OPTIMIZATION OF A WOOD-WASTE FUELLED, INDIRECTLY-FIRED GAS TURBINE COGENERATION PLANT FOR SAWMILL APPLICATIONS

by

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Abstract

Forests are a primary natural resource in the province of British Columbia. Harvested trees are delivered to sawmills which produce lumber for domestic and export markets, wood chips for the pulp and paper industry and large volumes of wood waste. Traditionally, wood waste has been disposed of by open incineration. The government of British Columbia has mandated that by 1996, all forms of open burning must be eliminated.

In the past this form of biomass waste had very limited economic value due to its limited application and use. The most common use for forest residues was in pulp and paper mills where it was utilized as a fuel for steam boilers for generating both heat and electricity.

Until recently, very little incentive existed for manufacturers of wood wastes to generate electricity and/or heat due to the very low electricity and natural gas prices. This scenario is beginning to change due to increased environmental standards.

Cogeneration with wood waste, i.e. the simultaneous production of heat and electricity, is proposed as a viable alternative for supplying the heat and power requirements of a sawmill. Cogeneration has been utilized in the past, in the pulp and paper sector, but has had very limited application in the sawmill industry.

In analyzing the application of a cogeneration system the amount of heat and power to be produced must be determined. In some cases, the system is sized to match the electrical power requirements, while in other cases it is sized to meet the thermal

requirements. In order to achieve the best economic return from the system, both heat and power must be produced accordingly. These amounts are not intuitively obvious and an optimization technique known as linear programming has been incorporated in this analysis to determine the optimum production levels of heat and power.

In general it was found that cash flow was maximized when the cogeneration system was sized to meet the thermal requirements of the sawmill. Production of electricity was not particularly attractive due to low electricity rates.

The overall conclusions indicate that cogeneration is an economically attractive option for disposing of wood wastes for those sawmills which require large amounts of process heat, typically in the range of 20,000 kW (68 MMBtu/hr).

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1.0 Introduction

1.1 Background

Forestry is a major primary industry in the province of British Columbia and relies heavily upon the harvesting and processing of lumber. Inherent to this industry are sawmills which produce dimension cut lumber for export to markets worldwide.

During the processing of logs into dimension cut lumber a large quantity of wood waste is produced in the form of bark, wood shavings, sawdust and trim ends. The production of these wastes presents a problem for both the sawmill operators and the environment. In the very recent past, these wastes were incinerated in large 'tee-pee' or 'bee-hive' burners which produced large volumes of suspended particles and smoke due to very low combustion temperatures. The British Columbia Ministry of Environment has recently mandated that by 1996, all bee-hive burners must be decommissioned due to their negative environmental impact. In addition to incineration, wood wastes have been disposed of by landfilling which introduces the problem of soil leachates. Both incineration and landfilling are rapidly becoming obsolete methods by which to dispose of forestry related wood wastes.

Inherent to the operation of a typical sawmill is the kiln drying of cut wood which occurs at the final processing stage. This energy is typically provided by natural gas, propane, butane or oil. Of these options natural gas is the least costly but may not always be available depending upon the location of the mill relative to the nearest natural gas pipeline. This introduces the problem of purchasing and/or transporting fuels to the site which is an added expense to the operation.

1.2 Potential Solution

An alternative to this problem, which will be investigated, is to introduce cogeneration to the sawmill. Cogeneration is the simultaneous production of thermal and electrical energy. This can be done by using either a gas or steam turbine, or both. Electricity is generated by the gas or steam turbine while thermal energy is a byproduct. Cogeneration utilizes this byproduct heat which would have otherwise been wasted and hence increases the overall system efficiency. The byproduct heat is often used to generate steam for the process and/or for space heating.

It is proposed to use cogeneration in a sawmill by using the available wood wastes to produce both electricity and process heat for the plant. Specifically, the intent is to develop a system which does not produce steam, hence the steam turbine/boiler option has been disregarded. This is due primarily to the high operating and maintenance costs associated with a steam plant. Additionally, the relative installed cost per kilowatt for a simple cycle combustion turbine is approximately one third the cost of an oil or gas fired steam plant (Butler, 1984). Therefore, the proposed cogeneration system will consist of a recuperated/indirectly-fired gas turbine with a wood waste furnace and high temperature heat exchanger.

1.3 System Description

A gas turbine consists of both an air compressor and turbine section with the turbine providing power to the compressor. Ambient air is drawn into the compressor where both the temperature and pressure are elevated depending upon the pressure ratio. The air is then passed into a combustion chamber where it is mixed with fuel and ignited. Upon completion of combustion, the combustion products' temperature is increased to the required level prior to entering the turbine section. When the hot exhaust gas reaches the turbine it expands across the blades to atmospheric pressure, causing rotation of a shaft to produce both electricity and/or shaft work, as well as the necessary power to drive the compressor.

A recuperated gas turbine is one in which the compressed air is preheated prior to entering the combustion chamber. Increasing this air temperature lowers the amount of fuel which must be consumed in the combustor, improving the overall system efficiency.

An indirectly-fired gas turbine is one in which the heat energy is provided entirely by an external source through a heat exchanger. Because no internal combustion takes place in this process, hot air, not combustion gases expand across the turbine.

1.4 Cogeneration Systems

In the sawmill cogeneration system, it is proposed to evaluate three different concepts of a recuperated/indirectly-fired gas turbine. These are labelled as Option #1, Option #2, and Option #3.

Option #1 - Recuperated Gas Turbine using a Metal Heat Exchanger

Option #2 - Indirectly-fired Gas Turbine using a Ceramic Heat Exchanger

Option #3 - Recuperated Gas Turbine using an Atmospheric Fluidized Bed Combustor complete with an In-Bed Heat Exchanger

1.5 Study Objectives

The overall objective of this study was to determine the optimum allocation of wood waste resources in a typical sawmill environment for the production of thermal and electrical energy.

The first step in this process was to develop a thermodynamic model for analyzing the mass and energy balances of the three cogeneration options. This was necessary in order to physically determine the amounts of heat and electricity produced for a specified amount of wood waste fuel consumed. For example, a given flow of wood fuel into the plant can generate various combinations of both heat and electricity.

The second step in the process was to develop an economic model which would utilize the information acquired in the thermodynamic model and assign costs to producing those quantities of heat and electricity. The main objective of the economic model was to maximize benefits and minimize costs. The optimum allocation of both the available and required resources was achieved by using linear programming.

A key point to consider is that the resulting size of the cogeneration system is not intuitive. Wood fuel consumption is a variable along with the amount of electricity and heat being generated. The established criteria is, the maximum amount of wood waste available, the sawmill average and peak electricity requirements, and the minimum heating requirements. The costs and savings associated with the cogeneration plant are functions of these variables. Given these variables, linear programming was used to determine the optimum size of the cogeneration system with respect to maximizing cashflow.

2.0 Reference Literature

The work of a number of authors, in both text books and journals, was reviewed. In particular, emphasis was placed on the combined use of linear programming and thermodynamics for the analysis and optimization of power and heat systems.

Hu (1985), in "Cogeneration", discusses the various levels of cogeneration systems with respect to sizing. He outlines four levels of cogeneration:

1. No Cogeneration - where only thermal energy is generated while electricity is purchased from the utility.
2. Thermal-match Cogeneration - where the cogeneration system is sized to meet only the thermal needs of the process.
3. Electrical-match Cogeneration - where the cogeneration system is sized to meet the electrical demand of the process.
4. Maximum Cogeneration - where the cogeneration system is sized according to a given set of criterion such as maximum cash flow, and also meets a minimum return on investment or constrained availability of waste fuels.

Hu (1985) states that there are many different criterion for determining the size of the system, one of which is maximizing the economic return. The criteria will differ between three different owners: an industry, a utility, or a society. For the industrial firm the only decision environment is the company, and the investment is judged by its cost effectiveness. For a society it may be judged by its energy efficiency. The sizing of a cogeneration system determines its economic attractiveness. Hu (1985) states that there is always an optimal size and that when the cash flow is to be maximized the optimal solution often occurs at or above the Thermal-match case.

The Thermal-match and Electrical-match cases are easily sized since the thermal and electrical requirements are known. Sizing of the Maximum Cogeneration case is not as simple since the optimum value will change depending on the stated objective and constraints. The objective and constraints may be stated as follows and incorporated into a linear programming problem:

Objective: Maximize size with respect to maximum cash flow, maximum electricity generation, least production cost, or other criterion.

Constraints: Technical characteristics of the cogeneration system; availability of waste products and/or inexpensive fuels; environmental limits; required rate of return on investment; and other imposed requirements.

Hu (1985) suggests the use of linear programming to solve the case of Maximum Cogeneration.

Butler (1984), in "Cogeneration", compares the relative installed cost of a cogeneration project consisting of a combustion turbine-generator and a combined cycled facility to a conventional electric utility fossil-fired steam plant. He indicates that the relative installed cost per kilowatt for a simple cycle combustion turbine is approximately one third the cost of an oil or gas-fired steam plant. However, many different combinations of equipment components, technology, and site specific parameters will cause this ratio to fluctuate. In general, the cost of the steam based system exceeds that of the combustion based system.

The following outlines Butlers' (1984) basis for a financial and cash-flow analysis:

1. Operating expenses consist of fuel costs, operating and maintenance costs; property taxes and insurance; and interest.
2. Fuel costs are based on the plant operating at 75% of its capacity.
3. Operating and Maintenance Costs: the operating staff provides supervision, administration, and technical support for the plant and is also involved in billing and collecting revenues. Technical maintenance includes repair and overhaul of the facility. Other maintenance costs include those for materials used in the maintenance of nontechnical items. The work is performed by the operating staff. On average, for a combined cycled operation with a combustion turbine and waste heat recovery steam generator, the cost is set at approximately 4.0% of the capital cost.
4. Property tax and insurance are assumed to be 2% of the equipment and materials capital cost per year.
5. Interest on a loan is a yearly cost depending on the amount of the loan, interest rate and amortization period.
6. Electricity revenues: electricity sales prices and/or savings are negotiated independently with the utility.

7. Thermal revenues: revenue from the sale of thermal energy or a savings resulting from the offset use of previous fuels.
8. Depreciation: no allowance is made for depreciation since it is assumed that the equipment can not be used for any other purpose. The scrap value of the equipment at the end of the project life is zero. The opportunity cost is zero.
9. Energy Investment Tax Credit: Butler states the conditions prevalent in the United States. Similar credits in Canada fall under the Class 34 Capital Cost Allowances.

Payne (1985), in "The Cogeneration Sourcebook", analyses the optimum operation of a cogeneration system by developing empirical relationships. The optimization is done by using non-linear programming. The model consists of developing physical relationships and constraints of the process. The objective is to minimize costs. This consists partly of placing limits on the flows as necessary as well as incorporating the appropriate mass balances.

Guinn discusses a procedure by which a cogeneration system is to be evaluated to determine whether or not it is cost effective. One indicator of project viability is a positive Net Present Value. In general, one of the industries in which cogeneration is viable is the Lumber and Wood Products Industry.

Consonni, Lozza, and Macchi (1989), found that the linear approach is adequate in a wide range of cogeneration operating conditions. They found that linear optimization allows the determination of the optimum control strategy.

Gustafsson and Karlsson (1991) evaluated the optimum operation of a combined heat and power (CHP) plant by using linear programming. The objective function was total cost which was to be minimized. The constraints basically consisted of providing the minimum amounts of heat and electricity required as well as the physical relationships between the amounts of heat and electricity produced. The study was concluded by determining the optimal solution for each month in the year by using linear programming.

Ehmke (1990) utilized a modified version of the ELMO (Electrical Load Management Optimization) computer model. The ELMO model does not take into account equipment capital costs but rather analyses the operation of an existing system. Ehmke (1990) incorporated these costs into the model since these costs are related to equipment size. The main goal was to determine the optimum size of cogeneration equipment.

The objective function was to minimize total cost while the constraints consisted of meeting the minimum heat and electricity requirements along with the physical limitations of the equipment. Ehmke models a physical temperature limitation by setting an upper bound on the maximum steam generation.

Based in part on the work of these authors, it is proposed to use the linear programming optimization technique to determine the optimum size of a combustion turbine based cogeneration system for a sawmill.

3.0 Linear Programming

The intent of this section is to very briefly describe the concept of linear programming rather than provide a detailed mathematical description of the technique.

A linear programming problem is one of maximizing or minimizing a linear function subject to a finite number of linear inequality constraints. The linear function that is to be maximized or minimized is called the 'objective function' of the problem. The problem is typically presented as follows:

$$\text{maximize:} \quad \Sigma\, c_j x_j$$

$$\text{subject to:} \quad \Sigma\, a_{ij} x_j \leq b_i \qquad (i = 1,2,....m)$$

$$x_j \geq 0 \qquad (j = 1,2,....n)$$

Linear programming first began in 1947 when G.B. Dantzig developed the simplex method for solving linear programming formulations of United States Air Force planning problems. Following this was the rapid development and use of this technique in production management problems. These problems had been traditionally analyzed by a trial and error, or hit and miss, approach guided only by experience and intuition. Linear programming will often show that the optimal solution is not always intuitively obvious.

Since the majority of linear programming problems consist of a large number of variables and equations, they must be solved by the use of a computer.

A number of software packages exist on the market today which use the simplex method for solving these types of problems. The software package which was used in this study was developed at the University of British Columbia, and is called 'LINEAR'.

4.0 Physical Model Development

The first step in the development of the physical model was to design a basic process flowsheet for the system which would incorporate an indirectly-fired/recuperated gas turbine. Two major criteria for the system were that it be technically feasible and realistic to build and operate.

Three slightly differing systems were decided upon based in part on previous work done by Canadian Resourcecon (1986, 1988, 1990). Each of the three systems has been slightly modified in order to incorporate the availability and physical limitations of equipment on the market. Operating parameters and pricing were obtained for each major piece of equipment from the respective manufacturers.

The next step was to determine the size range of sawmills to be analyzed along with their corresponding wood waste production, and consumption of heat and electricity. These variables are a function of the type of wood processed as well as the size of the sawmill. In British Columbia these values typically differ between coastal and interior sawmills.

The final step was to develop a thermodynamic model which would analyze the system and produce mass and energy balances for varying input and output parameters, specifically the consumption of wood waste which is the primary fuel. The intent of this model was to develop physical relationships between the wood waste fuel consumption and the production of electricity and process heat. This technique is similar to the method described by Payne (1985).

4.1 Option #1: Recuperated Gas Turbine using a Metal Heat Exchanger

Option #1 consists of a recuperated gas turbine coupled to a high temperature and pressure metal heat exchanger. A process flowsheet of the system is shown on Figure 1.

Wood waste is burned in an atmospheric pressure refractory lined furnace, generating high temperature flue gases. The flue gas temperatures vary depending upon the moisture content of the wood and the amount of excess combustion air. For the purposes of this analysis, the values of wood moisture content and excess air have been assumed to be 50% and 40%, respectively. The thermal content of wood decreases with increasing moisture content. At 50% moisture content and 40% excess air, the resulting flue gas temperature is 1095°C.

Upon combustion, the flue gases pass through a metal heat exchanger where heat is transferred to the compressed air leaving the gas turbine. Due to physical material restrictions of the heat exchanger, the maximum compressed air temperature achievable is 650 °C. Since this is lower than the rated turbine inlet temperature, a natural gas burner must be incorporated to top up the turbine inlet temperature.

Exhaust from the turbine, process flow #14 on Figure 1, is used as a source of process heat. The second source of process heat is the excess energy available from the flue gases exiting the metal heat exchanger. These gases, flow #4, are again passed through a heat exchanger where energy is transferred to clean ambient air. This is preferable to the optional case of 'direct firing' into the kiln since no particulate material is carried over. The remaining flue gases are passed through a cyclone prior to discharge into the atmosphere.

Direct firing into the kiln consists of bypassing the heat exchanger, as shown, which is slightly less expensive. The major problem associated with this configuration is the carry over of particulate into the kiln which are subsequently deposited onto the lumber.

The kiln air heat exchanger is labelled as an air/oil heat exchanger which is intended to indicate some of the currently available options for this purpose. Lumber kilns are often heated by hot oil which is subsequently used to generate hot air. They are also often heated by steam. In any case, an allowance has been made for process heat whether it is by air, oil or steam.

4.2 Option #2: Indirectly Fired Gas Turbine using a Ceramic Heat Exchanger

Option #2 is virtually identical to Option #1 with the exception of a ceramic heat exchanger replacing the metal heat exchanger. A process flowsheet of the system is shown on Figure 2.

The basic idea behind using the ceramic heat exchanger is to take advantage of its very high operating temperatures. Unlike the metal heat exchanger which is limited in its operating temperature, the ceramic heat exchanger can achieve the required turbine inlet temperature.

This configuration does not rely on natural gas for topping up of the turbine inlet temperature, although a gas burner is allowed for as an option as indicated on the flowsheet. This is particularly advantageous for those locations where natural gas is not readily available.

4.3 Option #3: Recuperated Gas Turbine using an Atmospheric Fluidized Bed Combustor complete with an In-Bed Heat Exchanger

Option #3 utilizes an atmospheric fluidized bed combustor (AFBC) complete with an in-bed heat exchanger. A process flowsheet of the system is shown on Figure 3. Wood waste is combusted and high temperature flue gases are generated. Energy is transferred to the turbine compressed air with a maximum achievable air temperature of 815 C. Natural gas is required for top up of the turbine inlet temperature, but less is required than Option #1. Energy from the flue gases exiting the combustor are used both as a source of process heat in the drying kiln and for preheating of the AFBC combustion air. Turbine exhaust is also used as a source of process heat.

4.4 Production of Wood Waste

In terms of a geographical description, sawmills in British Columbia are classified as being either on the coast or in the interior of the province. A large portion of the coastal sawmills typically process red cedar and a combination of hemlock and fir known as HemFir while interior mills process a combination of spruce, pine, and fir known as S.P.F. Due to the differences in wood species and geographical location, factors such as the amount of bark volume, moisture content, and wood density vary between these two areas.

<u>Units of Measure:</u>

A common unit by which to measure the production of a sawmill is the foot board measure, or fbm. A unit of fbm is a lumber volume and is equivalent to a piece of wood 1 foot long by 1 foot wide by 1 inch thick. Based on this nominal dimension, 1000 fbm are equivalent to 83.33 cubic feet of lumber. However, it is important to realize that the actual cubic content depends on the actual lumber size. Average actual cubic volume production of a coastal sawmill is 66 ft^3 of lumber per 1000 fbm while for an interior sawmill it is 56 ft^3 of lumber per 1000 fbm.

Bark Volume:

Bark volume is a difficult parameter to predict since it varies with the tree species. On the coast, the bark volume of Hemlock is approximately 19.5% of the log volume while the bark volumes of fir and red cedar are 13.4% and 16.1% of the log volume, respectively. A weighted average of these three species depending on the amounts processed results in an average bark volume of 17.3% of the log volume. Making an allowance for void volume in the bark of 27% and loss in transport of 25% results in a net bark volume of 8.3% of the total log volume for coastal mills.

With respect to interior mills, the bark volumes of spruce, pine and fir are 14.9%, 11.2% and 15.6% respectively, resulting in an average bark volume of 13.9%. Allowing for a 27% void volume and a reduced transport loss of 15%, net bark volume is approximately 8% of total log volume for an interior mill.

Wood Waste Volume:

The other major wood waste parameters are the production of sawdust, planar shavings, and chip fines. These parameters vary slightly between the coastal and interior sawmills. A summary of the wood waste produced as a percentage of the log volume is given as:

	Coast	Interior
1. Bark	8.3%	8.0%
2. Sawdust	10.0%	8.0%
3. Planar Shavings	8.0%	6.0%
4. Chip Fines	3.0%	3.0%

This distribution of wood waste is expressed as a percentage of total log volume.

It is common practice to express sawmill production in terms of cubic metres. The conversion factor between fbm and cubic metres is known as the lumber recovery factor, or 'LRF ', and is a ratio between lumber output to log volume input. The LRF is expressed as:

$$LRF = \frac{\text{nominal board ft. of lumber}}{\text{cubic metres of logs}}$$

The LRF varies slightly between coastal and interior sawmills, and based on typically values has been assumed to be 230 fbm/m^3 for coastal mills and 220 fbm/m^3 for interior mills.

Sawmill Sizes:

Three sawmill size ranges were analyzed in order to represent a range of sawmill wood waste production:

1. 50 Million fbm/yr
2. 150 Million fbm/yr
3. 250 Million fbm/yr

These represent small to very large sawmills.

Using the LRF, the average annual sawmill consumption in cubic metres of logs can be determined, and then based on wood waste distribution, annual wood waste production in cubic metres can be derived.

The next step is to convert this volumetric output to a mass output in terms of oven dry tonnes (ODT) per year. Moisture content plays a large role in determining actual mass amounts. ODT is used as a common unit of measure since it does not include any allowance for moisture. Wood and bark densities vary slightly, and average values are given as follows in terms of oven dry kilograms per cubic metre:

	Coastal	Interior
1. Bark	475	490
2. Wood	365	385

Using these results, the annual production of wood waste for the three sawmill sizes expressed in ODT/yr is as follows:

	Coastal	Interior
1. 50 MMfbm/yr	26,150	23,000
2. 150 MMfbm/yr	78,440	69,000
3. 250 MMfbm/yr	130,750	115,100

4.5 Thermodynamic Modelling

Mass and energy balances were conducted for each of the options to determine all of the design parameters. A computer program was written to calculate the process flow parameters at each stage in the system.

Temperature, pressure, enthalpy, entropy, mass flow rate and moisture content are calculated at each stage. These values vary depending on the incoming wood fuel flow-rate and turbine size, which ultimately determine the amounts of electricity generated, process heat generated and natural gas consumed. The resulting values are tabulated in Appendix A for each of Options #1, #2, and #3 for differing amounts of wood fuel flow-rate and turbine size.

The following sections will summarize the assumptions made in calculating the physical parameters in each of Options #1, #2 and #3.

4.5.1 Basic Assumptions

The first basic assumptions made were that of the ambient conditions. The conditions assumed for temperature and pressure were 20°C and 101.3 kPa, respectively.

Air was assumed to be the working fluid. Properties of air were taken from the thermodynamic tables at the relevant temperatures and pressures. Properties of combustion gases were approximated to be those of air at the same temperature and pressure.

The moisture content of wood can vary significantly between species and geographical location. It has been assumed that incoming moisture content of wood waste fuel is 50%. This parameter, in part, determines the amount of combustion gases produced as well as the heating value of the fuel. Heating values of the wood waste fuel as a function of moisture content are given as follows:

Moisture Content	Heating Value (MJ/kg)
1. 0%	16.00
2. 10%	14.13
3. 20%	12.24
4. 30%	10.36
5. 40%	8.64
6. 50%	6.70

These heating values allow for an average combustor efficiency of 80% which accounts for potential losses during energy conversion.

Percent excess air in the wood waste combustor has been assumed to be 40%. Without the actual conditions and specific manufacturers guidelines it is difficult to know the value of this parameter since it varies. The value of 40% was used only as an average and is in line with that used by industry. This parameter is a key factor in determining the amount of combustion gases produced.

4.5.2 Wood Waste Furnace/Combustor Analysis

The first step in analyzing the wood waste combustor was to determine the chemistry of the wood fuel. Since this will vary slightly depending on the wood species it was determined to use average values for the wood fuel based on results by Grace and Lim (1987). The percent dry ultimate (mass) analysis is as follows:

Component	Mass Percent
1. Carbon (C)	52.8%
2. Hydrogen (H_2)	5.4%
3. Oxygen (O_2)	36.9%
4. Nitrogen (N_2)	0.1%
5. Sulphur (S)	0.2%
6. Ash	4.6%

The resulting stoichiometric air fuel ratio based on this analysis is 6.35 kg-air/kg-fuel. Allowing for the previously stated excess air ratio of 40%, the resulting air fuel ratio is:

$$AF_{actual} = 8.89 \text{ kg-air/kg-fuel}$$

The next step was to determine the mass and energy balance for the wood waste combustor by taking a control volume approach. The first law and conservation of mass were used in determining the final conditions. For a given mass flow rate of wood fuel, and by calculating the enthalpy of the products, the resulting gas temperature was determined by interpolation.

4.5.3 Heat Exchanger Analysis

The heat exchangers were assumed to be shell and tube counterflow design and were analyzed based on energy balances and limiting temperatures. In the case of the metal heat exchanger, in Option #1, the maximum allowable compressed air temperature exiting the heat exchanger (flow #11) was set by the manufacturers to be 650°C. In the case of the ceramic heat exchanger in Option #2, no temperature limit was expressed for these operating conditions. In the case of the in-bed heat exchanger for Option #3, the maximum allowable compressed air temperature achievable is 870 °C.

It is also important for practical reasons to quantify an approach temperature for the heat exchangers. This is the temperature difference between the cold inlet stream and the hot outlet stream. Based on manufacturers recommendations, the minimum approach temperature was 111 °C.

Thermal energy available is determined by the amount of wood fuel being consumed, which determines the rate of combustion gas production. The basic relationship for determining heat exchanger temperatures is a simple energy balance:

$$M_h C_{ph}(T_{h1}-T_{h2}) = M_c C_{pc}(T_{c2}-T_{c1})$$

The cold side inlet conditions are known for a given turbine. The hot side inlet temperature is known as well as the minimum exit temperature based on the approach value. The cold side exit conditions are then determined. Should this resulting temperature exceed the maximum allowable, the approach temperature is increased accordingly until the maximum heat exchanger temperature is achieved.

Allowances have been made for pressure drops. Industry standard pressure drops of 0.50 kPa and 70 kPa have been assumed for the shell and tube sides, respectively. These pressure drops will contribute to decreasing the net electrical output of the cogeneration system.

4.5.4 Gas Turbine Analysis

In order to determine the performance characteristics of the gas turbine it was necessary to acquire specific operating information from the manufacturer. The information available consisted of: 1) turbine inlet and outlet temperatures; 2) air mass flow; 2) fuel consumption; 3) pressure ratio; and 4) rated output power. Critical information which was not available was the compressor exit temperature and the turbine and compressor isentropic efficiencies.

Based on given information, it was possible to determine these unknown parameters. Since both turbine inlet and outlet temperatures were known, as well as mass flow and rated output power, it was possible to determine compressor work required.

$$\text{Compressor work} = \text{Turbine Power} - \text{Rated Power}$$

where:

Turbine Power = f(mass flow, inlet & outlet temperature)

Given that compressor work can be calculated, and knowing mass flow and air inlet temperature, the compressor exit temperature can also be calculated.

Compressor exit temperature = f(mass flow, compressor work, inlet temperature)

The next step was to determine the compressor isentropic efficiency. Compressor isentropic efficiency is defined as:

$$\text{compressor isentropic efficiency} = \frac{\text{ideal work}}{\text{actual work}}$$

Ideal work occurs during isentropic compression where the isentropic temperature pressure relationship exists:

$$\frac{Tout_s}{Tin} = \left(\frac{Pout}{Pin}\right)^{\alpha-1/\alpha}$$

where: $Tout_s$ = isentropic exit temperature

Tin = inlet temperature

$Pout$ = exit pressure

Pin = inlet pressure

α = gas constant

By the above expression the compressor efficiency is a ratio of ideal to actual work. This can be simplified to a ratio of ideal to actual enthalpy, and ultimately, to a ratio between isentropic temperature difference and actual temperature difference.

$$n_c = \frac{Tout_s - Tin}{Tout - Tin}$$

where: $Tout$ = actual outlet temperature

n_c = compressor isentropic efficiency

Using the above relationships, the isentropic compressor efficiency can be simplified to:

$$\eta_c = \frac{Tin}{(Tout-Tin)}[(Pout/Pin)^{a-1/a} -1]$$

Although compressor isentropic efficiency is useful to know, for the purposes of this model it is more important to know the compressor exit temperature. And as shown above, this can readily be evaluated from the given information and physical relationships.

The compressor exit temperature is also the inlet temperature to the main heat exchanger in the cogeneration system. It is not possible to determine the performance characteristics of the system without knowing this value.

The turbine isentropic efficiency is calculated in a similar manner. The calculation is more straight forward since both the turbine inlet and outlet temperatures are known. Again, using the isentropic temperature pressure relationship, the turbine isentropic efficiency is calculated as follows:

$$\eta_t = [(Tin-Tout)/Tin]/[1 - (Pout/Pin)^{a-1/a}]$$

where: η_t = turbine isentropic efficiency

Tin = turbine inlet temperature

Tout = turbine outlet temperature

Pout = turbine outlet pressure

Pin = turbine inlet pressure

The turbine isentropic efficiency is useful to know since the actual turbine output power will be affected by the pressure drop in the heat exchanger. By assuming that this efficiency value will not change very much, the actual turbine output power and exit temperature can be calculated.

4.5.5 Natural Gas Burner Analysis

In the case of Options #1 and #3, the maximum heat exchanger temperature achievable is less than that required for the turbine inlet temperature. It was therefore necessary to introduce a natural gas burner into the system to elevate the compressed air temperature leaving the heat exchanger. Natural gas was chosen as the fuel due to its availability, low cost, and popularity for this application. Other fuels may also be used.

A control volume approach was used in determining the amount of natural gas required. Rather than calculate the flow-rate of natural gas required, the amount of energy required from the fuel was calculated. Natural gas is typically purchased based on unit energy consumption in gigajoules. Given that the turbine inlet temperature is known, along with the compressed air temperature leaving the heat exchanger and entering the gas burner, and the air mass flow rate, the natural gas energy required can be determined. Using the First Law:

$$\text{Gas Energy Required} = M_{out}*h_{out} - M_{in}*h_{in}$$

where: M_{out} = mass flow of air out of burner into turbine; an allowance has been made for the increased mass flow due to the natural gas fuel.

M_{in} = mass flow of air into burner

h_{out} = enthalpy of air out of burner; this is determined by the required turbine inlet temperature

h_{in} = enthalpy of air into burner; this is determined by the air temperature exiting the main heat exchanger

The amount of natural gas required to achieve the turbine inlet temperature is a function of both the amount of wood waste fuel as well as the size of the gas turbine. The amount of wood fuel will determine the rate of production of the high temperature flue gases and the amount of thermal energy available for transferring to the turbine compressed air. For a given size of turbine and flue gas flowrate, once the compressed air exiting the heat exchanger has achieved its maximum value, the amount of gas energy required becomes fixed. Once the flue gas flow-rate falls below this level the amount of gas required increases, until at a zero flue gas flow-rate the amount of gas required is defined by the turbine designed. Figures 12 and 13 show the resulting gas energy required versus the amount of wood fuel flow for a given size of gas turbine for Options #1 and #3 respectively. Option #2 does not require natural gas. The following relationships were developed for the gas energy required:

Relationship	Feasible Range
Option #1:	
Gas = 2.81 * genelec	6624 kg/hr ≤ Mf < 19908 kg/hr genelec ≤ 7962 kW
Gas = 2.85 * genelec	19908 kg/hr ≤ Mf ≤ 33156 kg/hr genelec ≤ 11943 kW
Option #3:	
Gas = 1.75 * genelec	6624 kg/hr ≤ Mf < 19908 kg/hr genelec ≤ 7962 kW
Gas = 1.80 * genelec	19908 kg/hr ≤ Mf ≤ 33156 kg/hr genelec ≤ 11943 kW

where: Gas = amount of natural gas consumed (kW)

Mf = flow rate of wood fuel (kg/hr)

genelec = electricity generated (kW)

4.5.6 Process Heat Energy Available

The exhaust gases from both the gas turbine and wood furnace contain substantial amounts of thermal energy. These two sources of energy are utilized for the process heat/kiln drying application. Depending upon the relative flow rates between the compressed air and flue gas, the energy available from this source will vary. It is assumed that the flow rate of the compressed air is proportional to the size of the turbine. Similarly, the flow rate of the flue gas is a function of the amount of wood fuel flowing through the plant. Therefore, the amount of process heat energy can be expressed as a function of both the wood fuel flow rate and the turbine size.

$$processheat = f(genelec, Mf)$$

The results for each of the three cogeneration options are plotted and shown on Figures 9, 10 and 11, respectively.

