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BIOMASS ELECTRICITY GENERATION TECHNOLOGIES: A REVIEW, TECHNOLOGY SELECTION PROCEDURE, AND POWER CAPACITY CALCULATION

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Abstract. *This paper presents a review of the technological, thermodynamic and economic aspects of the electricity generation from biomass. Technologies involved in an integrated system for the production of electricity from biomass usually are the conventional steam cycle, the Organic Rankine Cycle and the Internal Combustion Engines coupled to biomass gasifiers. Collecting up-to-date information allowed estimating the costs and performance of different electricity generation technologies from biomass. To be analyzed, the generation systems were divided according to their power ranges in industrial > 3 MWe, medium scale generation 0,1-3,0 kWe and small-scale generation < 0,1 kWe. Typical energy efficiencies of these cycles are between 8 and 30 %, with the conversion efficiency increasing with size. The investment cost of the technologies, that just reached the commercial stage - including erection - varies between 5.000,00 and 10.700,00 USD/kW. This review paper intends to be a contribution to summarizing the knowledge about using biomass for electricity generation and information needed for energy planning and energy system analysis. No such analyzes were found in the literature reviewed. Another novel contribution of the paper is the presentation of a methodology allowing do determine the power capacity of the generation unit starting from available biomass in ton/h, while defining the electricity generation technology, primary conversion reactors, and biomass pretreatment technology to be used, based on reviewed information from published papers and reports.*

Keywords: *biomass, electric generation, Organic Rankine Cycle, Internal Combustion Engine*

1. INTRODUCTION

Biomass is a versatile fuel which is possible convert to produce electricity, gaseous and liquid fuels. Considering the energy production, it can be classified in four wide categories: (1) wood/plant waste; (2) municipal solid waste (3) landfill gas (LFG); and (4) other biomass, including agricultural by-products, biofuels, and selected waste products (Hoseinzade and Adams, 2018).

Unlike fossil fuels, biomass represents a renewable source, to which has been attributed less impact in terms of greenhouse gas emissions (GHG) throughout its life cycle, when it is used as fuel for electricity generation (Al-Sulaiman et al., 2012). There is a growing research effort that seeks to quantify the GHG and environmental implications of biomass energy expansion (Abbasi and Abbasi, 2010; Schakel et al., 2014). It has been developed as an alternative energy source, to reduce the dependency on fossil fuels. The present state of the art of the electricity generation from biomass and future prospects are described in (Ecoprog, 2017):

- In 2017 there were 3520 biomass generation plants with an installed capacity of 52.5 GWe.
- In 2026 this number will increase up to 5400 and the installed capacity up to 76 GWe to be commissioned by the end of this year.

Brazil has a capacity of 14.02 GWe (244 biomass power plants), where the biomass sources represent 78.2% of the total with 11.01 GWe. Other biomass sources, such as animal waste, urban solid waste, liquid biofuels, and other agro-industrial goods, share 11.8% (Ecoprog, 2017).

Despite the many advantages of energy production from biomass, its uses on a commercial scale continue to be incipient, due to many challenges associated with supply chain management/logistics (Malladi and Sowlati, 2018) and the costs of conversion technologies (Asadullah, 2014).

On the other hand, there is an urgent need to intensify the electrification efforts in isolated rural areas and the renewable electrical microsystems, including biomass energy, have been considered a viable and competitive solution to bring electricity to these areas (Sorrell, 2015).

In this paper, an analysis of the technological development level and of the performance indexes of electric generation technologies from biomass at the industrial, medium and small-scale level, is done. The generation systems were grouped according to their potential power range in industrial > 3 MWe, medium scale generation 0,1 to 3,0 MWe and small generation < 0,1 MW, it was found that the medium and small capacity generation face the lack of high efficiency and low operation cost technologies.

The novelty of this article is in the holistic analysis of biomass generation systems, evaluating their technological and commercial maturity, power ranges and typical efficiencies as well as investment and generation costs for commercially available technologies. This review paper intends to be a contribution to summarizing the knowledge about using biomass for electricity generation and information needed for energy planning and energy system analysis. No such comparative analyzes were found in the literature reviewed. Another novel contribution of the paper is the presentation, as a closure remark, of a figure showing the relation between available biomass in ton/h and the electric capacity that could be achieved considering commercially available electricity generation technologies, using the reviewed information from published papers and reports.

