_{pa}	specific heat of air ($\text{kJ kg}^{-1} \text{ } ^\circ\text{C}^{-1}$)
C_{pg}	specific heat of combustion gases ($\text{kJ kg}^{-1} \text{ } ^\circ\text{C}^{-1}$)
C_{pm}	specific heat of ash ($\text{kJ kg}^{-1} \text{ } ^\circ\text{C}^{-1}$)
E_{inputs}	energy associated with the energy inputs in the FT process (MJ h^{-1})
$E_{liquid-fuel}$	combustion energy in the liquid fuel (MJ h^{-1})
E_{syngas}	combustion energy in syngas (MJ h^{-1})
F_{PH}	power–heat conversion factor
h	specific enthalpy (kJ kg^{-1})
k	specific heat ratio of the gas = 1.4
LHV	lower heating value of wood (MJ kg^{-1})
LHV_{sg}	lower heating value of syngas (MJ kg^{-1})
m_a	mass flowrate of air (kg h^{-1})
m_f	mass flowrate of wood (kg h^{-1})
m_g	mass flowrate of hot gases leaving a combustion process (kg h^{-1})
m_m	the mass flowrate of ash (kg h^{-1})
m_s	mass flowrate of steam (kg h^{-1})
m_{sg}	mass flowrate of syngas (kg h^{-1})
P	pressure (bar)
q	specific heat energy input in combustion processes (kJ kg^{-1})
Rea	excess air ratio
r_p	pressure ratio in Brayton cycle
T	temperature ($^\circ\text{C}$)
T_{amb}	ambient temperature ($^\circ\text{C}$)
T_b	combustion temperature of gases in boiler ($^\circ\text{C}$)
T_{ge}	temperature of combustion gases leaving the boiler ($^\circ\text{C}$)
T_{se}	temperature of combustion gases leaving the stove pipe ($^\circ\text{C}$)
w	wood water content

w_{comp}	real compressor specific work input (kJ kg^{-1})
w_{comp_s}	ideal compressor specific work input (kJ kg^{-1})
w_{net}	net specific work output from the Brayton cycle (kJ kg^{-1})
w_{turb}	real gas turbine specific work output (kJ kg^{-1})
w_{turb_s}	ideal gas turbine specific work output (kJ kg^{-1})
ϵ	effectiveness factor for the regenerator
λ_v	latent heat of vaporisation of steam (kJ kg^{-1})
η_B	boiler efficiency (%)
η_{BL}	biomass to liquid-fuel energy efficiency (%)
η_{comp}	compressor isentropic efficiency
η_{FT}	Fischer–Tropsch efficiency (%)
η_G	gasification efficiency (%)
η_{PHE}	power–heat equivalent energy efficiency of a system (%)
η_{Stove}	overall efficiency for a stove (%)
η_{turb}	gas turbine isentropic efficiency

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