For Options #1 and #3, the slope of the relationships are fairly constant for varying quantities of wood fuel flowrate. As expected, the amount of process heat energy increases with both the turbine size and available wood waste. This increase occurs as a multiple of each different wood fuel flowrate. The objective was to establish a single relationship which would depict all cases of wood flowrate. This was done by taking one relationship as the base case and scaling all the others from this value as well as taking an average slope.

The resulting relationships for Options #1 and #3 are as follows:

Option #1:

processheat = 1.926 * genelec + 1.26 * Mf

Option #3:

processheat = 2.428 * genelec + 0.892 * Mf

The results for Option #2 are slightly different. The amount of process heat available actually decreases over a range of turbine power for a given amount of wood waste consumed. This is easily explained since the only source of fuel in this process is the wood waste unlike in Options #1 and #3 where natural gas is consumed. As the size of the turbine increases, for a given amount of wood waste consumption, more energy is required to run the turbine to achieve turbine inlet temperature and hence less energy is available for the process heat. In order for the turbines to generate the rated power, natural gas must be introduced since insufficient energy is available from the wood waste. This transition is the low point on each curve. This analysis only considers those values leading up to the point where wood waste is the sole source of fuel for the process. Beyond this point it would defeat the purpose of using the ceramic heat exchanger since its main objective is to eliminate the need for natural gas. The resulting relationship is as follows:

Option #2:

processheat = -1.11 * genelec + 1.26 * Mf (kW)

4.5.7 Induced Draft Fan Power Requirements

In addition to generating electricity, the cogeneration system also consumes electricity to operate its own induced draft and combustion fans. This draw of energy reduces the electricity available for the sawmill. The net electricity available is expressed as follows:

$$netelec = genelec - idfan \quad (kW)$$

where:

- netelec = net electricity available from the cogeneration system;
- genelec = amount of electricity being generated by the cogeneration system;
- idfan = amount of electricity required to operate the induced draft and combustion fans.

The amount of electricity required to operate the induced draft fan is a function of both the pressure drop through the system and volumetric flow rate of the flue gases. Since pressure drop is specific to the site layout of the plant, it has been assumed, for Options #1 and #2, that a pressure drop of 40 inches water gauge is sufficient for a general calculation. Due to the fluidization requirements of Option #3 a pressure drop of 90 inches water gauge has been assumed. Volumetric flow rate of the flue gases, however, is directly proportional to the flow of wood fuel into the system. Figure 14 shows the rate of flue gas production as a function of the flow of wood fuel. The relationship is as follows:

fluegas = 2.4824 * Mf (SCFM)

where fluegas = flowrate of flue gas in standard cubic feet per minute (SCFM)

This relationship assumes that the amount of excess air available for combustion is 40% and that the moisture content of the wood fuel is 50%.

Actual flue gas production is then used to determine the power required to operate the induced draft fan. Since pressure drop has been fixed, the only variable is gas flow, or ultimately, flow of wood fuel (Mf). The resulting relationships for Options #1, #2 and #3 are as follows, and are also plotted on Figures 15, 16 and 17 respectively:

Option #1:
idfan = 0.013 * Mf (kW)

Option #2:
idfan = 0.013 * Mf (kW)

Option #3:
idfan = 0.029 * Mf (kW)

where idfan = amount of electricity required, in kilowatts, to operate the induced draft and combustion fans.

4.5.8 Sawmill Sizes Analyzed

In addition to evaluating a range of sawmill output production rates (MMfbm/yr), both the electricity and process heat requirements must be known. Since these parameters can vary for sawmills of the same output production rate, a different range of sizes were analyzed.

In terms of electricity requirements, there are two values which must be evaluated, the average demand and the peak demand. These are explained in more detail in section 5.2.4.

In terms of the process heat requirements, this will vary by the amount of lumber that is kiln dried. Sawmills of similar size will dry differing amounts of lumber depending on their product and target markets.

The sizes analyzed are as follows:

Sawmill Size (Mfbm/yr)	Electricity (MW) Average Demand (MW)	Peak Demand (MW)	Process Heat (MW)
50	3.0 to 4.0	4.0 to 8.0	10.0 to 30.0
150	3.0 to 4.0	4.0 to 8.0	10.0 to 30.0
250	3.0 to 4.0	4.0 to 8.0	10.0 to 30.0

4.6 Equipment Pricing

In order to determine the actual costs and required sizes of the various components in the cogeneration system, it was necessary to determine the range of feasible sizes to meet the process heat and electrical requirements. Physical relationships, based on the results of the computer model, were determined for given flows of wood fuel into the plant versus a range of gas turbine sizes. These relationships determine the effects upon the thermal and electrical output of the system for a given set of inputs. Budget pricing information was received directly from the manufacturers and distributors of all the major equipment components.

4.6.1 Gas Turbine

The cost of the gas turbine was received from Kawasaki for a range of their gas turbine models ranging in size from 660 kW to 3981 kW. Although the Kawasaki turbine is not an indirectly fired unit it was felt that due to its off-axis, or external combustor design, it would be the best suited for modification. An additional cost of 15% of the original cost was added for this potential modification. All sizes above 3981 kW were assumed to be multiples of the existing sizes. Pricing was also received from Solar Turbines. The only applicable turbine available from Solar is the 3 MW Centaur which in the past was configured for recuperated operation. It was decided to use the pricing available from Kawasaki due to the greater flexibility and ease of establishing an indirectly fired unit. A regression analysis was performed on the price data to determine a linear relationship between the cost and size. Figure 4 shows a graph depicting these data. The resulting linear relationship for the turbine cost versus size is:

	Turbine cost	= f(turbine size)
	turbcost	= 883 * genelec + 514,975 ($)
		for genelec $\geq$ 660 kW
	turbsize	= genelec
Where:	turbcost	= the variable representing the cost of the gas turbine ($)
	genelec	= size of the gas turbine, ie amount of electricity generated (kW)
	turbsize	= size of the gas turbine (kW)

4.6.2 Wood Waste Furnace/Combustor

The cost of the wood fuel furnace was acquired by both a manufacturer of cogeneration systems for sawmills, Wellons, and a local manufacturer of a wood furnace, Heuristic Engineering.

The cost of the Wellons unit includes an allowance for a multiclone, used for removing air laden particulate from the flue gas, and an induced draft fan used to maintain the continuous flow of the flue gas. The cost of the Heuristic system includes all required fans and motors. The Heuristic unit does not require a multiclone.

The cost of the system versus the rate of wood fuel flow is shown on Figure 5. The cost of the system is directly proportional to the rate at which wood fuel is fed into the furnace. The design of the system assumes that 40% excess combustion air is used along with a wood moisture content of 50%. Both these factors will affect the temperature and flow rate of the flue gas exiting the furnace. The Wellons unit was used as the base case system due to its slightly higher cost. The resulting cost relationship is as follows:

	Furnace cost	= f(wood fuel flow rate)
	furnacecost	= 73.7 * Mf + 1,023,583 ($)
		for Mf ≥ 6800 kg/hr
	furnacesize	= Mf
where:	furnacecost	= cost of the wood furnace system ($)
	furnacesize	= size of the furnace (kg/hr)
	Mf	= flow of wood fuel (kg/hr)

4.6.3 High Temperature Heat Exchanger

The price of the high temperature metal heat exchanger was received from both "Thermal Transfer Corporation" and "American Schack Corporation Ltd." (specialty manufacturers of high temperature equipment). The cost of the ceramic heat exchanger was received from "Hague International" which is one of the few manufacturers of this type of heat exchanger.

It was decided to determine the cost of this component based upon equal flow rates between the flue gas and compressed air. Figures 6 and 7 graphically show the heat exchanger cost versus the amount of wood fuel flow rate for the metal and ceramic heat exchangers, respectively. A regression analysis was performed in order to determine a linear cost relationship. The relationships are as follows:

Heat exchanger cost = f(wood fuel flow rate)

Metal Heat Exchanger:

Hxcost = 14.76 * Mf + 88,074 ($)

Hxsize = Mf

Ceramic Heat Exchanger:

CeHxcost = 103 * Mf + 4,433,914 ($)

CeHxsize = Mf

Where:
Hxcost = cost of the metal heat exchanger ($)
Hxsize = size of the metal heat exchanger (kg/hr)
CeHxcost = cost the ceramic heat exchanger ($)
CeHxsize = size of the ceramic heat exchanger (kg/hr)

The cost of the kiln/air heat exchanger which is used to heat the kiln drying air is assumed to be the same as the cost of the metal heat exchanger.

4.6.4 Atmospheric Fluidized Bed System

The cost of the atmospheric fluidized bed system was received from ABB Combustion. Pricing was provided for a complete system including all ancillary equipment with the exception of the gas turbine, and is based on the amount of wood waste consumed. The prices are graphed on Figure 8. A linear regression was performed in order to determine the linear pricing relationship. The resulting price relationship is:

ABBcost = f(wood fuel flow rate)

ABBcost = 551 * Mf - 800,000 ($)

ABBsize = Mf

Where: ABBcost = cost of the complete AFBC system ($)

ABBsize = size of the ABB system (kg/hr)

5.0. Economic Model

The main objective in sizing the cogeneration system is to maximize its net present value or cashflow. A project life of 20 years has been assumed in order to be in line with B.C. Hydro's expectations of an independent power producer. Inherent to this cashflow calculation are the savings realized by generating both heat and electricity as opposed to the purchase of these two commodities. Additional savings are realized by not disposing of the wood waste fuel. Costs that arise as a result of the cogeneration system are the initial capital investment, yearly operating and maintenance, and yearly insurance and taxes.

5.1 Linear Programming (LP) Model Formulation

A Linear Programming (LP) model was developed in order to determine the optimum size of a wood waste fired cogeneration system. The model was solved using a linear programming software package developed in the Mathematics department at UBC. The model varies slightly between Options #1, #2, and #3.

Options #1 and #2 currently have 45 parameters, 58 constraints and 54 variables. Option #3 has 45 parameters, 52 constraints and 50 variables. A printout of the actual LP model formulation for each Option is provided in Appendix B.

5.2 LP Parameters

In the context of this LP model, parameters are defined as those variables which are known and remain constant throughout the evaluation.

5.2.1 Discount Factor

It is necessary to discount the future cashflow into todays dollars for the 20 year project life. A real rate of interest, or the marginal time preference rate (MTPR) has been assumed to be 8%. In addition, inflation was accounted for and is assumed to be 4%. The resulting nominal interest rate is:

$$i_r = (1+i)*(1+f)-1 = 12.3\%$$

where: i_r = nominal discount factor (%) = 12.3%

i = real interest rate (%) = 8%

f = rate of inflation (%) = 4%

A discount factor β_i is then applied to each year i of the cashflow:

$$\beta_i = 1/(1+i_r)^i$$

where i = i'th year in which the cash flow takes place

β_i = resulting discount factor

i = 1,....,20 years

Twenty discount factors are used in the LP model. There is one discount factor for each project year with the exception of year 0.

It has been assumed that the system start-up will occur in year 1, with construction occurring fully in year 0.

5.2.2 Hours of Operation

Three different hours of operation have been assumed for the sawmill and cogeneration plant. The sawmill is assumed to operate on two shifts per day, 5 days per week, and 8 hours per shift. This equates to 4,160 sawmill working hours per year which is used to calculate any potential electricity savings incurred by self generation. This factor is stated as follows:

hours1 = 4160 sawmill hours/year

The second hourly factor is the number of hours that electricity is actually being generated. This is assumed to operate on a continuous basis, 24 hours/day, and 90% of a full year (ie 90% of 365 days). This factor is stated as follows:

hours2 = 7884 cogeneration hours/year

The third hourly factor is that time during which the sawmill is not operating and electricity is being generated. Since electricity is generated continuously and the sawmill only operates at specific times, this time period is simply the difference between hours2 and hours1.

hours3 = hours2 - hours1

5.2.3 Wood Disposal Cost

Sawmills typically pay a price to dispose of their unwanted wood wastes. Often they are able to sell these wastes to pulp mills. This economic model assumes that disposal is the only alternative. The cost of this disposal varies greatly between sawmills. Some mills are located near disposal sites while others pay a high price for the disposal. A number of sawmill operators were questioned about their disposal costs and it was decided to use an average figure of $5/wet tonne or 0.5¢/kg.

Assuming that disposal is the only alternative, any wood which is consumed in the cogeneration process presents a savings or credit in this amount. Given that the consumption of this waste occurs during the operation of the cogeneration plant, or 7884 hours/year, the resulting unit credit is:

dispcredit = 39.42 $-hrs/kg-yr

When this disposal credit is multiplied with the actual amount of wood being consumed on an hourly basis in the cogeneration system, a savings will result.

Savings = dispcredit * Mf ($/yr)

5.2.4 Electricity Prices

The consumption of electricity is essentially divided into two separate charges; demand charge and energy charge.

Demand Charge:

Consumers are charged for their maximum peak kilowatt demand consumption over a billing period which is typically one month. The charge is based on the value of this peak quantity in kilowatts. The demand charge is treated as a parameter in this economic model and follows B.C. Hydro's rate schedules 1200 for general service of 35 kW and over. The demand charge is expressed as follows:

dc = $6.37/kW/month or $76.44/kW/year

where dc = demand charge ($/kW/yr)

Energy Charge:

Energy charge is based on the continuous consumption of electricity over the billing period and is a reflection of the consumers average demand. This charge is based on the continuous kilowatt-hour consumption of electricity and is set as a parameter in this model again using B.C. Hydro's rate schedules 1200. The resulting energy charge is expressed as follows:

ec = 3.12 ¢/kWh

where ec = energy charge ($/kWh)

Combining the demand and energy charges into a single average unit can be done by taking the capacity charge per kilowatt-hour and adding this value to the energy charge. Assuming that the sawmill operates 4160 hours in a year, the demand charge of \$76.44/kW-yr becomes, 1.84¢/kWh. Adding to the energy charge, a net energy charge based on continuous consumption becomes:

Net charge = 4.95 ¢/kWh

This represents a potential unit savings of electricity when self generation of electricity takes place.

5.2.5 Excess Electricity

Firm Electricity:

Should a company be willing and/or able to sell excess generated power, B.C. Hydro will pay to purchase this electricity. The purchase price is set by B.C. Hydro at its long term marginal cost for producing this electricity in that specific part of the province. This model combines the price of both energy and demand prices into one unit cost per kilowatt-hour. For the Lower Mainland beginning in 1994/95 and over a project life of 20 years, the cost of new firm energy is 3.0¢/kWh. The cost of new capacity is 34 \$/kW/yr. Taking one year to be 8760 hours, the cost of new capacity is converted to 0.39¢/kWh in hourly units. The total cost of this electricity is then the sum of both the energy and capacity costs and is expressed as:

exc1 = 3.39 ¢/kWh

where exc1 = price paid per kWh for purchase by BC Hydro of firm electricity

In general, firm electricity is available only during those hours when the sawmill is operating.

Secondary Electricity:

Secondary electricity is that which is available during off-peak periods and is worth less than firm energy. In this model, secondary electricity is available only during those hours when the sawmill is shutdown. Since the sawmill operates 4160 hours per year out of a possible 6240 hours (which represents a 3 shift operation), secondary electricity will be produced approximately 30% of the total time. Based on this assumption, the value for secondary electricity is expressed as:

exc2 = 1.5 ¢/kWh

5.2.6 Natural Gas Prices

Natural gas prices vary between summer and winter, as well as on the end use. Based on discussions with B.C. Gas, it was found that gas prices may be higher when consumed for heating purposes versus a cogeneration application. This is due mostly to the utilities attempt to begin to promote cogeneration in the province. Four natural gas prices have been accounted for and provided by B.C. Gas. These prices are assumed to be parameters in the model and are stated as follows:

Heating:	1) Winter = $3.35/GJ = gascost1w
	2) Summer = $2.75/GJ = gascost1s
Cogeneration:	1) Winter = $2.50/GJ = gascost2w
	2) Summer = $1.95/GJ = gascost2s

The heating prices, cost per gigajoule consumed, are used to calculate any savings introduced by generating heat from the wood fuel as opposed to purchasing natural gas. The cogeneration prices are used to calculate the cost of providing supplemental fuel to the gas turbine.

5.2.7 Available Wood Waste

The amount of wood waste available is a function of many parameters, but most typically of the size of the sawmill. The size of a sawmill is usually stated as a function of the amount of board feet of dimension cut lumber produced annually. This factor can range anywhere between 50 million board feet per year (50 Mfbm/yr) to 300 million board feet per year (300 Mfbm/yr). Given that the majority of sawmills fall into the small to medium size range, three sawmill sizes will be analyzed: 50 Mfbm/yr; 150 Mfbm/yr; and 250 Mfbm/yr. The amount of wood waste produced annually is directly proportional to the size of the sawmill and was previously calculated in Section 4.4:

50 Mfbm/yr: woodwaste = 26,150 ODT/yr

150 Mfbm/yr: woodwaste = 78,440 ODT/yr

250 Mfbm/yr: woodwaste = 130,750 ODT/yr

where: woodwaste = the variable describing the amount of wood waste produced annually.

ODT/yr = a unit of measure used to describe a quantity of wood with zero moisture content.

5.2.8 Corporate Tax

A corporate tax rate of 43% has been assumed for this model in order to calculate any savings due to capital cost allowances introduced for energy efficient producers of electricity and heat. The most common capital cost allowance is the Class 34 accelerated capital cost allowance. The purpose of the allowance is to encourage industry to install new capital equipment to reduce energy waste, decrease dependence on oil and use renewable energy.

5.2.9 Material Handling

An allowance has been made for the cost of installing wood waste fuel material handling equipment for the cogeneration system. An allowance of $600,000, for Options #1 and #2, has been made for this factor and includes a 1 to 2 day storage bin, screw conveyor and all necessary controls.

Options #1 and #2:

mathand = $600,000

A material handling system for Option #3 was quoted by ABB combustion as part of their overall package.

Option #3:

mathand = $800,000

where: mathand = the variable representing the cost of the material handling equipment.

5.3 LP Variables

There are over 50 variables in each of the models for Options #1, #2 and #3. A detailed description of each variable can be found within the LP model printouts in Appendix B. Some of the key variables are highlighted below:

Mf: Is a measure of the amount of wood waste fuel being processed by the plant in kg/hr. The cost and sizes of other components in the system are a function of this variable.

genelec: Is the amount of electricity being generated by the cogeneration plant. This variable determines the size and cost of various pieces of equipment as well as the amount of excess heat energy available.

heatenergy: Is the yearly savings realized by displacing natural gas for heating purposes and using the heat generated by the cogeneration process.

gasenergy: Is the yearly cost of fuelling the gas turbine in order to achieve the rated turbine inlet temperature.

processheat: Is the amount of heat energy being produced by the cogeneration system.

5.4 Objective Function

The objective of this model is to maximize cashflow (net present value) which is defined as benefits minus costs. The objective function is stated as follows:

Objective Function:

Maximize: Net Present Value (NPV) = benefits - costs

benefits = Σdispcredit*Mf*β_i + Σ electricsave*β_i +
Σexc1*hours1*exelec1*β_i +Σ exc2*hours3*exelec2*β_i +
Σheatenergy*β_i +Σ capital cost allowances

where:

dispcredit = disposal credit

Mf = amount of wood fuel consumed

electricsave = savings realized by self generation of electricity

exc1 = price paid by B.C. Hydro for purchasing firm electricity

exc2 = price paid by B.C. Hydro for purchasing secondary electricity

hours1 = hours of firm electricity generation during sawmill operation

hours3 = hours of secondary electricity generation during sawmill shutdown

exelec1 = amount of firm excess electricity available for sale to B.C. Hydro

exelec2 = amount of secondary excess electricity available for sale to B.C. Hydro

heatenergy= savings in natural gas cost due to self generation of heat energy

β_i = discount factor for year i =1,....,20 years

$$\text{costs} = \text{total} + \Sigma\ \text{gasenergy}*\beta_i + \Sigma\ \text{IT}*\beta_i + \Sigma\ \text{O\&M}*\beta_i$$

where: total = total project capital cost in year 0

gasenergy = cost of supplying natural gas to the gas turbine

IT = yearly cost for insurance and property tax

O&M = yearly operating and maintenance cost

β_i = discount factor for year i i=1,.....,20 years

It is assumed that the full capital cost occurs in year 0 since financing is a very specific variable. Unlike the assumptions of Butler (1984), no loan financing is assumed. This is largely dependent on the owner and their respective bank. In addition, no allowance for depreciation has been made since it has been assumed that the equipment can not be used for any other purpose. The scrap value of the equipment at the end of the project life is zero. This assumption is in line with Butler (1984).

5.5 Constraints

There are over 50 constraints in each of the models for Options #1, #2 and #3. The following description highlights some of the key constraints. A detailed description of each constraint is provided in the LP model printouts in Appendix B.

5.5.1 Electricity Demands and Charges

Three possible cases of electricity generation must be considered in order to determine the optimum generating capacity. For given peak and average electricity demands for the sawmill, these three cases are stated as follows:

Case 1: The net electricity production falls somewhere between the sawmill peak and average demand.

averagedemand ≤ netelec ≤ peakdemand;

```
netelec         = genelec - idfan;
demandsave      = dc*netelec;
energycharge    = ec*hours1*averagedemand;
electricsave    = energycharge + demandsave;
exelec1         = netelec - averagedemand;
exelec2         = netelec;
```

The variable electricsave is a measure of the savings incurred by generating electricity in the range between the peak and average demands.

Case 2: The net electricity production falls somewhere below the sawmill average demand.

netelec ≤ averagedemand;

```
netelec         = genelec - idfan;
```

```
demandsave     = dc*netelec;
electricsave   = ec*hours1*netelec + demandsave;
exelec1        = 0;
exelec2        = netelec;
```

No excess electricity is produced during the sawmill operation in this case and the electric savings is only a portion of the demand and energy charges.

Case 3: The net electricity production falls somewhere above the peakdemand.

```
netelec ≥ peakdemand;
netelec        = genelec - idfan;
demandsave     = dc*peakdemand;
energycharge   = ec*hours1*averagedemand;
electricsave   = energycharge + demandsave;
exelec1        = netelec - averagedemand;
exelec2        = netelec;
```

In this case, the total electricity savings adds up to the entire electric bill of the sawmill. The greatest amount of excess electricity is produced in this case.

5.5.2 Capital Costs

The capital costs of the wood furnace, heat exchanger and gas turbine were outlined in section 4.6. In each case, these costs were a function of the size of the equipment. In addition to the equipment costs, there are other costs associated with designing and constructing the plant. These costs are outlined as follows:

a) The total equipment capital cost:

```
totalcap1      = mathand + furnacecost + turbcost + hxcost;
```

b) Installation of the equipment is 10% of the equipment capital cost:

```
install        = 0.10 * totalcap1;
```

c) The equipment plus installation cost:

```
totalcap2      = totalcap1 + install;
```

d) Ducting for the equipment is 10% of totalcap2:

```
ductwork       = 0.10 * totalcap2;
```

e) Electrical is 14% of the totalcap2:

```
electrical     = 0.14 * totalcap2;
```

f) Instrumentation is 5% of totalcap2:

```
instrument     = 0.05 * totalcap2;
```

g) Piping is 5% of the totalcap2

```
piping         = 0.05 * totalcap2;
```

h) Structural including the building, concrete and civil works is 15% of totalcap2

```
structural     = 0.15 * totalcap2;
```

i) Totalcap3 is the overall equipment, installation and connection costs:

```
totalcap3      = totalcap2 + ductwork + electrical +
                 instrument + piping + structural;
```

j) Engineering costs are 7% of totalcap3:

```
engineering    = 0.07 * totalcap3;
```

k) Construction management is 5% of totalcap3:

```
constructm     = 0.05 * totalcap3;
```

l) Totalcap4 includes all direct and indirect costs:

```
totalcap4      = totalcap3 + engineering + constructm;
```

m) A contingency of 10% is allowed for any potential changes to the design:

contingency = 0.10 * totalcap4

n) The total capital cost of the project results in being approximately 2 to 2.5 times the equipment costs. This is in line with published estimating guidelines in the Means Building Construction Cost Data Handbook.

total = totalcap4 + contingency;

5.5.3 Costs and Savings of Fuel and Heat

Gas Energy Required:

The amount of natural gas required for the gas turbine was outlined in Section 4.5.5.

The associated cost of this gas consumption is expressed as:

gasenergy = (7/12)*0.0036*hours2*gascost2s*gas +
(5/12)*0.0036*hours2*gascost2w*gas

The two parts of this equation represent the amount of gas consumption cost in the summer and winter months (seven out of twelve months in the summer and five out of 12 months in the winter).

Plant Thermal Requirements:

For a given amount of kiln heat used in the sawmill, the cogeneration system must be able to at least meet this requirement. Therefore:

kilnheat ≥ processheat;

where: kilnheat = amount of heat energy required in the sawmill (kW).

processheat = amount of heat energy produced by the cogeneration system.

The physical relationship representing the amount of process heat produced was outlined in Section 4.5.6 for each of Options #1, #2 and #3.

<u>Heat Energy Savings:</u>

Assuming that natural gas is displaced by the available process heat, a savings will result. This is stated as follows:

heatenergy = (7/12)*0.0036*hours2*gascost1s*processheat + (5/12)*0.0036*hours2*gascost1w*processheat

where: heatenergy = represents the dollar savings realized by displacing natural gas.

The first and second parts of this equation represent savings realized in the summer and winter, respectively.

<u>Maximum Available Wood Waste:</u>

As stated previously, the amount of wood waste available is a function of the size of the sawmill.

Mf ≤ woodwaste;

exwood = woodwaste - Mf;

where exwood = the amount of wood waste which is not consumed by the process.

5.5.4 Operating and Maintenance Costs

At the feasibility study level of any project, the operating and maintenance costs are usually taken to be a percentage of the total capital cost. For a steam based plant Butler (1984) assumes this value to be 4% of the total capital cost. These costs will be lower for a plant which does not produce steam as is the case for the three cogeneration systems proposed herein. An operating and maintenance cost of 2.5% of equipment capital has therefore been assumed. Operating and maintenance costs are yearly expenses of the plant.

OM = 0.025 * totalcap3;

The variable totalcap3 does not include contingency.

5.5.5 Insurance and Property Tax

Yearly insurance and property taxes are assumed to be a percentage of the total capital cost less the contingency. Butler (1984) assumes this value to be 2% while the study by H.A. Simons Ltd. assumes a value of 1.5%. This analysis assumes a value of 1.5%.

IT = 0.015 * totalcap3;

5.5.6 Capital Cost Allowance

A class 34 capital cost allowance is applicable for this project since the cogeneration system uses both a source of waste fuel and is energy efficient. This allowance is applicable only if the company has profits in excess of this amount. It is assumed that profits are sufficient for the company to take advantage of this tax credit. The credit has been applied only against the capital cost of the gas turbine and wood furnace. This credit is 25% in year 0, 50% in year1 and 25% in year2. It is calculated as follows:

class34_1 = 0.25*corptax*(equipment capital costs) in year0

class34_2 = 0.50*corptax*(equipment capital costs) in year1

class34_3 = 0.25*corptax*(equipment capital costs) in year2

This tax credit is in line with the assumptions by Butler

(1984) who states an allowance for an Energy Investment Tax Credit.

5.6 Summary of the LP Model Base Case Assumptions:

The Base Case model of this economic analysis attempts to represent a conservative estimate of the current market conditions.

Electricity Prices:

Based on B.C. Hydro Schedule 1200 for general service (35 kW and over)

Demand Charge = \$6.37/kW-demand/month

Energy Charge = 3.12 ¢/kWh

Net energy price = 4.95 ¢/kWh

Electricity Purchase Prices:

Firm electricity purchase prices were assumed for the Lower Mainland over a 20 year term beginning in 1994/95

Cost of New Capacity = \$34/kW/yr

Cost of firm energy = 3.0 ¢/kWh

Net energy purchase price = 3.43 ¢/kWh

Secondary electricity purchase prices were also assumed for the Lower Mainland at approximately 30% availability. This source occurs only during off-peak periods.

Cost of secondary electricity = 1.5 ¢/kWh

Natural Gas Prices:

Based on B.C. Gas rates for use in process heating and cogeneration applications.

Price for process heat in winter = \$3.35/GJ

Price for process heat in summer = \$2.75/GJ

Price for cogeneration in winter = \$2.50/GJ

Price for cogeneration in summer = \$1.95/GJ

Cogeneration prices are based on discussions with B.C. Gas indicating that these gas prices would be evaluated on an individual basis. These prices would potentially be, cost plus delivery.

Discount Rate:

The nominal discount rate was used for calculation of the net present value.

Real discount rate	= 8%
Inflation rate	= 4%
Nominal discount rate	= 12.3%

Wood Waste Disposal Cost:

Based on discussions with operating sawmills, an average cost of disposal of $5/wet tonne was assumed.

Hours of Operation:

The sawmill was assumed to operate on 2 shifts per day, at 8 hours/shift, 260 days per year resulting in 4160 operating hours per year.

The cogeneration plant was assumed to operate continuously 24 hours/day at 90% capacity resulting in 7884 hours per year.

The lumber drying kiln was assumed to operate the same number of hours per year as the cogeneration plant.

Standby electricity rates:

No allowance was made for standby power since it became evident that the majority of optimal solutions in the analysis indicated very low levels of power production and self generation.

Corporate Tax Rate:

A tax rate of 43% was assumed for calculation of the value of capital cost allowances.

Capital Cost Allowance:

A Class 34 capital cost allowance was assumed against the cost of the wood furnace and gas turbine. This allowance occurs in years 0,1 and 2, with respective allowances of 25%, 50% and 25%.

Project Duration:

A project duration of 20 years was assumed. The cost of capital occurs in year 0 (no financing assumptions made) with the resulting revenues and costs beginning in year 1 and ending in year 20.

Size of sawmill:

Three sawmill sizes were evaluated; 50 Mfbm/yr, 150 Mfbm/yr and 250 Mfbm/yr. The size is directly proportional to the amount of wood waste produced.

Sawmill Kiln heat requirements:

Three levels of heating requirements were evaluated; 10,000 kW, 20,000 kW, and 30,000 kW. A typical coastal sawmill with a lumber drying facility would require approximately 10,000 kW of heat while an Interior sawmill would require 20,000 kW. The case of 30,000 kW is unrealistic but was used as an upper bound.

Sawmill electricity requirements:

Sawmill average demand was varied between 3000 and 4000 kW. Peak demand was varied between 4000 and 8000 kW.

5.7 Sensitivity Analysis

A number of parameters were varied from the Base Case in order to establish the effects on the outcome of the optimal solution.

Sensitivity #1: Decrease the real discount rate from 8% to 6%.

Sensitivity #2: Increase both the firm and secondary electricity purchase prices from 3.43 ¢/kWh and 1.5 ¢/kWh, respectively, to the current net electricity prices of 4.95 ¢/kWh.

Sensitivity #3: Increase all electricity prices by 100% to reflect potential electricity prices in other areas of North America.

Sensitivity #4: Double the wood waste disposal cost from \$5/wet tonne to \$10/wet tonne.

Sensitivity #5: Increase natural gas prices by 25%.

6.0 Results of the Economic Model

6.1 Option #1

Each of the system components was evaluated and priced independently. None of these components are in the development stage and all are available for purchase. Natural gas is required for top-up of the turbine inlet temperature since the metal heat exchanger can not achieve this temperature.