2. BIOMASS ELECTRICITY GENERATION TECHNOLOGIES

2.1 General scheme of the conversion of biomass into electricity.

Figure 1 shows a general scheme of the biomass energy conversion; it´s clear that a pretreatment will always be required to adequate the characteristics of the biomass for the downstream conversion processes.

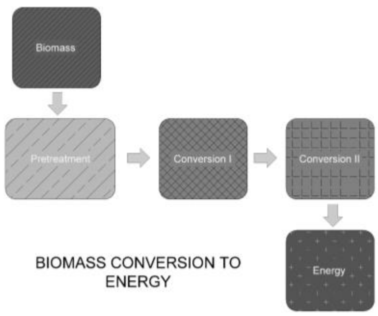


Figure 1. The general scheme of the energy conversion of biomass (electricity or biofuel).

On the other hand, in any conversion process, it´s possible to identify two stages. A particular application of Figure 1 general energy conversion scheme to the case of biomass electricity generation through the thermochemical route is shown in Figure 2. In the frame "Conversion 1" primary conversion processes as combustion (with or without steam generation), gasification and pyrolysis could be included. In the frame "Conversion 2" prime movers such as internal combustion engines, steam and gas turbines, fuel cells, etc could be considered accordingly to the proposed primary conversion process. Thermodynamic cycles (such a Rankine, Brayton, etc.) includes conversion processes 1 and 2.

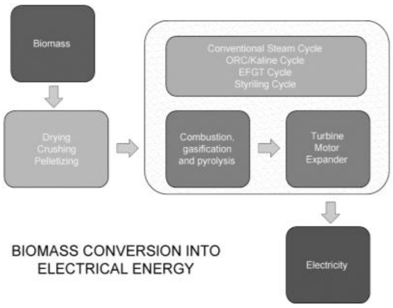


Figure 2. Scheme of biomass conversion into electrical energy.

Some published papers are related to electricity generation using biomass, but most of them are not updated and do not include all available technologies (Strzalka et al., 2017). No recommendations or methodologies are published indicating how to choose the most suitable electricity generation technology for a specific case.

2.2 Available technologies, applications power ranges and technological/market maturity,

The information about the efficiency and mainly about costs, related to the technologies that had been analyzed, is scarce. Table 1 shows the results of the authors`evaluation of the "State of the Art" of these technologies. It´s possible to conclude that the most remarkable technology, at the commercial stage, is the Steam Conventional Rankine Cycle. At the initial stage of commercialization are the Organic Rankine Cycle (ORC) systems, the steam cycle with piston and screw engines, as well as the gasification/engine systems. These findings are supported also by Fiorese et al. (2014) and IFC-World Bank Group (2017) that classify main electricity generation technologies in Commercial (Conventional Rankine Cycle) and early commercial (ORC and Gasifier/internal combustion engine systems). According to Aslani et al. (2018) by analyzing Hype diagrams (a combination of the life cycle and adaptation diagrams) gasification, pyrolysis and combustion technologies are in the plateau of productivity i.e are attractive for investment.

Table 1. "State of the Art" of different biomass electric generation technologies

Technology	State-of-the-art		
	In the development stage	The pilot and demonstration stage	Commercial
Conventional Rankine Cycle - CRC			***
Organic Rankine Cycle – ORC			**
Steam Piston Engines			*
Steam screw or scroll engines			*
Radial steam turbine	***		
Externally fired gas turbine – EFGT		***	
Stirling engines		***	
Gasifier/internal combustion engine			**

The data about Investment, Operations, and Maintenance (O&M) costs, and generation costs, for the different technologies, are very limited; however, it´s evident that the expected costs of generation, at small scale, will always be relatively high.

3. BRIEF INFORMATION ABOUT COMMERCIAL TECHNOLOGIES: CRC, ORC, G/ICE.

3.1 Industrial scale generation: Conventional Rankine Cycle (CRC)

The CRC that uses steam and axial turbines is a viable scheme from the technical and economic point of view for electric power levels higher than 2-3 MWe. Figure 3 shows a general scheme of a steam cycle with its main elements: boiler, steam turbine, condenser, and feeding pump.

