COGENERATION USING RESIDUAL FOREST BIOMASS - A CASE OF STUDY UNDER CHILEAN ECONOMIC FRAMEWORK CONDITIONS

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Abstract: The combined heat and power systems, also known as CHP technologies, is a simultaneous generation of multiple forms of useful energy in a single an integrated system. Most of the commercial CHP technologies that use biomass as a fuel are still based on the Rankine Cycle (RC), being the Organic Rankine Cycle (ORC), Stirling engines and biomass gasification technologies still under development or in the early stage of commercialization.

In the present work an economic assessment is carried out considering biomass as a fuel for medium size biomass CHP plants (in the range of 14-25 MWe) under the economic framework of Chile, estimating the cost of production of electricity as main product.

The estimated cost of electricity production for medium size CHP ranges from 39 to 56 US$/$MW_e$h, with a cost of biomass supply at the gate of plant of 13 US$/(DMt). This estimation was obtained with a selling price of steam in the 2.5 – 3 US$/t range, considering it as a sub product, and therefore without a cost of production associated to the global balance.

INTRODUCTION

A cogeneration process is defined as a sequential or simultaneous generation of multiple forms of useful energy, usually mechanical and thermal, in a single integrated system.

Power generation as well as cogeneration by combustion can be divided into **closed thermal cycles** and **open processes** [1]. In the former, among which the steam turbine is the most important application, the combustion process and the power generation cycle are physically separated by a heat transfer from the hot combustion gas to a process medium used in a secondary cycle. Due to the separation (between the fuel-engine) the engine is solely in contact with a clean process medium.

In contrast open cycles are commonly applied for gaseous and liquid fuels used in internal combustion engines and gas turbines. The fuel is burnt either directly inside the internal combustion engine, which is operated cyclically as a four-stroke or two-stroke engine, or it is burnt continuously in an external combustion chamber and then led through an open gas turbine for expansion. The use of solid fuels in internal combustion engines is technically not feasible and their application in gas turbines is considered as complex [2].

Since biomass fuels and the resulting flue gases contain components that may damage engines, such as fly-ash particles, metals and chlorine components, the technologies for power production through biomass combustion used nowadays are based on closed thermal cycles. The main process and engine types are shown in table 1.

Table 1. Closed processes for power production by biomass combustion.

Engine Type	Range Size	Technological Status
Steam turbine	0.5 MW_e-5 MW_e	Proven technology
Steam piston engine		Proven technology
Steam screw turbine	25 kW_e-1.5 MW_e	On demonstration
Steam turbine with organic medium (ORC)	400 kW_e-1.5 MW_e	On demonstration – some commercial plants
Stirling engine	1 kW_e-100 kW_e	Under development

Many of the benefits of a CHP system stem from its relatively high efficiency compared to others, due to CHP simultaneous production of electricity and useful thermal energy. Although CHP efficiency is measured and expressed in a number of different ways, it is going to be defined as traditionally is done for a conventional Rankine cycle, as the relationship between net energy outputs (E_e) and the amount of potential energy from a fuel for power generation (Q).

$$\varepsilon = \frac{E_e}{Q} \quad (1)$$

In general, efficiency of power and CHP plants based on steam cycles are highly sensitive to scale economies. In small plants (up to 2 MW_e) electrical efficiencies leads around 8-12 %, while medium size plants (5-10 MW_e) reach around 20-25 %.

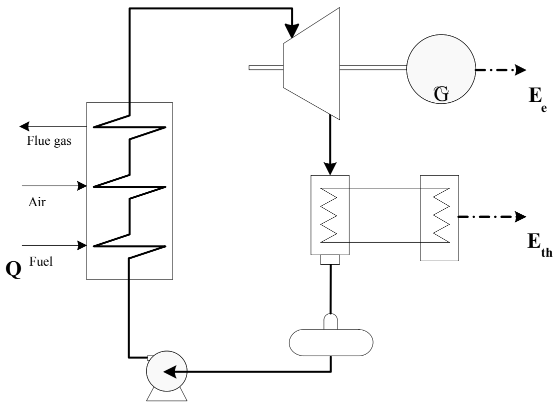

Figure 1. Flow of back-pressure plants based on the Rankine cicle. ***Source***: Adapted from *The Handbook of Biomass Combustion & Co-firing (2008).*