Overall Results:

Tables 1 to 6 show the results of the optimum level of electricity generation and the resulting net present value for the base case and all the sensitivity cases. Note that both the optimum electricity generation and the net present value are solved for a case which exactly meets the 'Required' Process Heat, as well as for an 'Optimum' level of Process heat.

In general, the optimum level of process heat meets or exceeds that required, with some exceptions at 20,000 kW and 30,000 kW of heat required. These exceptions only occur when an insufficient amount of wood waste is available to meet the process heat requirement. It is more economical to displace the heat load by burning more wood waste rather than increase the size of the gas turbine for the same application. Process heat is derived from two sources, the turbine exhaust and the high temperature flue gases from the wood furnace.

Wood Waste Utilization:

Tables 1 to 6 also show the results of the optimum level of wood waste usage for a given amount of wood waste availability. In all cases, when the required amount of process heat is generated, only a portion of the wood waste available is utilized.

When the optimum level of process heat is generated, the full amount of wood waste is utilized. Any excess heat produced is waste heat.

Net Present Value and Optimum Electricity Generation:

Tables 1 to 6 represent results for an average sawmill electricity consumption of 3000 kW and a peak demand of 4000 kW. As the peak demand increased, the net present value (NPV) also increased, with very little change to the optimum level of electricity generation. The only exception occurred when the electricity prices were increased by 100%. In this case, the optimum level of electricity generation equalled the peak demand. In all other cases, the optimum level of electricity generation was the minimum required to meet the optimum level of process heat. Based on this observation, very little incentive exists to produce electricity beyond that which is required by the sawmill. However, it is advantageous to at least produce the required amounts of process heat and a portion of the electricity.

Process Heat Demand of 10,000 kW:

Figure 18 is a plot of the results of the optimum level of electricity generation versus the available amount of wood waste, for a sawmill requiring 10,000 kW of process heat. In all cases, except sensitivity case #3, that the optimum level of electricity generation is that which is required to meet and/or exceed the process heat demand. This value increases slightly with the available wood waste since an increasingly larger induced draft fan is required, hence more electricity is consumed.

The results for case #3 indicate that when electricity prices are doubled, the optimum level of electricity generation is set to meet the peak demand.

Figure 19 shows the resulting net present value (NPV) for the same sawmill depicted in Figure 18. The base case represents the most conservative results, with an increasing NPV for each sensitivity case. Sensitivity case #4, increased wood disposal cost, has the greatest impact on the NPV and is the most sensitive to the amount of wood waste available. The base case and the remaining sensitivity cases are indifferent to the amount of wood waste available. This is due to the relatively low amount (10,000 kW) of process heat required by this sawmill. Although much excess heat is produced, credit is only given for that which is required. It is encouraging to see that the NPV is positive in all cases.

Process Heat Demand of 20,000 kW:

Figure 20 shows the optimum level of electricity generation versus the available amount of wood waste, for a sawmill requiring 20,000 kW of process heat. Similar to Figure 18, with the exception of cases #2 and #3, the optimum level of electricity generation is that which is required to meet and/or exceed the process heat requirement.

The first exception, case #2, indicates that at the low level of wood waste availability, a greater amount of electricity generation is required in order to meet the process heat requirement. This quickly tapers off as the amount of available wood waste increases and eventually meets up with the base case results.

The second exception, case #3, indicates that the optimum level of electricity generation is set to meet the peak demand. This is slightly greater at the lower end of the available wood waste since an insufficient amount of wood waste is available to meet the process heat requirement and hence the size of the gas turbine must be increased.

Figure 21 shows the resulting net present value for the same sawmill depicted in Figure 20. Again, the base case is clearly conservative compared with the other sensitivity cases.
Case #4 provides the best results at the higher levels of available wood waste while case #3 provides the best results at the lower levels.

In general, the results steadily increase up to approximately 80,000 ODT/yr of wood waste which is representative of a 150 Mfbm/yr sawmill. After that point, the NPV results begin to taper off. This is due primarily to the steadily increasing optimum amount of process heat production which is a result of the increasing amount of available wood waste. At the low levels of available wood waste, it is difficult to achieve the required 20,000 kW of heat. Once sufficient amounts of wood waste are available, this process heat savings has less of an impact on the NPV.

6.2 Option #2

The ceramic heat exchanger evaluated in this application is currently in the development and testing stage and is not readily available on the market. The cost of the heat exchanger is exceptionally high reflecting its initial design and development costs. As a result, it was difficult to conduct a fair evaluation of this concept in comparison to the equipment utilized by Options #1 and #3.

An additional sensitivity analysis, case #6, was required for this option in order to investigate the effects of the capital cost of the heat exchanger. The cost of the heat exchanger was reduced by 50% in order to simulate a more commonly produced item.

Overall Results:

Tables 7 to 13 show the results for the analysis of Option #2 for the base case and sensitivity cases. Due to the nature of the indirectly fired turbine, it was necessary to increase the minimum size of sawmill evaluated from 50 MMfbm/yr to 100 MMfbm/yr. Insufficient wood waste energy was available from the smaller sawmill to independently run a gas turbine in the size range analyzed and provide process heat. It should also be pointed out that this process derives all its energy from the wood waste and is completely independent of natural gas.

Similar to Option #1, the optimum level of process heat generated meets or exceeds that required.

For a given amount of wood waste available, there is a maximum size of gas turbine which can be indirectly fired since no natural gas is utilized in this option. These maximums are 2043 kW for a 100 MMfbm/yr mill, 3981 kW for a 150 MMfbm/yr mill and 7962 kW for a 250 MMfbm/yr mill. These values are also limited since some process heat must also be made available. In some of the sensitivity cases, it is optimal to generate these maximum amounts of electricity.

Wood Waste Utilization:

Tables 7 to 13 also show the results of the optimum level of wood waste usage for a given amount of wood waste availability. The results indicate that only a portion of the available wood wastes are utilized. This is due to the high cost of the heat exchanger which is directly proportional to the amount of wood waste consumed.

Net Present Value and Optimum Electricity Generation:

Tables 7 to 13 represent a sawmill with an average electricity consumption of 3000 kW and a peak demand of 4000 kW. It was observed that as the peak demand increased the NPV correspondingly increased, with very little change to the optimum level of electricity generation.

Process Heat Demand of 10,000 kW:

Figure 22 is a plot of the results of the optimum level of electricity generation versus the available amount of wood waste, for a sawmill requiring 10,000 kW of process heat. The base case and sensitivity cases #1, #4, #5 and #6 recommend a very minimal optimal electricity generation (less than the sawmill average demand) for production of the optimum amount of process heat required. The results for cases #2 and #3 indicate that the maximum amount of electricity should be generated for the specified amount of wood waste available. This maximum exceeds the sawmill average demand thereby producing surplus electricity.

Figure 23 shows the resulting net present value for the same sawmill depicted in Figure 22. The base case represents the most conservative results, with increasing NPV's for each sensitivity case. Unfortunately, the NPV is negative in all cases. It is evident that the decreased heat exchanger cost, case #6, has a large impact on the results. Should this have been used as the base case, the results of some of the sensitivity analyses would have been shifted upwards into a potentially positive NPV.

Process Heat Demand of 20,000 kW:

Figure 24 is a plot of the results of the optimum level of electricity generation for a sawmill requiring 20,000 kW of process heat. Similar to Figure 22, the optimum level of electricity generation for all cases except #2 and #3 is that which is required to meet the process heat demand. This value is less than the sawmill average demand. On the other hand, the solution recommends generating the maximum amount of electricity possible for cases #2 and #3, which is in excess of the sawmill average demand.

Figure 25 depicts the corresponding NPV for the same sawmill depicted in Figure 24. The majority of NPV values are negative with a few exceptions. Both case #3 and #6 result in positive NPV's over a given range of wood waste availability.

The present costs of this heat exchanger are not favourable for this application. However, once the initial design and development costs have been eliminated, to potentially 50% of the present cost, this technology becomes economically feasible. This system also has the added advantage that it does not rely on natural gas which for many sawmills is difficult and/or impossible to acquire due to geographical location.

6.3 Option #3

The entire system with the exception of the gas turbine has been quoted as a turnkey plant by ABB Combustion. This has lowered the overall cost of the system when compared to the individual pricing scheme for Option #1 and #2. It is also important to note that the technology is readily available for all components in this system. Compared with Option #1, a smaller amount of natural gas is required since the in-bed heat exchanger operates at higher temperatures.

Overall Results:

Tables 14 to 19 show the results of the optimum level of electricity generation and the resulting net present value for the base case and all the sensitivity cases. As before, both the optimum level of electricity generation and NPV are solved for both a case which exactly meets the 'Required' process heat, as well as for an 'Optimum' level of process heat production. It is interesting to see that in most cases the required amount of process heat is equal to the optimum level of process heat. It is also encouraging that the NPV is positive in all cases.

Wood Waste Utilization:

Tables 14 to 19 show results for the optimum level of wood waste usage. A minimal amount of wood waste is used. The optimal solution does not recommend full utilization of the wastes as in Option #1. This is due to the very efficient means by which the in-bed heat exchanger recovers energy for the gas turbine. Since the size and cost of the system are directly proportional to the amount of wood waste consumed, it is recommended to keep the system as small as possible to meet the process heat requirement. Inherent to this high efficiency is an overall increase in the optimal size of the turbine generator. In all cases, the turbine generators are considerably larger than in Option #1. This is also due to the higher fan operating requirements of the fluidized bed system. There is however, very minimal electricity generated above and beyond that which is required for both the sawmill and cogeneration plant once again suggesting that it is not very attractive to generate electricity for sale.

Process Heat Demand of 10,000 kW:

Figure 26 is a plot of the results of the optimum level of electricity generation versus the available amount of wood waste, for a sawmill requiring 10,000 kW of process heat. Note that in all cases, with the exception of case #3, that the optimum level of electricity generation is that which is exactly required to meet the process heat requirement. It also does not change with the amount of wood waste available since, as mentioned previously, the optimal amount of wood waste usage has been kept at a minimum. Case #3 on the other hand recommends a much higher level of electricity generation, above what is required to meet the process heat requirement. This is due to the very high electricity prices which were modelled for this case.

Figure 27 shows the resulting net present value for the same sawmill depicted in Figure 26. As expected, the base case is clearly the most conservative. The case which has the greatest impact on the results is, once again, case #3. The NPV values do not change with the amount of available wood waste since the solution recommends using only the minimum amount of wood waste available to meet the process heat requirement.

Process Heat Demand of 20,000 kW:

Figure 28 is a plot of the results of the optimum level of electricity generation versus the available amount of wood waste, for a sawmill requiring 20,000 kW of process heat. Note that in all cases at the lower end of available wood waste, the optimum level of electricity generation is the same in order to meet the process heat demand. Once the available amount of wood waste increases, the optimum levels of electricity generation begin to vary for each case. Case #4 recommends the lowest levels of electricity generation and the highest levels of wood waste usage. The base case and cases #1 and #5 recommend slightly higher levels of electricity generation but lower levels of wood waste usage. Cases #2 and #3 recommend the highest levels of electricity generation with minimum levels of wood waste usage. In all cases the process heat requirement is exactly met with varying combinations of wood waste usage and electricity generation.

Figure 29 is a plot of the resulting net present value for the same sawmill depicted in Figure 28. As expected, the base case is clearly conservative with case #3 returning the highest NPV. Case #4 shows an increasing NPV over a range of available wood waste since the actual wood waste usage is increasing.

6.4 Comparison of the Base Case Analysis of Options #1, #2, #3

Figure 30 compares the Base Case results of the optimum level of electricity generation for Options #1,#2, and #3 for both 10,000 kW and 20,000 kW of process heat. In general, the results for Option #3 recommend the highest levels of electricity generation whereas Options #1 and #2 have very similar results, around 1 MW.

It is important to note that in all cases, the results for Option #3 exactly meet the process heat requirements. Options #1 and #2 do not necessarily meet the process heat requirements being either less than or greater than what is required. In those cases in which the optimum process heat is less than the required process heat, it would be difficult from a practical viewpoint to introduce a new source of heat, or maintain a portion of the existing heat source, into the system. This would slightly favour Option #3.

Figure 31 compares the Net Present Value of the Base Case for Options #1, #2, and #3. It is clear that at the present time Option #2 is not feasible due to the very high developmental costs of the ceramic heat exchanger.

At 10,000 kW of process heat both Options #1 and #3 have very similar results. This trend changes as the process heat is increased to 20,000 kW. At the low end of available wood waste, Option #3 is more favourable. But as the amount of wood waste increases, Option #1 becomes increasingly more competitive and eventually surpasses Option #3 to become the most favourable option.

6.5 Payback Periods

Payback periods were calculated based on a sawmill producing 80,000 ODT/yr of wood waste which would correspond to a sawmill size of approximately 150 Mfbm/yr. The results are shown for the Base Case only since this most closely models the current market conditions in British Columbia.

The results for Option #1 are shown on Figures 32 and 33. Figure 32 indicates an 18 year payback for a sawmill requiring 10,000 kW of process heat, while Figure 33 indicates a payback of 7 years for a process heat requirement of 20,000 kW. These results are not surprising since greater savings will be realized when a larger amount of process heat is displaced. However, this trend begins to decrease when a greater amount of process heat is displaced due to the increasing capital cost.

The results for Option #2 are shown on Figures 34 and 35. It appears that no positive cash flow is reached in 20 years for

10,000 kW or 20,000 kW of process heat. This was to be expected due to the very high capital cost of the ceramic heat exchanger.

The results for Option #3 are shown of Figures 36 and 37. Figure 36 indicates a 15.5 year payback for a sawmill requiring 10,000 kW of process heat while Figure 37 indicates a 12 year payback for 20,000 kW of process heat.

In general, Option #3 is favourable at the low end of both process heat requirements and available wood waste. It is quickly surpassed by Option #1 at the higher process heat and wood waste availability. This trend is due largely to the observation that it is more attractive to displace the process heat required rather than the electricity required. This is seen by the analysis results which indicate that the optimum level of electricity generation is that which is only required to meet the process heat demand, while in most cases the optimum process heat produced meets or exceeds that required.

It is important to note that the fluidized bed system, Option #3, is more efficient in transferring thermal energy to the turbine due to the in-bed heat exchanger. Therefore, less energy is 'wasted' and more is available for the process heat application. On the other hand with Option #1, less energy is transferred to the turbine due to the relatively inefficient external heat exchanger, and more is available for the process heat. Because more energy is 'wasted' in Option #1, the optimum size of the gas turbine is much smaller compared with the more efficient usage of Option #3 which dictates a larger gas turbine. Based on the current economic climate, the results have indicated smaller electricity production and greater process heat production. Therefore Option #1 is more attractive.

Option #2 is not economically attractive at this time due to the high heat exchanger capital cost. The ceramic heat exchanger does offer the very significant advantage that it's operating temperatures are not effectively limited, and that an additional source of energy is not required.

7.0 Conclusions

The overall objective of this study was to determine the optimum allocation of wood waste resources in a typical sawmill environment for the production of thermal and electrical energy, also known as cogeneration. Both physical and economic conditions were utilized in a linear programming model to determine this optimum. Three slightly varying systems were analyzed and it was found that in each case the resulting trends were similar with some having advantages over the others. The method of using linear programming for this purpose appears to provide feasible results which are in line with those achieved by the aforementioned authors.

Option #1 is technically feasible with the key equipment items readily available on the market. Option #3 is technically feasible and is available from ABB Combustion as a turnkey unit. This is an added advantage since the system can be purchased complete. Both Options #1 and #3 rely on a source of natural gas.

Although Option #2 is also technically feasible, the ceramic heat exchanger is not yet available on the market. This has drastically increased its capital cost making it economically unattractive for this application. The major benefits are that it does not rely on a source of natural gas and the operating temperature limit is able to satisfy turbine inlet conditions.

The dependence on natural gas by Options #1 and #3 could be eliminated by using a turbine which is fired at lower temperatures or one which is specifically designed for hot air application. At the present time, with relatively low natural gas prices, this does not appear to be a significant advantage.

It was determined that it is economically feasible to displace the process heat requirements with cogeneration by maximizing the heat production and minimizing the power production. This conclusion is directly in line with that determined by Hu (1985). Hu stated that the optimal solution often occurs at or above the Thermal-match case when cash flow is to be maximized.

In addition, it is economically feasible to efficiently burn the entire volume of wood waste produced by the sawmill to generate kiln heat. This conclusion is not offset by the fact the amount of heat generated is in excess of that which is required by the process. The surplus heat is effectively wasted but can be made available for future power generation.

It is not attractive at this time to generate excess electricity for sale. The production and sale of electricity becomes more attractive when the purchase price is increased to approximately 5 ¢/kWh, as was shown by sensitivity case #2.

The Net Present Value of the project increases as greater amounts of process heat are displaced. Option #3 is favourable at both the lower process heat requirement and available wood waste. Option #1 becomes more attractive as the process heat and available wood waste are increased.

Payback periods range from 7 to 18 years and decrease as greater amounts of process heat are displaced. Option #3 offers the best payback period at lower levels of process heat while Option #1 is advantageous at higher levels of process heat. Option #2 does not reach a positive cashflow in the established project term.

Table 1: Base Case Results for Option #1

SAWMILL SIZE (MMfbm/yr)	AVAILABLE WOOD WASTE (ODT/yr)	PROCESS HEAT (kW)		OPTIMUM ELECTRICITY (kW)		WOOD WASTE UTILIZATION (ODT/yr)		NET PRESENT VALUE (1994$)	
		Required Heat	Optimum Heat	Required Heat	Optimum Heat	Required Heat	Optimum Heat	Required Heat	Optimum Heat
50	26,147	10,000	9,943	858	830	26,147	26,147	$52,475	$58,767
150	78,440	10,000	27,050	830	1,020	26,320	78,440	$79,929	$256,685
250	130,734	10,000	44,111	830	1,212	26,320	130,734	$79,929	$433,551
50	26,147	20,000	9,943	6,050	830	26,147	26,147	($1,590,000)	$58,767
150	78,440	20,000	27,050	942	1,020	56,972	78,440	$6,420,000	$6,490,000
250	130,734	20,000	44,111	942	1,212	56,972	130,734	$6,420,000	$6,670,000
50	26,147	30,000	9,943	11,243	830	26,147	26,147	($4,860,000)	$58,767
150	78,440	30,000	27,050	2,552	1,020	78,440	78,440	$10,500,000	$10,900,000
250	130,734	30,000	44,111	1,054	1,212	87,622	130,734	$12,800,000	$12,900,000

Table 2: Sensitivity Case #1, Decreased Discount Rate; Results for Option #1

SAWMILL SIZE (MMfbm/yr)	AVAILABLE WOOD WASTE (ODT/yr)	PROCESS HEAT (kW)		OPTIMUM ELECTRICITY (kW)		WOOD WASTE UTILIZATION (ODT/yr)		NET PRESENT VALUE (1994$)	
		Required Heat	Optimum Heat	Required Heat	Optimum Heat	Required Heat	Optimum Heat	Required Heat	Optimum Heat
50	26,147	10,000	9943	858	830	26147	26147	$1,020,000	$1,020,000
150	78,440	10,000	27050	830	1020	26320	78440	$1,040,000	$1,640,000
250	130,734	10,000	44111	830	1212	26320	130734	$1,040,000	$2,230,000
50	26,147	20,000	9943	6050	830	26147	26147	$250,638	$1,020,000
150	78,440	20,000	27050	941	1020	56972	78440	$8,520,000	$8,770,000
250	130,734	20,000	44111	941	1212	56972	130734	$8,520,000	$9,360,000
50	26,147	30,000	9943	11243	830	26147	26147	($2,390,000)	$1,020,000
150	78,440	30,000	27050	2552	1020	78440	78440	$13,700,000	$13,800,000
250	130,734	30,000	44111	1054	1212	87622	130734	$16,000,000	$16,500,000

Table 3: Sensitivity Case #2, Electricity Purchase Price of 4.95 ¢/kWh; Results for Option #1

SAWMILL SIZE (MMfbm/yr)	AVAILABLE WOOD WASTE (ODT/yr)	PROCESS HEAT (kW)		OPTIMUM ELECTRICITY (kW)		WOOD WASTE UTILIZATION (ODT/yr)		NET PRESENT VALUE (1994$)	
		Required Heat	Optimum Heat	Required Heat	Optimum Heat	Required Heat	Optimum Heat	Required Heat	Optimum Heat
50	26,147	10,000	10,000	858	858	26,147	26,147	$698,448	$698,448
150	78,440	10,000	27,050	830	1,020	26,320	78,440	$700,810	$877,565
250	130,734	10,000	44,111	830	1,212	26,320	130,734	$700,810	$1,050,000
50	26,147	20,000	20,000	6,050	6,050	26,147	26,147	$4,550,000	$4,550,000
150	78,440	20,000	27,050	941	1,020	56,972	78,440	$7,040,000	$7,110,000
250	130,734	20,000	44,111	941	1,212	56,972	130,734	$7,040,000	$7,290,000
50	26,147	30,000	30,000	11,243	11,243	26,147	26,147	$7,830,000	$7,830,000
150	78,440	30,000	30,000	2,552	2,552	78,440	78,440	$12,500,000	$12,500,000
250	130,734	30,000	44,111	1,054	1,212	87,622	130,734	$13,400,000	$13,500,000

Table 4: Sensitivity Case #3, 100% Increase in Electricity Prices; Results for Option #1

SAWMILL SIZE (MMfbm/yr)	AVAILABLE WOOD WASTE (ODT/yr)	PROCESS HEAT (kW)		OPTIMUM ELECTRICITY (kW)		WOOD WASTE UTILIZATION (ODT/yr)		NET PRESENT VALUE (1994$)	
		Required Heat	Optimum Heat	Required Heat	Optimum Heat	Required Heat	Optimum Heat	Required Heat	Optimum Heat
50	26,147	10,000	17,090	858	4,540	26,147	26,147	$1,370,000	$2,720,000
150	78,440	10,000	34,197	858	4,732	26,147	78,440	$1,350,000	$2,810,000
250	130,734	10,000	51,258	858	4,923	26,147	130,734	$1,350,000	$2,990,000
50	26,147	20,000	20,000	6,050	6,050	26,147	26,147	$8,160,000	$8,160,000
150	78,440	20,000	34,197	4,572	4,732	35,064	78,440	$8,890,000	$9,040,000
250	130,734	20,000	51,258	4,572	4,923	35,064	130,734	$8,890,000	$9,220,000
50	26,147	30,000	30,000	11,243	11,243	26,147	26,147	$11,700,000	$11,700,000
150	78,440	30,000	34,197	4,684	4,732	65,715	78,440	$15,200,000	$15,300,000
250	130,734	30,000	51,258	4,684	4,923	65,715	130,734	$15,200,000	$15,500,000

Table 5: Sensitivity Case #4, Increased Wood Waste Disposal Cost; Results for Option #1

SAWMILL SIZE (MMfbm/yr)	AVAILABLE WOOD WASTE (ODT/yr)	PROCESS HEAT (kW)		OPTIMUM ELECTRICITY (kW)		WOOD WASTE UTILIZATION (ODT/yr)		NET PRESENT VALUE (1994$)	
		Required Heat	Optimum Heat	Required Heat	Optimum Heat	Required Heat	Optimum Heat	Required Heat	Optimum Heat
50	26,147	10,000	9943	858	829	26,147	26,147	$1,960,000	$1,970,000
150	78,440	10,000	27050	830	1,020	26,147	78,440	$2,000,000	$6,000,000
250	130,734	10,000	44111	830	1,212	26,320	130,734	$2,000,000	$10,000,000
50	26,147	20,000	9943	6,050	829	26,147	26,147	$323,880	$1,970,000
150	78,440	20,000	27050	942	1,020	56,972	78,440	$10,600,000	$12,200,000
250	130,734	20,000	44111	942	1,212	56,972	130,734	$10,600,000	$16,200,000
50	26,147	30,000	9943	11,243	829	26,147	26,147	($2,950,000)	$1,970,000
150	78,440	30,000	27050	2,552	1,020	78,440	78,440	$16,300,000	$16,600,000
250	130,734	30,000	44111	1,054	1,212	87,622	130,734	$19,200,000	$22,500,000

Table 6: Sensitivity Case #5, Increased Natural Gas Prices; Results for Option #1

SAWMILL SIZE (MMfbm/yr)	AVAILABLE WOOD WASTE (ODT/yr)	PROCESS HEAT (kW)		OPTIMUM ELECTRICITY (kW)		WOOD WASTE UTILIZATION (ODT/yr)		NET PRESENT VALUE (1994$)	
		Required Heat	Optimum Heat	Required Heat	Optimum Heat	Required Heat	Optimum Heat	Required Heat	Optimum Heat
50	26,147	10,000	9,943	858	829	26,147	26,147	$1,340,000	$1,350,000
150	78,440	10,000	27,050	830	1,020	26,320	78,440	$1,370,000	$1,500,000
250	130,734	10,000	44,111	830	1,212	26,320	130,734	$1,370,000	$1,600,000
50	26,147	20,000	9,943	6,050	829	26,147	26,147	($397,897)	$1,350,000
150	78,440	20,000	27,050	942	1,020	56,972	78,440	$9,240,000	$9,300,000
250	130,734	20,000	44,111	942	1,212	56,972	130,734	$9,240,000	$9,400,000
50	26,147	30,000	9,943	11,243	829	26,147	26,147	($3,770,000)	$1,350,000
150	78,440	30,000	27,050	2,552	1,020	78,440	78,440	$14,400,000	$14,800,000
250	130,734	30,000	44,111	1,054	1,212	87,622	130,734	$17,100,000	$17,200,000

Table 7: Base Case Results for Option #2

SAWMILL SIZE (MMfbm/yr)	AVAILABLE WOOD WASTE (ODT/yr)	PROCESS HEAT (kW)		OPTIMUM ELECTRICITY (kW)		WOOD WASTE UTILIZATION (ODT/yr)		NET PRESENT VALUE (1994$)	
		Required Heat	Optimum Heat	Required Heat	Optimum Heat	Required Heat	Optimum Heat	Required Heat	Optimum Heat
100	52,294	10,000	15,666	–	925	–	52,294	–	($12,400,000)
150	78,440	10,000	15,666	–	925	–	52,294		($12,400,000)
250	130,734	10,000	15,666	6,030	925	52,294	52,294	($13,600,000)	($12,400,000)
100	52,294	20,000	15,666	–	925	–	52,294	–	($8,890,000)
150	78,440	20,000	20,000	975	975	66,037	66,037		($6,840,000)
250	130,734	20,000	20,000	975	975	66,037	66,037	($6,840,000)	($6,840,000)
100	52,294	30,000	15,666	–	925	–	52,294	–	($8,890,000)
150	78,440	30,000	23,950	–	1,020	–	78,440	–	($4,980,000)
250	130,734	30,000	30,000	1,091	1,091	97,767	97,767	($2,120,000)	($2,120,000)

Table 8: Sensitivity Case #1, Decreased Discount Rate; Results for Option #2

SAWMILL SIZE (MMfbm/yr)	AVAILABLE WOOD WASTE (ODT/yr)	PROCESS HEAT (kW)		OPTIMUM ELECTRICITY (kW)		WOOD WASTE UTILIZATION (ODT/yr)		NET PRESENT VALUE (1994$)	
		Required Heat	Optimum Heat	Required Heat	Optimum Heat	Required Heat	Optimum Heat	Required Heat	Optimum Heat
100	52,294	10,000	14,424	–	2,043	–	52,294	–	($11,400,000)
150	78,440	10,000	12,273	–	3,981	–	52,294	–	($11,300,000)
250	130,734	10,000	11,546	6,030	4,635	52,294	52,294	($11,700,000)	($11,200,000)
100	52,294	20,000	15,666	–	925	–	52,294	–	($7,420,000)
150	78,440	20,000	20,000	975	975	66,041	66,041	($4,890,000)	($4,890,000)
250	130,734	20,000	20,000	975	975	66,041	66,041	($4,890,000)	($4,890,000)
100	52,294	30,000	15,666	–	925	–	52,294	–	($7,420,000)
150	78,440	30,000	23,950	–	1,020	–	78,440	–	($2,580,000)
250	130,734	30,000	30,000	1,091	1,091	97,767	97,767	$953,226	$953,226

Table 9: Sensitivity Case #2, Electricity Purchase Price of 4.95 ¢/kWh; Results for Option #2

SAWMILL SIZE (MMfbm/yr)	AVAILABLE WOOD WASTE (ODT/yr)	PROCESS HEAT (kW)		OPTIMUM ELECTRICITY (kW)		WOOD WASTE UTILIZATION (ODT/yr)		NET PRESENT VALUE (1994$)	
		Required Heat	Optimum Heat	Required Heat	Optimum Heat	Required Heat	Optimum Heat	Required Heat	Optimum Heat
100	52,294	10,000	14,424	–	2,043	–	52,294	–	($11,000,000)
150	78,440	10,000	12,273	–	3,981	–	52,294	–	($9,410,000)
250	130,734	10,000	10,000	7,962	7,962	59,008	59,008	($6,620,000)	($6,620,000)
100	52,294	20,000	14,424	–	2,043	–	52,294	–	($8,300,000)
150	78,440	20,000	20,000	3,981	3,981	76,493	76,493	($4,440,000)	($4,440,000)
250	130,734	20,000	20,000	7,962	7,962	90,335	90,335	($1,960,000)	($1,960,000)
100	52,294	30,000	14,424	–	2,043	–	52,294	–	($8,300,000)
150	78,440	30,000	20,665	–	3,981	–	78,440	–	($4,130,000)
250	130,734	30,000	30,000	7,962	7,962	121,658	121,658	$2,690,000	$2,690,000

Table 10: Sensitivity Case #3, 100% Increase in Electricity Prices; Results for Option #2

SAWMILL SIZE (MMfbm/yr)	AVAILABLE WOOD WASTE (ODT/yr)	PROCESS HEAT (kW)		OPTIMUM ELECTRICITY (kW)		WOOD WASTE UTILIZATION (ODT/yr)		NET PRESENT VALUE (1994$)	
		Required Heat	Optimum Heat	Required Heat	Optimum Heat	Required Heat	Optimum Heat	Required Heat	Optimum Heat
100	52,294	10,000	14,424	–	2,043	–	52,294	–	($9,380,000)
150	78,440	10,000	12,273	–	3,981	–	52,294	–	($6,230,000)
250	130,734	10,000	10,000	7,962	7,962	59,008	59,008	($2,930,000)	($2,930,000)
100	52,294	20,000	14,424	–	2,043	–	52,294	–	($6,620,000)
150	78,440	20,000	20,000	3,981	3,981	76,493	76,493	($1,310,000)	($1,310,000)
250	130,734	20,000	20,000	7,962	7,962	90,335	90,335	$1,730,000	$1,730,000
100	52,294	30,000	14,424	–	2,043	–	52,294	–	($6,620,000)
150	78,440	30,000	20,665	–	3,981	–	78,440	–	($1,000,000)
250	130,734	30,000	30,000	7,962	7,962	121,658	121,658	$6,380,000	$6,380,000

Table 11: Sensitivity Case #4, Increased Wood Waste Disposal Cost; Results for Option #2

