ABSTRACT

This paper presents a technical and economic analysis of electricity generation using planted eucalyptus and ORC system as prime mover. In several developing countries, like Brazil, biomass is an important source of energy. Among many species of biomass, eucalyptus can be distinguished by its fast growth – up to 165 g/day (in the first two years) – and reaching a production of 55 ton/ha.year.

Nowadays, small scale electricity generation technologies, using biomass as fuel, is expensive and inefficient. Among them, the only one commercially available is the ORC, and that is why it was chosen for evaluation in this paper.

In this paper is presented a techno-economical evaluation of the utilization of ORC based generation units using eucalyptus wood as fuel for three different scenario related to the biomass and land costs.

Key Words: Eucalyptus, Organic Rankine Cycle, Energy crops.

1. INTRODUCTION

The increased use of biomass started in the seventies, after the petroleum crisis. It is possible to find examples of successful programs to in the use of biomass: the Pro alcohol in Brazil; the biogas in China; the coke plants in Brazil; the energy forests in the USA; the use of wood for energy purposes in Sweden; the use of agricultural residues, in Great Britain; the eucalyptus plantations, in Ethiopia; the leveraging of bagasse, in Mauritius. Many of these programs have a certain grade of government incentives (1, 2).

Currently, biomass accounts roughly for 13-16% of the energy worldwide produced (3). In developing countries, it is an important source of energy, especially in rural areas; sometimes is the cheapest way to produce electricity or hot air for drying agricultural products. Unfortunately the technology used has low efficiency and low power output (1).

With the gradual "internationalization" of fossil fuels (energy) prices and considering the decreasing costs of wood production, associated with investments in technologies to increase conversion efficiency of small capacity systems, the use of biomass is becoming a reality. The use of renewable energy sources, such as biomass, aims to ensure the future and prosperity of a sustainable energy sector, in addition, the burning of biomass has as its main objective, the reduction in emission of pollutants in the atmosphere.

Despite energy plantations appear always as a final option, after all the residues (which is normally cheaper) were exhausted, it is important to consider the fact that today the cost of wood planted in Brazil is extraordinarily low, due to the growth of our cellulose and charcoal industry (4).

In this paper three alternatives are evaluated:

I. The independent power producer buys biomass paying its market price;
II. The independent power producer buys the land to grow the biomass paying its market price, and the biomass prices corresponds only to its production cost;
III. The independent power producer is also the land owner, and the biomass prices, corresponds only to its production cost.

2. BIOMASS

Diverse cultures are being proposed or tested for commercial agriculture. Energy crops potentially include woody crops, grasses/herbs, plants, starch and sugar and oils seeds cultures. In General, the characteristics of the ideal energy culture are:

- Maximum production of dry matter per hectare;
- High energy output/input relation;
- Low production cost;
- Low pesticides needs;
- Low nutrient needs.

Other desirable features are related to the local conditions, like weather and soil characteristics. In some areas of the world there can be restrictions to water consumption, so the resistance of the culture to drought can be an important factor. Among many species of biomass, the eucalyptus stands out due to its rapid growth, reaching up to 165g/day, in its early year of, even in low quality soil (5 and 6). It also has a low market cost, about 70 USD/m³ in Brazil.

Brazil has a great experience in eucalyptus production, and also with others kinds of cultures, like coffee, corn, soybeans, sugarcane and several other crops grown widely in our country. The eucalyptus is been used in cellulose and paper mills, steel industry, energy and construction sector. In summary, it is possible to say that the eucalyptus is a tree like any other in nature, but it is a very special tree, which produces wood to meet human needs and, if correctly produced, it also helps to preserve native forests (7).

The belief that the eucalyptus dries the soil also do not hold. Your consumption of water is very similar to one of the native forests, around 0.43m³/kg, and their roots remain distant from aquifers. Eucalyptus takes approximately seven years before being harvested, thus requires few human actions on the ground for a long time. It can be cultivated in lands of low natural fertility and don't require a high quantity of nutrients (192kg/ha.year) and pesticides, in comparison with other cultures (7).

Handled properly, the eucalyptus also helps to provide the protection and conservation of biodiversity. The belief that it creates a green desert is not justified. With its rapid growth, the eucalyptus helps to absorb a significant quantity of carbon dioxide from the atmosphere, returning pure oxygen to the nature. The role of planted eucalyptus forests is therefore vital in humanity's effort to counteract the action of the greenhouse gases, responsible for global warming (7).

In Brazil there is an imbalance between supply and demand of wood; new government guidelines are stimulating the use of energy crops in Brazilian energy matrix.