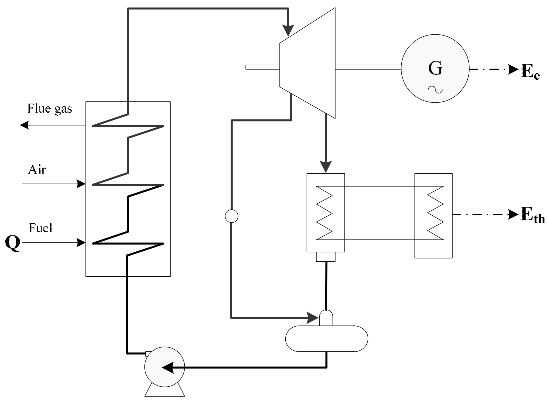

Figure 2. Extraction condensing plant with use of intermediate pressure for heat production. ***Source***: Adapted from *The Handbook of Biomass Combustion & Co-firing (2008).*

In CHP systems *the total CHP efficiency* seeks to capture the energy content of both electricity and usable steam, and is the net electrical output plus the net useful thermal output. In this way the total efficiency is defined as follows.

$$\eta = \eta_e + \eta_{th} \qquad (2)$$

For a CHP energy generation, for specific conditions, two operational modes can be distinguished. In general, small CHP plants with low electrical efficiency should be operated in a heat controlled mode, while large CHP plants are usually operated in a electricity-controlled mode. Figure 3 shows a qualitative outlook of how efficiency for heat and electricity can be achieved, in comparison with power and heat production as limits.

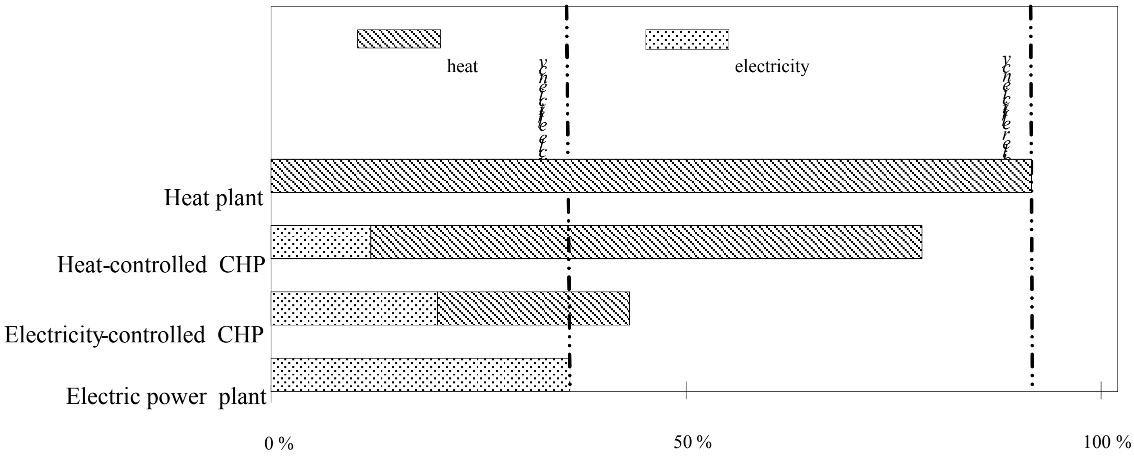

Figure 3. Share of efficiency in terms of heat and electricity production for heat, CHP and power plants.

An important operational parameter to consider is the power to heat ratio, which is defined as the relationship between the net electricity output and the net heat output:

$$\varepsilon = \frac{E_e}{E_{th}} \tag{3}$$

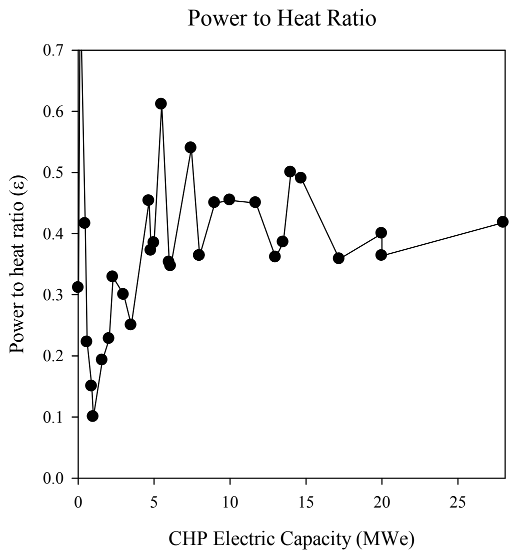

Figure 4. Power to heat ratio as a function of the plant size of biomass-fuelled CHP plants in Finland, Sweden and Denmark. ***Source***: personal compilation based on information from *Small-scale Biomass CHP Technologies- Situation in Finland, Denmark and Sweden* (2004).

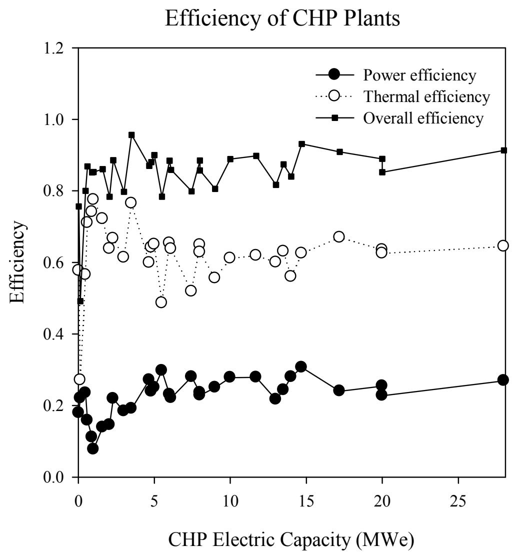

Figure 5. Power, thermal and overall efficiency as a function of the plant size of biomass-fuelled CHP plants in Finland, Sweden and Denmark. ***Source***: personal compilation based on information from *Small-scale Biomass CHP Technologies- Situation in Finland, Denmark and Sweden* (2004).

Figure 4 and 5 show the relationship between power to heat ratio and capacity for 32 plants located in Finland, Sweden and Denmark. As it is possible to see, the increasing of power heat ratio corresponds with CHP plant size.

MAIN TECHNOLOGIES FOR COMBUSTION IN COGENERATION

Pile burners is the most traditional technology for biomass combustion, where biomass is dumped on piles in a furnace and burnt with the aid of combustion air flowing from under and above the pile. Advantages of this technology are the fuel flexibility and the simple design. Important disadvantages are generally low boiler efficiency and relatively poor combustion control [1].

In the group of **grate-fired boilers**, it is possible to distinguish boilers with *stationary sloping grate*, *travelling grate* and *vibrating grate* [4]. Common to these types is a fuel feeding system which puts a thin layer of fuel on the grate and distributes it more evenly as in the case of pile burners. In a stationary sloping grate, the grate does not move, but the fuel burns as it slides down the slope. Disadvantages of this type of boiler are the difficult control of the combustion and the risk of avalanching the fuel. In a travelling grate boiler the fuel is fed in at one side of the grate and has to be burnt before it reaches the ash dumping site of the furnace. In a vibrating grate boiler the fuel is fed evenly over the whole grate. The grate makes a shaking movement and therefore has lower maintenance requirements.

Table 2. Electricity production in Chile based on combined and heat power systems fuelled by biomass. ***Source***: (1) Informe Annual 2007-Energía Eléctrica. Comisión Nacional de Estadística: (2) Declaración de Impacto Ambiental (www.seia.cl).