SAWMILL SIZE (MMfbm/yr)	AVAILABLE WOOD WASTE (ODT/yr)	PROCESS HEAT (kW)		OPTIMUM ELECTRICITY (kW)		WOOD WASTE UTILIZATION (ODT/yr)		NET PRESENT VALUE (1994$)	
		Required Heat	Optimum Heat	Required Heat	Optimum Heat	Required Heat	Optimum Heat	Required Heat	Optimum Heat
100	52,294	10,000	15,666	–	925	–	52,294	–	($8,590,000)
150	78,440	10,000	23,950	–	1,020	–	78,440	–	($7,930,000)
250	130,734	10,000	40,430	6,030	1,212	52,294	130,156	($9,800,000)	($6,610,000)
100	52,294	20,000	15,666	–	925	–	52,294	–	($5,060,000)
150	78,440	20,000	23,950	975	1,020	66,037	78,440	($2,010,000)	($1,690,000)
250	130,734	20,000	40,430	975	1,212	66,037	130,734	($2,010,000)	($370,805)
100	52,294	30,000	15,666	–	925	–	52,294	–	($5,060,000)
150	78,440	30,000	23,950	–	1,020	–	78,440	–	$766,357
250	130,734	30,000	40,430	1,091	1,212	97,767	130,734	$5,020,000	$5,860,000

Table 12: Sensitivity Case #5, Increased Natural Gas Prices; Results for Option #2

SAWMILL SIZE (MMfbm/yr)	AVAILABLE WOOD WASTE (ODT/yr)	PROCESS HEAT (kW)		OPTIMUM ELECTRICITY (kW)		WOOD WASTE UTILIZATION (ODT/yr)		NET PRESENT VALUE (1994$)	
		Required Heat	Optimum Heat	Required Heat	Optimum Heat	Required Heat	Optimum Heat	Required Heat	Optimum Heat
100	52,294	10,000	15,666	–	925	–	52,294	–	($10,900,000)
150	78,440	10,000	20,000	–	925	–	52,294	–	($10,900,000)
250	130,734	10,000	30,000	6,030	925	52,294	52,294	($12,100,000)	($10,900,000)
100	52,294	20,000	15,666	–	925	–	52,294	–	($6,440,000)
150	78,440	20,000	20,000	975	975	66,037	66,037	($3,720,000)	($3,720,000)
250	130,734	20,000	20,000	975	975	66,037	66,037	($3,720,000)	($3,720,000)
100	52,294	30,000	15,666	–	925	–	52,294	–	($6,440,000)
150	78,440	30,000	20,000	–	1,020	–	78,440	–	($1,230,000)
250	130,734	30,000	30,000	1,091	1,091	97,767	97,767	$2,570,000	$2,570,000

Table 13: Sensitivity Case #6, Decreased Ceramic Heat Exchanger Cost; Results for Option #2

SAWMILL SIZE (MMfbm/yr)	AVAILABLE WOOD WASTE (ODT/yr)	PROCESS HEAT (kW)		OPTIMUM ELECTRICITY (kW)		WOOD WASTE UTILIZATION (ODT/yr)		NET PRESENT VALUE (1994$)	
		Required Heat	Optimum Heat	Required Heat	Optimum Heat	Required Heat	Optimum Heat	Required Heat	Optimum Heat
100	52,294	10,000	15,666	–	925	–	52,294	–	($5,180,000)
150	78,440	10,000	15,666	–	925	–	52,294	–	($5,180,000)
250	130,734	10,000	15,666	6,030	925	52,294	52,294	($6,380,000)	($5,180,000)
100	52,294	20,000	15,666	–	925	–	52,294	–	($1,640,000)
150	78,440	20,000	20,000	975	975	66,037	66,037	$850,211	$850,211
250	130,734	20,000	30,000	975	975	66,037	66,037	$850,211	$850,211
100	52,294	30,000	15,666	–	925	–	52,294	–	($1,640,000)
150	78,440	30,000	23,950	1,020	1,020	78,440	78,440	$3,120,000	$3,120,000
250	130,734	30,000	30,000	1,091	1,091	97,767	97,767	$6,600,000	$6,600,000

Table 14: Base Case Results for Option #3

SAWMILL SIZE (MMfbm/yr)	AVAILABLE WOOD WASTE (ODT/yr)	PROCESS HEAT (kW)		OPTIMUM ELECTRICITY (kW)		WOOD WASTE UTILIZATION (ODT/yr)		NET PRESENT VALUE (1994$)	
		Required Heat	Optimum Heat	Required Heat	Optimum Heat	Required Heat	Optimum Heat	Required Heat	Optimum Heat
50	26,147	10,000	10,000	1,685	1,685	26,147	26,147	$595,262	$595,262
150	78,440	10,000	10,000	1,685	1,685	26,147	26,147	$595,262	$595,262
250	130,734	10,000	10,000	1,685	1,685	26,147	26,147	$595,262	$595,262
50	26,147	20,000	20,000	5,804	5,804	26,147	26,147	$2,600,000	$2,600,000
150	78,440	20,000	20,000	4,750	4,750	37,461	37,461	$2,710,000	$2,710,000
250	130,734	20,000	20,000	4,750	4,750	37,461	37,461	$2,710,000	$2,710,000
50	26,147	30,000	25,240	–	7,962	26,147	26,147	–	$2,950,000
150	78,440	30,000	30,000	5,082	5,082	78,143	78,143	$3,780,000	$3,780,000
250	130,734	30,000	30,000	5,082	5,082	78,143	78,143	$3,780,000	$3,780,000

Table 15: Sensitivity Case #1, Decreased Discount Rate; Results for Option #3

SAWMILL SIZE (MMfbm/yr)	AVAILABLE WOOD WASTE (ODT/yr)	PROCESS HEAT (kW)		OPTIMUM ELECTRICITY (kW)		WOOD WASTE UTILIZATION (ODT/yr)		NET PRESENT VALUE (1994$)	
		Required Heat	Optimum Heat	Required Heat	Optimum Heat	Required Heat	Optimum Heat	Required Heat	Optimum Heat
50	26,147	10,000	10,000	1,685	1,685	26,147	26,147	$1,700,000	$1,700,000
150	78,440	10,000	10,000	1,685	1,685	26,147	26,147	$1,700,000	$1,700,000
250	130,734	10,000	10,000	1,685	1,685	26,147	26,147	$1,700,000	$1,700,000
50	26,147	20,000	20,000	5,803	5,803	26,147	26,147	$4,880,000	$4,880,000
150	78,440	20,000	20,000	4,750	4,750	37,461	37,461	$5,010,000	$5,010,000
250	130,734	20,000	20,000	4,750	4,750	37,461	37,461	$5,010,000	$5,010,000
50	26,147	30000	25,240	–	7,962	26,147	26,147	–	$5,740,000
150	78,440	30000	30,000	5,082	5,082	78,149	78,149	$7,120,000	$7,120,000
250	130,734	30000	30,000	5,082	5,082	78,149	78,149	$7,120,000	$7,120,000

Table 16: Sensitivity Case #2, Electricity Purchase Price of 4.95 ¢/kWh; Results for Option #3

SAWMILL SIZE (MMfbm/yr)	AVAILABLE WOOD WASTE (ODT/yr)	PROCESS HEAT (kW)		OPTIMUM ELECTRICITY (kW)		WOOD WASTE UTILIZATION (ODT/yr)		NET PRESENT VALUE (1994$)	
		Required Heat	Optimum Heat	Required Heat	Optimum Heat	Required Heat	Optimum Heat	Required Heat	Optimum Heat
50	26,147	10,000	10,000	1,685	1,685	26,147	26,147	$1,840,000	$1,840,000
150	78,440	10,000	10,000	1,685	1,685	26,147	26,147	$1,840,000	$1,840,000
250	130,734	10,000	10,000	1,685	1,685	26,147	26,147	$1,840,000	$1,840,000
50	26,147	20,000	20,000	5,803	5,803	26,147	26,147	$8,280,000	$8,280,000
150	78,440	20,000	20,000	5,803	5,803	26,147	26,147	$8,280,000	$8,280,000
250	130,734	20,000	20,000	5,803	5,803	26,147	26,147	$8,280,000	$8,280,000
50	26,147	30,000	25,240	–	7,962	26,147	26,147	–	$11,400,000
150	78,440	30,000	30,000	7,962	7,962	47,210	47,210	$11,700,000	$11,700,000
250	130,734	30,000	30,000	7,962	7,962	47,210	47,210	$11,700,000	$11,700,000

Table 17: Sensitivity Case #3, 100% Increase in Electricity Prices; Results for Option #3

SAWMILL SIZE (MMfbm/yr)	AVAILABLE WOOD WASTE (ODT/yr)	PROCESS HEAT (kW)		OPTIMUM ELECTRICITY (kW)		WOOD WASTE UTILIZATION (ODT/yr)		NET PRESENT VALUE (1994$)	
		Required Heat	Optimum Heat	Required Heat	Optimum Heat	Required Heat	Optimum Heat	Required Heat	Optimum Heat
50	26,147	10,000	17,217	1,685	4,657	26,147	26,147	$3,140,000	$5,690,000
150	78,440	10,000	17,217	1,685	4,657	26,147	26,147	$3,140,000	$5,690,000
250	130,734	10,000	17,217	1,685	4,657	26,147	26,147	$3,140,000	$5,690,000
50	26,147	20,000	20,000	5,803	5,803	26,147	26,147	$11,900,000	$11,900,000
150	78,440	20,000	20,000	5,803	5,803	26,147	26,147	$11,900,000	$11,900,000
250	130,734	20,000	20,000	5,803	5,803	26,147	26,147	$11,900,000	$11,900,000
50	26,147	30,000	25,240	–	7,962	26,147	26,147	–	$15,000,000
150	78,440	30,000	30,000	7,962	7,962	47,210	47,210	$15,300,000	$15,300,000
250	130,734	30,000	30,000	7,962	7,962	47,210	47,210	$15,300,000	$15,300,000

Table 18: Sensitivity Case #4, Increased Wood Waste Disposal Cost; Results for Option #3

SAWMILL SIZE (MMfbm/yr)	AVAILABLE WOOD WASTE (ODT/yr)	PROCESS HEAT (kW)		OPTIMUM ELECTRICITY (kW)		WOOD WASTE UTILIZATION (ODT/yr)		NET PRESENT VALUE (1994$)	
		Required Heat	Optimum Heat	Required Heat	Optimum Heat	Required Heat	Optimum Heat	Required Heat	Optimum Heat
50	26,147	10,000	10,000	1,685	1,685	26,147	26,147	$2,510,000	$2,510,000
150	78,440	10,000	10,000	1,006	1,006	33,438	33,438	$2,800,000	$2,800,000
250	130,734	10,000	10,000	1,006	1,006	33,438	33,438	$2,800,000	$2,800,000
50	26,147	20,000	20,000	5,803	5,803	26,147	26,147	$4,510,000	$4,510,000
150	78,440	20,000	20,000	1,338	1,338	74,122	74,122	$6,850,000	$6,850,000
250	130,734	20,000	20,000	1,338	1,338	74,122	74,122	$6,850,000	$6,850,000
50	26,147	30,000	25,240	–	7,962	26,147	26,147	–	$4,860,000
150	78,440	30,000	30,000	5,042	5,042	78,583	78,583	$9,510,000	$9,510,000
250	130,734	30,000	30,000	1,670	1,670	114,807	114,807	$10,900,000	$10,900,000

Table 19: Sensitivity Case #5, Increased Natural Gas Prices; Results for Option #3

SAWMILL SIZE (MMfbm/yr)	AVAILABLE WOOD WASTE (ODT/yr)	PROCESS HEAT (kW)		OPTIMUM ELECTRICITY (kW)		WOOD WASTE UTILIZATION (ODT/yr)		NET PRESENT VALUE (1994$)	
		Required Heat	Optimum Heat	Required Heat	Optimum Heat	Required Heat	Optimum Heat	Required Heat	Optimum Heat
50	26,147	10,000	10,000	1,685	1,685	26,147	26,147	$1,820,000	$1,820,000
150	78,440	10,000	10,000	1,685	1,685	26,147	26,147	$1,820,000	$1,820,000
250	130,734	10,000	10,000	1,685	1,685	26,147	26,147	$1,820,000	$1,820,000
50	26,147	20,000	20,000	5,803	5,803	26,147	26,147	$4,570,000	$4,570,000
150	78,440	20,000	20,000	4,750	4,750	37,464	37,464	$4,890,000	$4,890,000
250	130,734	20,000	20,000	4,750	4,750	37,464	37,464	$4,890,000	$4,890,000
50	26,147	30,000	25,240	–	7,962	26,147	26,147	–	$5,310,000
150	78,440	30,000	30,000	5,082	5,082	78,149	78,149	$7,460,000	$7,460,000
250	130,734	30,000	30,000	5,082	5,082	78,149	78,149	$7,460,000	$7,460,000

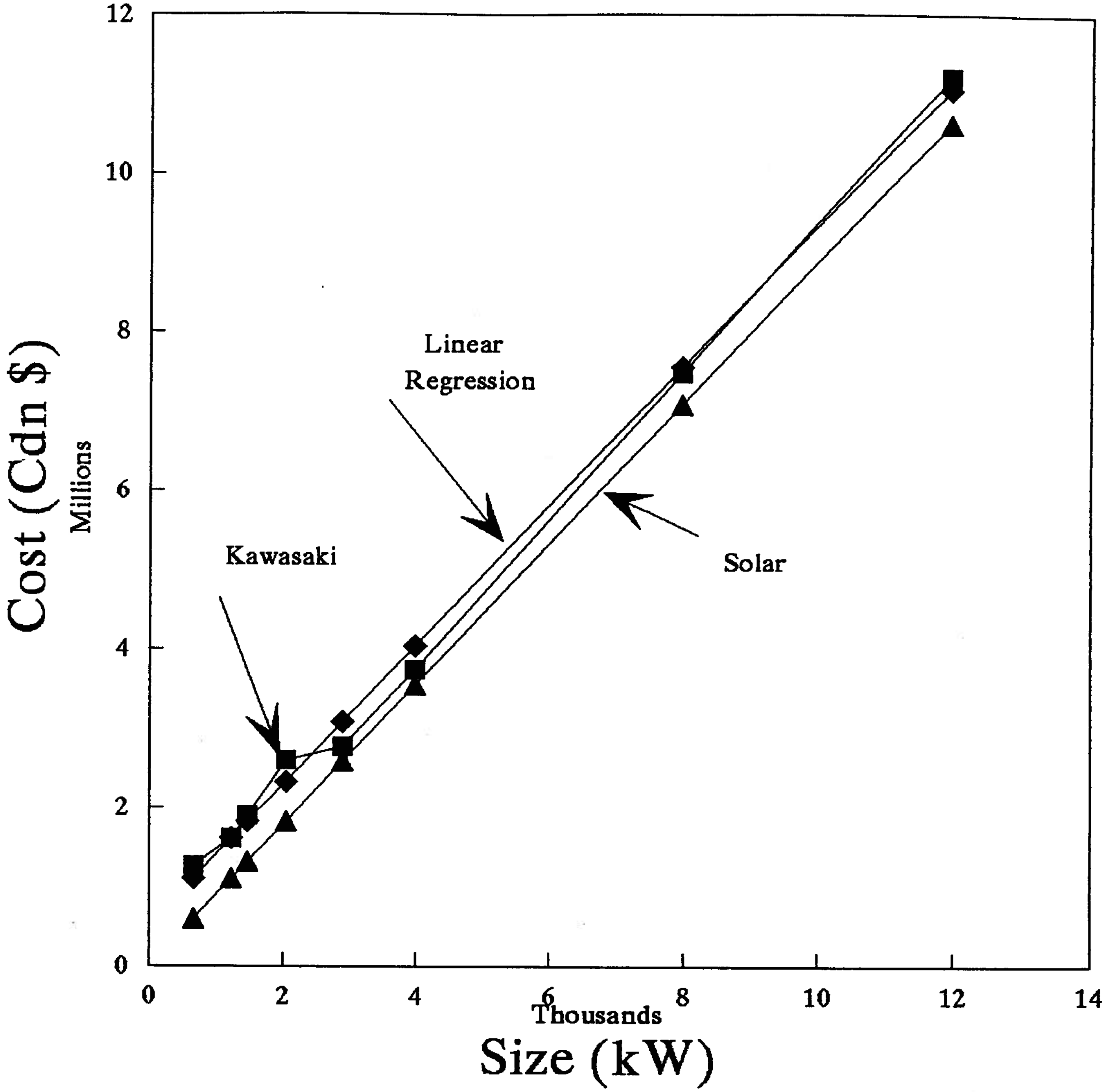

Figure 4: Gas Turbine Cost as a Function of Size

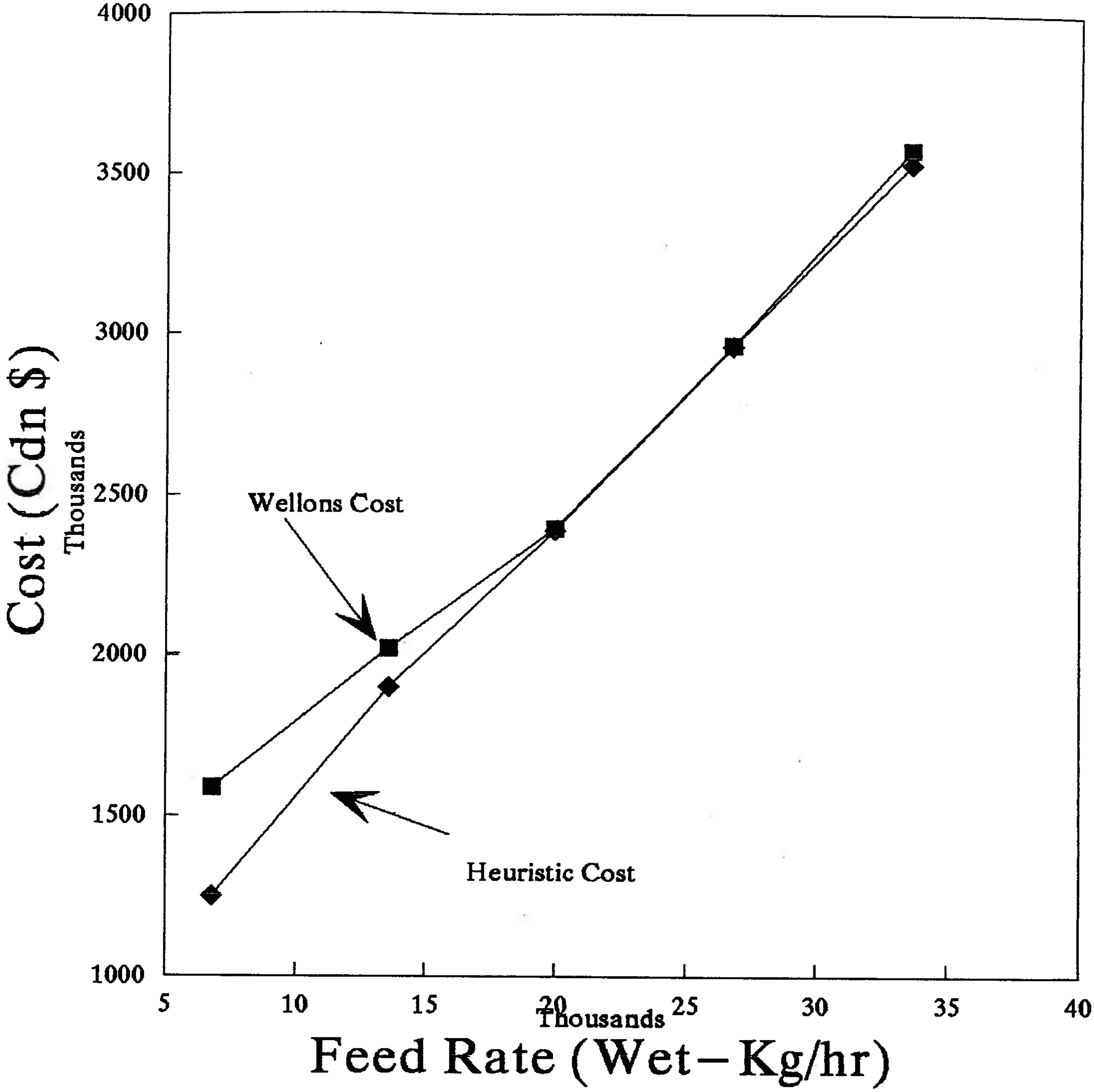

Figure 5: Wood Waste Furnace/Combustor Cost vs Wood Fuel Feed Rate

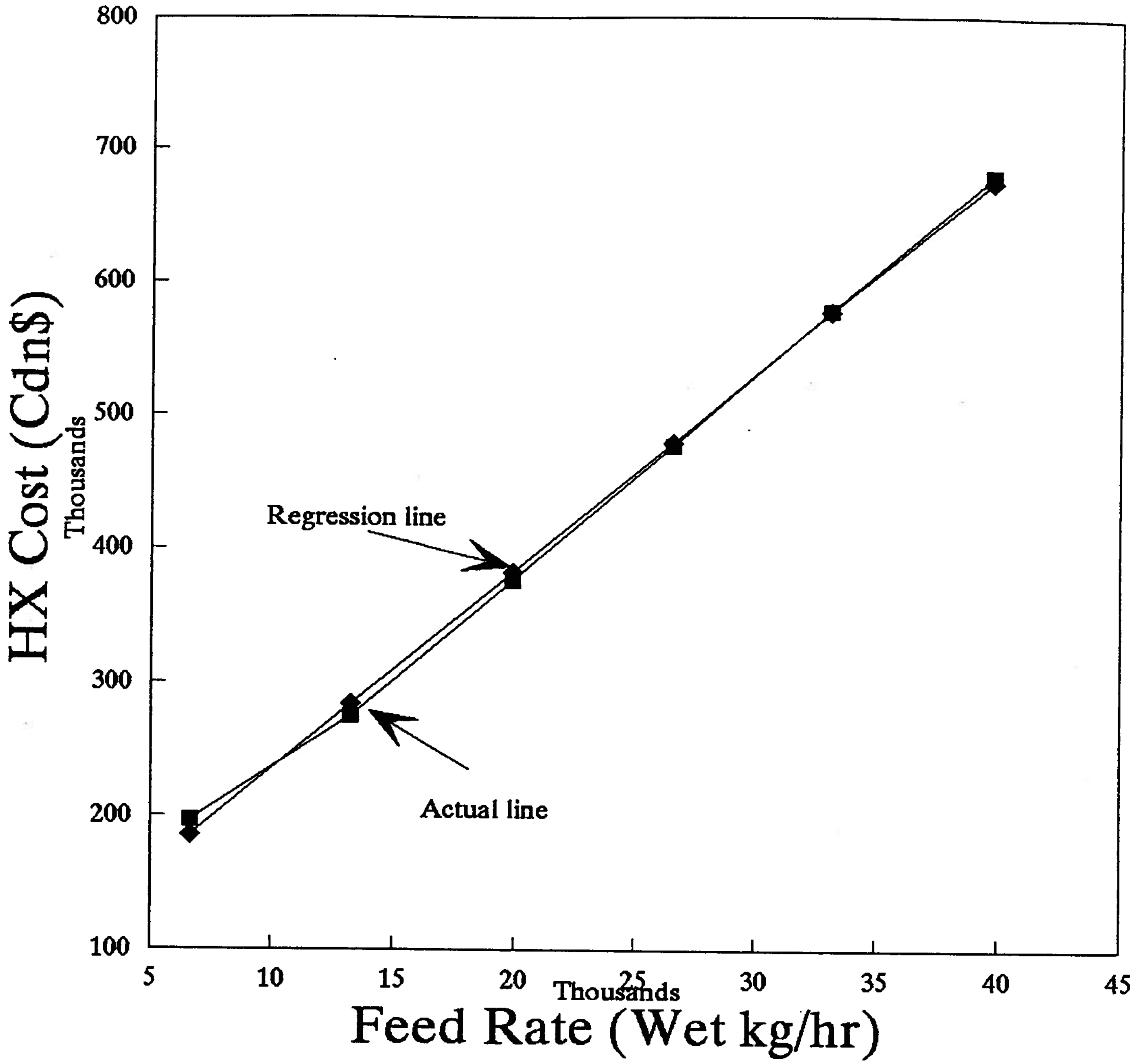

Figure 6: Metal Heat Exchanger Cost vs Wood Fuel Feed Rate

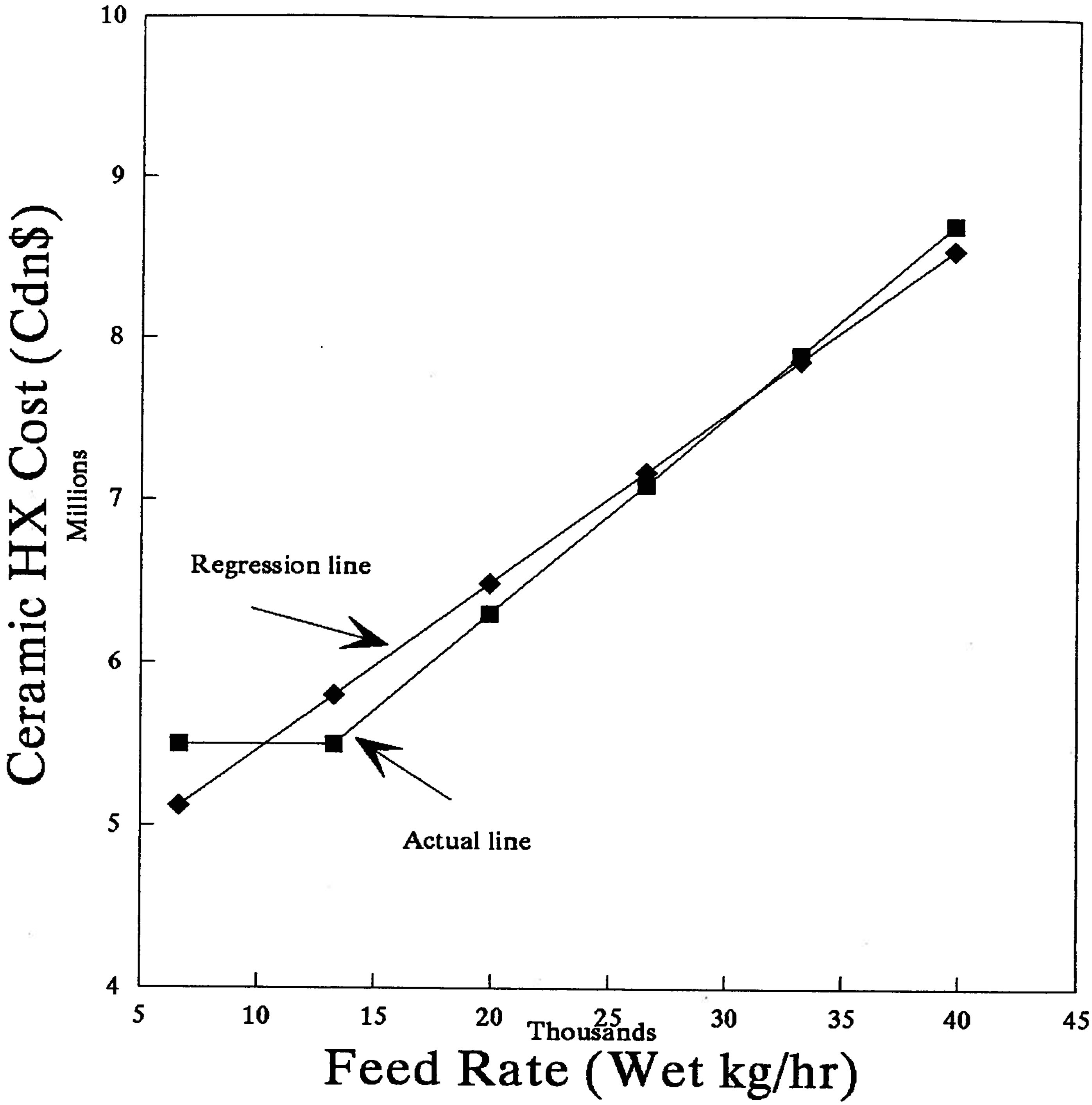

Figure 7: Ceramic Heat Exchanger Cost vs Wood Fuel Feed Rate

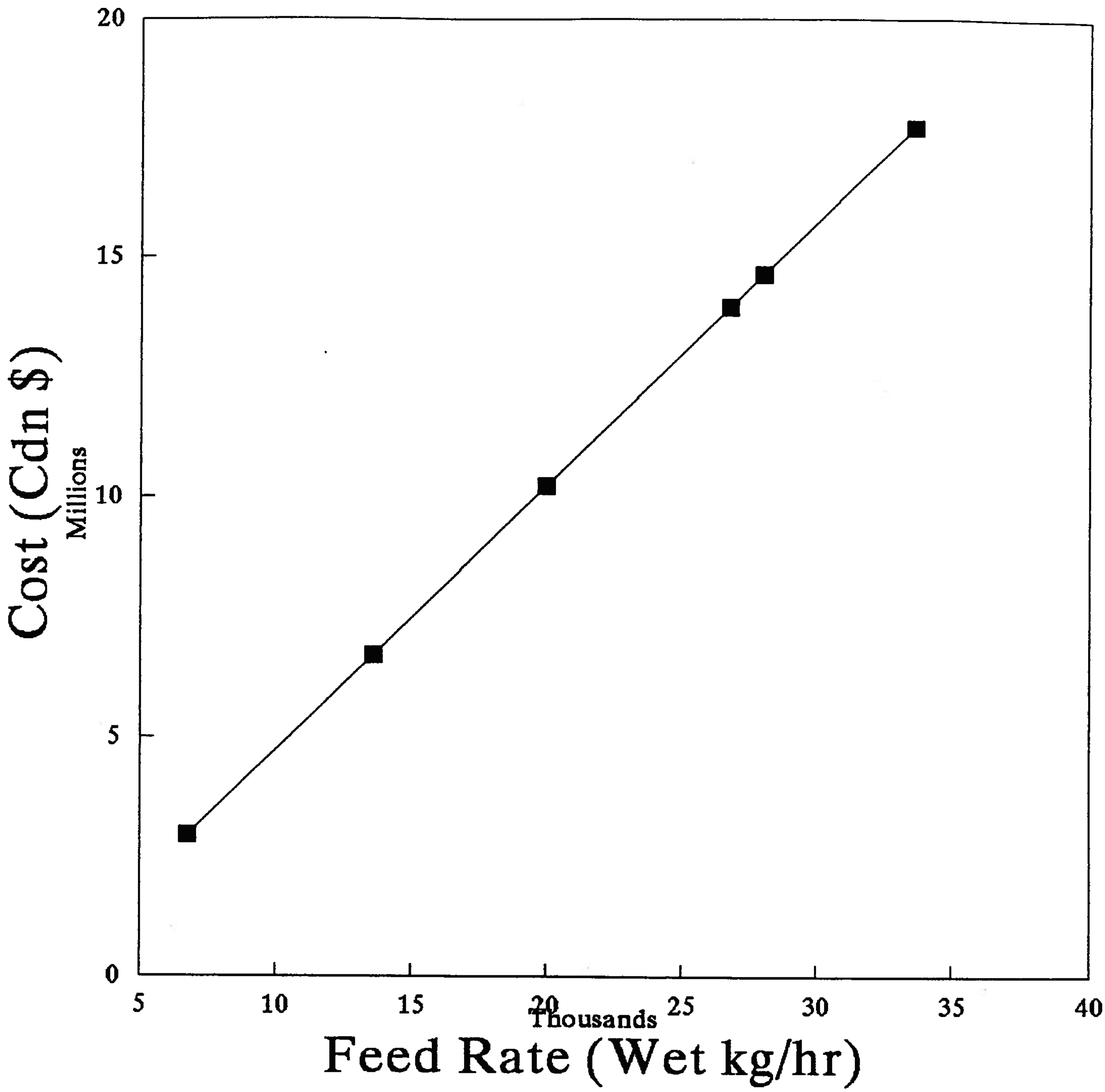

Figure 8: ABB System Cost as a Function of Wood Fuel Feed Rate

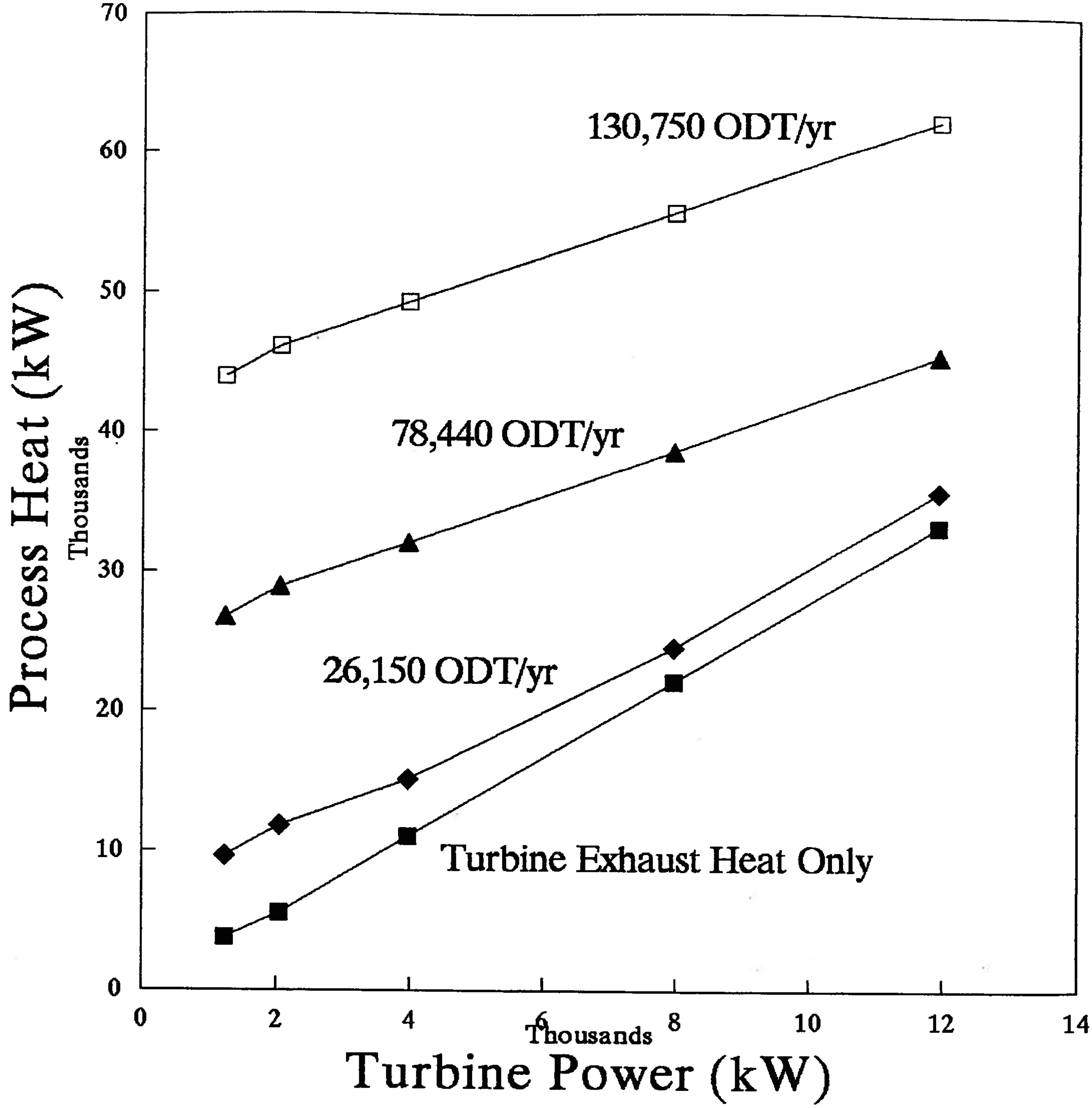

Figure 9: Process Heat Generated as a Function of Turbine Power and Wood Waste Availability For Option #1

