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Biomass Cogeneration Technologies: A Review

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Abstract

Currently, fossil fuels such as oil, coal and natural gas represent the prime energy sources in the world. However, it is anticipated that these sources of energy will deplete within the next 40 - 50 years. Moreover, the expected environmental damages such as the global warming, acid rain and urban smog due to the production of emissions from these sources have tempted the world to try to reduce carbon emissions by 80% and shift towards utilizing a variety of renewable energy resources (RES) which are less environmentally harmful such as solar, wind, biomass, etc. in a sustainable way. Biomass is one of the earliest sources of energy with very specific properties. In this review, we present the different cogeneration systems to provide electrical power and heating for isolated communities. It has been found that the steam turbine process is the most relevant for biomass cogeneration plants for its high efficiency and technological maturity. The future of CHP plants depends upon the development of the markets for fossil fuels and on policy decisions regarding the biomass market.

Keywords

Cogeneration, Biomass, CHP, Ericsson Motor, ORC, Steam Turbine, Sterling Motor

1. Introduction

Currently, as shown in **Figure 1**, fossil fuels such as oil, coal and natural gas constitute the world's primary energy sources (about 80 percent of over 400 EJ total usage per year). However, these power sources are expected to be depleted in the next 40 - 50 years. Moreover, the expected environmental damages such as the global warming, acid rain and urban smog due to the production of emissions from these sources have tempted the world to try to reduce carbon emissions by 80% and shift towards utilizing a variety of renewable energy resources (RES) which are less environmentally harmful such as solar, wind, biomass, etc.

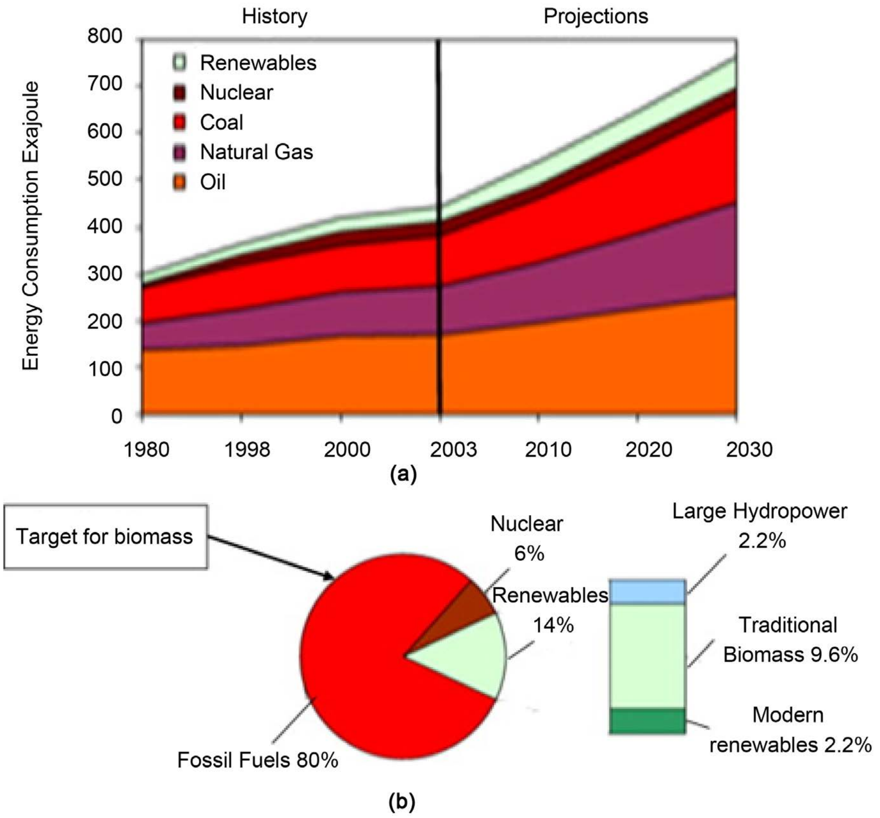

Figure 1. (a) World marketed energy consumption; (b) Different fuels contribution to total world energy consumption [4].

in a sustainable way [1] [2]. The Intergovernmental Panel on Climate Change (IPCC) reported that continued fossil fuel emissions would result in temperature increases between 1.4˚C and 5.8˚C over the 1990-2100 era [3]. World energy supplies have been dominated by fossil fuels for decades. Today biomass contributes about 10% - 15% (or 45 ± 10 EJ) of this demand. On average, in the industrialized countries biomass contributes some 9% - 14% to the total energy supplies, but in developing countries this is as high as one-fifth to one-third [4]. According to the world energy council projections, if the adequate policy initiatives are provided in 2025, 30% of the direct fuel use and 60% of global electricity supplies would be met by renewable energy sources.

