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PERSPECTIVES OF ELECTRICITY GENERATION FROM WOODY AND HERBACEOUS CROPS IN BRAZIL

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Abstract. *Interest in energy from biomass - bioenergy - has increased in the last decade, due to high oil prices, concerns about energy security, food security conflicts related with water and soil use and commitments for carbon emissions reductions. In this context, energy crops from herbaceous and woody biomass are an alternative for electricity generation, as they have the ability to provide renewable fuels to generate electricity and heat, while allowing to take advantages of the agro-climatic potentials without compete with food production. Energy crops also capture the CO_2 emitted in the different stages of the production chain through photosynthesis, so it is considered a carbon neutral fuel. After the multicriteria analysis of eight plant species were selected two with the greater potential as biofuels: Pennisetum purpureum that can be considered that capture CO_2 for immediate consumption as carbon energy, while the Eucalyptus would store CO_2 for long-term consumption, similar to fossil fuel deposits but renewable and recycling CO_2 in a much shorter time scale. Several thermo-chemical technologies were analyzed for the conversion of biomass into electricity, such as: the Conventional Rankine Cycle (CRC) and Organic Rankine Cycle (ORC) with different types of expanders. Results shown that ORC system with the radial turbine has the highest efficiencies in the range of 0.5 to 3.0 MWe. In the range from 0.1 to 0.5 MWe the highest efficiency corresponded to ORC system with Screw Expander. The analyzed biomass fuel systems, can overcome the currently installed generation capacity in Brazil by using 28% of the land suitable for growing Penissetum purpureum and 42% of the land suitable for the cultivation of Eucalyptus. In combination with both crops in a proportion of 50% per hectare planted is required only 32%. This paper presents the maximum potential of electricity generation with the studied technologies without taking into account reducing productivity by the degree of degradation from soils.*

Keywords: *Biomass, ORC, Eucalyptus, Pennisetum purpureum, turbine, screw expander*

1. INTRODUCTION

The population growth, associated to the increasing, of the economic income, especially in developing countries, together with the globalization process, require a combined effort to meet the higher food and energy demand (De Oliveira et al., 2010). But it is important to pay attention to the inevitable risk of the unavoidable advance of the agricultural frontier, the growth of mining and of the urban areas and the decrease in natural forests extension (natural carbon sinks) leading to deforestation, land use conflicts and hydrologic cycles changes, desertification and progressive worsening of the global environmental problems: global warming and climate change.

Currently there is a renewed interest in power generation based on energy crops, with projects being developed in Nigeria, Colombia, Uruguay and Brazil, as a consequence of the high costs of fossil fuels, the urgent need of mitigating the climate change through the capture of CO_2, the need to regulate the hydrological cycle, the use and recovery of degraded areas according to their potential, the definition of the land use through agro-ecological zoning, the development of new and make productive varieties of woody and herbaceous energy crops having high productivity, adaptability to degraded soil conditions and also the pre-commercial and commercial availability of high efficiency new thermo chemical technologies for the pre-treatment and conversion of biomass.

The objective of this paper is to analyze the potential of electricity generation from herbaceous and woody energy crops, as a viable alternative in the agricultural, technological and environmental context in Brazil, through conventional and more advanced thermo chemical routes.

2. BIOMASS, ENVIRONMENT AND ENERGY SUPPLY

The fourth IPCC[1] report states that there is an increase of the global mean temperature by 0.3 to 0.6 ° C and, the increase between 10 and 25 centimeters in the sea level in the past century (Wee, 2010), mainly due to the irrational emissions of greenhouse gases and the changes from forest to agriculture land use, driving. A significant land degradation and affective the biodiversity, according to FAO (2012), the 25% of the lands have high degree of degradation and 8% suffer a moderate one, forcing to use degraded land for energy crops cultivation.

It has been proved that energy crops - woody and herbaceous - capture CO_2 and fix to it in it lignocellulosic structure through photosynthesis, using water and minerals from the soil, according to: (1,466 kg) CO_2 + (0,600 kg) H_2O + 15,66 kJ $\rightarrow$1 kg $C_6H_{12}O_6$ + 1,066 kg O_2. These crops have less soil quality requirement, are less water demanding and need little mechanization, in this was being able to offset emissions of GHG from burning fossil fuels, while accumulating energy as renewable carbon.