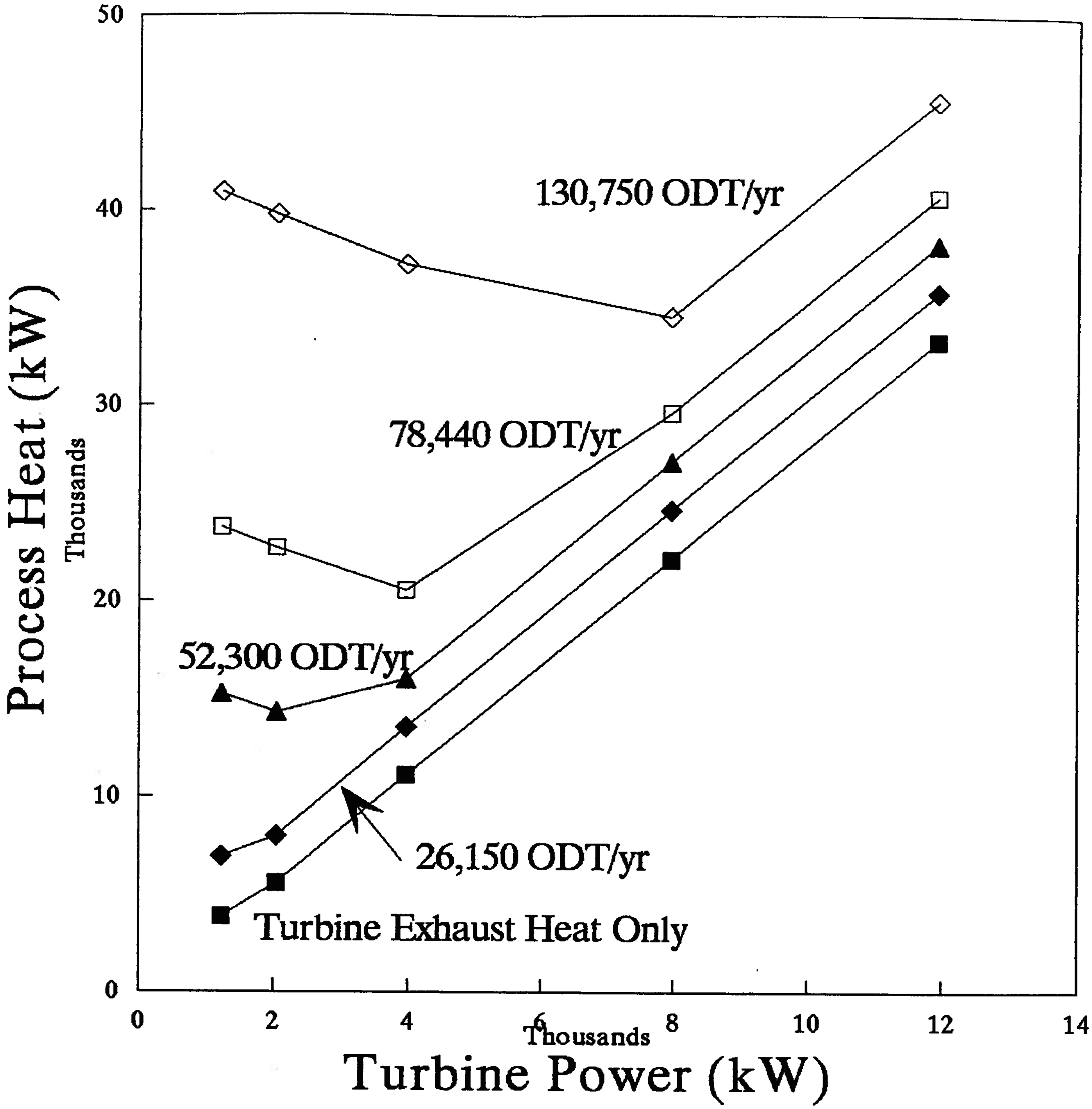

Figure 10: Process Heat Generated as a Function of Turbine Power and Wood Waste Availability For Option #2

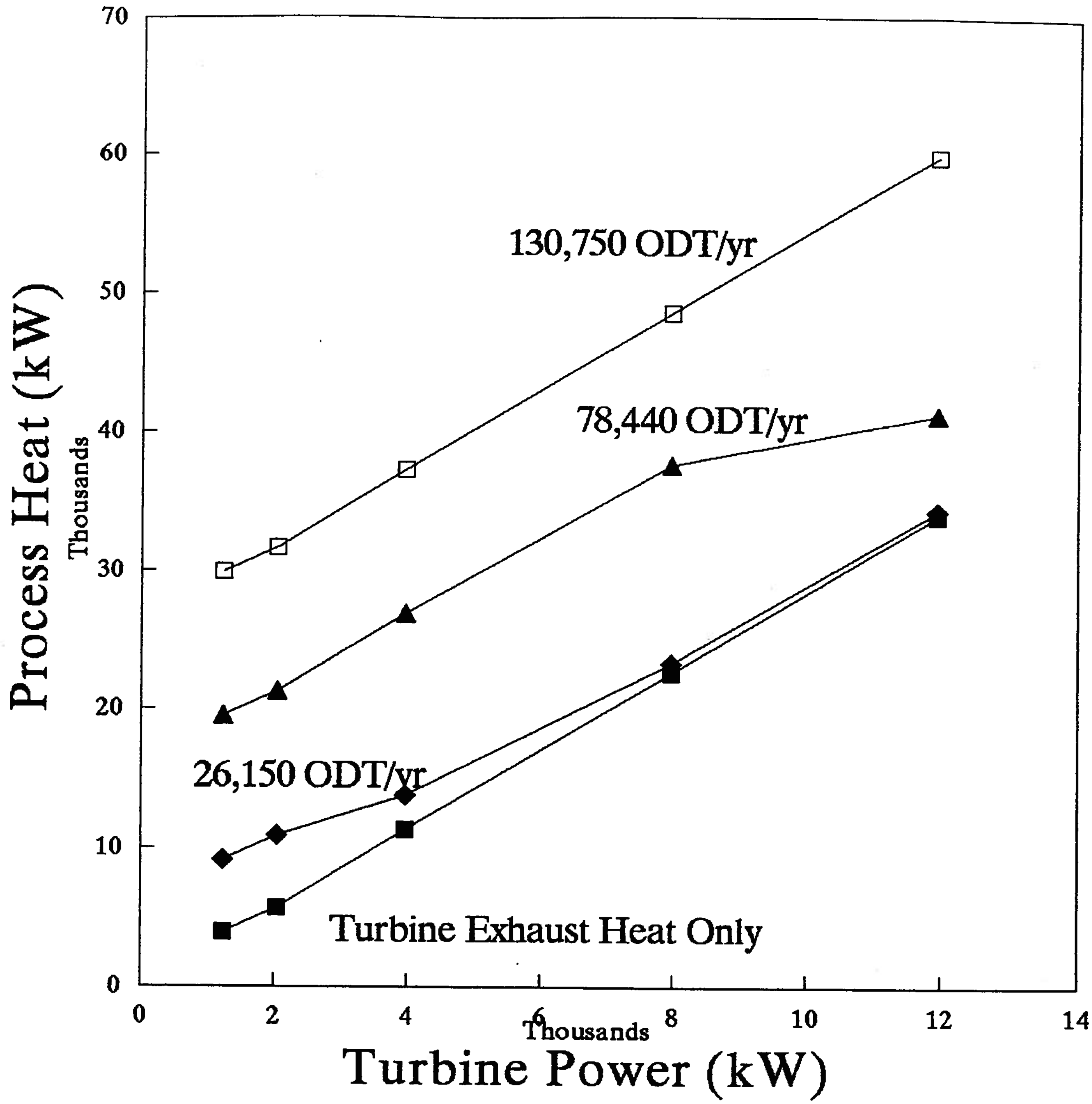

Figure 11: Process Heat Generated as a Function of Turbine Power and Wood Waste Availability For Option #3

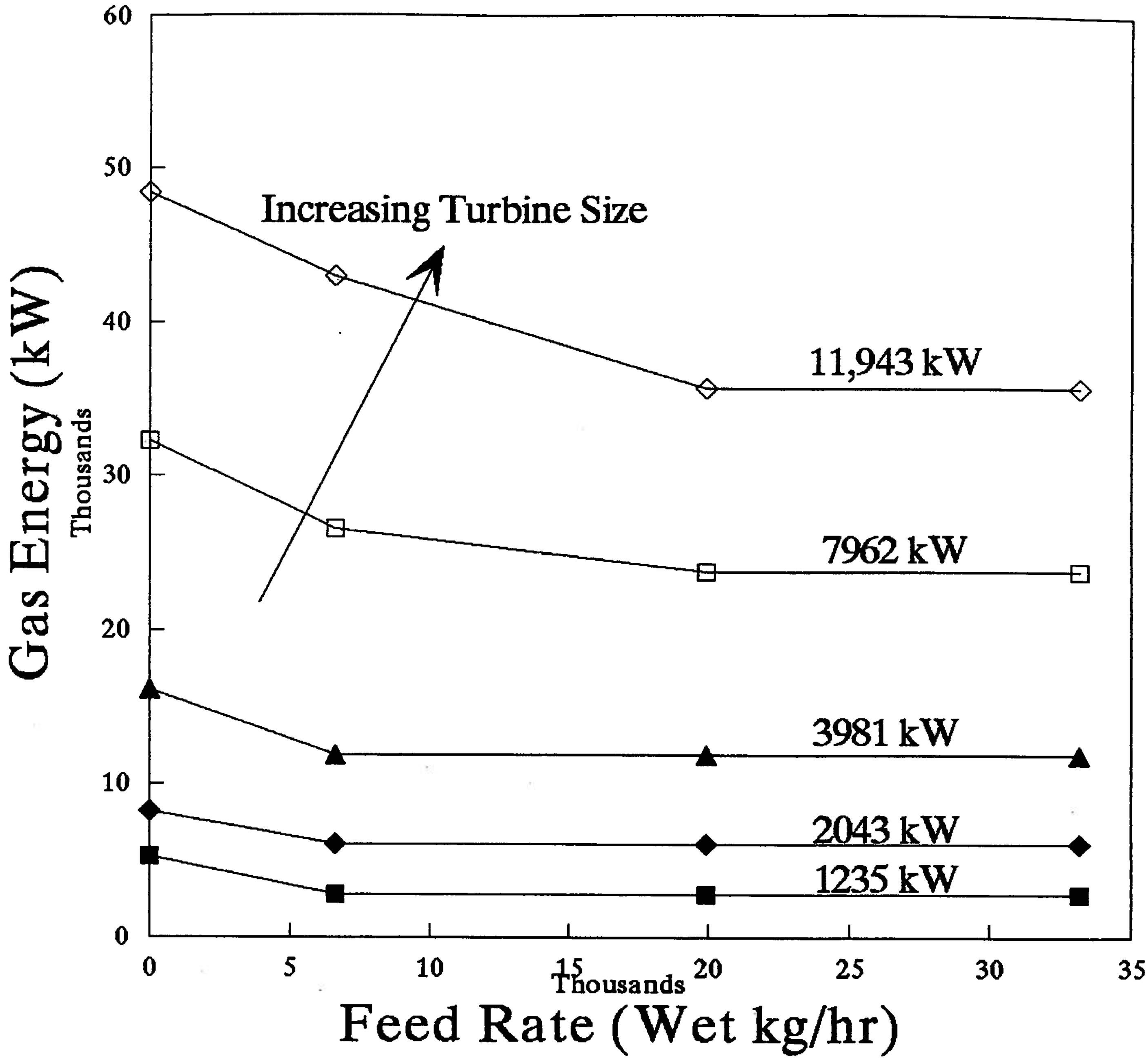

Figure 12: Natural Gas Consumption Required For Top-Up of Turbine Inlet Temperature For Option #1

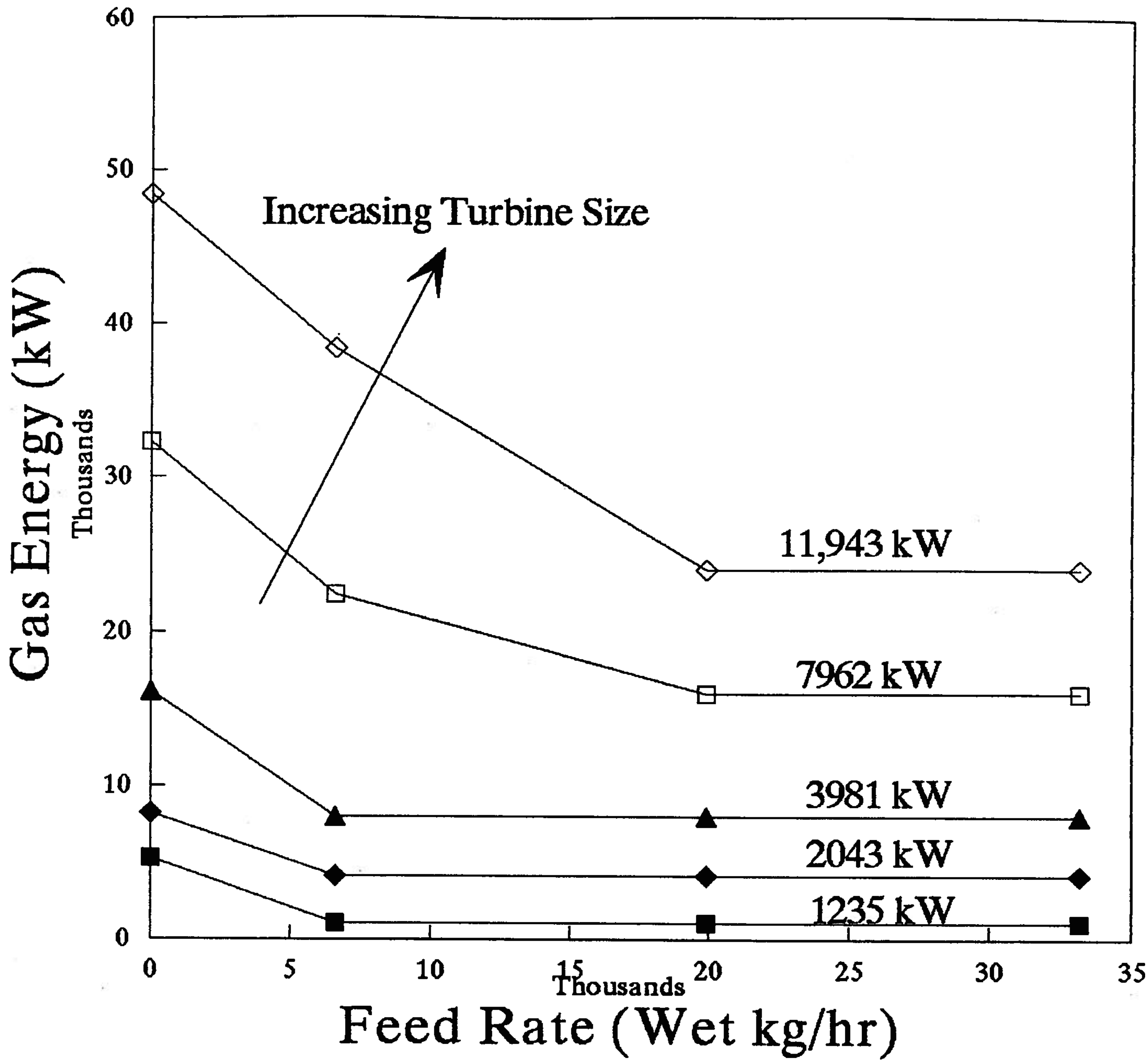

Figure 13: Natural Gas Consumption Required For Top-Up of Turbine Inlet Temperature For Option #3