Biomass can be used directly or indirectly by converting it to a liquid or gaseous fuel such as alcohol or biogas from animal waste. The net energy available in biomass when burned varies from about 8 KJ/kg for greenwood (50% moisture) to 20 MJ/kg for dry plant matter to 55 MJ/kg for methane, against about 27 Mj/Kg for coal [5]. Biomass energy production is carried out by different techniques and transformation mechanisms. The pyrolysis technique requires heating the raw material to about 500˚C in the absence of air. Pyrolysis is used to vaporize the volatile components of a solid carbonaceous material during the reaction. Pyrolysis is a thermochemical technology that converts biomass into energy and chemicals composed of liquid bio-oil, pyrolytic gas and ash [6]. Pyrolysis bio-oil can replace fossil fuel in diesel engines. The operation of diesel engines with pyrolysis oil has been successfully completed [7]. The gasification technique is a form of pyrolysis, which is carried out at high temperature to optimize gas production. The resulting gas is a mixture of carbon monoxide, hydrogen and methane, as well as carbon dioxide and nitrogen. Gas is very versatile; it can be burned to produce heat and steam, or used in gas turbines to produce electricity [8]. The liquefaction technique is a process that is carried out at low temperature and high pressure with a catalyst. The process produces an oily liquid called bio-oil or bi-brut [9].

Direct combustion of biomass for energy production is the most widely used technology in the world, with about 95% to 97% of the world's bioenergy currently produced by direct combustion [10] [11]. It is the most advanced and promising technology for the near future while pyrolysis, gasification and liquefaction processes are still in the development stage [12], direct combustion of wood and all organic matter has existed since the discovery of fire, it is the most primitive and direct method for the conversion and use of biomass energy [13]. Direct combustion is the main process adopted; it produces hot gases at temperatures between 800˚C and 1000˚C. It is possible to burn any type of biomass with a moisture content of <50%. The scale of installations ranges from very small scales such as domestic heating to large industrial installations ranging from 100 to 3000 MW [14]. On a larger scale, solid biomass of different sizes can be burned in furnaces or boilers. There are two types of boilers that are the most common, grate heating systems and fluidized bed combustion chambers, these systems offer good fuel flexibility they can be completely fed with biomass or co-heated with coal. Fluidized-bed combustion chambers accept a wide range of particle sizes up to 50 mm [15]. Industrial and commercial combustion plants can burn many types of biomass, ranging from woody biomass to municipal solid waste. The simplest combustion technology is a furnace that burns biomass in a combustion chamber, the selection and design of any biomass combustion system is mainly determined by fuel characteristics, environmental constraints, equipment costs and plant size [16]. Direct biomass combustion produces heat, which is used directly to meet district, industrial and institutional heating needs, or to produce high-pressure steam, which will turn a steam turbine and drive a generator to produce electricity. Gasification produces a combustible biogas that is burned in a combustion chamber to turn a gas turbine that carries an alternator with it. The combustion of biomass produces thermal energy and/or electrical energy. Biomass combustion plants that produce electricity from steam turbogenerators have a conversion efficiency of between 17% and 25%, cogeneration can increase this efficiency to 85% [16] [17].

2. Biomass Cogeneration Systems

2.1. Cogeneration

The cogeneration is a combined production of heat and electricity, suitable for fossil fuel or biofuel (biomass) combustion systems. Cogeneration is the best solution for energy saving and environmental preservation [18] [19]. Cogeneration is a well-advanced technology that has existed for more than a century. At the end of the 19th century several manufacturing plants adopted this technology. Cogeneration requires a heat exchanger to absorb and recover exhaust heat [17] [20]. Biomass cogeneration is considered an effective alternative to reduce greenhouse gas emissions due to their low CO_2 emission [21] [22] [23]. Many researches have been conducted in recent years to improve the economic and environmental efficiency and effectiveness of biomass cogeneration systems [17] [19]-[28]. Biomass cogeneration systems are becoming increasingly popular [29]. Several cogeneration technology and systems have been developed in recent years, some of which are suitable for large power plants and other for medium power and micro-cogeneration.