2.1. Quality of biomass for energy production

For the production of energy, it is of fundamental importance, both from a technical and economical point of view, to have a close control of the variables that affect the wood quality. The quality requirements of the wood used for energy generation are not the same as the wood used for cellulose production. Actually, most of them are opposite in numeric trends. Among the most important properties of the wood used for energy generation, one can find:

- Chemical composition – In general the carbon content in eucalyptus is near 49%, oxygen 44% and hydrogen 4.9%. High carbon content provides a high calorific value and the higher the content of lignin in the wood, the higher its calorific value (8).
- Density – Normally between 300 to 700 kg/m³ (dry basis) (9). For energy purposes, wood with high density is desirable, normally above 530 kg/m³.
- Moisture content – is one of the most important parameters in wood combustion efficiency. The presence of water in the wood represents a reduction of its calorific value, making harder to control the combustion process, making it unstable (8). Depending on the harvest time during the year and the storage time before its use, the moisture can decrease almost in 60%, influencing the biomass consumption in the furnaces.
- Calorific value – It depends on the moisture content, chemical composition (lignin, ash and extractives, e.g.), storage time (moisture loss), the harvest season and species of wood used. Normally, for dry biomass, it is approximately 18,828 kJ/kg (HHV), and with 50% of moisture 7,128 kJ/kg (LHV), which could fit in a linear function based on quantity of moisture, using a -19080 slope with 18828 of increment (8).
- Mineral content – In wood, usually expressed as content of ash, corresponds, in general, to less than 1% of the wood on a dry basis. The main minerals are calcium, magnesium, phosphorus, and Silicon.

2.2. Planting techniques

There are more than 21 commercial species of eucalyptus. A culture considered capable to recover soil, having deep roots, it seeks, in the lower layers of soil, for mineral nutrients that are already out of reach of surface roots. For this reason, the eucalyptus trees can control soil erosion and also occupy areas that are infertile for agriculture. In addition it also can help to restore groundwater reserves in long term (7). During planting there are certain
precautions to be taken, like an effective combat against leafcutter ant, the main plague (10).

Spacing is the most important factor for determining productivity. In energy wood production, it is possible to use shorter spacing, starting with 0.3x3m up to 3x3m; smaller spacing are not so effective, its obligates the trees roots to fight for space(8). Recent researches suggest that eucalyptus crop using new techniques, with normal spacing 3 x 3m, can exceed a production of 100m³/ha.year (11).

The planting should be standardized and homogeneous batch. Studies show that the seedlings planted evenly (batch type, executed in a single day) showed growth of 13% larger than with greater heterogeneity (due to a planting in season, spread in several months) (12, 13). During the seeding it is needed to use a fertilizer with high phosphorus content, and after 3 to 6 months fertilization with nitrogen and potassium, about 150 to 250 grams per plant, is required (10).

The irrigation has showed to be one of the most important factors (if compared with the nutrients and the standardization of seedlings) to eucalyptus growth. A proper irrigation can increase around 30% the tree trunk (13). On average, the eucalyptus water consumption (measured through transpiration) is around 1.1 thousand liters/m³/year, which is equivalent to annual average rain in many regions in Brazil (7).

Without the Sun, we would not have photosynthesis and without it the plant will not developed. Contrary to popular belief, there is no influence between the shadowing that makes a big tree on smaller tree, its growth efficiency and the amount of sun irradiation versus growth rate, will always be the same (6).

After the plantation, comes other steps like cutting, storage and transport, and normally the customer is in charge of these steps. According to Sims (14) the cost depends on the type of machinery that is chosen. According to the author the storage time varies depending on the chosen harvest technology and purpose of planting. This cost can be 3 times (simple machines) to 6 times (complex machines) the purchasing value of eucalyptus (24 USD$/m³) for a delivery radius of 25 to 70 km away.

3. CONVERSION TECHNOLOGY

Currently there are several types of technologies that allow converting thermal energy, in an efficient way, into mechanical work. A suitable heat engine, based on a properly chosen thermodynamic cycle, can be matched with the heat source temperature and capacity (Figure 1). New technologies are presently in different stages of developing for the capacity range up to 1-2 MWₑ. Here is possible to mention the Organic Rankine cycle – ORC, the externally fired gas turbine – EFGT, the screw and scroll expanders, the radial steam turbines and the gasifier/engine technologies. Among them the only one that is commercial available is the ORC and that is the reason why it was chosen it for this paper.