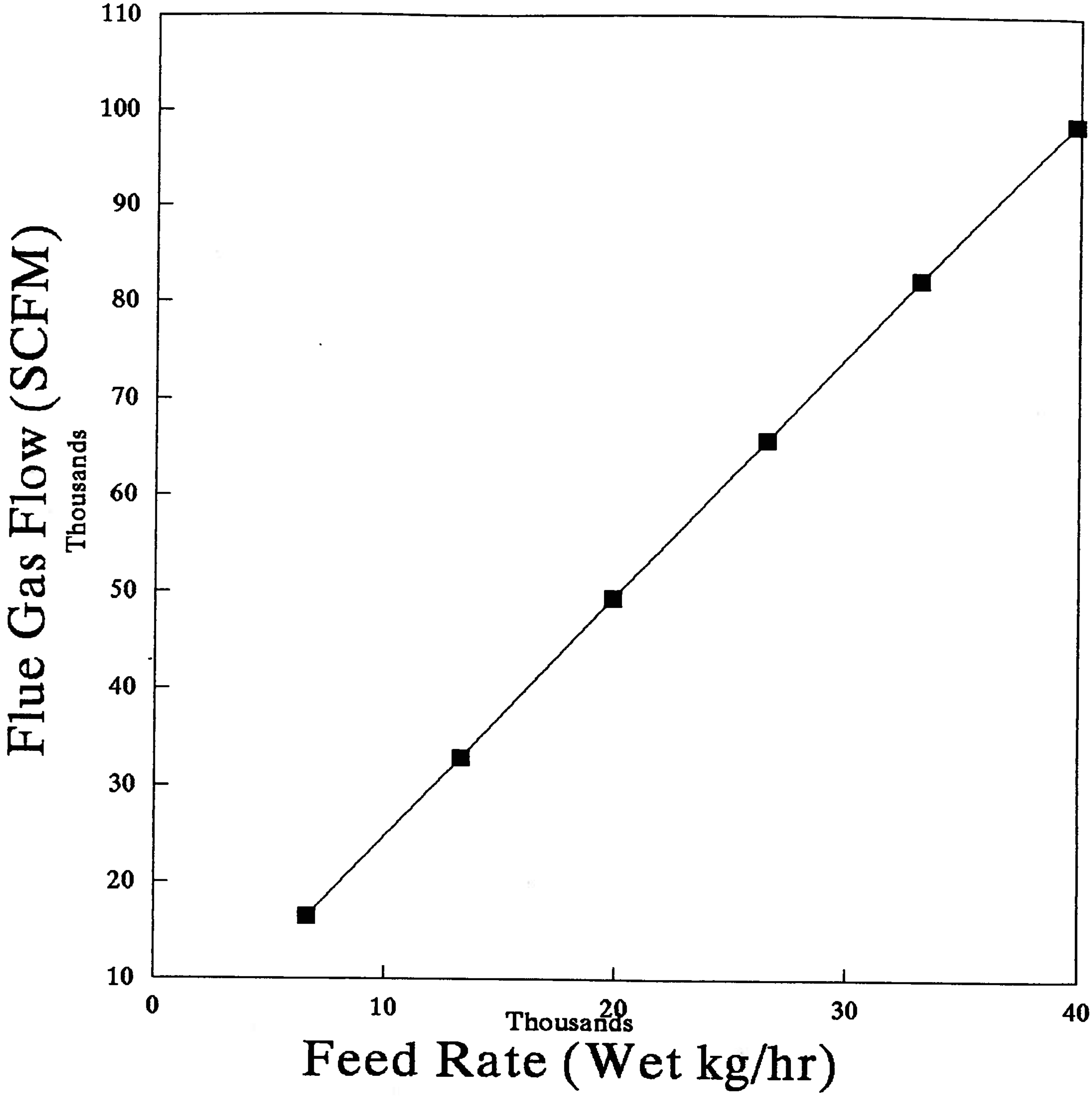

Figure 14: Rate of Flue Gas Production vs Wood Fuel Feed Rate Into System

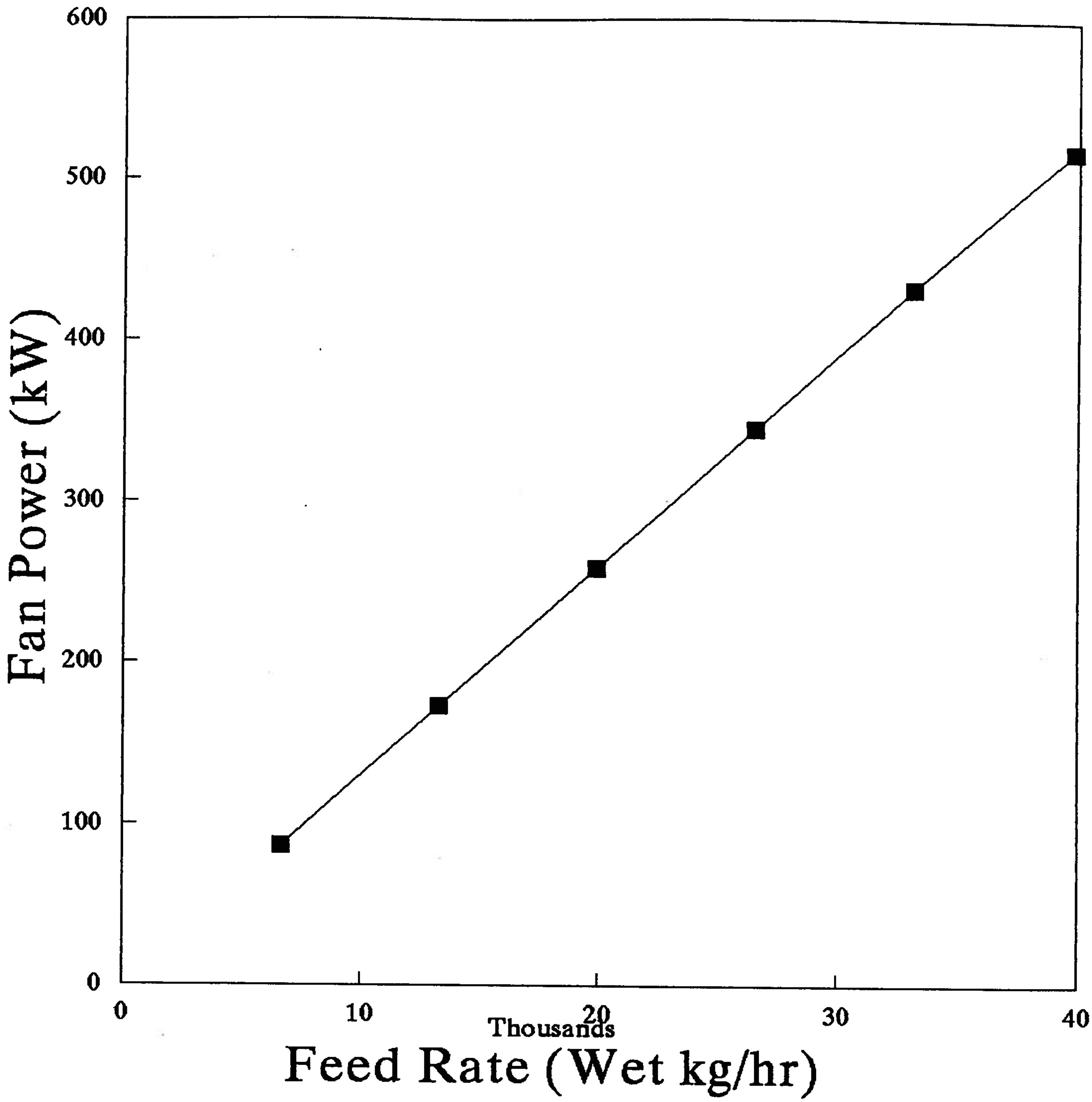

Figure 15: Fan Power Required vs Wood Fuel Feed Rate Into System For Option #1

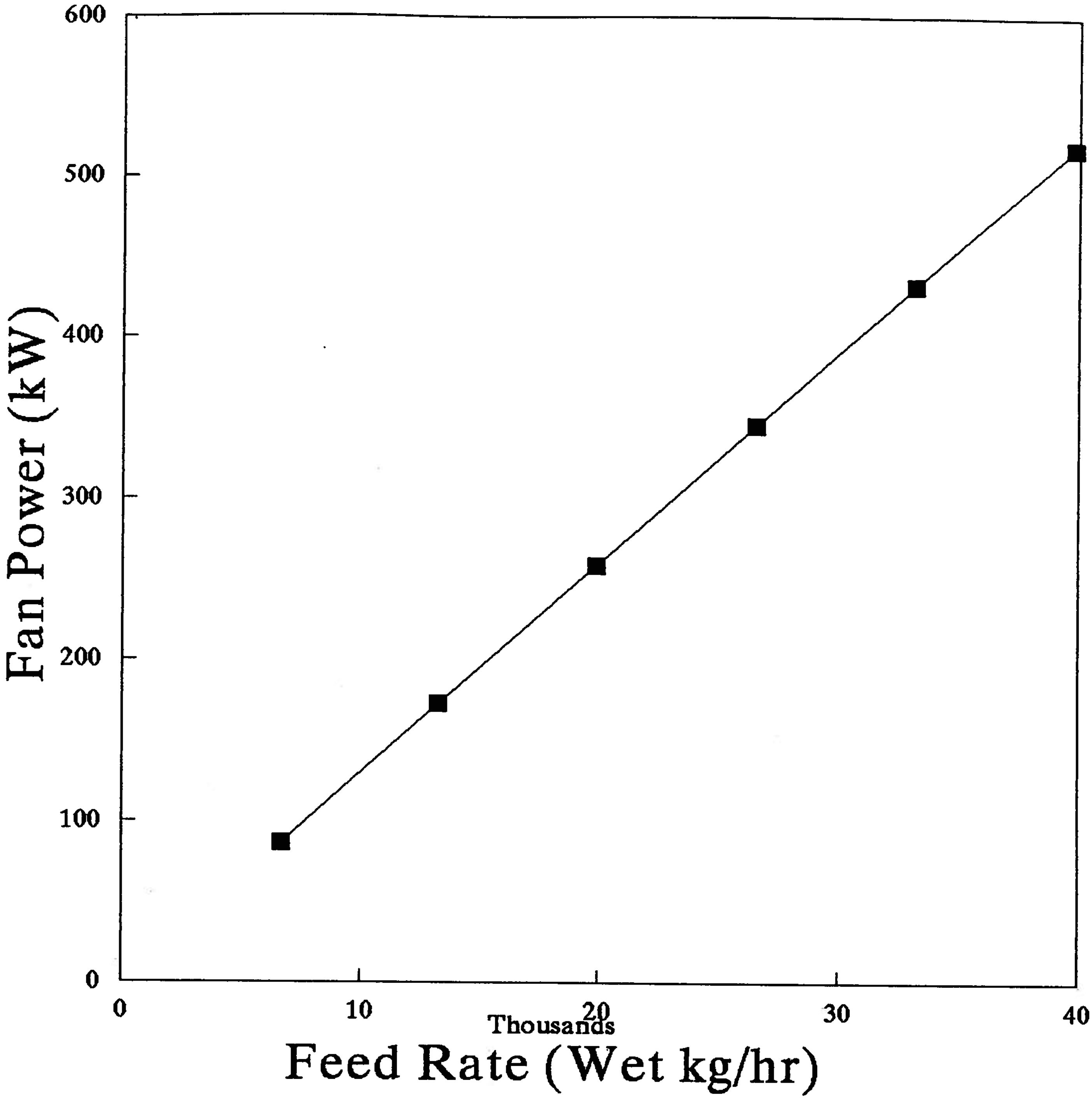

Figure 16: Fan Power Required vs Wood Fuel Feed Rate Into System For Option #2

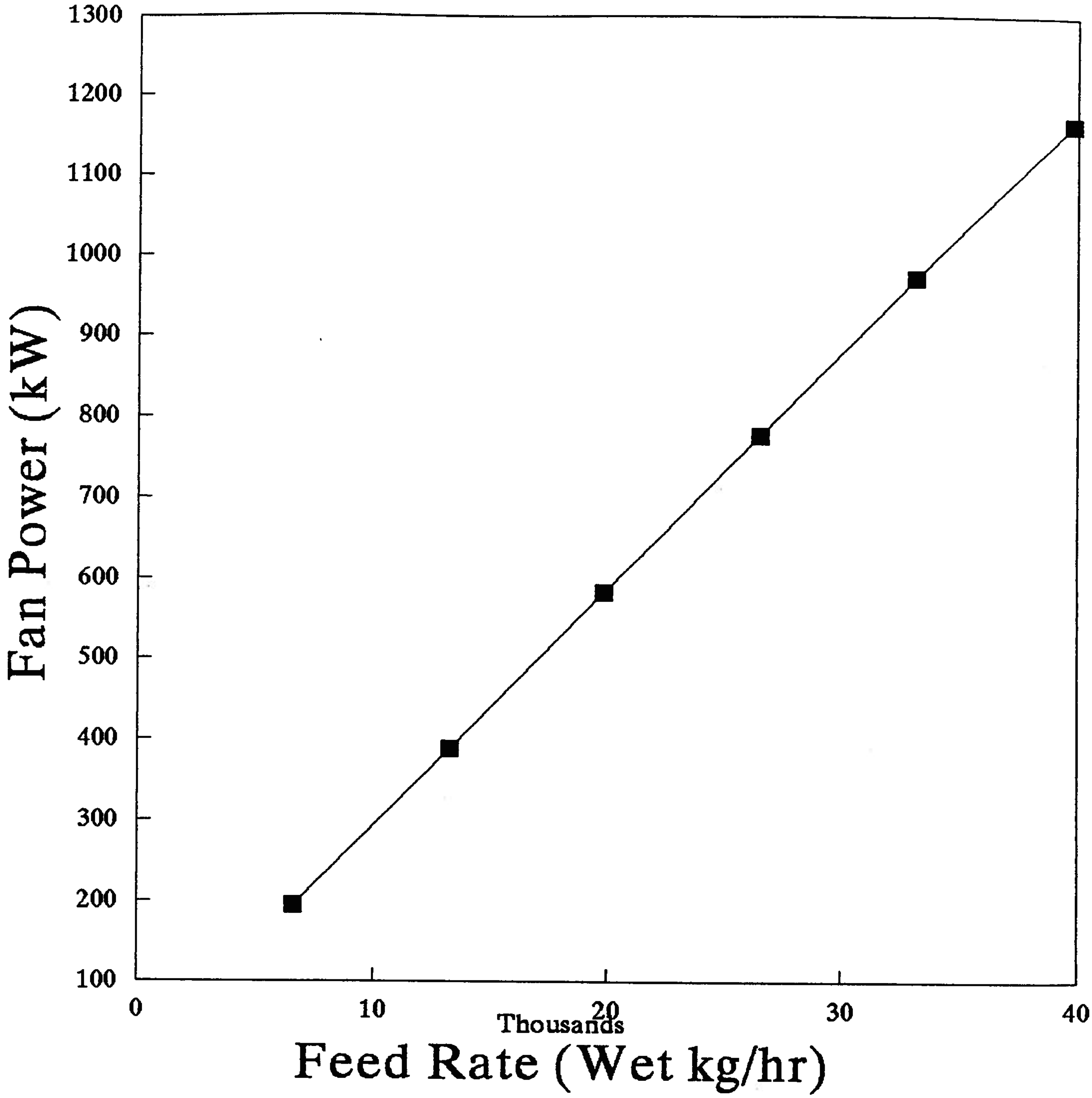

Figure 17: Fan Power Required vs Wood Fuel Feed Rate Into System For Option #3

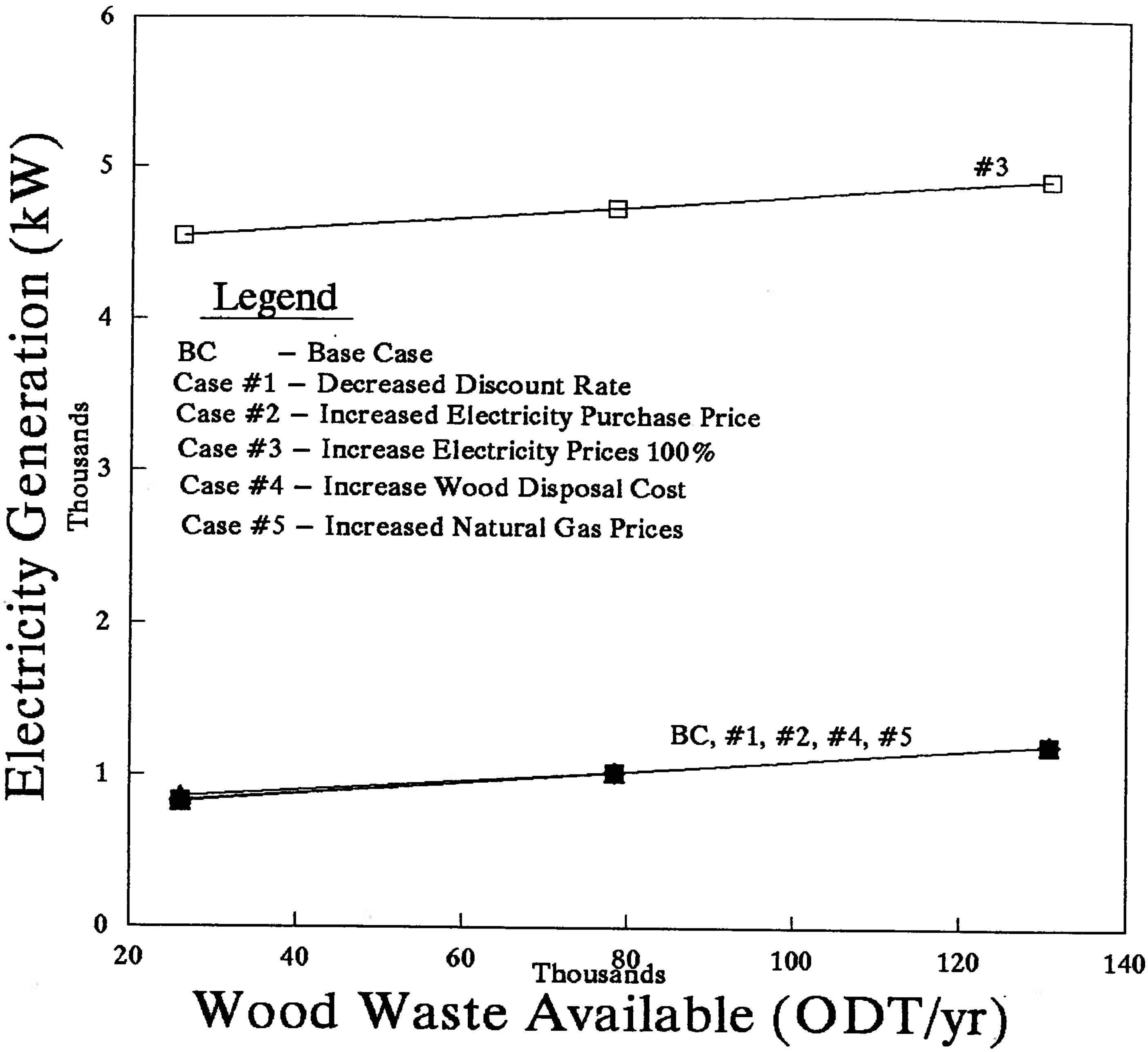

Figure 18: Optimum Electricity Generation for Option #1 with a Process Heat Requirement of 10,000 kW

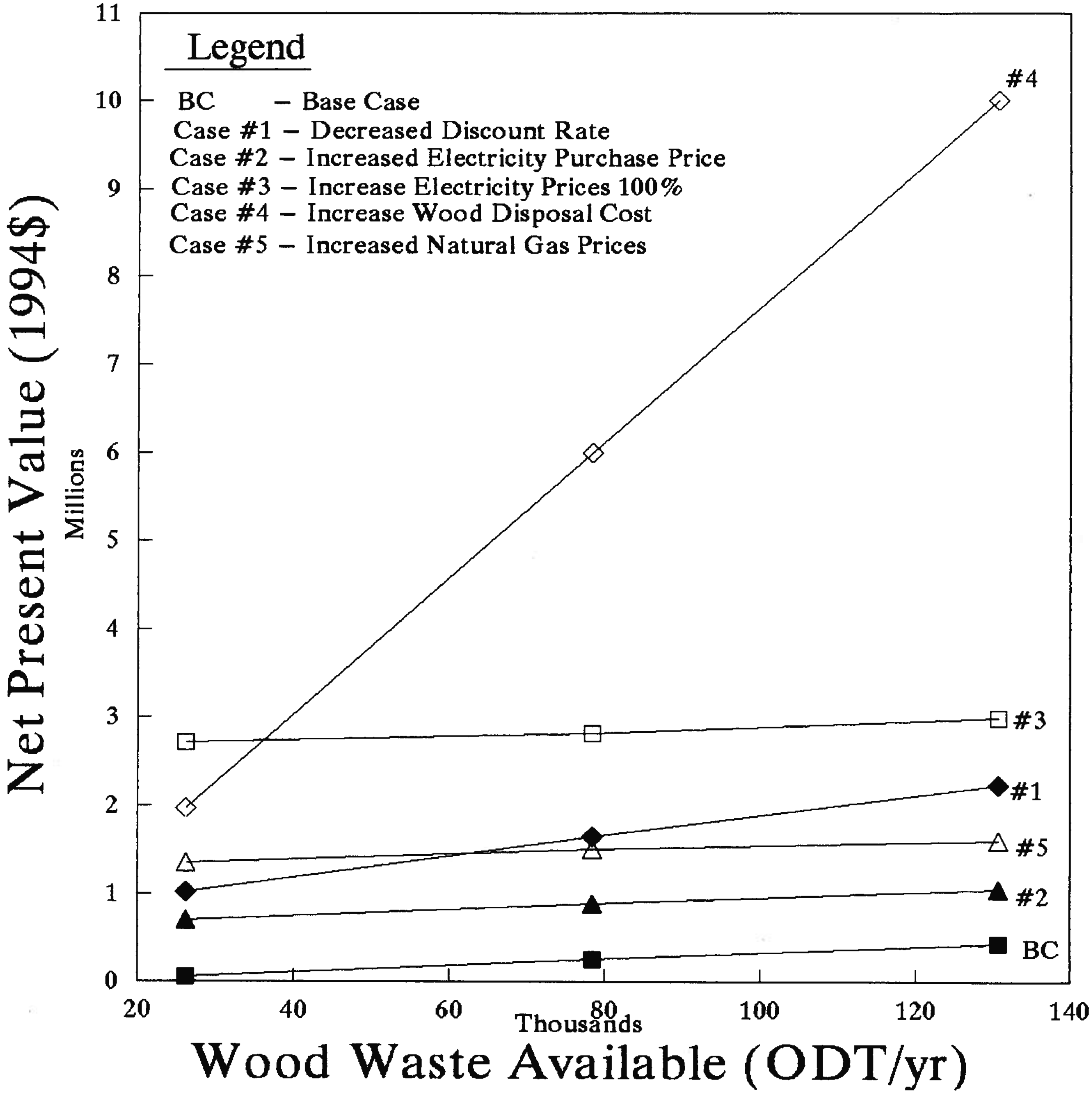

Figure 19: Net Present Value for Option #1 with a Process Heat Requirement of 10,000 kW

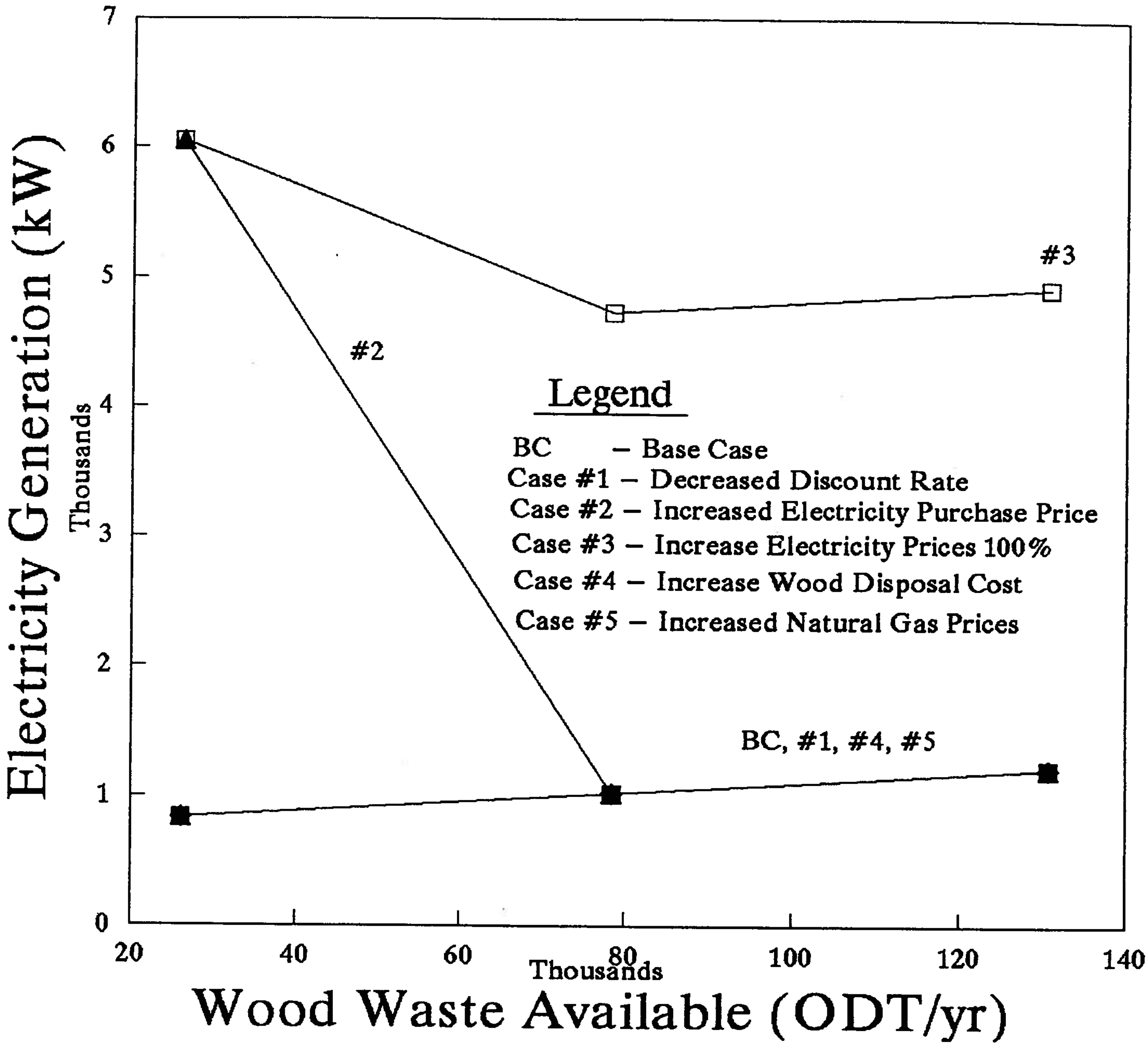

Figure 20: Optimum Electricity Generation for Option #1 with a Process Heat Requirement of 20,000 kW

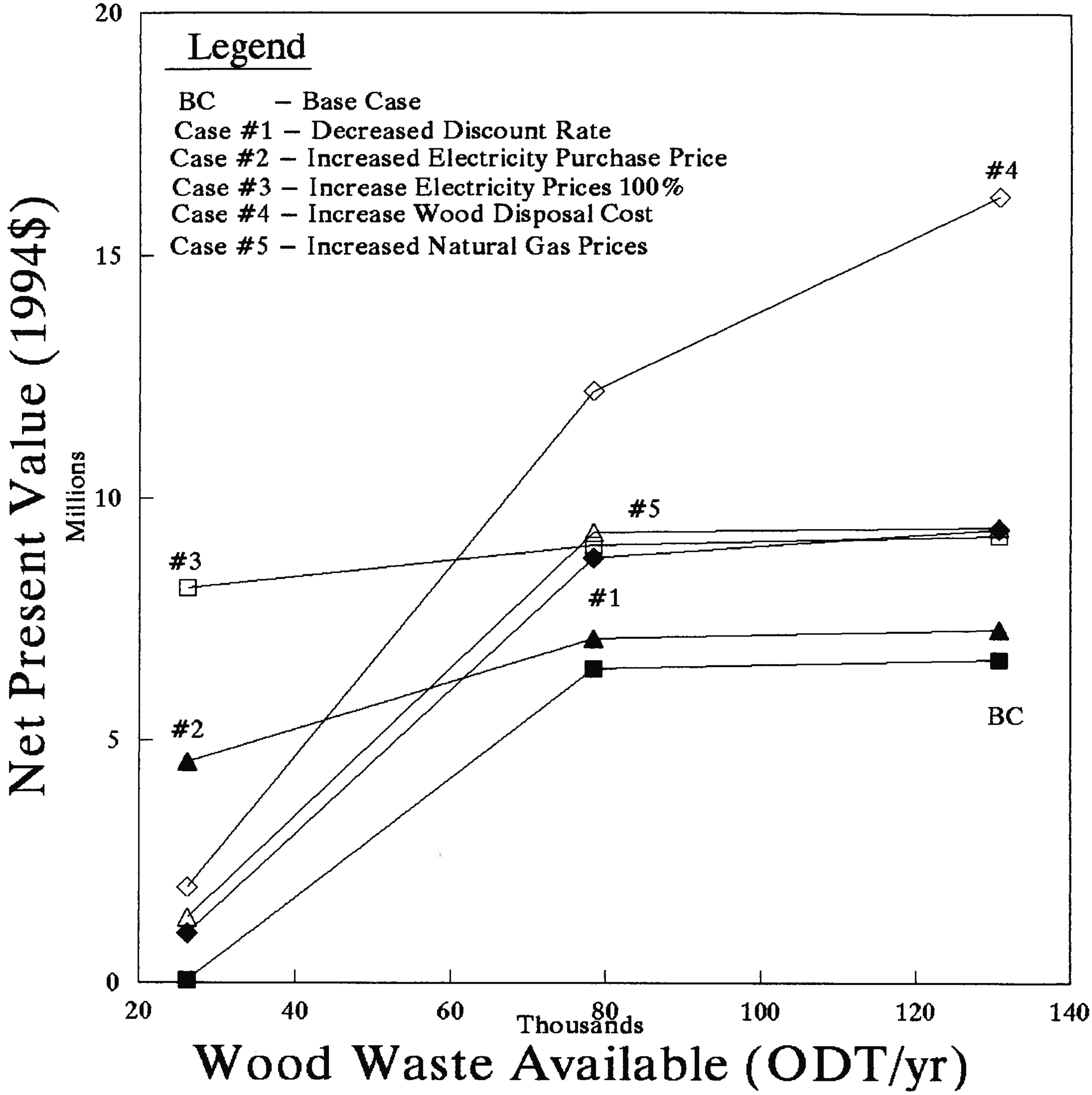

Figure 21: Net Present Value for Option #1 with a Process Heat Requirement of 20,000 kW

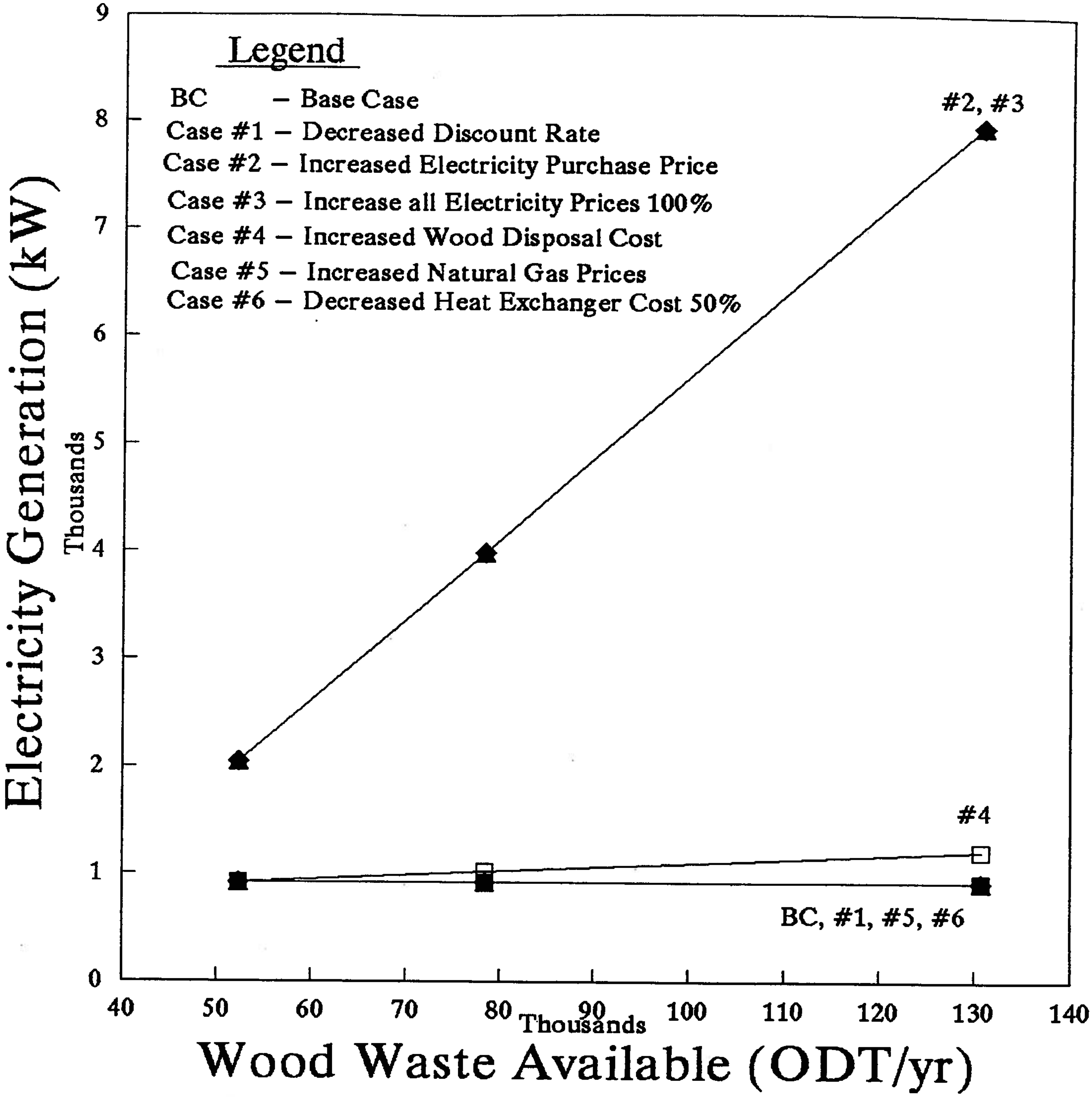

Figure 22: Optimum Electricity Generation for Option #2 with a Process Heat Requirement of 10,000 kW

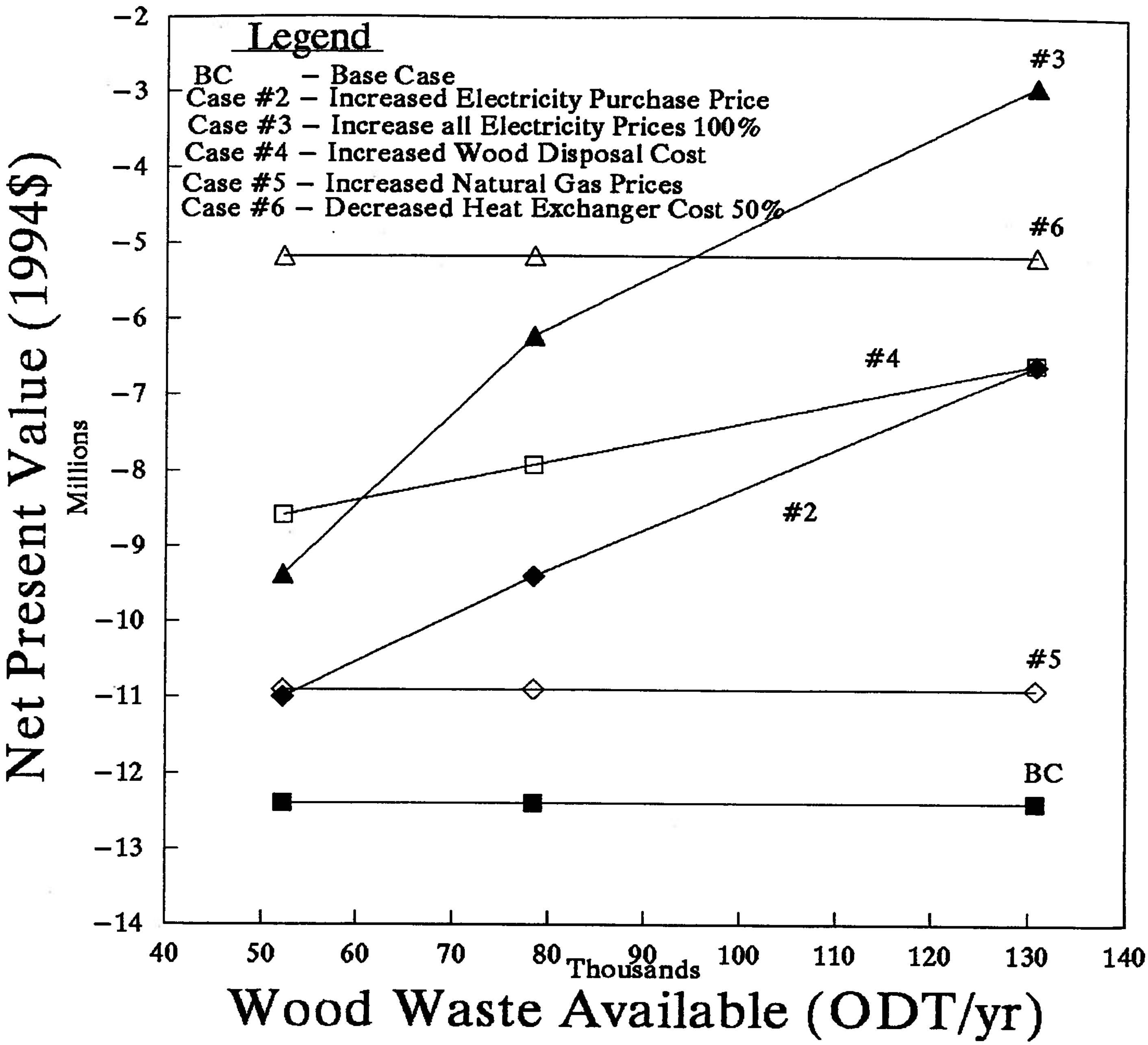

Figure 23: Net Present Value for Option #2 with a Process Heat Requirement of 10,000 kW

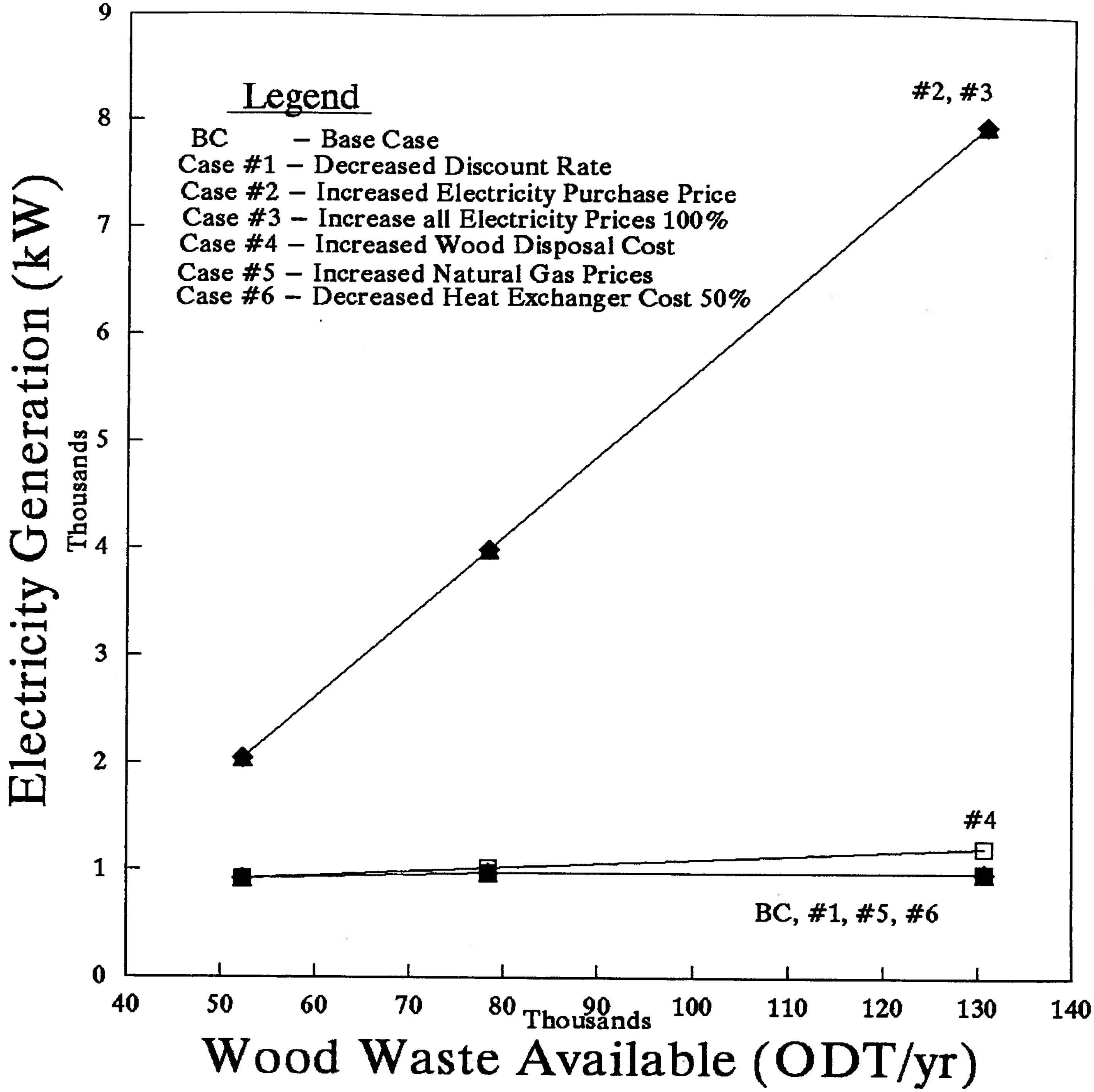

Figure 24: Optimum Electricity Generation for Option #2 with a Process Heat Requirement of 20,000 kW