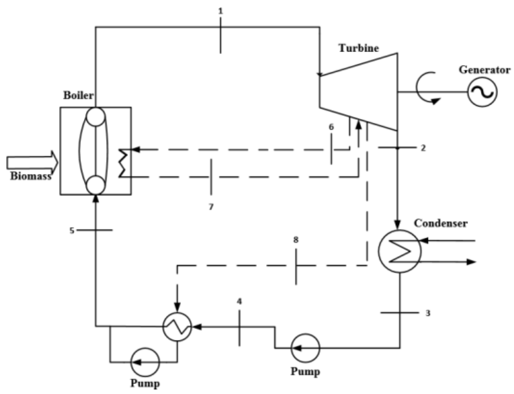


Figure 3. A general scheme of a steam cycle

The CRC, due to its nature and parameters has a relatively low efficiency, being possible to expect, for conventional pressures of 20 bars, efficiencies in the range of 7-15 %, depending on the efficiency of the equipment that integrates the cycle and on the type of turbine used: backpressure or condensing one (Müller and Fréchette, 2002). The efficiency increase of CRC can be attained through the use of higher steam parameters and/or the implementation of improvements in the plant thermal scheme, such as the steam reheating and the regenerative heating of the condensates. All these improvements require a techno-economic analysis to compare the necessary additional investment with the profit obtained due to efficiency increase.

3.2 Organic Rankine Cycle (ORC)

An ORC unit works similar to a CRC, where thermal oil is heated by burning biomass. In this case, an organic working fluid is pumped through a heat exchanger where it is vaporized and passed through a turbine and then re-condensed (see Figure 4) (Zhang et al., 2016).

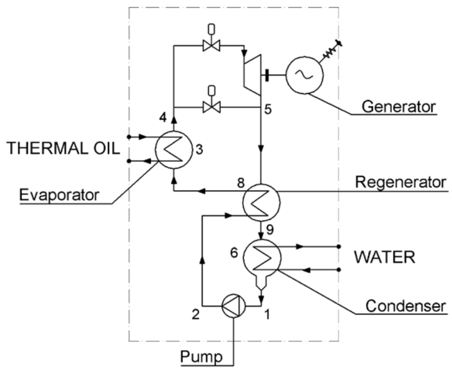


Figure 4. Scheme of an ORC system (Quoilin et al., 2013).

The choice of the working fluid will depend on the heat source. These fluids are characterized by a smaller enthalpy drop and higher density, that make easier, and more efficient, the design of low capacity expander (up to 1-2 MWe) (Quoilin et al., 2013). In this way, the necessary steam flow to generate the same mechanical power is much higher than the CRC cycle.

As working fluids, it could be used, hydrocarbons, chlorofluorocarbons, silicone oil, among others. The most significant differences between the organic working fluids and the steam are the boiling and condensing temperatures (Saleh et al., 2007). All this can contribute to the utilization of low-temperature heating sources, as well as the cogeneration with the use of the condenser.

Tartière and Astolfi (2017) and Lecompte et al. (2014) compared ORC and CRC for biomass-fuelled power plants and highlighted the ORC advantages: higher efficiencies, lack of water treatment, less system complexity, not qualified operators and electrical outputs around 1 MWe.

3.3 Gasifier/internal combustion engine (G/ICE) systems

The gasification is defined as the high-temperature biomass conversion into a fuel gas (composed mainly of CO, H2, and CH4), at sub-stoichiometric conditions. The resulting fuel gas could be used to operate internal combustion engines and even gas microturbines, SE, and fuel cells, as shown in Figure 5 (Bang-Møller and Rokni, 2010).

In the case of the ICE the available technological options, for the use of the fuel gas, are gasoline-fueled engines, Diesel engines with the mix of 10-20% of Diesel fuel, Diesel engines converted to Otto Cycle and engines fueled with natural gas (Bartela et al., 2018).

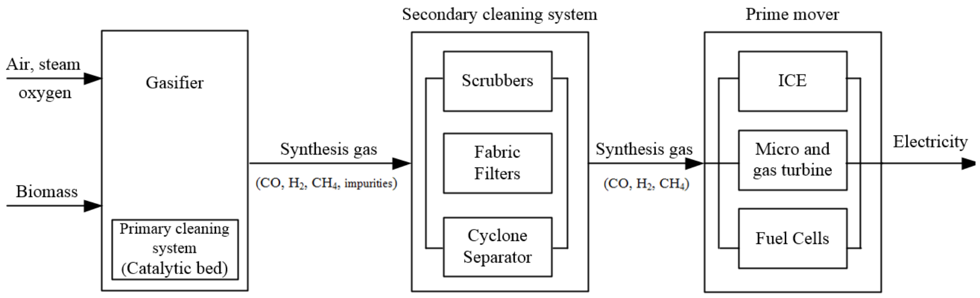


Figure 5. Electricity and fuels synthesis through biomass gasification showing the gas cleaning stage.