Plant Name	**Fuel**	**Combustion Technology**	**Power (MW_e)**	Date of Start Up
Valdivia	Forest sub product (1)	Fluidised boiler	61.0	2004
Arauco	Black liquor (1)	Recovery boiler	33.0	1996
Arauco Hor-cones	Forest sub product (2)	Fluidised boiler	31.0	2008
Celco	Black liquor (1)	Recovery boiler	20.0	1996
Nueva Aldea III	Black liquor (1)	Recovery boiler	20.0	2007
Nueva Aldea I	Forest sub product (1)	Travelling grate	13.0	2005
FPC	Forest sub product (1)	Travelling grate	10.0	2006
Masisa Cabrero	Forest sub product (2)	Travelling grate	9.6	2008
Cholguán	Forest sub product (1)	Travelling grate	9.0	2003
Laja	Forest sub product (1)	Stationary grate	8.7	1995
Constitución	Forest sub product (1)	Travelling grate	8.7	1995
CBB	Forest sub product (2)	Travelling grate	6.3	2006
Licantén	Forest sub product (1)	Travelling grate	5.5	2004
Total (MWe)			**236**	

In **suspension fired boilers** the fuel is fired as small particles which burn while they are being fed into the boiler, analogously to pulverised coal firing technology. A disadvantage of this system is that the fuel requires a considerable amount of pre-treatment. Its main advantage is the high boiler efficiency.

In **fluidised bed boilers** the speed of the combustion air from below the boiler is so high that the fuel becomes a seething mass of particles and bubbles. On a commercial scale one can distinguish between bubbling and circulating fluidised beds. A general feature of fluidised bed systems is that they are flexible with regard to the kind of fuel that is fired, which makes them quite suitable for co-firing different kinds of fuel.

SHORT OVERVIEW ON ELECTRICITY SECTOR AND PRICES IN CHILE

In Chile, except for the small isolated systems of *Aysén* and *Punta Arenas*, generation activities are principally developed in two electric systems. The former corresponds to Central Interconnected Grid (SIC), which covers the area from the south of *Región de Antofagasta* to *Región de los Lagos*, covering 326,412 square kilometers and supplying approximately 90% of the country's population. Its installed capacity is 9,118 MW_e and represents 70.9% of the installed capacity of the country. The second one is the Northern Interconnected Grid (SING), which covers the first and second regions of Chile (*Región de Arica y Parinacota* and partially *Región de Antofagasta*), where the principal users are mining and industrial customers. Its installed capacity is 3,569 MW_e and covers 185,142 square kilometers [5]. In each of these grids, electricity generation is coordinated by the respective independent Economic Load Dispatch Centre (CDEC) in order to minimize operational costs and ensure the highest economic efficiency of the system, while fulfilling all quality of service and reliable requirements established by current legislation.

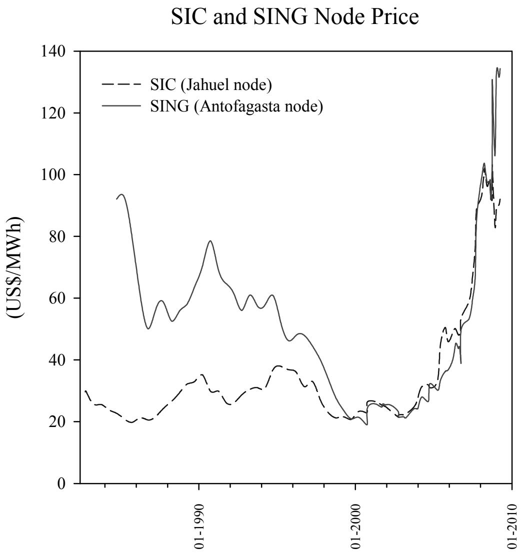

Figure 6. Energy price in the Chilean market. ***Source***: personal compilation based on information from *Comisión Nacional de Energía* (www.cne.cl)

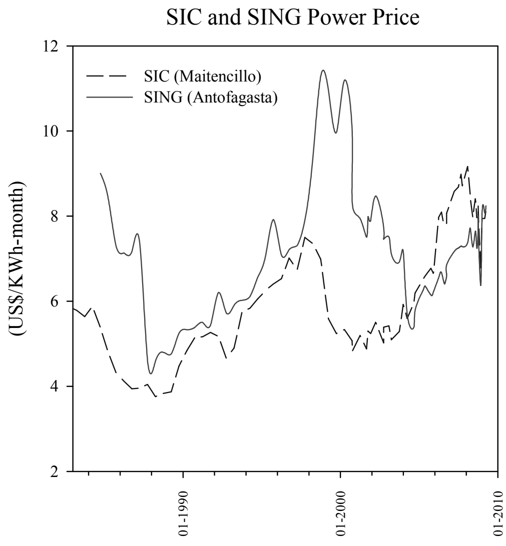

Figure 7. Energy price in the Chilean market. ***Source***: personal compilation based on information from *Comisión Nacional de Energía* (www.cne.cl)