2.2. Steam Cycle

The operating principle is in line with the classic Clausius-Rankin process (**Figure 2**). High temperature, high pressure steam generated in the boiler and then enters the steam turbine. In the steam turbine, the thermal energy of the steam is converted into mechanical work. The low-pressure steam leaving the turbine enters the condenser housing and condenses on the condenser tubes. The condensate is transported by the water supply system to the boiler, where it is reused in a new cycle [30] [31] [32].

The process of producing electricity and heat from steam includes the following components: a biomass combustion system (combustion chamber), a steam system (boiler plus distribution systems), a steam turbine, an electricity generator and the heat distribution system for heating from the condenser. At present, electricity and heat generation in biomass power plants with a steam cycle remains the most developed technology, adapted to high temperatures and high power; however, this technology is not suitable for cogeneration systems with a power of less than 100 kW compared to its low electrical efficiency and high investment costs [33] [34].

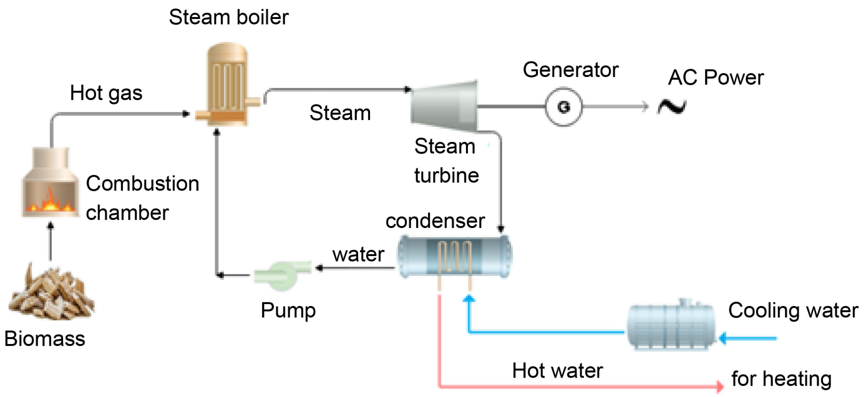

Figure 2. Principle of operation of a steam turbine biomass cogeneration plant.

Biomass cogeneration plants generally use grid combustion systems with a thermal combustion capacity of 20 to 30 MW. In the case where chemically untreated wood biomass is used, the steam temperature reaches 540˚C. The achievable annual electrical efficiency depends on the steam parameters (temperature and pressure) and the temperature level required for the heating process. Annual electricity efficiencies generally range from 18% to 30% for biomass cogeneration plants between 2 and 25 MW [30]. Below the advantages of the use of steam cycle:

- The use of water as a heat transfer fluid has great advantages, such as its high availability, non-toxic, non-flammable, chemical stability, low viscosity (less friction losses);
- Thermal efficiency greater than 30%;
- Low pump consumption.

2.3. Organic Rankin Cycle (ORC)

Since the 1980s, the ORC market has grown exponentially [34]. ORC applications have generated a lot of economic and environmental interest, because of which much work has been done on ORC systems and working fluids that can be found in the literature [35]-[40].

ORC technology (**Figure 3**) has reached a very high degree of maturity for biomass applications; it only requires a sufficient source of heat. The ORC system can be integrated into any industrial facility equipped with a low temperature heating system to recover waste energy in the form of heat and convert it into electricity. Electricity produced by biomass ORC systems is considered carbon neutral, thus improving a company's environmental profile and promoting the transformation of the forest sector towards the use of more environmentally friendly energy sources [39] [41].