Fig. 1: Comparative chart of heat engines with applicable temperature range (15).

For power production of 1MWₑ through biomass combustion, there are two commercial possibilities, the most commonly used systems employed is the traditional Rankine Cycle, with a steam boilers and turbines. This is a relatively robust technology, but the boilers need close monitoring and maintenance and turbines are designed for larger scale operations (Figure 1). For this technology, plants with 1MW have a net electrical efficiency of 10 - 15%. On the other hand, the investment for power generation based on steam turbines are comparatively low, about 800 – 2500 USD$/kW, since it is a widely used technology.

Another possibility is the use of Organic Rankine Cycle (ORC), which is a new technology with a high potential for small-scale biomass-fired system, especially when combining heat and power production. Instead of steam, the ORC system vaporizes an organic fluid, characterized by a molecular mass higher than water, resulting in an enthalpy differences significantly lower for organic substances compared with water. This implies higher mass flows for the same power output, leading to a slower rotation of the turbine and lower pressure and erosion of the metallic parts and blades (15). Advantages of this technology also include the low operation costs and low emissions. Investment are in the range is 1000 – 3000 USD$/kW (16). On the other hand its efficiency are higher, reaching 18 - 24% (17).

The success of the ORC technology can be partly explained by its modular feature: a similar ORC system can be used, with little modifications, in conjunction with various heat sources, reinforced by the high technological maturity of most of its components, due to their extensive use in refrigeration applications. ORC technology is spread in over 23 countries, generating about 2,1GWₑ, normally divided in four basics applications (Figure 2):
biomass, waste heat recovery (WHR), geothermal and solar sources.

Fig.2: Most common ORC applications (18).

In an ORC engine, the expansion device is the most important component of the cycle. The performance and efficiency of the cycle strongly depend on the expander (15). Expanders are broadly divided into two categories: turbo-machines and positive displacement machines. The use of turbo-machines (radial turbine) is advantageous compared to positive displacement expanders (screw and scroll machines) for high temperatures (200-300°C), and high capacity applications, normally over 100kW (19 and 20).

The selection of organic fluid for use with high temperatures heat sources, requires some attention in order to obtain higher cycle efficiencies (15):

- Boiling point;
- Freezing point;
- Rate of chemical deteriorations and decompositions;
- Latent heat of vaporization;
- Ozone Depletion Potential (ODP), Global Warming Potential (GWP) and toxicity of the working fluids should be considered.

3.1. Consumption

Today, there are a few ORC systems manufactures, producing units with capacity varying from 1kW up to 25MW. Several articles and documents are available, that proves its efficiency and justifies the use of the ORC system. Aiming to produce of 1MW$_{el}$ burning biomass and using ORC systems, there are two options: generate only power or generate heat and power (CHP).

Normally a CHP system has 18.3% of electrical efficiency, generation 1MW$_{el}$ of electricity and also producing 4 MW of thermal power, with a temperature in the range of 60°C and 80°C. This temperature level is ideal for drying the eucalyptus before it is burned in the furnace (21), increasing the biomass heat value and also making the system more stable to control. The furnace should provide approximately 5, 5 MW of thermal energy, in order to supply the system that operates at a maximum temperature of 300°C.

Starting from the eucalyptus high heating value and adopting a boiler efficiency of 88%, it is possible to determine the minimum amount of biomass needed for the production of energy, which is1.116 kg/h (17).

4. ECONOMIC EVALUATION

4.1. Energy crop

As an example, the price of one hectare of land (10,000 m²) in Mato Grosso State, varies between 4,500 to 6,000 USD$. In this area it’s possible to plant approximately 6600 eucalyptus seeds with a production of about 55 ton/ha, year in 3 cycles of 5 years each. Assuming that the power plant operates 90% of that time, the area demanded for biomass plantation is estimated in about 800 hectares.

The seed cost varies between 0.11 - 0.18 cents; for this type of application the most used eucalyptus variety is urograndis (cloned) and certified. Large quantity makes price reduce drastically, authors like Müller (22) adopt 0.064 cents per seedlings. The initial plantation price of eucalyptus will have a specific investment of 1,320 USD$/ha. The average cost of plantation maintenance during the 1st year is about 90 USD$/ha, already including plague control and fertilization, considering an already clean area. We need to plant 160 ha per year over 5 years, so when we will be planting the latest batch we will harvest the first one of 160 ha. Considering also the costs of wood harvesting, transportation and storage its results in a total cost of 915 USD$/ha (22).