When using forest energy crops as a CO_2 sink, is imperative to carry – out a correct land management, in order to positively influence the global carbon cycle, considering the possible impact of change in soils utilization, the sustainability of forest or soils management procedures, the productivity index and the form and effectiveness of the energy utilization of biomass and by-products, according to its variation in the time (Schlamadinger and Marland, 1996). Figure 1 shows that carbon dynamics in forest energy crops - FEC - is different from the native forest one and depends on rotation time, which in turn affects the amount of sequestered carbon. This lead, to the conclusion that the sustainability of the FEC as carbon sinks, is based on the complementarity of the simultaneous use of the soils and of crops production cycles, where the long-cycle energy crops will be the long term carbon accumulators (woody crops: 2 - 7 years) and them short cycle (herbaceous crops: 4 - 6 months) are carbon accumulators in the short term, with the immediate availability of the primary renewable energy. Giving in such a way a well balanced system.

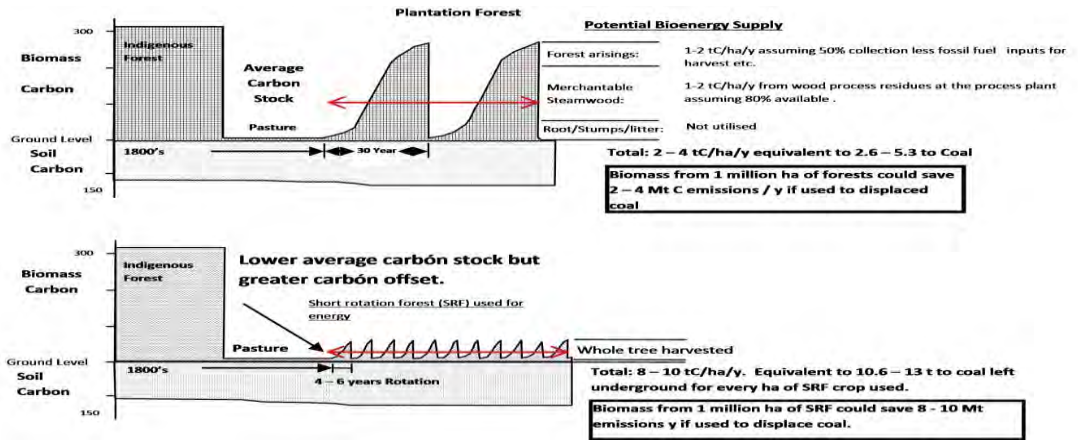

Figure 1. Carbon sequestration in biomass and upper soil layer.
Source: Sims (2004)

Regarding the global energy consumption and availability, up to the year 2008 the per capita of energy consumption had been continuously increasing at a rate of +5% per year since 1992) (Enerdata, 2011). This increase, far above the global population growth (1.3% per year), is mainly due to the increase in industrial production and the improvement of living standards in many developing countries (PNUMA, 2011). Electricity and heat generation represent more than 40% of all CO_2 emissions, however until the year 2010, 1,440 million habitants (20% of the world's population) suffered from "energy poverty", in other words, lacking electricity supply with total dependence on direct an ineffective use of biomass for cooking and lighting (UNEP, 2011).

In this context, the woody and herbaceous energy crops offer significant opportunities for electricity generation, economically and sustainable appealing while providing additional environmental services (CO_2 capture, water

[1] Intergovermental Pannel on Climate Change.

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resources regulation, recycling of nutrients in the soil, carbon renewable storage, substitution of fossil fuel), enhancing land revalorization, production of co-products with high added value and the generation of employment.

3. THE PHOTOSINTETIC MECHANISM AND THE SELECTION OF THE TYPE OF BIOMASS FOR ENERGY CROPS PROGRAMS.

When talking about biomass, it's necessary to mention the photosynthesis, its efficiency and the botanical classification of plants, linked to the carboxylation route: C3 or C4. The C3 plants are photo-synthetically most efficient at temperatures below 20 °C while for the C4 plants the temperature variability is not significant for the photosynthetic efficiency, up to 10 °C, such behavior influence the rate of carbohydrates synthesis, which for the C3 is approximately 25.5 % to 20 °C and for the C4 is almost constant at 28.5% (Ehleringer and Bjorkman, 1977). The main components of the biomass are: lignin, cellulose and hemicellulose, combined with traces of minor constituents (Hood, Nelson and Powell, 2011).