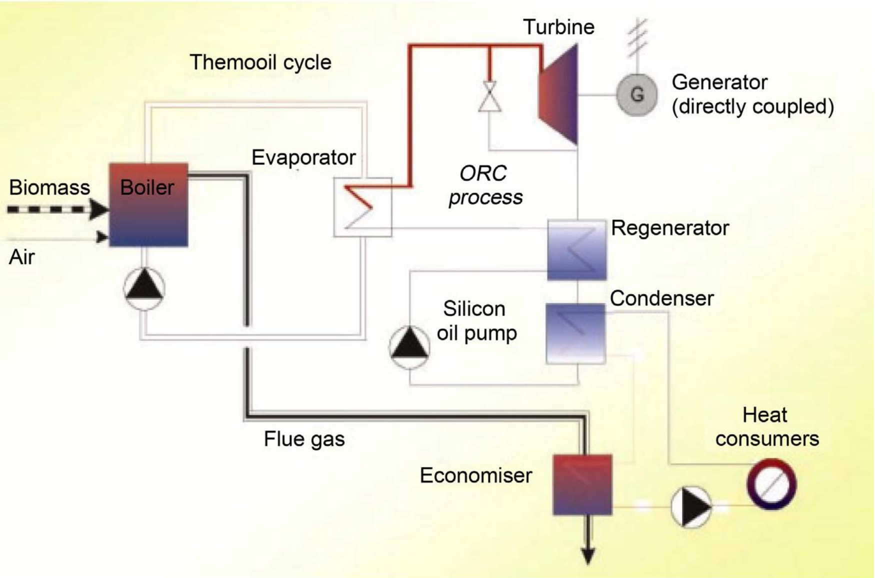

Figure 3. Schematic of Rankine's organic cycle [19].

Instead of water, the Rankine organic cycle uses an organic fluid with favorable thermodynamic properties as a heat transfer fluid. The evaporation temperature of organic fluids is lower than the evaporation temperature of water, which results in higher efficiency in cogeneration installations with an ORC cycle.

The ORC has two circuits, one for thermal oil and the other for organic fluid. The heat released by the combustion of biomass is transmitted through an oil cycle by an exchanger to the organic fluid, which evaporates at high temperature and high pressure. The ORC system consists of four main components, namely a pump, an evaporator, a turbine and a condenser. The superheated organic steam is expanded in a turbine and then condensed in a condenser and returned to the circulation pump to start a new cycle. The condenser can act as a heat exchanger for sending heat remotely at low temperatures (e.g. district heating [42]). The condensed organic liquid is pumped through the regenerator to the evaporator [43]. ORC technology is suitable for medium power [19]. Heat is generally supplied at a temperature of about 300˚C and condensation occurs at about 90˚C [44]. There are more than 50 biomass cogeneration plants that have adopted CRO technology with a capacity greater than 5 MWe and have approved the technical and economic feasibility of this technology on a medium scale (200 - 2000 kW) [45]. The thermal efficiency of ORCs at high temperatures does not exceed 24% [34].

The organic fluids used in these systems are dry and do not require overheating, they are not corrosive or erosive; they evaporate at low and medium temperatures [47] [48]. When temperatures exceed 500˚C, the organic liquid degrades and turns into small particles [43].

Table 1 shows the largest suppliers and manufacturers of ORC technologies in a wide range of power and temperature levels.

According to [34] [41] [48] and [49] advantages of ORC installations are:

- Long service life due to the characteristics of the working fluid;
- Less complex installation with a high efficiency cycle;
- More economical than a water steam turbine in terms of investment and maintenance costs;
- The isentropic efficiency of a turbine varies with its power scale and design;
- No water treatment system is required;
- The system pressure is low, which makes the installation safer;
- No need for fluid control;
- Efficient solution for low temperature installations.

2.4. Stirling Engine

In a Stirling engine (**Figure 4**), the regenerator is an internal heat exchanger and temporary heat store placed between the hot and cold spaces such that the working fluid passes through it first in one direction then the other, taking heat from the fluid in one direction, and returning it in the other. It can be as simple as metal mesh or foam, and benefits from high surface area, high heat capacity,

Table 1. List of the largest manufacturers and suppliers of ORC Modules [34].

	ORC Technologies			
Manufacturer	Power Range (kWe)	Heat source temperature (˚C)	Applications	Technology
ORMAT, US	200 - 70,000	150 - 300	GEO, WHR, Solar	Fluid: N-pentane and others, two-stage axial turbine, Synchronous Generator
ELECTRATHERM, US	50	>93	WHR, Solar	Fluid: R245FA, Twin Screw Expander
TURBODEN, IT	200 - 2000	100 - 300	Biomass-CHP, WHR, GEO	Fluid: OMTS, SOLKATHERM two-stage axial turbine
ADORECTEC, DE	315 - 1600	<120	WHR	Fluid: Ammonia, Lysholm turbine
BOSCH, DE	65 - 325	120 - 150	WHR	FLUID: R245FA
GE CleanCycle	125	>121	WHR	FLUID: R245FA, Single-State inflow turbine, 3000 RPM
CROYSTAR, Fr.	n/a	100 - 400	WHR, GEO	Fluid: R245FA, R113A, inflow turbine
TRI-OGEN, NE	160	>350	WHR	Radial Turbo-expander, Fluid: Toluene
Electratherm, US	50	>93	WHR, SOLAR	Fluid: R245fa, twin screw expander