When air is used as a working fluid in the gasification process the gas obtained is named “poor gas”, due to its low calorific value of around 5-6 MJ/Nm^3. This fact, plus its composition, that is different to the one of the conventional motor fuels, induce a 20-30% reduction in the power obtained and also requires ignition “times” adjustments (Antolini et al., 2019). Martínez et al. (2012) present an extensive study on the difficulties faced when coupling internal combustion engines to gasifiers.

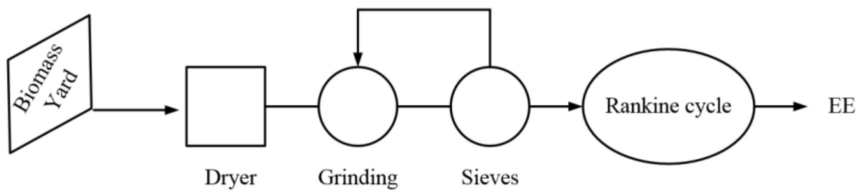
Another factor to take into account, is the need for a gas cleaning system, to reduce the presence of impurities in the gas to the limits established by the engines´ manufacturers, generally at the level of 100 mg/Nm^3 for tar and 50 mg/Nm^3 for solid particles, under 3 µm size (De Filippis et al., 2015). The conventional cleaning systems in use in the gasifier/engine systems, include, in different combinations, ceramic filters, scrubbers, wet electrostatic precipitators and /or bag filters (Basu, 2010).

4. PRETREATMENT TECHNOLOGIES

For biomass energy utilization, and depending on the conversion technologies and reactors to be used, its particles size distribution, moisture, and other properties should be adjusted to ensure processes higher efficiency (Jahirul et al., 2012). For example, combustion and fixed bed reactors gasification can be fed with biomass chips, while fluidized bed systems requires particle sizes around 1-2 mm and the entrained bed ones require a sub millimeter fine milling, possible only after torrefaction, or a previous pyrolysis for liquefied biomass spray injection using nozzles (Porcu et al., 2019). In all these cases, moisture should be fixed around 30 % for combustion processes and 10 % for pyrolysis/gasification to ensure maximum process efficiency (Haque and Somerville, 2013). When using fibrous biomass in fixed bed reactors its densification (briquetting or pelleting) is recommended to avoid operational problems.

Figure 6 shows the pretreatment schematic typologies usually applied to the evaluated commercial technologies: CRC, ORC and G/MCI.

a) CRC



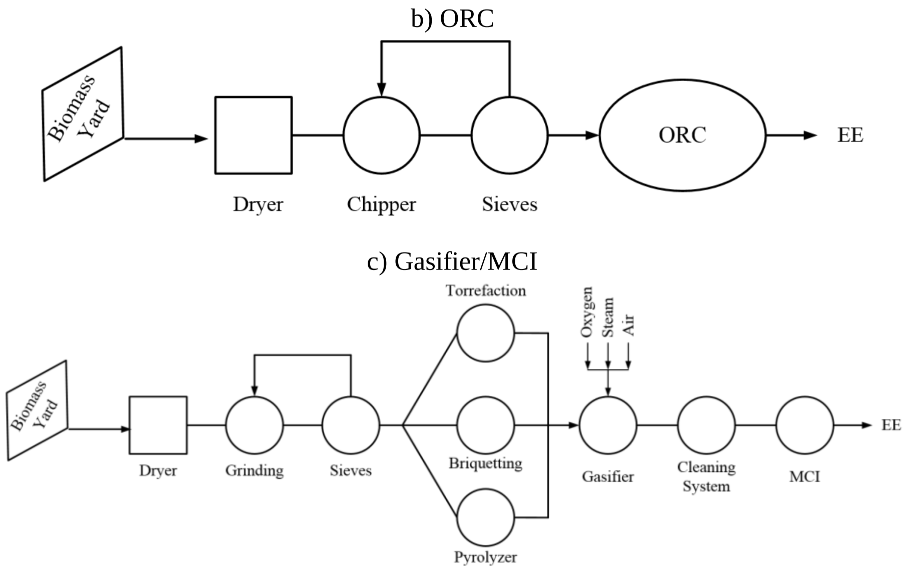


Figure 6. Pretreatment schematic typologies for biomass electricity generation commercial technologies.