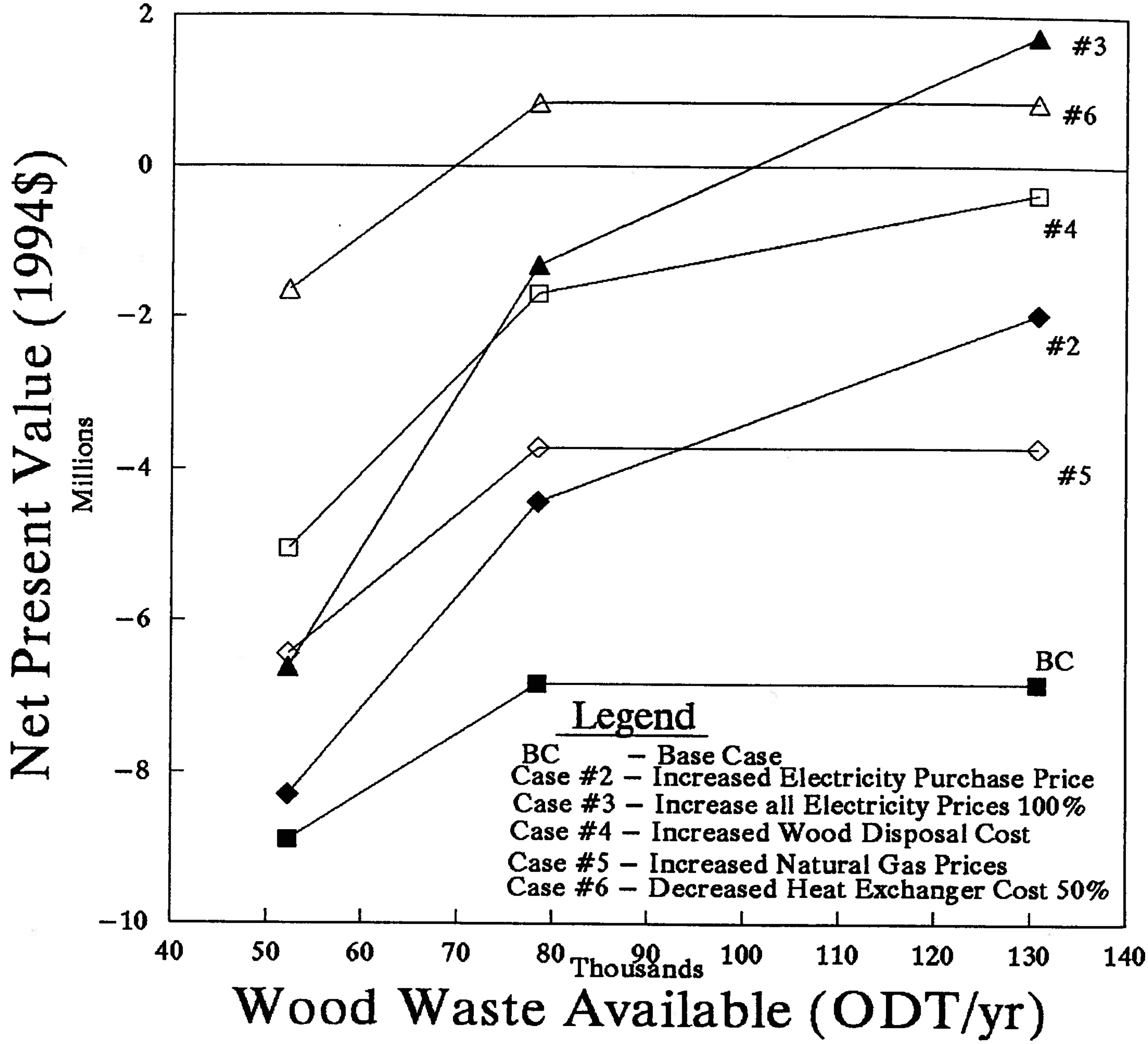

Figure 25: Net Present Value for Option #2 with a Process Heat Requirement of 20,000 kW

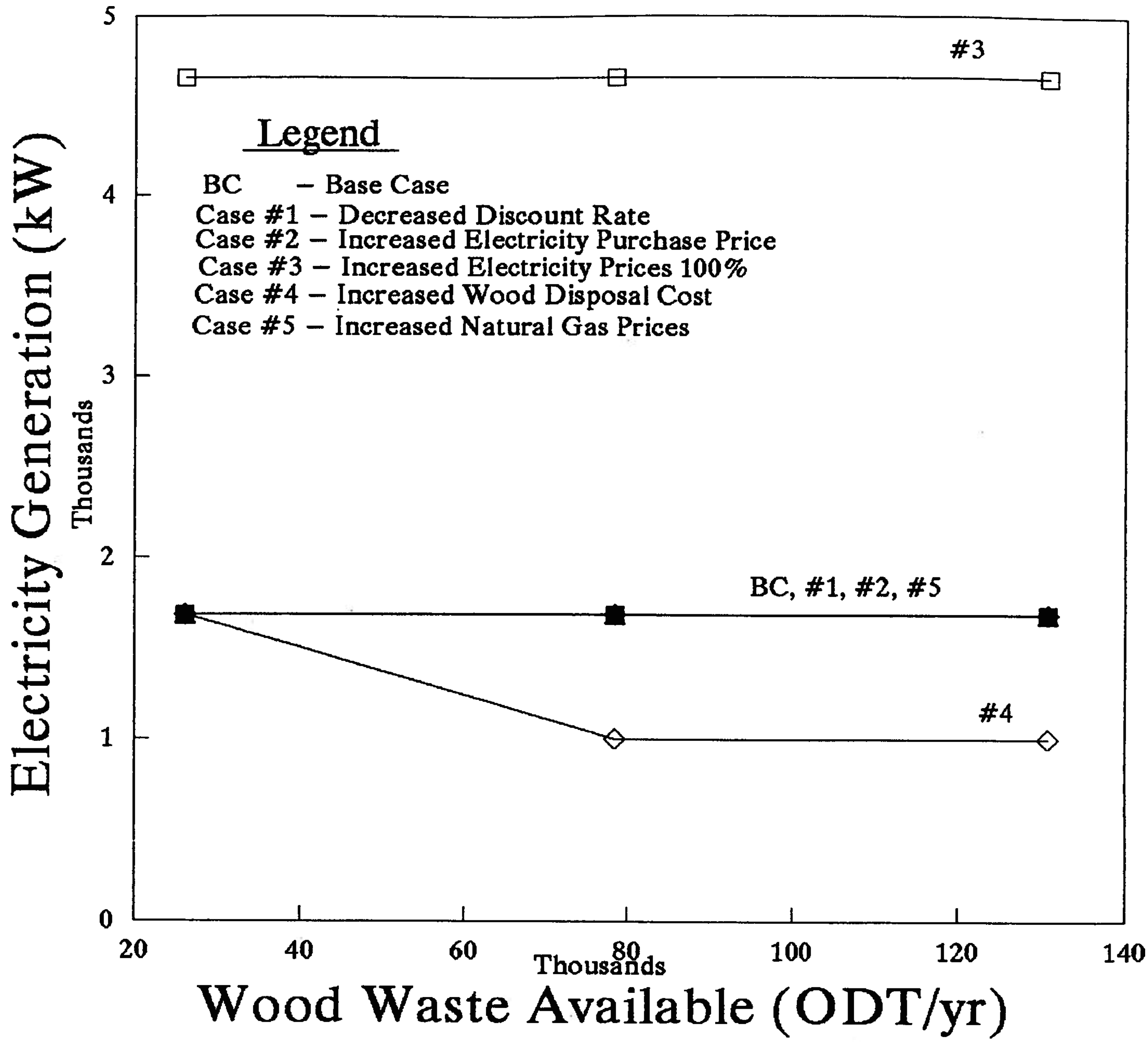

Figure 26: Optimum Electricity Generation for Option #3 with a Process Heat Requirement of 10,000 kW

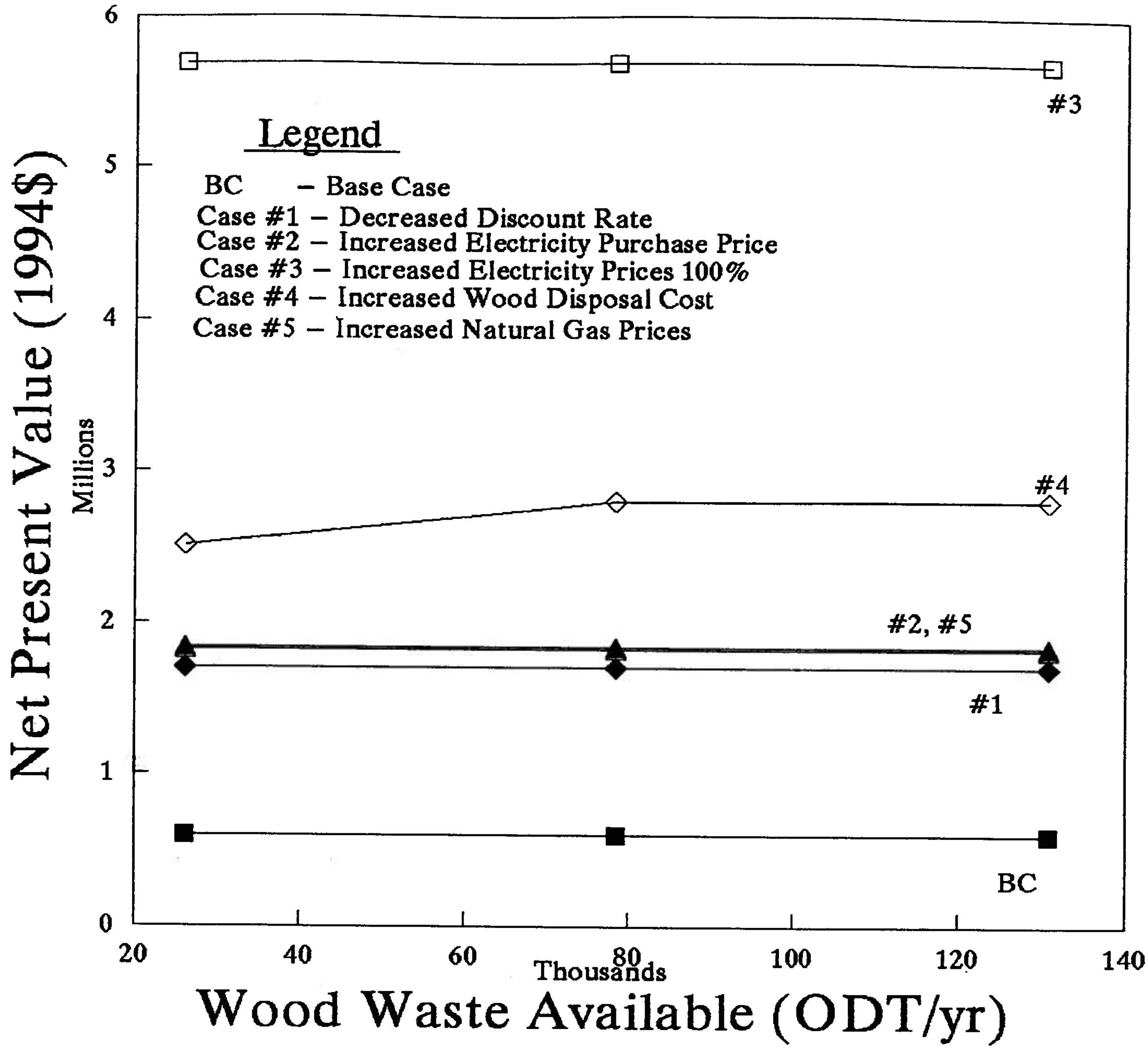

Figure 27: Net Present Value for Option #3 with a Process Heat Requirement of 10,000 kW

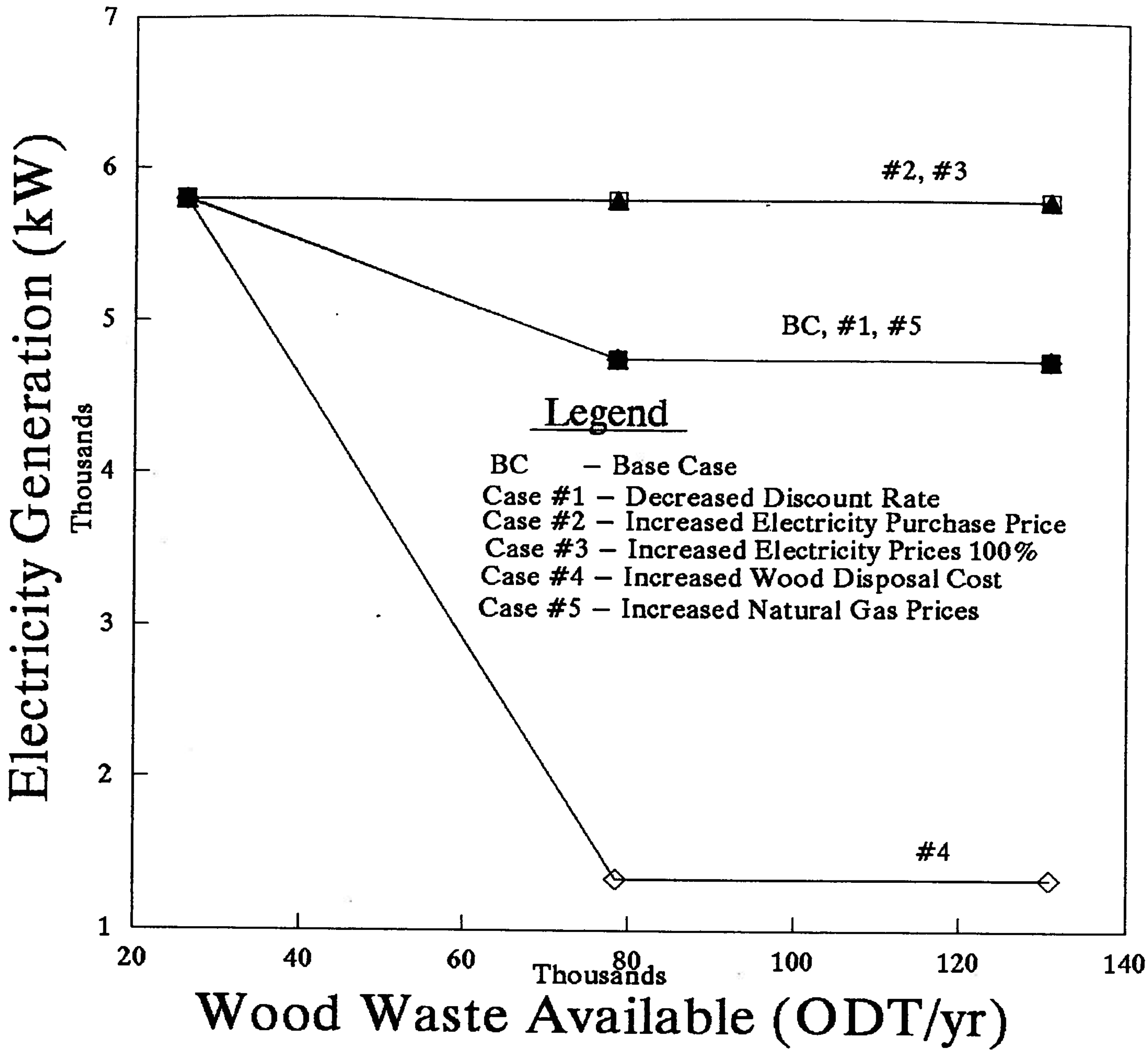

Figure 28: Optimum Electricity Generation for Option #3 with a Process Heat Requirement of 20,000 kW

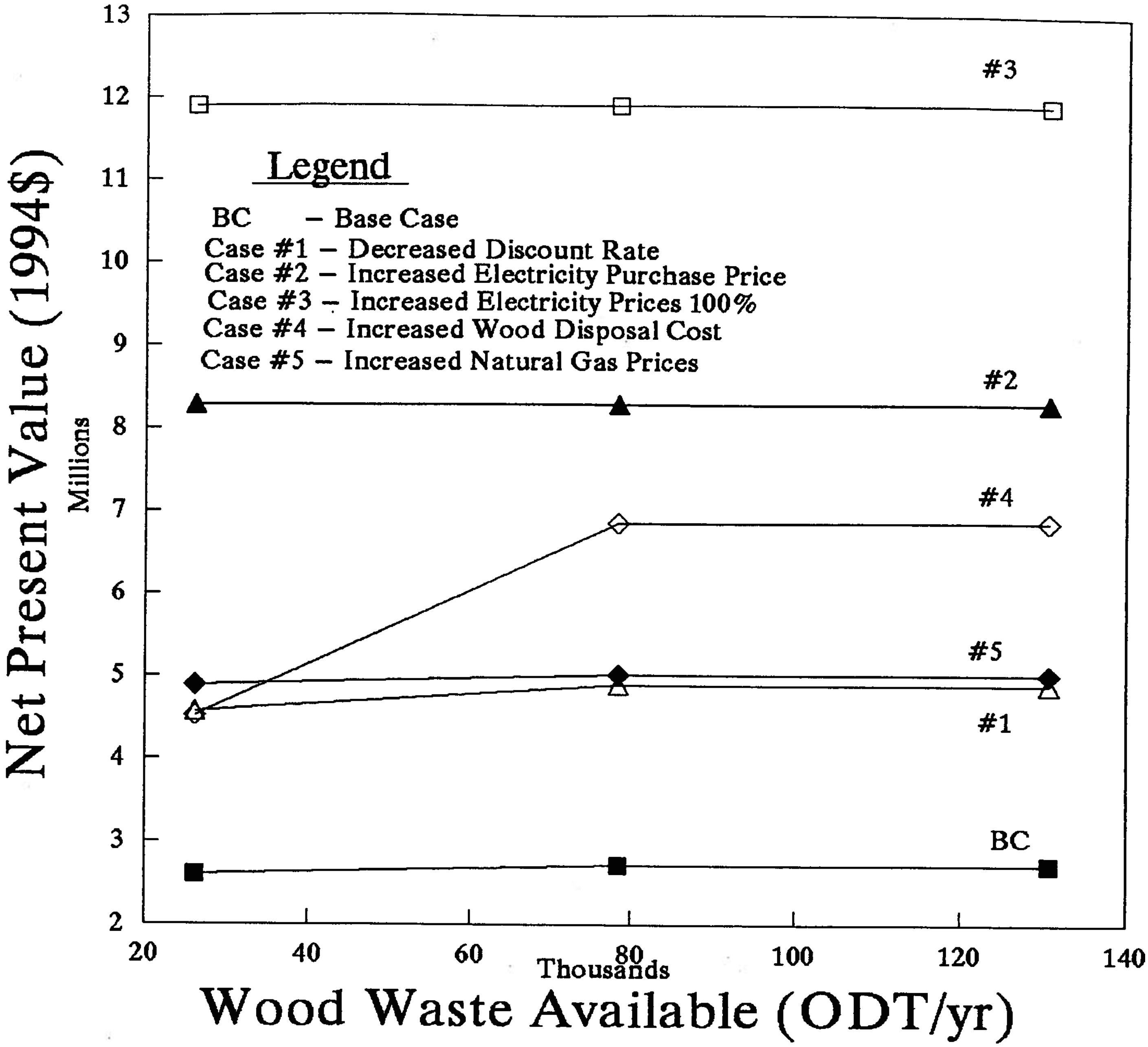

Figure 29: Net Present Value for Option #3 with a Process Heat Requirement of 20,000 kW

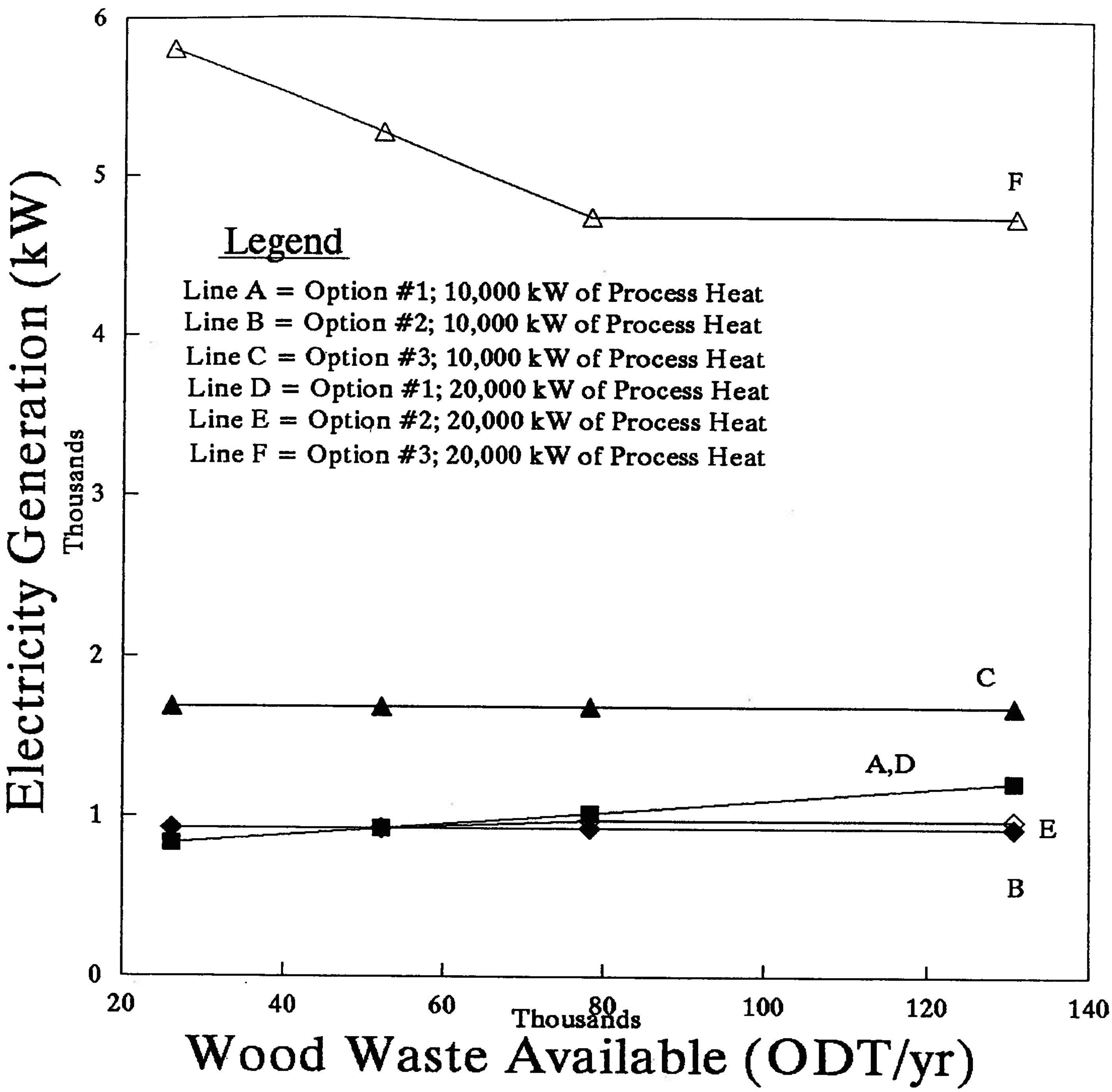

Figure 30: Comparison of the Optimum Electricity Generation for the Base Case Results for Options #1, #2, #3

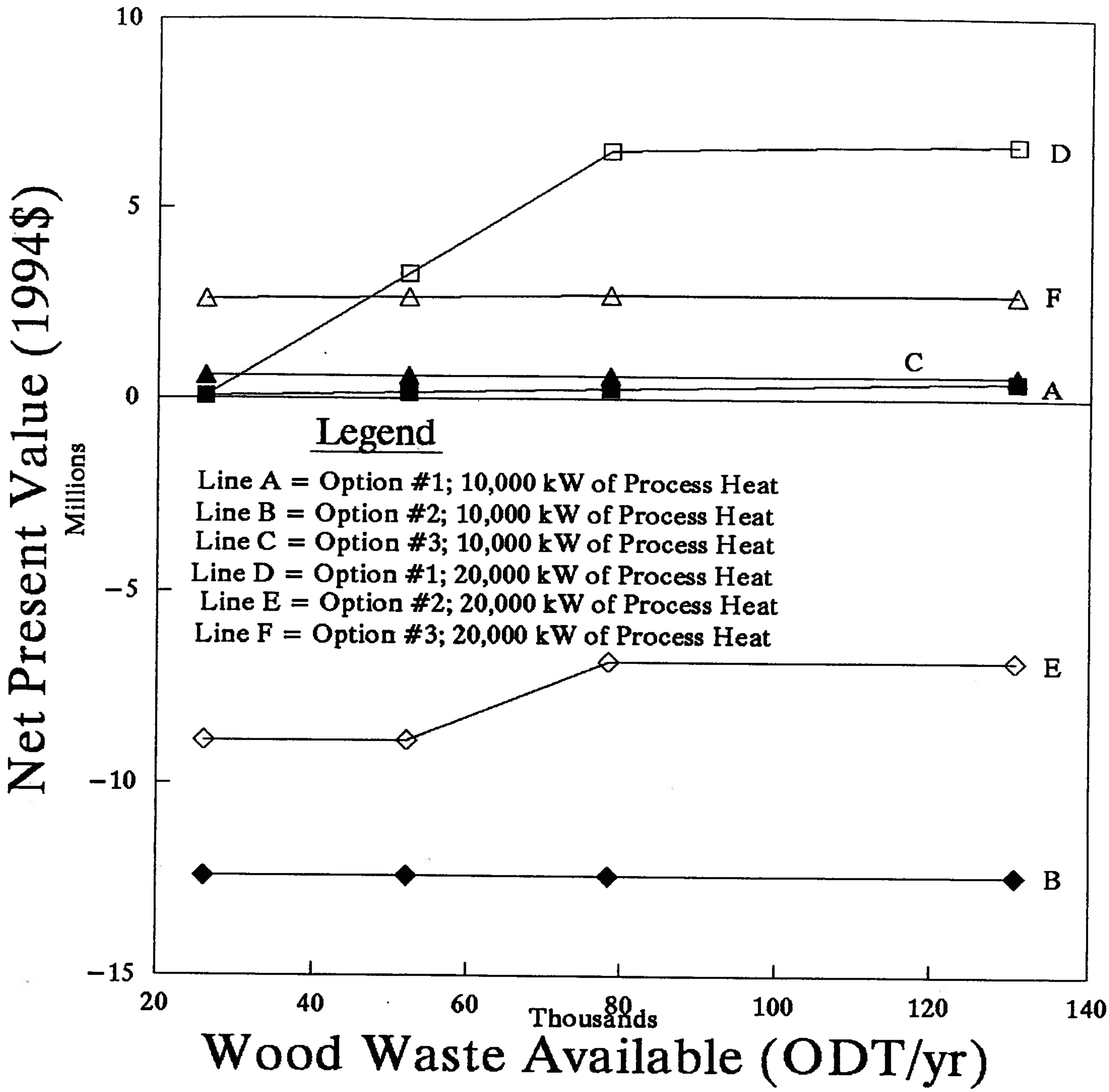

Figure 31: Comparison of the Net Present Value for the Base Case Results for Options #1, #2, #3

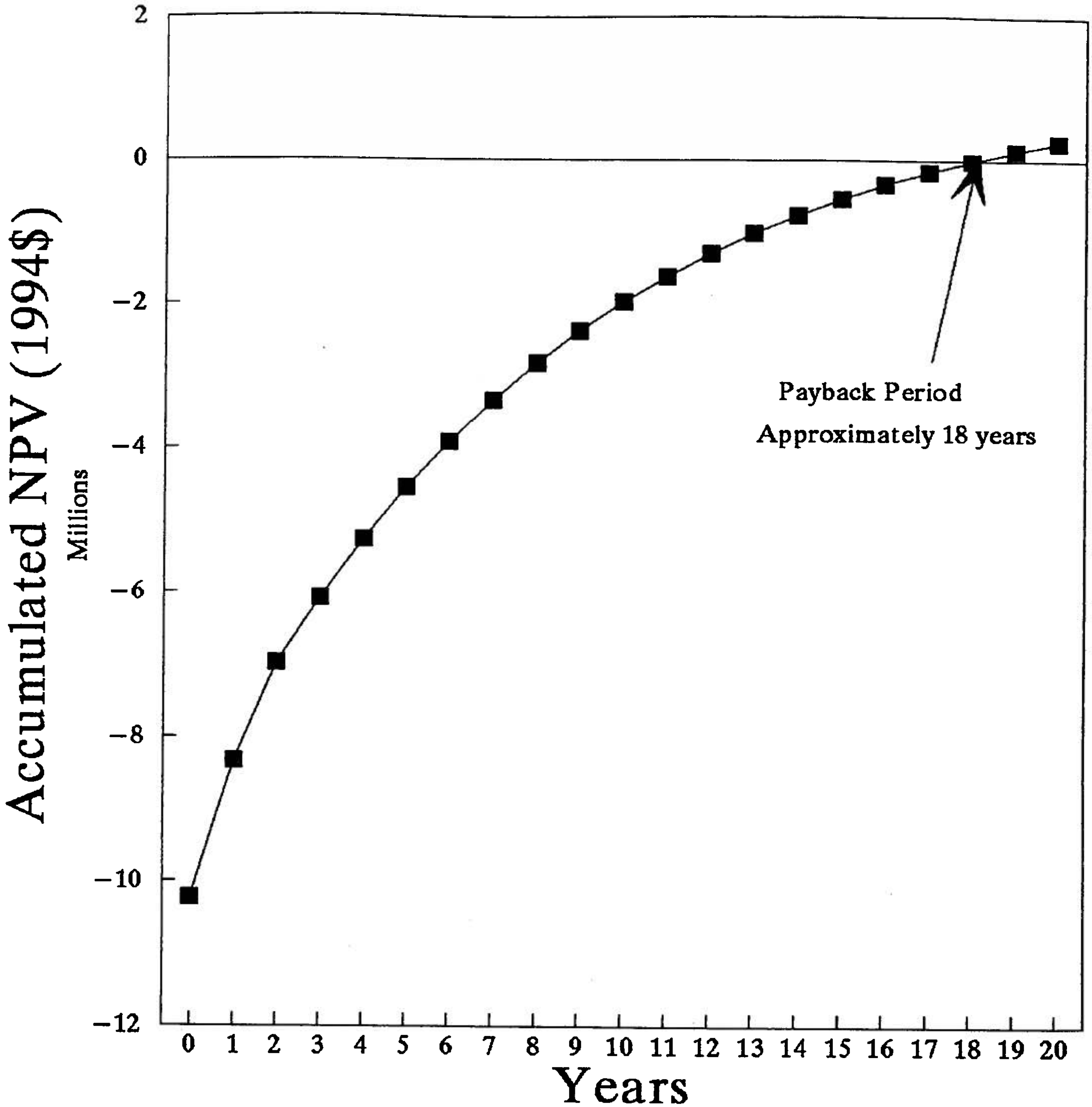

Figure 32: Option #1 Payback Period for a Sawmill Producing 80,000 ODT/yr of Wood Waste and Requiring 10,000 kW of Process Heat