The selection of woody or herbaceous species as energy crop, requires a multi-criteria analysis combining economical, political, social, agri-environmental, technical and technological aspects. The scope of this study includes the technical characteristics of some native and introduced species in Brazil (Table 1). The analysis for the eligibility of the species with higher potential as energy crops is a function of the following issues: domestication of the species, availability of improved germplasm, productivity, calorific value, ash fusibility and equilibrium moisture content. The authors attempt to quantify these indicators on a scale of 1-3, based on data from literature and the author´s personal experience.

In accordance with the results shown in Table 1, we can select the *Eucalyptus* and *Pennisetum purpureum* for a further analysis as energy crops in this work. It should be stressed that the domestication of the species and the availability of improved germplasm are the most relevant variables as they are the central axis of a productive system. So, a specie that is not eligible now may be eligible years later. Hereafter it will be presented the description, main features and indicators of these two crops.

Table 1. Analysis of woody and herbaceous species characteristics for it utilization as solid biofuel.

Especies		Technical Aspects						
		DE	AIG	Pr	LHV	FA	EMC	Elegibility
Wood	*Acacia mearnsii*	2	2	2	3	2	2	**13**
	Pinus	3	2	2	2	3	3	**15**
	Eucalyptus	3	3	3	3	2	3	**17**
	Anadenanthera macrocarpa	1	1	3	3	2	2	**12**
	Enteroplobium contortosiliquum	1	1	3	3	2	2	**12**
Herbaceuos	*Mischantus*	1	1	2	2	2	2	**10**
	Pennisetum purpureum	3	3	3	3	2	2	**16**
	Sorghum lignocellulósic	2	1	3	3	2	2	**13**

Remarks: 1=low; 2 = medium; 3 = high. DE: domestication of the especies; AIG: availability of improved germplasm; Pr: productivity; LHV: lower heating value; FA: fusibility of ash; EMC: equilibrium moisture content.

3.1 ELEPHANT GRASS (Pennisetum purpureum Schumacher)

There exist between 200 to 300 different varieties of elephant grass. This is a grass similar to sugarcane and mainly used for livestock feeding. It is also rich in fiber (65%) and can also be used as a source of renewable solid fuel (Kauter, Lewandowski, & Claupein, 2003). It is a perennial specie of erect growth, with sturdy stems and solid center. It can reach between 2 to 8 m of height and up to 2.5 cm of diameter at the base. The leaves are 50 to 90 cm long and 1 to 3 cm wide. It has a high photosynthetic efficiency due to the C4 fixation mechanism of atmospheric CO_2. It requires less nitrogen and water than other energy crops, is fast growing and it harvest can be mechanized. As a consequence of being a cespitose specie, doesn't completely cover the soil, allowing to be cultivated in hilly areas giving a reasonable erosion control. It can grow from the sea level up to 2,200 m, being better adapted up to 1,500 m in a wide variety of soils and showing higher yields in humid soils, of medium texture nutrient-rich and of a pH of 4.5 to 8.2. The precipitation and temperature required are in the range from 800 to 4000 mm and 18 to 30 ° C, the optimum being 1500 mm and 24 ° C respectively. It has low tolerance to drought, so its performance can be affected by the lack of moisture. It can grow and produce under shade but not under a complete one (Piketty et al., 2009; USDA, 2012; Sage and Monson, 1998), so it can be grown in association with woody species in agro forest system.