The requirements on moisture and particle size are established according to the fluidodynamics of the reactors used for combustión and gasification: FB-fixed bed, BFB- bubbling fluidized bed, CFB – Circulating Fluidized bed and pneumatic transport (Suspension burning in combustión furnaces, known in gasification technology as EF- Entrained flow). Table 2 shows a review of data obtained from different sources. In some applications requesting could be necessary to adequate polydisperse materials to gasification. Torrefaction and pyrolysis are being proposed as pretreatment technology for EF gasifiers, due to the small size distribution they require and the high energy consumption of the grinding to reach the required particle sizes.

Table 2 Biomass pretreatment requirements for different thermochemical conversion technologies (own elaboration using data from Koppejan and van Loo (2012), e4TECH (2009), Naimi et al. (2006), Worley and Yale (2012), Mahr (2011).

Pretreatment technology	Combustion				Gasification			
	FB (grate stockers)	BFB	CFB	Suspension burning	FB	BFB	CFB	EF
Biomass capacity dry basis, ton/h	0,01-9,00	0,96-25,00	3,60-108,00	0,96-6,3	0,01 -3,30	0,41-4,16	3,33-25,00	25,00-416,00
Drying (required moisture),	< 65 %	< 65	<60	10	15	<20	5-60	15
Grinding (particle size, mm)	6-50	50	<50	< 6 mm	6-100	6-50	<20	1
Briquetting	x				x			
Torrefaction								x
Pyrolysis								x

The investment costs and energy consumption of selected pretreatment equipment should be considered efficiency and Levelized Cost of Electricity (LCOE) calculations. Gebreegziabher et al. (2013) and Brammer and Bridgwater (2002) presented models and equations referred to biomass dryer costs and energy consumption, Marrs et al. (2016) compiled this information related to grinding equipment, Willson et al.(2014) related to briquetting and Svanberg et al. (2013) e Maski et al. (2010) related to torrefaction.

5. POWER CAPACITY VS BIOMASS AVAILABILITY INCLUDING TECHNOLOGY SELECTION

This issue will be developed only for commercial generation technologies: CRC, ORC and G/ICE. The capacities and efficiencies characteristic ranges, for each technology, are presented in Figure 7, that was built based on available information from technical papers, manufacturers information and authors experience.

The information related to the specific costs of different installed generation systems is poor and imprecise; the higher values are referred to as complete installations (IRENA, 2012; Kosmadakis et al., 2013; Preto, 2014). It varies in wide ranges: 1) Steam cycle: approx. 6500 USD/kWe, 2) ORC: from 6200 to 10700 USD/kWe, 3) Steam engine: 6100 USD/kWe and 4) Gasification/ICE: 5300 to 8000 USD/kWe.

Based on biomass availability and properties such as calorific value, moisture and size distribution a methodology is proposed for the calculation of the power capacity and the selection of the conversion technology including the following stages:

1) An initial value of the conversion efficiency is assumed and a first approximation of the power capacity is obtained to make a preliminary selection of the commercial technologies available in that range. The technologies (Primary Energy Conversion + Prime mover) are selected based on the information available in the efficiency versus power range Figure 7, assuming a linear dependence of electricity generation efficiency from power capacity.

2) The types of primary conversion reactors are selected considering the electricity technology defined in the previous item and the range of available biomass flows. For example grate (fixed bed), fluidized, circulating bed or entrained flow (See table 2). Pretreatment technologies are selected according to the moisture and particles size requirements for each of the selected technologies.

3) Efficiency values are corrected by considering energy consumption by pretreatment equipment.

4) The actual efficiency is determined from Figure 7 and after that, this set of calculations is repeated until the efficiency is assumed and the calculated values differ by only 0.5%. There may occur a change of generation technology.

5) Cost of biomass: including agricultural practices expenditures, in the case of energy crops, and collecting in the case of residues. Logistics costs to deliver biomass up to the generating unit should be considered also. These are the main components of the biomass cost at the gate of the generation plant.

6) LCOE is calculated using available investment data and operation and maintenance cost of main pretreatment primary conversion equipment and prime movers.

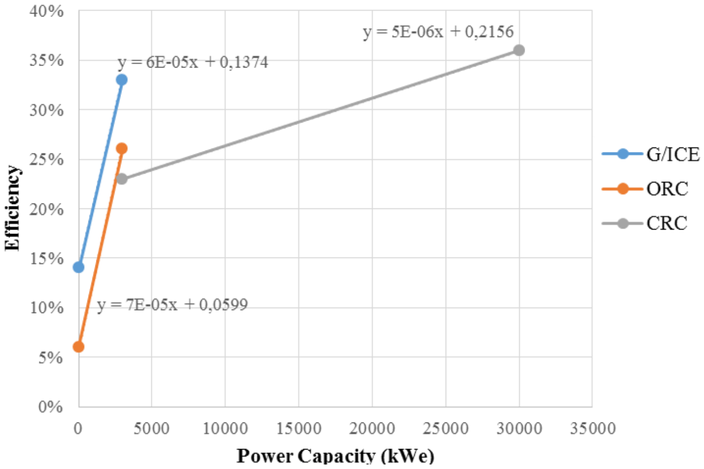


Figure 7. Relationship between electric efficiency and power capacity for commercial generation technologies: CRC, ORC and G/ICE.