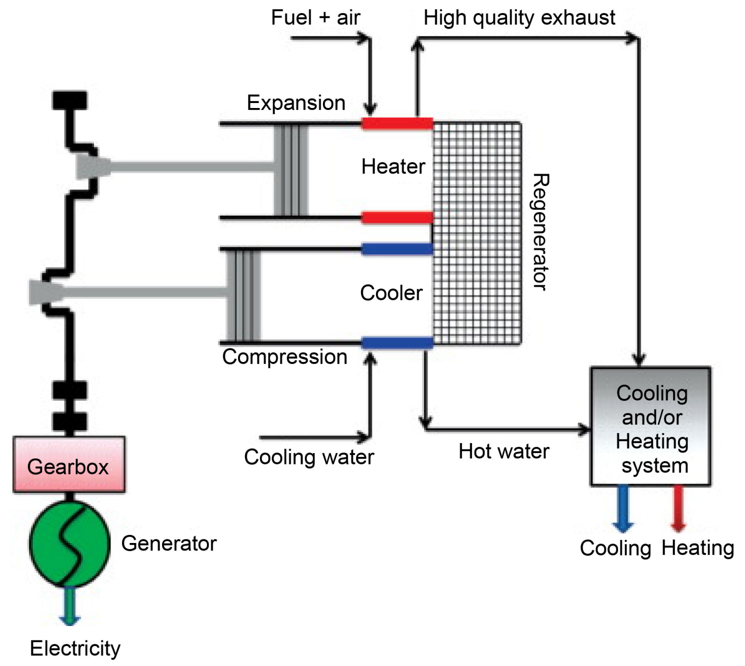

Figure 4. Diagram of the operating principle of the Stirling engine [54].

low conductivity and low flow friction. The primary effect of regeneration in a Stirling engine is to increase the thermal efficiency by "recycling" internal heat that would otherwise pass through the engine irreversibly. As a secondary effect, increased thermal efficiency yields a higher power output from a given set of hot and cold end heat exchangers. These usually limit the engine's heat throughput. In practice, this additional power may not be fully realized as the additional "dead space" (unwept volume) and pumping loss inherent in practical regenerators reduces the potential efficiency gains from regeneration [50].

The Stirling engine is based on a closed cycle where the working fluid which is usually hydrogen or helium is compressed in the cold cylinder and expanded in the hot cylinder [50] [51] [52] [53]. The design challenge for a Stirling engine regenerator is to provide sufficient heat transfer capacity without introducing additional internal volume ("dead space") or flow resistance. These inherent design conflicts are one of many factors that limit the efficiency of practical Stirling engines. A typical design is a stack of fine metal wire meshes, with low porosity to reduce dead space, and with the wire axes perpendicular to the gas flow to reduce conduction in that direction and to maximize convective heat transfer.

Stirling engines are mainly used in residential micro CHP, *i.e.* the local production of electrical and thermal energy in residential buildings [55] [56]. Sterling engines are the most commonly cited technology in biomass micro cogeneration and the greatest advantage of this engine is its ability to burn any type of biomass [55] [56] [57] [58] [59]. The use of Stirling engines as electricity generators in domestic cogeneration systems has attracted a lot of interest in recent years due to the ever-increasing price of energy [60] [61] [62]. **Figure 5** shows the diagram of the operating principle of cogeneration with the Stirling engine, while **Table 2** illustrates the largest manufacturers and suppliers of Stirling engines.

According to [52]-[64] advantages Stirling installations are:

- Very long service life;
- The motor runs quietly, which makes it ideal for use in tertiary and residential sectors;

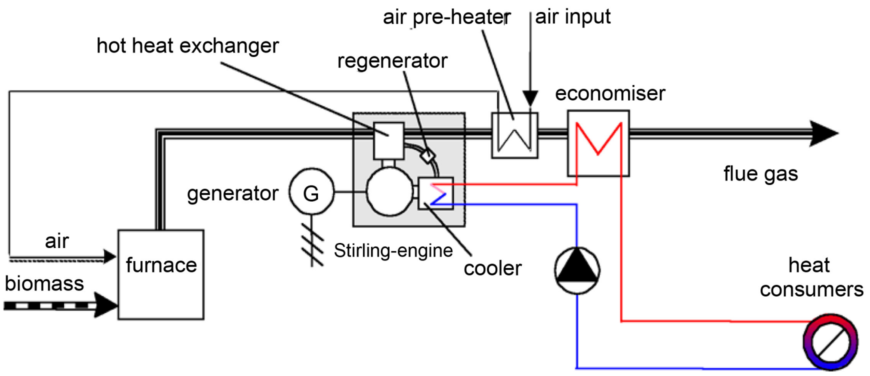

Figure 5. Diagram of the operating principle of the cogeneration using the Stirling engine [63].