Each generator company is required to declare availability and plant marginal operating cost every hour. These declarations are used to dispatch power plants and to set the basic marginal energy price or spot price. This price has to be used by the power generators to trade electricity among themselves to meet contracts. The spot price is heavily influenced by the opportunity cost of water in the SIC system and always equals this price. Under normal conditions the opportunity cost is equal to the operating cost of the most expensive thermal plant dispatched. If there is a water shortage the spot price becomes the outage cost. The outage cost is equal to an amount based on consumer willingness to accept compensation for a planned outage of a particular magnitude.

Regulated prices for generated electricity are determined on the basis of the expected spot price of energy over the next 4 years, and this price is fixed for six months in April and November. This node price is then converted into the regulated price of generated electricity at each of the basic substations of the system by an energy penalization factor (to reflect system losses). This gives the node energy prices. To these are added the node peak capacity charges which reflect the annual marginal cost of increasing system capacity assuming a specified reserve margin. This is paid to available generators and reflects the capital and operating costs including a 10% return of the newest technology on the system. This is similarly adjusted by a capacity penalization factor [6].

TECHNO-ECONOMIC ASSESSMENT OF CHP PLANTS – A CASE OF STUDY

Information of three prefeasibility projects was collected, which concerns investment, technology and performance, cost of labour and operation as well as fuel and administrative costs. The key aspects of all this information is summarized in the table 3.