While Eucalyptus in Brazil produces up to 20 Mg ha^{-1} $yr^{-1}$of dry matter, the elephant grass reaches 30 to 40 Mg ha^{-1} yr^{-1}, accumulating a total of 12.6 to 16.8 tC ha^{-1} $year^{-1}$. These high yields of the elephant grass are associated with its ability to fix nitrogen (essential element in plant productivity). The existence inside the plant of diazotrophic bacteria

(Glucanocetobacter diazotrofhicus and Herbaspirillum) contributes significantly to the nitrogen biological fixation, making possible to explain its high biomass production in extremely poor N available soils (Mazzarella, 2012; Morais, 2008). For energy production, the most important part is the stem, as it have a fiber content higher than 52% (Quesada et al., 2004). The low calorific value is greater than 17.00 $MJ.kg^{-1}$ (Zanetti, 2010).

3.2 EUCALYPTUS (*Eucalyptus sp*)

Eucalyptus is the common name for several species, belonging to the Myrtaceae family, which includes other 130. Over 700 species of eucalyptus are cataloged (Vital, 2007). The species recommended for energy use are: E. grandis, Corimbya citriodora, E. cloeziana, E. camaldulensis, E. urophylla hybrid urogandis (E. urophylla x E. grandis) (Silva de Castro, 2008).

The agro climatic conditions, the selected seeding density, the managing practices, plus the genetic particularities of each specie are reflected in their carbon content, mainly in the form of cellulose, lignin and hemicelluloses, affecting the calorific values. For the Eucalyptus the calorific value is slightly lower than 19.26 MJ kg^{-1} for different seeding densities, the highest calorific value correspond to the spacing of 3m x 2m, with a value of 19.05 MJ kg^{-1} (Roger Q. et al., 2011), which is higher than the reported of for elephant grass (Alves, 2009).

4. CONVERSION TECHNOLOGIES

Figure 2, shows the possible conversion routes of lignocellulosic biomass into electricity and heat. In this paper, the analysis of power generation technologies will be carried out based on combustion and gasification, as they are the more developed technologies.

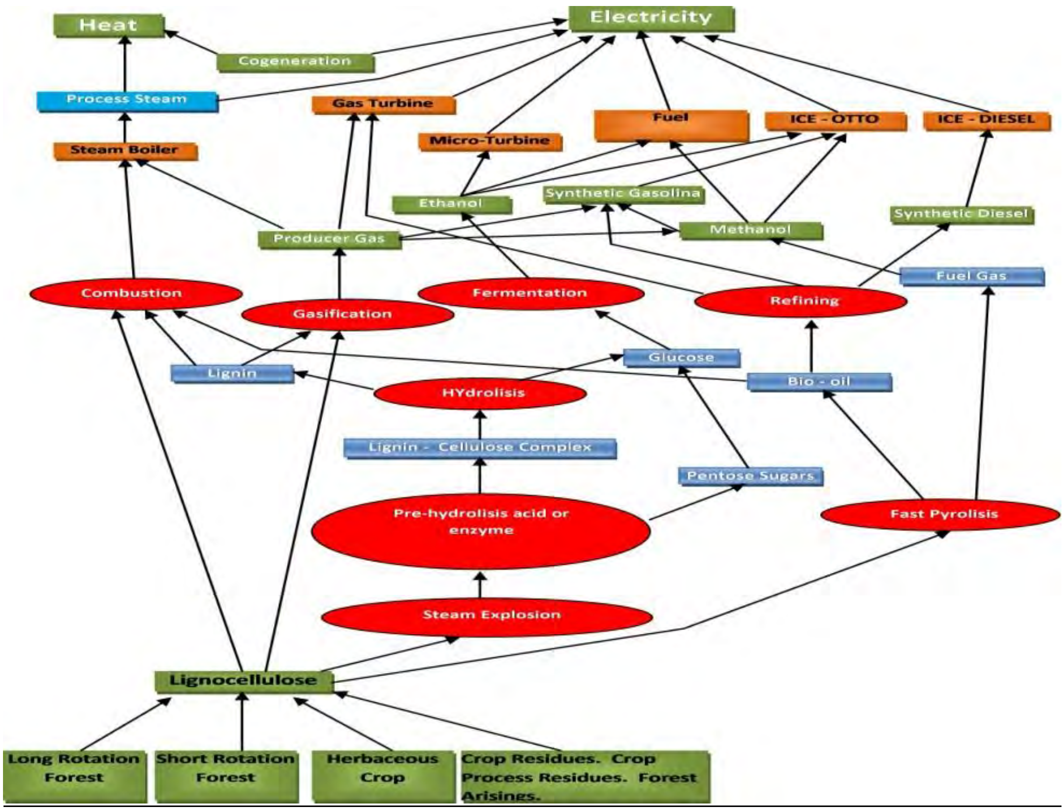

Figura 2. Technological routes for biomass conversion into electricity and heat
Source: adapted of Sims (2004)