Table 2. Some cogeneration plants using ORC in Europe [46].

Manufacturer	Location	Electric capacity [kWe]	Thermal capacity [kWth]
ORC-STIA	Admont (austria)	400	n/a
ORC-STIA (improved version)	Lienz (austria)	1000	8000
ORC	Scharnhauser (Germany)	1000	6000

- The torque produced is very regular, which maintains the good condition of the parts;
- The Stirling engine does not require periodic oil change because the lubricant is not in contact with combustion residues (external combustion);
- Low maintenance needed;
- Low GHG emission, which favors its carbon footprint.

The largest suppliers and manufacturers of cogeneration systems with Stirling engines are listed in **Table 3**.

2.5. Ericsson Engine

The Ericsson engine is a member of the hot air or external combustion engine family. It is a reciprocating engine that operates with the open Joules cycle, it is composed of two cylinders (compression cylinder and expansion), a heat exchanger that allows the adjustment of the inlet and valve temperature levels at the inlet and outlet of the cylinders [65] [66]. The working fluid, which is air, enters the compression cylinder at atmospheric pressure and ambient temperature, is compressed and then sent to the heat exchanger, its temper increases and then enters the expansion cylinder where it expands so that it is finally discharged outside the engine [67] (**Figure 6**).

Numerous studies found in the literature have shown that the Ericsson engine has high performance for low power levels such domestic micro-cogeneration with renewable energies such as solar and biomass, mainly for micro-cogeneration with solar concentrators [66] [67] [68] [69] [70].

Advantages of the Ericsson engine according to [70] and [71] are:

- Low maintenance;
- Silence operation;
- Simple technology;
- Low costs and better performance;
- Valves can contribute to engine control and command;
- Low GHG emissions.

3. Conclusions

To date, the most developed and commercialized biomass cogeneration technologies are steam turbines, ORC process and external combustion engines. The

Table 3. List of the largest manufacturers of Stirling engines [54].

Manufacturer	Thermal capacity [kW]	Electric capacity [kW]	Electrical efficiency [%]
Whisper Tech	n/a	1	12
Sigma	9	3	25
Sunpower Inc.	n/a	7	n/a
Enatec et BG Group	n/a	1	16
DTE Energy	n/a	20	29.6

Table 4. Characteristics of different biomass cogeneration systems.

Manufacturer	Power	Capacity	Working Fluid	Use
Steam turbine	Hoigh power	2 - 25 MW	Water	CHP Plants
ORC process	Medium power	200 - 2000 kW	Organic	Industry and small CHP plants
Striling engine	Low power	1 - 35 kW	Hydrogen/ helium	Residential micro CHP
Ericsson engine	Low power	1 - 35 kW	Air	Residential micro CHP

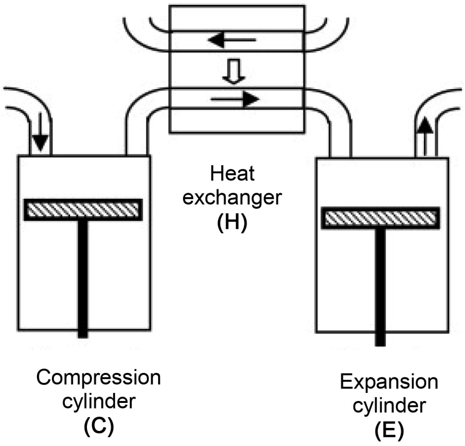

Figure 6. Ericsson engine principle [68].

steam cycle is best suited for high powers above 2000 kW while the steam turbine process is most relevant for biomass cogeneration plants for its high efficiency and technological maturity.

The ORC process has reached a high level of maturity this lasts years; it is the most appropriate for cogeneration plants with a medium power output ranging from 200 to 2000 kW.

Meanwhile, external combustion engines are the most suitable for micro CHP applications. In this category, the Stirling engine remains the best solution for residential heating for its benefits and the growth of this technology that has been sold for years. In the meantime, a lot of researchers demonstrate that the ERICSON engine is a promising micro-CHP technology, but it still under growth.

Finally, the distinct features of the distinct cogeneration technologies for biomass are mentioned in Table 4.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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