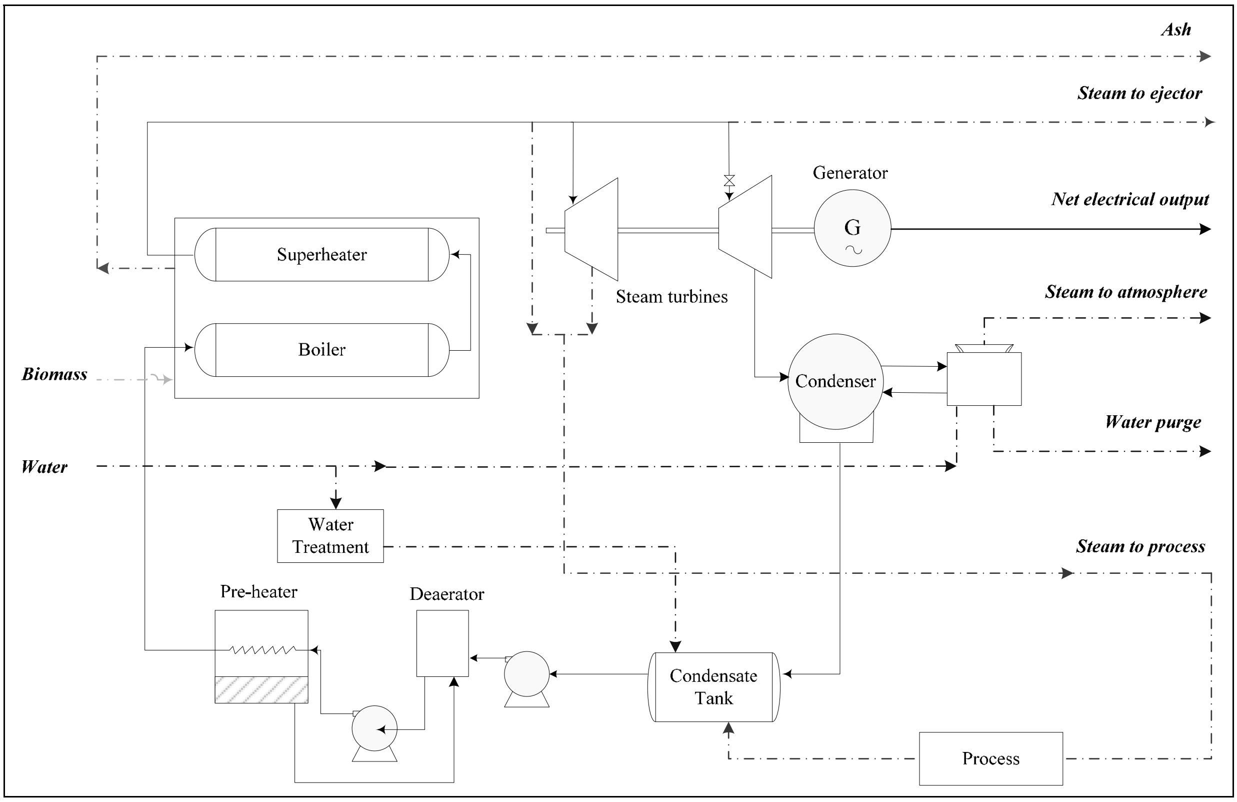

Figure 8. Common flow diagram of assessed CHP plant. ***Source***: Own elaboration with personal communications with plant managers.

A general flow diagram of the three assessed CH|P plants is shown in figure 8. The two smaller ones use travelling grate as combustion technology, while the largest one use a fluidised bed system with ad of silicate sand for improving the combustion and, in this way, the boiler efficiency. All plants use cooling towers with mechanical draft to condensate the steam from the turbine. For the requirement of water, a treatment plant is included, which covers the supply from the cooling tower system as well as from the boiler circuit.

Table 3. Key economic and performance parameters of the assessed CHP plants in Chile

Number of CHP assessed plants	: 3 with full mass and energy balance
Working hours	: 7,200 h/y
Net electrical power	: 14 MW_e, 18 MW_e and 25 MW_e
Steam to process	: flow 50 t/h; pressure 8-10 bar(g), 170-230 °C
Labor cost	: four shift of personnel
Non-Fuel costs	: water supply for boiler from 2.50 to 3.50 US$/$m^3$ water supply for cooling from 0.06 to 0.10 US$/$m^3$ ash disposal 8-10 US$/t; sand from 10 to 15 US$/t
Fuel cost	: biomass with 13 US$/(DM t)
Maintenance cost	: general maintenance as a percentage of investment
Others	: Insurance, permissions, among others

Annual operating hours in Chile typically vary from 7,200 to 8,300 for cogeneration plants fuelled by biomass, but it has been considered the lower limit, in order to estimate unitary cost under the most realistic scenario.

The cost structure was organized in five items, corresponding to *Technology*, which represent the amortization of the investment for thirty years of lifetime, *Labour*, regarding to the staff for the complete operation of the plant, *Fuel*, that for this case is only biomass at the gate of plant and under condition for its direct burn (it is not considered back fuel), with an estimated cost of supply of 13 US$ per dry tonne, for biomass recovered after harvesting and in appropriate conditions [7]. The *Non-Fuel* item is related with cost of water supply (both for the boiler circuit and for the cooling tower) and ash disposal as main items. Finally *Others* covers administrative, maintenance and overhead costs, all estimated as a percentage of the investment.

MAIN RESULTS AND DISCUSSIONS

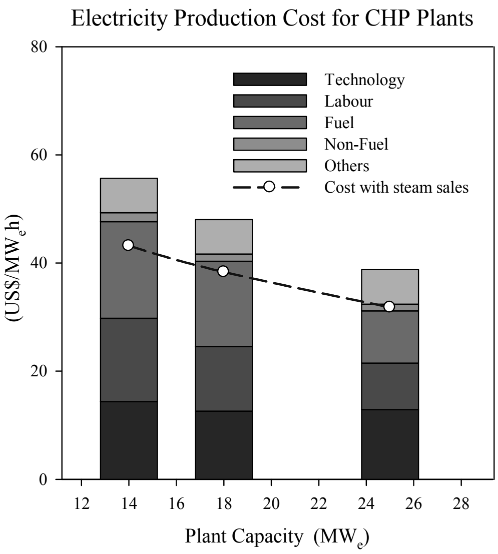

Figure 9. Electricity cost of production from assessed CHP plant fuelled by forestry biomass.