4.1 POWER GENERATION THROUGH COMBUSTION BASED TECHNOLOGIES

Currently combustion is a technology alternative for small and medium scale power generation from biomass. The combustion technologies consist in burning the biomass with enough stoichiometric oxygen to release high temperature gases, that are used directly to heat water or thermal fluids, also for steam generation to drive an expander (radial or axial turbine, or screws expanders) or an Stirling Engine to generate electricity with relatively high efficiency. All

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because the combustion is less demanding in comparison with gasification in relation to the fuel quality, allowing to use biomass with up to 60% moisture content, polydispersity and with various particle size.

Once the heat is released, the most common technology in biomass power generation is the conventional Rankine Cycle (CRC) or water steam cycle, but it is rarely used at small scale, as it tends to be non-viable below 2 to 5 MWe because of the dramatic efficiency reduction and the high investment cost. However other technologies are becoming available for energy cogeneration in the reference range.

The Organic Rankine Cycle (ORC) is a technology with high potential for small-scale electricity generation when using woody or herbaceous biomass as fuel for the production of heat and electricity, due to: its commercial availability, its relatively high efficiency in small-scale applications and its easy operation. Unlike the Conventional Rankine cycle, the working fluid is not water but an organic fluid which is vaporized to drive an expander (radial or axial turbine or screw expander). Taking advantage of the harnessing of the thermodynamic properties of these fluids, as they are mainly "dry" ones (the working fluid leaves the expander in superheated state), and of high density, is be has more technically feasible than water, a “wet” fluid. This allows to reduce the temperature of operation because, it doesn’t require steam superheating to achieve competitive electrical efficiency at low temperatures and with low emissions. There are some applications in industrial scale using commercially available ORC modules in the range of 1 kW to 3 MW (Vankeirsbilck and Vanslambrouck, 2011; Tennigkeit, Kallweit and Buchholz, 2006) and up to 7 MW for CRC. (Table 2)

Table 2. ORC and CRC commercially available technologies for biomass power generation.

System, cycle	Prime mover	Power capacity	Technology development	Reference
ORC	Screw Expander	4 kW– 350 kW	Prototype	(Qiu, Liu and Riffat, 2011; “Ormat Technologies Inc.,” 2012; “WSK Kehl,” 2012; “ElectraTherm,” 2012; “Heliex Power,” 2012; “Bosch KWK Systeme,” 2012)
	Two-stage Radial Turbine	300 kW – 2 MW	Commercial Module	(“Turboden,” 2012)
	Axial Turbine	300kW – 2.4 MW	Commercial Module	(“GMK ORC,” 2012; “Adoratec,” 2012)
	Radial Turbine	1 kW – 50 kW	Prototype	(Kang, 2012; Welch and Boyle, 2009; “Infinity Turbine ®,” 2012; “Green Energy Australasia,” 2012)
CRC	Screw Expander	4 kW – 300 kW	Prototype	(Environmental Protection Agency – EPA, 2008)
	Axial Turbine	2 MW – 7 MW	Commercial Module	(“Turboden,” 2012)
	Radial Turbine	300 kW	Commercial Module	(Welch & Boyle, 2009; “ergion gmb,” 2012)

The amount of installed plants is growing rapidly and the technology is maturing and proving to be profitable. Today there are more than 100 ORC units in operation worldwide. Table 3 shows some investment specific costs of some thermo chemical routes that work with forest of biomass and residual heat.