Under the expectation of a lack of eucalyptus wood to occur in Brazil, the Government provides lines of credit for energy forest development. Today there are available resources of the National Bank of Development - BNDES for forests implementations with a maximum interest rate of 5% per year with a payback period of 11 years, covering up to 80% of the investment. Taking into account all these factors, and considering the land cost to be variable in a range between 3000 – 8000 USD per hectare, we carried out an economic analysis, which results are shown in figure 3.

It is concluded that the feasibility of eucalyptus plantations depends heavily on the land cost, considering that the basic interest rate in Brazil (Selic) is 11% and the return of a simple savings application is 7% per year, many are the companies that establish an internal rate of return (IRR) at least 15% of profit for investments decisions. In this economic scenario the maximum land cost for eucalyptus plantation feasibility is ~ 4100 USD$/ha. In the case of a specific scenario where the land cost is zero (donation or degraded land), the internal rate return is over than 50% using a market cost for eucalyptus wood of 70 USD$/m³.
This fact explains why some of livestock farmers in the west of São Paulo State are moving from cattle raising to eucalyptus plantations. During the economic crisis of 2005 and 2009, and today, the meat market is trading at 50 USD$/@. The planting of eucalyptus is more profitable, having a gross revenue of 7280 USD$/ha.year, the net profit value depends on the land cost. Some farmers propose to combine cattle raising and eucalyptus plantation, producing both products: meat and wood, this practice is known as "silvipastoral" system, which is less susceptible to market variations. Generally the eucalyptus plantations are conceived for other purposes such as the production of cellulose or charcoal production.

2.3. ORC module

Unfortunately ORC systems are not manufactured in Brazil and to the final cost we must add customs taxes. In table 1 we have ranges of cost indicators for an ORC system considering purchase, import, installation and necessary infrastructure. These data were obtained from (16 and 17) and also from information supplied from different manufacturers.

The system requires an annual maintenance, and for this it was assumed a cost of 3% on the total value of the investment, resulting 100,000-260,000 USD$/year. In the experience of the implementation of a 1 MW ORC Plant in Linz Austria (23), resulted in a cost in the order of 3,660.00 USD/kW.

If we compare the ORC installation cost with the one of an hydropower plant, like Belo Monte probably the 3rd biggest plant in the world, located in Xingu River, in the last quotation, the installation cost is about 1041 USD$/kW, selling electricity for less than 47 USD$/MWh (24).

Currently the value of electricity prices are usually controlled by governmental auction are in the range between 40 to 120 USD$/MWh (depending on the generation source and demand and when the auction takes places). For this study it was considered the smallest value. Currently the Brazilian Government has a special programme to encourage the electricity generation using renewable energy (PROINFA), the government funds up to 70% of the initial investment, with loan taxes at 4.0% per year, and a payback period of 11 years.

<table>
<thead>
<tr>
<th>Description</th>
<th>Price [USD$/kW_{el}]</th>
</tr>
</thead>
<tbody>
<tr>
<td>System</td>
<td></td>
</tr>
<tr>
<td>ORC Module</td>
<td>$1000-3000</td>
</tr>
<tr>
<td>Biomass furnace</td>
<td>$400-800</td>
</tr>
<tr>
<td>Auxiliary equipment</td>
<td>$300-800</td>
</tr>
<tr>
<td>Transport and import charges</td>
<td></td>
</tr>
<tr>
<td>Maritime transport</td>
<td>$4-6</td>
</tr>
<tr>
<td>Insurance</td>
<td>$25-65</td>
</tr>
<tr>
<td>Import service</td>
<td>$8-20</td>
</tr>
<tr>
<td>Civil infrastructure</td>
<td></td>
</tr>
<tr>
<td>Basic engineering design center</td>
<td>$40-100</td>
</tr>
<tr>
<td>Executive project and civil works</td>
<td>$450-1100</td>
</tr>
<tr>
<td>Environmental licenses and records</td>
<td>$180-470</td>
</tr>
<tr>
<td>Installation</td>
<td></td>
</tr>
<tr>
<td>Grid connection</td>
<td>$400-1000</td>
</tr>
<tr>
<td>Installation and mounting of equipment</td>
<td>$500-1300</td>
</tr>
<tr>
<td>Total investment cost</td>
<td>$3300-8700</td>
</tr>
</tbody>
</table>

A report of the Federation of Industries of Rio de Janeiro State (Firjan), shows that the average electricity tariff in Brazilian industry is 193 USD$/MWh, about 50% higher than the international average value of 126 USD$/MWh. In Brazil electricity tariffs vary according to the federation states where the consumer is located, in Mato Grosso State the electricity tariff is the highest.
one resulting in an average value of 245.2 USD/MWh, while the lowest is found in Roraima State of 149.7 USD/MWh. For residential consumers, in Minas Gerais State the electricity tariff could reach 358.6 USD/MWh.