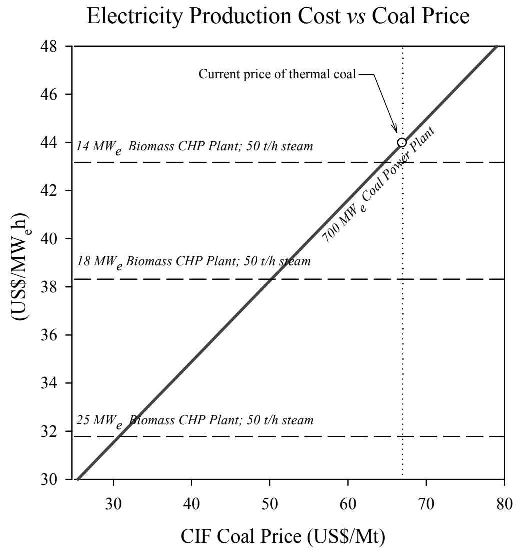

Figure 10. Electricity cost of production from coal in comparison with fuelled biomass CHP plant. ***Source***: For coal power plant, personal compilation based on information from Environmental assessment registry (www.seia.cl)

Figure 9 shows the cost structure for the production of electricity from forestry biomass for the three assessed plants. It is possible to observe that the unitary cost of electricity is very sensitive to the plant capacity, an expected result confirmed by the evaluation. The main two costs of production are concentrated on technology and fuel, representing both around 80 % of the total cost.

Due to steam is classified as sub product, with a trade price from 2 US$ to 3 US$ per tonne, its sales reduce the electricity cost of production, making it more competitive. In each case, the reduction in electricity cost range from 18 to 23 % of the original cost.

Considering the electricity production from a coal fuelled power plant, the current cost of production is around 44 US$ per MW_e for a large scale plant, in which the cost of fuel represent more than 50% of the total cost of production.

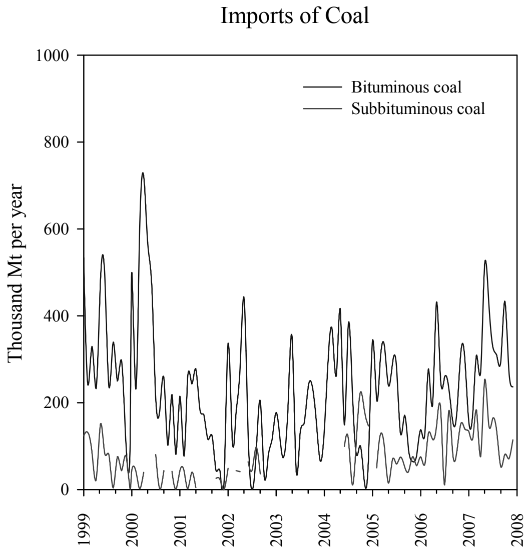

Figure 11. Imports of thermal coal to Chile the last ten years.

Source: personal compilation based on information from *Comisión Nacional de Energía* (www.cne.cl).

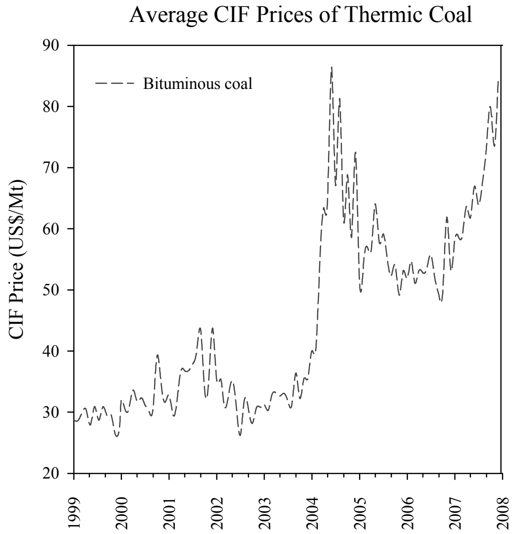

Figure 12. CIF price of coal in Chile the last ten years.

Source: personal compilation based on information from *Comisión Nacional de Energía* (www.cne.cl).

As figure 11 shows, the coal consumption for electricity production has been stable, although the price has been steadily increasing during the last years, and consequently the cost of electricity production.

Under these conditions, biomass can compete with coal electricity production only for large size plant, otherwise Clean Development Mechanism (CDM) have to be considered in order to make this kind of project financially attractive.

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