Table 3. Specific investment costs for thermo chemical conversion technology

Thermochemical Routes	Power (kWe)	Specific Investment cost (USD$ kWh)	Reference
Waste Heat - ORC	4 – 250	2900 - 1800	(Quoilin, Declaye, Tchanche, & Lemort, 2011; Saxena, Seal, Kumar and Goyal, 2008; Vanslambrouck and Vankeirsbilck, 2011)
Combustion - CRC	500 – 3000	2800 - 1500*	(Environmental Protection Agency – EPA, 2008)
Combustion - ORC	150 – 2000	3950 – 1300	(Vanslambrouck and Vankeirsbilck, 2011)

* Remark: *Costs updated to 2013 with an inflation rate of 6%.

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4.2 TECHNICAL POTENTIAL FOR POWER GENERATION WITH WOODY AND HERBACEOUS ENERGY CROPS IN BRAZIL

The IPCC (2012) reported a projected global primary energy potential consumption by 2050, of 500 EJ $year^{-1}$, based on the literature and mathematical models distributed as:

- Improving the management of agriculture and livestock supported by technology - 140 EJ $year^{-1}$,.
- The use, marginal, degraded and water limited lands estimated at 5 million km^2 worldwide: 70 EJ $year^{-1}$
- Using good quality surplus land, estimated at 3 million km^2 worldwide: 120 EJ $year^{-1}$
- Using surplus forest 60-100 EJ $year^{-1}$,
- Using agricultural and forestry residues and urban solid waste. 140 EJ $year^{-1}$,

In this scenario, the Brazilian State Company "Embrapa Solos" evaluated in 96.4 million hectares the area suitable for seeding grasses and in 94.1 million hectares the one for natural pastures and forestry in the country (Ramalho F. and Charlet P., 1999), in this way, Brazil has a great potential for the cultivation of woody and herbaceous energy crops. Figure 4, shows the potential of primary energy production sowing from only *Eucalyptus* or only *Pennisetum purpureum* or combination with both crops in a proportion of 50% per hectare planted, for being the species selected as having nowadays the greatest potential as energy crops in Brazil currently.

The calculation of the primary energy production potential was done taking into account the parameters listed in Table 6. Note in figure 4, for the *Pennisetum purpureum* if only 30% of the area with aptitudes for establishing these crops is used, a primary energy of 22.0 EJ $year^{-1}$ can be produced, equivalent to 4.4% of the global potential in the world or 31.4% of the potential that could be produced form with water limitation, marginal and degraded lands. In the case from Eucalyptus, it will produce 13.0 EJ $year^{-1}$ equivalents to 2.6% and 18.6% for the same conditions. If sowing is combining from both crops in the 50% proportion for each species for hectare, will produce 18.0 Ej $year^{-1}$ equivalents to 3.6% of the global potential in the world or 25.7% of the potential that could be produced form with water limitation, marginal and degraded lands. The latter, although it produces less power, has greater environmental benefits due to the fact that the land is not use for monoculture and the existence of a positive interaction between the involved ecosystems. The CO_2 is also captured for immediate use -6 month- in the *Pennisetum purpureum* and accumulates for long-term saving (2 ages or much) in the *Eucalyptus*.

Table 6. Parameters used for the calculation of the energetic potential of *Eucalyptus* and *Pennisetum purpureum* as energy crops in Brazil.

Eucalyptus		***Pennisetum purpureum***	
Parameter	**Value**	**Parameter**	**Value**
LHV (MJ kg^{-1})	*12.8	LHV (MJ kg^{-1})	**15.5
Moisture Content (%)	30	Moisture Content (%)	10%
Density (kg m^{-3})	500	Density (kg m^{-3})	-no requerid-
Productivity (m^3 ha^{-1} $año^{-1}$)	50	Productivity (ton dm ha^{-1} $año^{-1}$)	30
Seeding density (Tree ha^{-1})	6.667	Seeding density (Plants ha^{-1})	22.222

Observation:*Adjusted values considering de moisture content in the biomass of 30% in dry base.
**Adjusted values considering de moisture content in the biomass of 10% in dry base.