Considering that the ORC plant has a useful life of 15 years with 7884 hours of operation per year, and as mentioned before the three different scenarios evaluation:

1. The ORC owner buys biomass for wood fire retailers paying the market price, at an average value of 70 USD$/m³ which means 147.7 USD$/biomass cost per MWh produced. In figure 4 are shown the result a of the financial economic evaluation of this scenario;
2. The ORC owner owns also the land and paid for it the market price of 4,100 USD$/ha. So for him the biomass cost is equal to the biomass production cost in his own land. (figure 5); 3. When the ORC owner is also the land owner, but he did not pay for it (the case of governmental degraded lands or financed by the government for energy projects). In this case the biomass price corresponding to it production cost is much lower than in the scenario 2 (figure 6).

Analyzing the first and the second option (figure 4 and 5), and adopting a minimum interest rate of 11%, none of both the systems are feasible if the electricity is negotiated with the auction price. Only in the third option (figure 6) we have a small range (white triangle in the intersected areas) where it’s possible to have reasonable profits.

For the first scenario (figure 4) the investment starts to be profitable only with an electricity commercialization tariff over 230 USD$/MWh even though, this system configuration is more reliable when it works off-grid in isolated regions. Another possibility is to reduce the biomass cost in 63%, reducing the whole biomass cost down to 55.5 USD$/MWh of electricity produced.

For the second scenario (figure 5), the price of the land influence heavily the internal return rate, showing that buying biomass in the market could be more profitable than to have an energy forest for its own consumption. This is true only in the case when the biomass cost in the market stays stable. Comparing first and second scenarios, the second option seems to be more secure in long term than the first one, been less vulnerable and susceptible to eucalyptus wood market prices variation. Both scenarios begin to be profitable for the same initial minimum electricity tariff.

The third scenario (figure 6), seems to be an unreal situation, although, it’s possible to find an available or degraded land with an extremely low cost. However it’s useful for our analysis to set a minimum cost boundary for biomass ORC technology electricity. On the other hand the first scenario (figure 4) represents the maximum cost boundary.

An important point to mention is the observed decreasing investment cost of this technology in the last decade, so it is very likely to expect the wide spreading of ORC technology in the market. Nationalization of the manufacture can force this cost to decrease the making viable biomass ORC projects in a medium term.

![Fig.4: ORC module economic evaluation based on electricity cost, buying biomass with the market price.](image-url)
5. **CONCLUSIONS**

Electricity production using eucalyptus from energy forest becomes attractive only when the investor is the owner both of the land and of the generation system, or when the land cost is lower than 4100 USD/ha. Considering the use of the Brazilian governmental bank BNDES loans it’s possible to obtain a IRR of 15%, with a Payback-Time of 8 years, only 4 years after the first harvest, with a net average profit of 690 USD/ha.year during 20 years.

For 1MW$_3$ biomass ORC, the specific investment cost is in the range 3300-8700 USD per kW installed, being observed a tendency of this technology price to decrease steadily in the last decade, so it is very likely to expect the wide-spreading of ORC technology in the market in the near future. Nationalization of the manufacture can force this cost to decrease making viable biomass ORC projects in a medium term. Without the existing governmental incentives, investments in this type of technology are unthinkable, essentially if we work with an interest rate charged by banks, often exceeding 20% per year.

Based on this study we can conclude that the biomass ORC electricity commercialization in Governmental auctions is not feasible, because of the low electricity commercialization prices. For isolated regions the investment in this biomass ORC equipment, to work off-grid, becomes an interesting perspective. Another possibility is to use low cost of biomass residues with a price reduction from an actual eucalyptus wood price of 70 USD$/kg to 23 USD$ /kg.

---

**Fig.5:** ORC module economic evaluation based on electricity cost, buying lands and producing its own eucalyptus wood.

**Fig.6:** ORC module economic evaluation based on electricity cost, using its own land and producing biomass.
6. ACKNOWLEDGEMENTS

The authors want to thank to the Coordination of Improvement of Higher Education (CAPES), National Council of Technological and Scientific Development (CNPq) and Foundation for Research Support of Minas Gerais State (FAPEMIG) for their collaboration and financial support in the development of this work.

7. REFERENCES