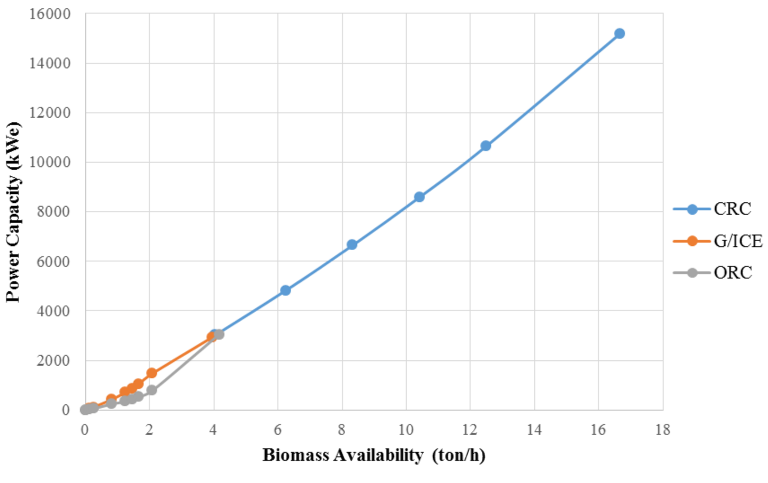


Figure 8. Power capacity vs biomass availability (40% moisture) for ORC, G/ICE, and CRC technologies.

The application of the proposed methodology for different biomass flows and electricity generation technologies allowed to build a graphic relating the generation unit power capacity with the biomass flow, that at the same time indicates the suitable generation technology.

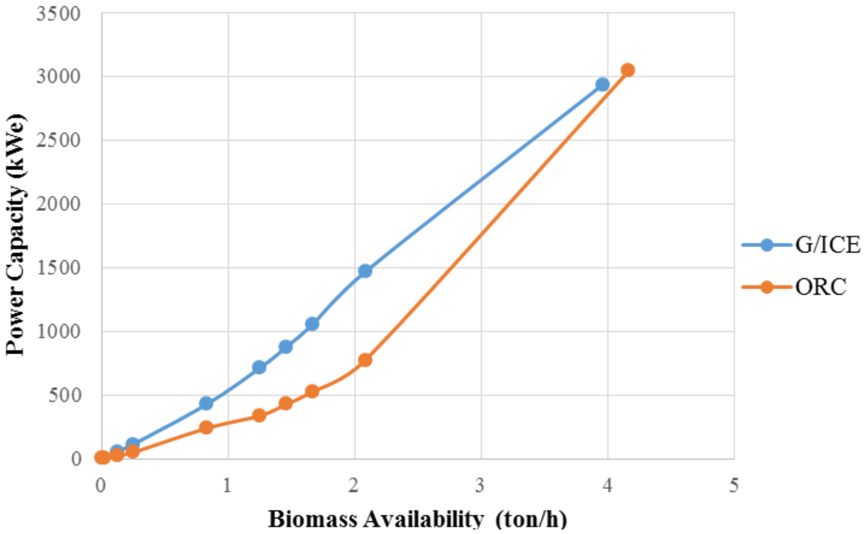


Figure 9. Power capacity vs biomass availability (40% moisture) for ORC and G/ICE (A detailed view of the lower part of figure 8).

6. CONCLUSIONS

In the present work, a methodology is being proposed for calculating a proximate value of the electric capacity starting from biomass availability in ton/h, while defining the most feasible technology to be used. Considering requirements linked with the fluid dynamics of the combustion and gasification reactors, technical data and biomass availability were provided for the adequate selection of pretreatment equipment. On the other hand, the recommendations included in the article indicated how to calculate the cost and electricity consumption of pretreatment equipment and how to consider them in efficiency and LCOE calculations. Finally, the information provided in the paper allows applying a logical approach to the preliminary design of biomass electricity generation systems.

7. ACKNOWLEDGMENTS

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