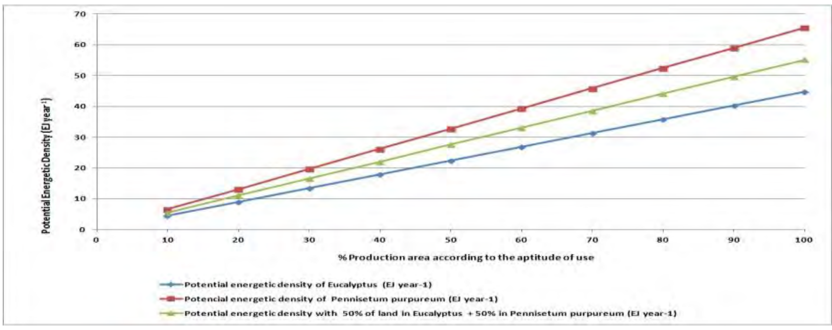

Figure 4. Primary energy potential of Brazil, considering the utilization percentage of available land with aptitudes for seeding grasses and forestry.

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For the analysis of the technological potential of this primary energy conversion, simulations using the cycle tempo software for CRC system and the Hysys software for ORC system were done using combustion technologies for both systems, with different expanders: radial turbine (RT), axial turbine (AT) and screw expander (SE) for the rated power currently produced. Note in Figure 5 that the highest efficiencies, based on biomass combustion technologies, correspond to ORC system, with the radial turbine and screw expander, whit values of 21.6% and 21.2% respectively in the power of 3 MW for the TR and 350 kW for SE.

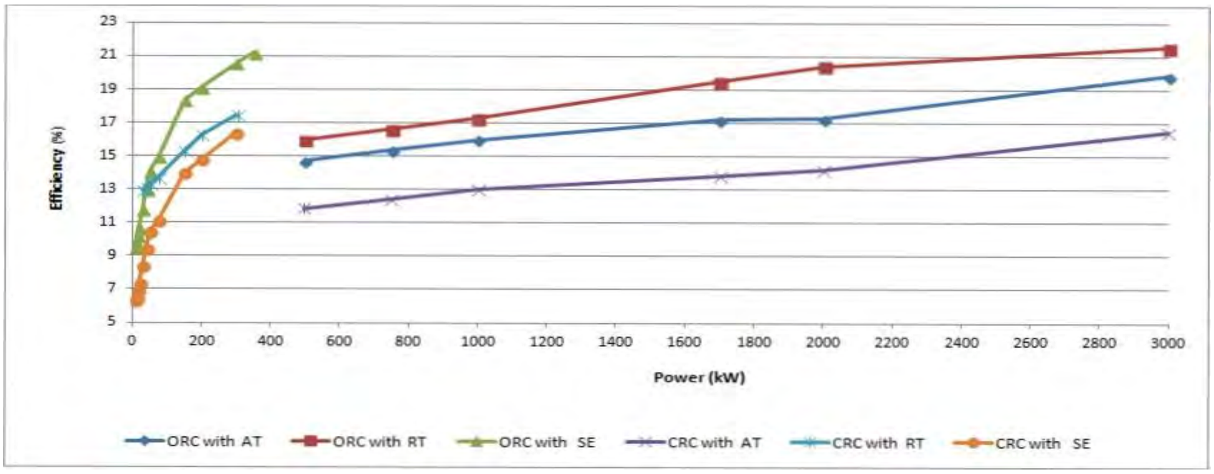

Figura 5. CRC and ORC systems global efficiencies when using different expanders.

By conjugating the potential energy crops and conversion systems efficiencies, it´s possible to the power generation capacity potential of Brazil, as shown in Figure 6.

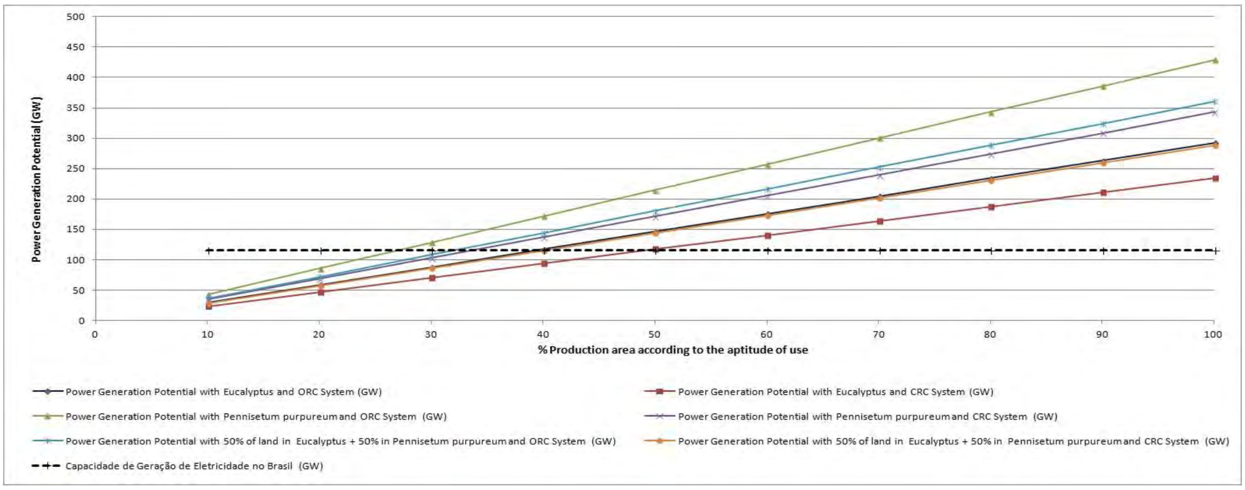

Figure 6. Electricity generation potential of Brazil with different conversion technologies considering different percentages of utilization of the available land for pastures and forestry.

Note in Figure 6 that the power generation potential with *Pennisetum purpureum* and *Eucalyptus* using the evaluated technologies can overcome the current installed capacity in Brazil is 115 GW (ANEEL, 2012). With the implementation of the combustion-ORC system, the achievement of the present Brazilian installed capacity for electricity generation required the planting of 28% of the land with pasture aptitudes with *Pennisetum purpureum*, while about 42% of the land with forestry aptitudes will be require to be planted with Eucalyptus.

When combining both crops in a 50% proportion of each specie per hectare, with ORC systems, is necessary to plant 32% 0f the land with aptitude for natural pastures and forestry, while when using CRC systems is necessary to plant 35% of the same land. It is relevant the little difference in percentage of the necessary land. It can be concluded that the association of both crops is beneficial in the decision making about the technology to be used, considering that the steam cycle is fully commercial and cheaper than ORC system.

By analyzing the combinations of different energy crops and conversion technologies, in the same graphic, it is possible to conclude that with the ORC system it is required to plant 20% of the land with forestry aptitude with *Eucalyptus* to generate about 55 GW and for the CRC system it required to plant 20% of the land with pasture aptitudes with *Pennisetum purpureum* to generate about 65 GW, for a total of 120 GW, which is greater than the current installed capacity in Brazil.

Other important aspect important shown in figure 6, is the little difference between the power generation with Eucalyptus-ORC system and the case of both crops combination in a in a 50% proportion when using CRC system.

The results presented here correspond to a maximum technical potential, susceptible to adjustment according with the reduction in the productivity of crops, depending on the degree of soil degradation and climate in the area of interest.

5. CONCLUSIONS

The energy cropping of eucalyptus and elephant grass could be a renewable carbon source suitable for Brazilian agro climatic potential as they have less requirements in precipitation, temperature and soil condition. They also fix the CO_2 and have a high level of domestication with the availability of improved germplasm that allows achieving a high productivity in Brazil. They offer the possibility of producing enough electricity in relatively small cultivated areas and with high efficiency, using available technologies. It may be exceeded in approximately 5% the present electricity generation installed capacity in Brazil, with only 20% of the planted land suitable for *Eucalyptus* and 20% with *Pennisetum purpureum* using ORC and CRC systems respectively.

The combination of woody and herbaceous energy crops has greater potential than in the case when only Eucalyptus is considered. It has also environmental benefits due to a less intensive use of the land, runoff regulation, erosion control and best conditions to biodiversity.

Among the analyzed combustion based technologies in the range of 1-3 MW, the ORC with radial turbine has the highest overall efficiency and on the range of 1-300 kW is the ORC with screw expander, both with over 20%.

The four evaluated technologies are viable strategies to ensure energetic sustainability, with CO_2 capture through energy crops utilization in decentralized electricity generation systems, without affecting the food security and the environmental protection. Further economic and environmental analysis of each case is recommended.

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