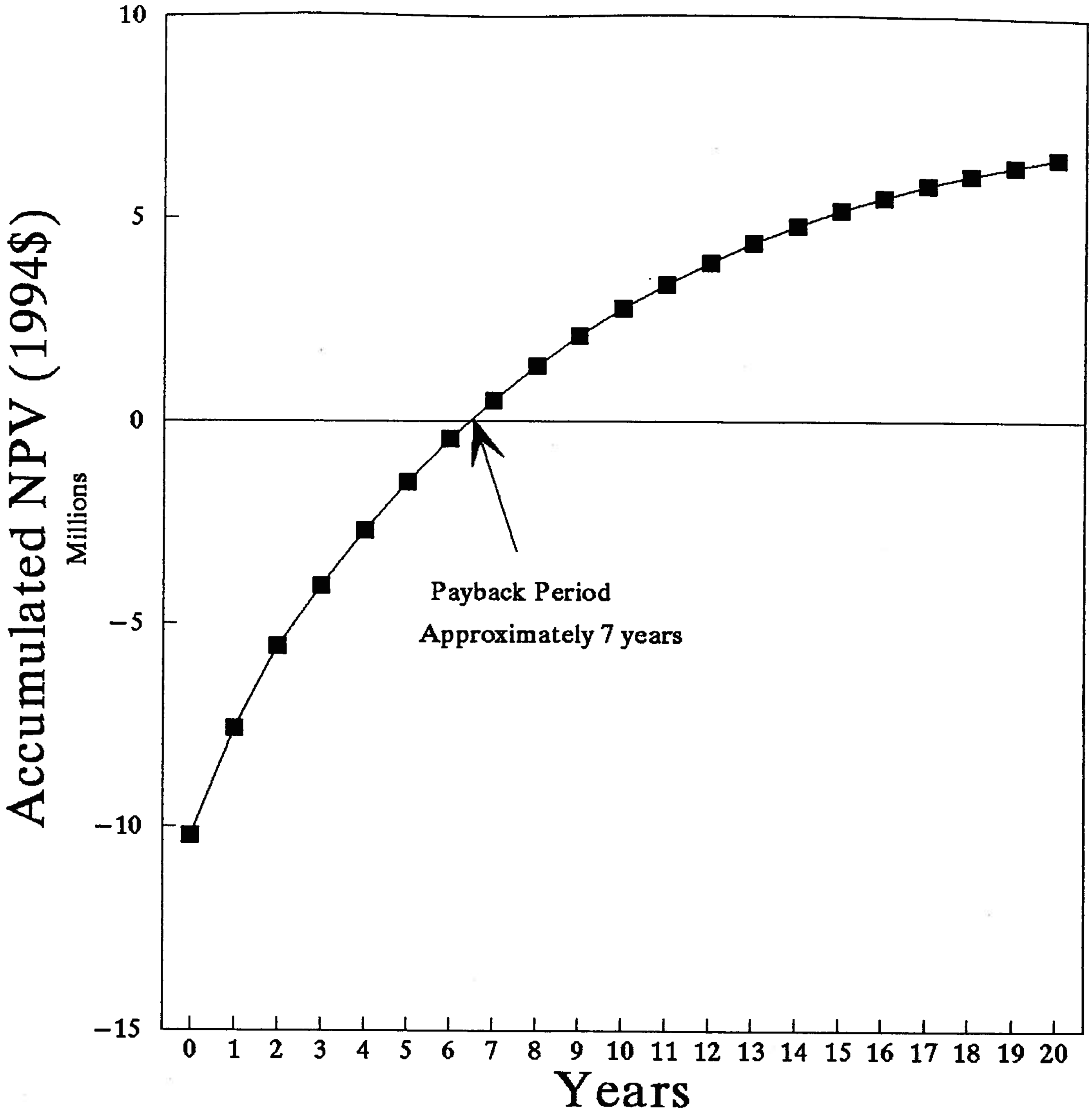

Figure 33: Option #1 Payback Period for a Sawmill Producing 80,000 ODT/yr of Wood Waste and Requiring 20,000 kW of Process Heat

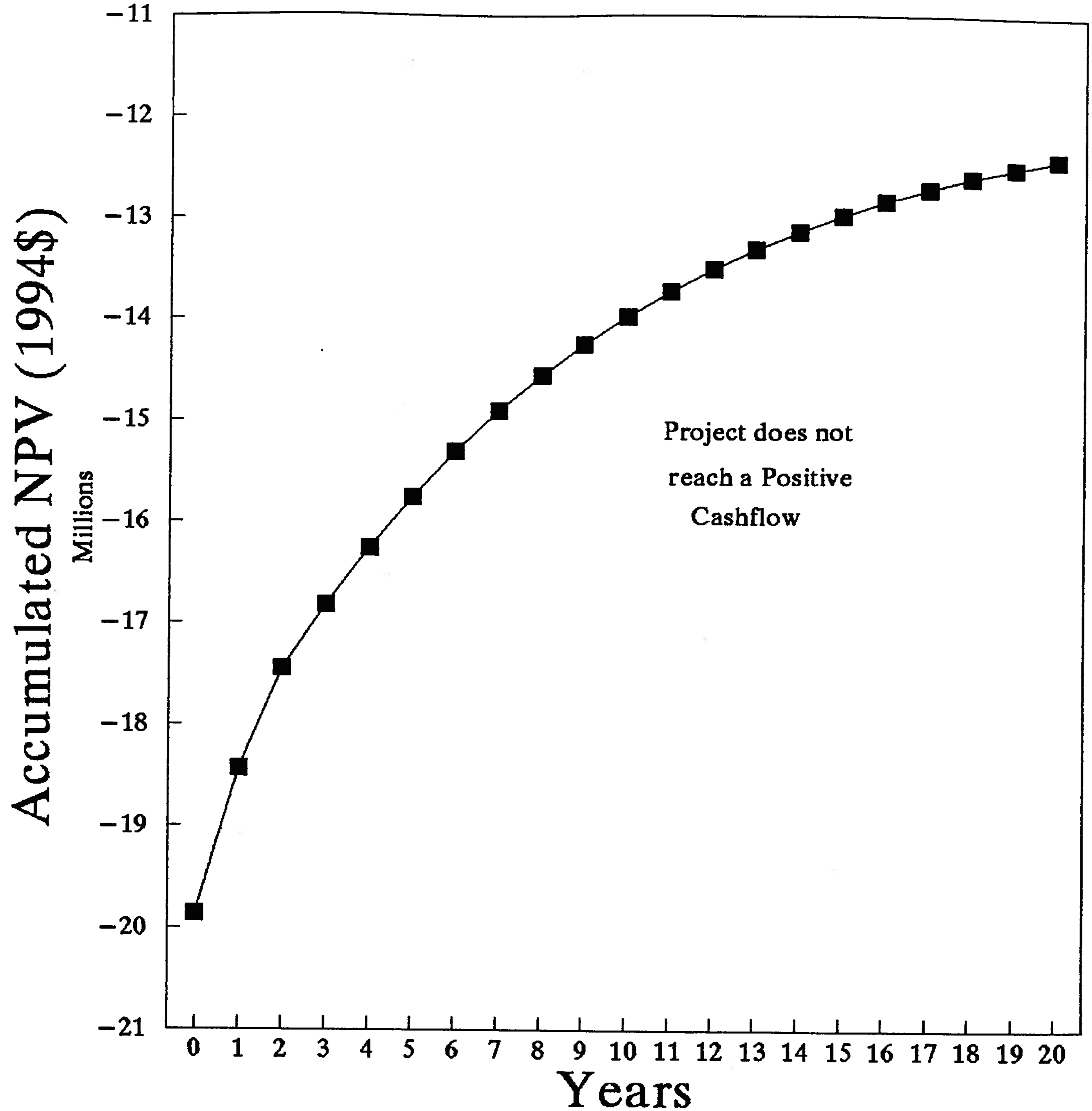

Figure 34: Option #2 Payback Period for a Sawmill Producing 80,000 ODT/yr of Wood Waste and Requiring 10,000 kW of Process Heat

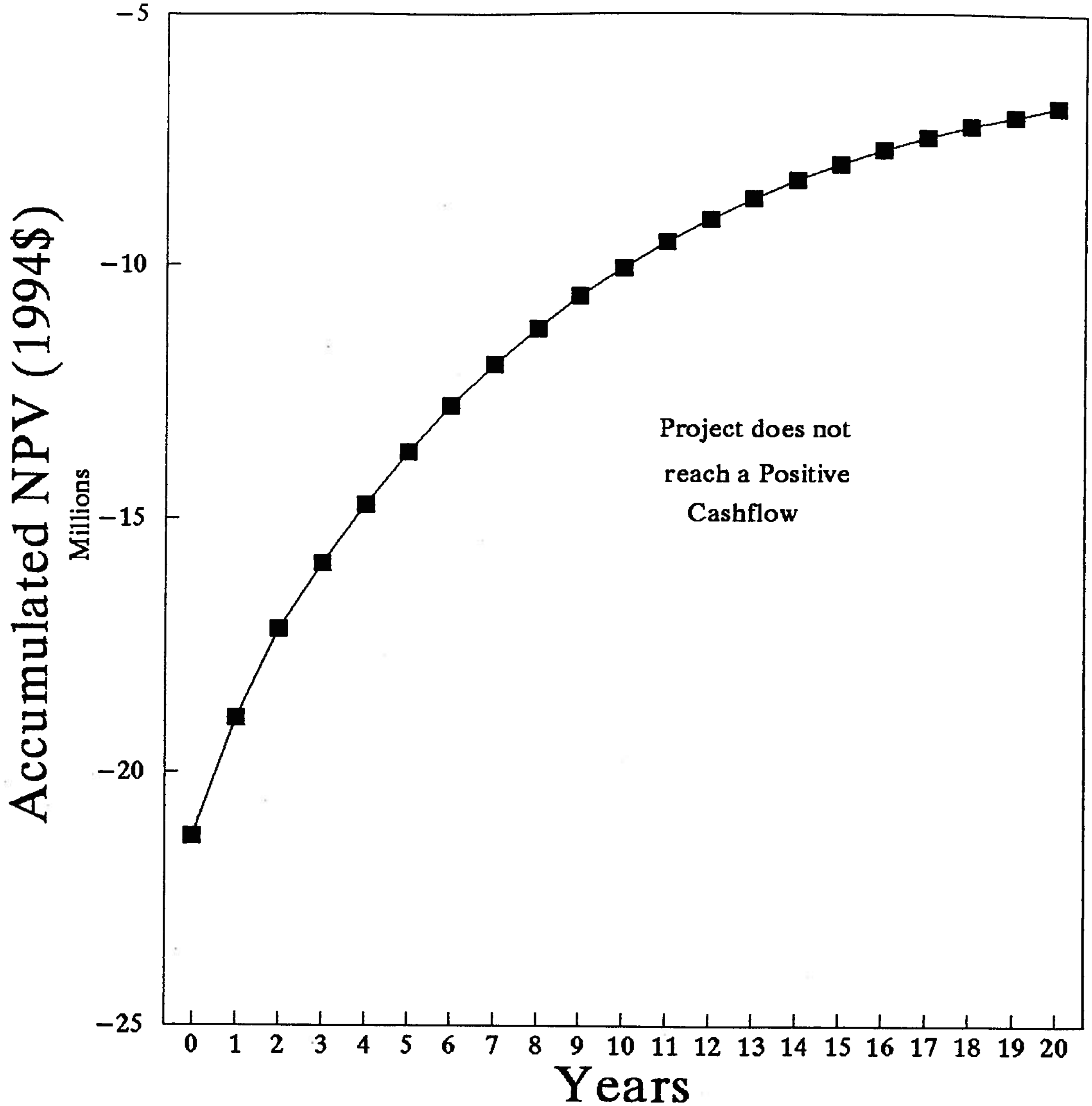

Figure 35: Option #2 Payback Period for a Sawmill Producing 80,000 ODT/yr of Wood Waste and Requiring 20,000 kW of Process Heat

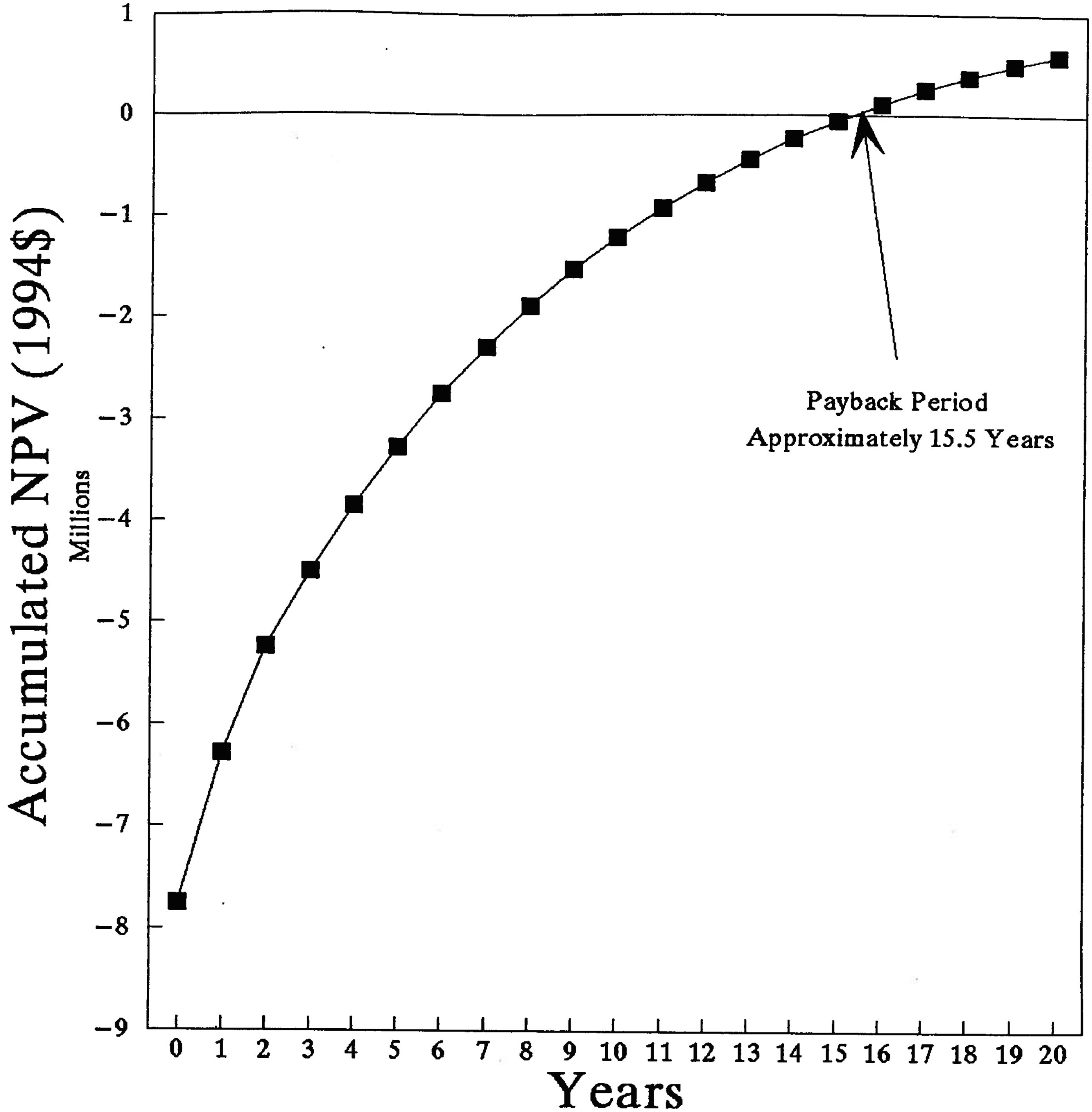

Figure 36: Option #3 Payback Period for a Sawmill Producing 80,000 ODT/yr of Wood Waste and Requiring 10,000 kW of Process Heat

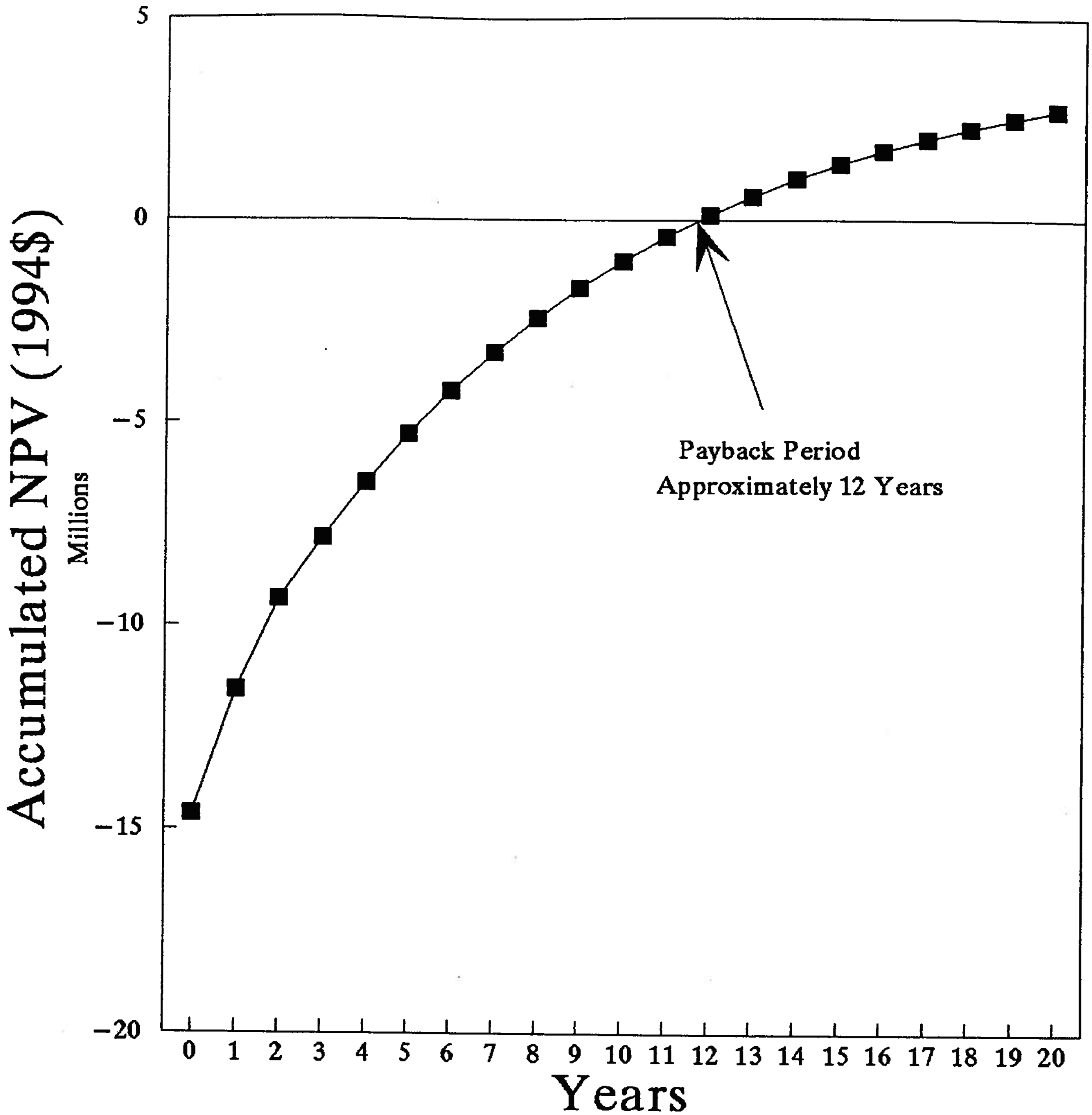

Figure 37: Option #3 Payback Period for a Sawmill Producing 80,000 ODT/yr of Wood Waste and Requiring 20,000 kW of Process Heat

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Appendix A:

Process Flow Values for Options #1, #2, #3

OPTION #1: METALLIC HEAT EXCHANGER

Ambient Temperature (C) = 20
Atmospheric Pressure (kPa) = 101.3
PLANT CONDITIONS:
Sawmill annual capacity (Mfbm) = 50
Annual wood waste production (ODT) = 26,147
Initial wood waste moisture content (%) = 50
Target wood waste moisture content (%) = 50
Max compressed air temperature via HX (C) = 650

PROCESS FLOW CONDITIONS

FLOW	TEMP deg C	PRESSURE kPa	ENTHALPY kJ/kg	ENTROPY kJ/kgK	EXERGY kJ/kg	MASS kg/sec	MOISTURE %H2O
#1	20.0					1.8	50.0
#2	20.0					1.8	50.0
#3	1,094.1	103.1	1,476.0	4.1	698.8	9.1	10.2
#7	20.0	101.3	293.2	2.5	0.0	8.2	0.0
#15	20.0	171.2	293.2	2.3	44.1	9.1	0.0

Cp3 and Cp15 = 1.21 1.01
Turbine No.1:
Manufacturer:Kawasaki
Model No.: M1A -11A

FLOW	TEMP deg C	PRESSURE kPa	ENTHALPY kJ/kg	ENTROPY kJ/kgK	EXERGY kJ/kg	MASS kg/sec	MOISTURE %H2O
#4i	863.6	102.6	1,203.6	3.9	489.9	9.1	10.2
5i	315.0	101.3	594.5	3.2	92.9	9.1	10.2
6i	315.0	103.8	594.5	3.2	94.9	9.1	10.2
#8i	0.0	0.0	0.0	0.0	0.0	0.0	0.0
#9i	20.0	101.3	293.2	2.5	0.0	8.2	0.0
#10i	378.1	942.1	661.1	2.7	315.4	8.2	0.0
#11i	650.0	872.2	958.8	3.1	495.1	8.2	0.0
#12i	20.0	872.2				8.2	0.0
#13i	910.0	872.2	1,257.9	3.4	710.5	0.1	0.0
#14i	469.4	101.3	759.1	3.4	184.8	8.3	0.0
#16i	625.1	101.3	930.8	3.7	294.9	8.3	0.0
#17i	551.4	101.3	848.9	3.6	242.3	9.1	0.0
						17.4	0.0

Cp4i and Cp5i = 1.17 1.05
Cp10i and Cp11i = 1.06 1.13
Cp16i = 1.12

POWER GENERATED (kW) and RATED OUTPUT POWER (kW) = 1,114 1,235
ENERGY RELEASED IN COMBUSTOR (kW) =12,345
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW) = 3,859 5,783
KILN HEAT AVAILABLE (kW) = 9,642
ENERGY REQUIRED IN DRYER (kW) = 0
ENERGY INPUT FROM NATURAL GAS (kW) = 2,839
HEAT EXCHANGER EFFECTIVENESS =0.322
FIRST LAW EFFICIENCY =70.8
SECOND LAW EFFICIENCY =54.7

Turbine No.2:
Manufacturer:Kawasaki
Model No.: M1A - 23

#4ii	899.4	102.6	1,245.4	4.0	521.1	9.1	10.2
#5ii	315.0	101.3	594.5	3.2	92.9	9.1	10.2
#6ii	315.0	103.8	594.5	3.2	94.9	9.1	10.2
#8ii	0.0	0.0	0.0	0.0	0.0	0.0	0.0
#9ii	20.0	101.3	293.2	2.5	0.0	9.3	0.0
#10ii	449.0	1,134.6	737.0	2.7	374.8	9.3	0.0
#11ii	650.0	1,064.7	958.8	3.0	495.1	9.3	0.0
#12ii	20.0	1,064.7				0.1	0.0
#13ii	1,140.0	1,064.7	1,531.0	3.5	938.6	9.4	0.0
#14ii	586.4	101.3	887.7	3.6	266.2	9.4	0.0
#16ii	666.6	101.3	977.5	3.7	326.7	9.1	0.0
#17ii	626.0	101.3	931.8	3.7	296.0	18.5	0.0

Cp4ii and Cp5ii = 1.17 1.05
Cp10ii and Cp11ii = 1.08 1.13
Cp16ii = 1.13

POWER GENERATED (kW) AND RATED OUTPUT POWER (kW) = 1,915 2,043
ENERGY RELEASED IN COMBUSTOR (kW) =12,345
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW) = 5,584 6,206
KILN HEAT AVAILABLE (kW) =11,790
ENERGY REQUIRED IN DRYER (kW) = 0
ENERGY INPUT FROM NATURAL GAS (kW) = 6,071
HEAT EXCHANGER EFFECTIVENESS =0.312
FIRST LAW EFFICIENCY =74.4
SECOND LAW EFFICIENCY =60.9

Turbine No.3:
Manufacturer:Kawasaki
Model No.: M1T - 23

#4iii	712.5	102.6	1,029.6	3.8	364.1	9.1	10.2
#5iii	315.0	101.3	594.5	3.2	92.9	9.1	10.2
#6iii	315.0	103.8	594.5	3.2	94.9	9.1	10.2
#8iii	0.0	0.0	0.0	0.0	0.0	0.0	0.0
#9iii	20.0	101.3	293.2	2.5	0.0	18.6	0.0
#10iii	453.2	1,124.4	741.5	2.8	370.3	18.6	0.0
#11iii	650.0	1,054.5	958.8	3.0	504.7	18.6	0.0
#12iii	20.0	1,054.5				0.2	0.0
#13iii	1,130.0	1,054.5	1,519.0	3.5	921.9	18.8	0.0
#14iii	581.9	101.3	882.7	3.6	256.5	18.8	0.0
#16iii	452.9	101.3	741.3	3.4	174.1	9.1	0.0
#17iii	540.3	101.3	836.6	3.6	229.7	27.9	0.0

Cp4iii and Cp5iii = 1.14 1.05
Cp10iii and Cp11iii = 1.08 1.13
Cp16iii = 1.08

POWER GENERATED (kW) AND RATED OUTPUT POWER (kW) = 3,615 3,981
ENERGY RELEASED IN COMBUSTOR (kW) =12,345
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW) =11,074 4,064
KILN HEAT AVAILABLE (kW) =15,138
ENERGY REQUIRED IN DRYER (kW) = 0
ENERGY INPUT FROM NATURAL GAS (kW) =11,891
HEAT EXCHANGER EFFECTIVENESS =0.595
FIRST LAW EFFICIENCY =77.4
SECOND LAW EFFICIENCY =65.7

OPTION #1: METALLIC HEAT EXCHANGER

Ambient Temperature (C)	= 20
Atmospheric Pressure (kPa)	= 101.3
PLANT CONDITIONS:	
Sawmill annual capacity (Mfbm)	= 50
Annual wood waste production (ODT)	= 26,147
Initial wood waste moisture content (%)	= 50
Target wood waste moisture content (%)	= 50
Max compressed air temperature via HX (C)	= 650

PROCESS FLOW CONDITIONS

FLOW	TEMP deg C	PRESSURE kPa	ENTHALPY kJ/kg	ENTROPY kJ/kgK	EXERGY kJ/kg	MASS kg/sec	MOISTURE %H2O
#1	20.0					1.8	50.0
#2	20.0					1.8	50.0
#3	1,094.1	103.1	1,476.0	4.1	698.8	9.1	10.2
#7	20.0	101.3	293.2	2.5	0.0	8.2	0.0
#15	20.0	171.2	293.2	2.3	44.1	9.1	0.0

Cp3 and Cp15 = 1.21 1.01

Turbine No.1:

Manufacturer:Kawasaki

Model No.: 1 Unit of the M1T - 23

FLOW	TEMP deg C	PRESSURE kPa	ENTHALPY kJ/kg	ENTROPY kJ/kgK	EXERGY kJ/kg	MASS kg/sec	MOISTURE %H2O
#4i	712.5	102.6	1,029.6	3.8	364.1	9.1	10.2
5i	315.0	101.3	594.5	3.2	92.9	9.1	10.2
5i	315.0	103.8	594.5	3.2	94.9	9.1	10.2
#8i	0.0	0.0	0.0	0.0	0.0	0.0	0.0
#9i	20.0	101.3	293.2	2.5	0.0	18.6	0.0
#10i	453.2	1,124.4	741.5	2.7	376.7	18.6	0.0
#11i	650.0	1,054.5	958.8	3.0	511.0	18.6	0.0
#12i	20.0	1,054.5				0.2	0.0
#13i	1,130.0	1,054.5	1,519.0	3.5	928.2	18.8	0.0
#14i	581.9	101.3	882.7	3.6	262.9	18.8	0.0
#16i	452.9	101.3	741.3	3.4	174.1	9.1	0.0
#17i	540.3	101.3	836.6	3.5	234.0	27.9	0.0

Cp4i and Cp5i = 1.14 1.05

Cp10i and Cp11i = 1.08 1.13

Cp16i = 1.08

POWER GENERATED (kW) and RATED OUTPUT POWER (kW)	= 3,615 3,981
ENERGY RELEASED IN COMBUSTOR (kW)	=12,345
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW)	=11,074 4,064
KILN HEAT AVAILABLE (kW)	=15,138
ENERGY REQUIRED IN DRYER (kW)	= 0
ENERGY INPUT FROM NATURAL GAS (kW)	=11,891
HEAT EXCHANGER EFFECTIVENESS	=0.595
FIRST LAW EFFICIENCY	=77.4
SECOND LAW EFFICIENCY	=66.2

Turbine No.2:
Manufacturer:Kawasaki
Model No.: 2 Units of the M1T - 23

#4ii	564.2	102.6	863.0	3.6	251.1	9.1	10.2
#5ii	315.0	101.3	594.5	3.2	92.9	9.1	10.2
#6ii	315.0	103.8	594.5	3.2	94.9	9.1	10.2
#8ii	0.0	0.0	0.0	0.0	0.0	0.0	0.0
#9ii	20.0	101.3	293.2	2.5	0.0	37.2	0.0
#10ii	453.2	1,124.4	741.5	2.7	376.7	37.2	0.0
#11ii	589.9	1,054.5	891.5	2.9	511.0	37.2	0.0
#12ii	20.0	1,054.5				0.5	0.0
#13ii	1,130.0	1,054.5	1,519.0	3.5	928.2	37.6	0.0
#14ii	581.9	101.3	882.7	3.6	262.9	37.6	0.0
#16ii	287.3	101.3	565.5	3.2	78.8	9.1	0.0
#17ii	526.1	101.3	821.0	3.5	227.1	46.6	0.0

Cp4ii and Cp5ii = 1.11 1.05
Cp10ii and Cp11ii = 1.08 1.13
Cp16ii = 1.04

POWER GENERATED (kW) AND RATED OUTPUT POWER (kW) = 7,230 7,962
ENERGY RELEASED IN COMBUSTOR (kW) =12,345
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW) =22,148 2,470
KILN HEAT AVAILABLE (kW) =24,618
ENERGY REQUIRED IN DRYER (kW) = 0
ENERGY INPUT FROM NATURAL GAS (kW) =26,565
HEAT EXCHANGER EFFECTIVENESS =0.827
FIRST LAW EFFICIENCY =81.9
SECOND LAW EFFICIENCY =78.1

Turbine No.3:
Manufacturer:Kawasaki
Model No.: 3 Units of the M1T - 23

#4iii	564.2	102.6	863.0	3.6	251.1	9.1	10.2
#5iii	315.0	101.3	594.5	3.2	92.9	9.1	10.2
#6iii	315.0	103.8	594.5	3.2	94.9	9.1	10.2
#8iii	0.0	0.0	0.0	0.0	0.0	0.0	0.0
#9iii	20.0	101.3	293.2	2.5	0.0	55.8	0.0
#10iii	453.2	1,124.4	741.5	2.8	370.3	55.8	0.0
#11iii	544.3	1,054.5	841.0	2.9	426.6	55.8	0.0
#12iii	20.0	1,054.5				0.8	0.0
#13iii	1,130.0	1,054.5	1,519.0	3.5	921.9	56.4	0.0
#14iii	581.9	101.3	882.7	3.6	256.5	56.4	0.0
#16iii	287.3	101.3	565.5	3.2	78.8	9.1	0.0
#17iii	542.2	101.3	838.7	3.6	231.9	65.4	0.0

Cp4iii and Cp5iii = 1.11 1.05
Cp10iii and Cp11iii = 1.08 1.13
Cp16iii = 1.04

POWER GENERATED (kW) AND RATED OUTPUT POWER (kW) =10,84511,943
ENERGY RELEASED IN COMBUSTOR (kW) =12,345
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW) =33,222 2,470
KILN HEAT AVAILABLE (kW) =35,692
ENERGY REQUIRED IN DRYER (kW) = 0
ENERGY INPUT FROM NATURAL GAS (kW) =42,977
HEAT EXCHANGER EFFECTIVENESS =0.827
FIRST LAW EFFICIENCY =84.1
SECOND LAW EFFICIENCY =77.2

OPTION #1: METALLIC HEAT EXCHANGER

Ambient Temperature (C)	= 20
Atmospheric Pressure (kPa)	= 101.3
PLANT CONDITIONS:	
Sawmill annual capacity (Mfbm)	=150
Annual wood waste production (ODT)	= 78,440
Initial wood waste moisture content (%)	= 50
Target wood waste moisture content (%)	= 50
Max compressed air temperature via HX (C)	= 650

PROCESS FLOW CONDITIONS

FLOW	TEMP deg C	PRESSURE kPa	ENTHALPY kJ/kg	ENTROPY kJ/kgK	EXERGY kJ/kg	MASS kg/sec	MOISTURE %H2O
#1	20.0					5.5	50.0
#2	20.0					5.5	50.0
#3	1,094.1	103.1	1,476.0	4.1	698.8	27.2	10.2
#7	20.0	101.3	293.2	2.5	0.0	24.6	0.0
#15	20.0	171.2	293.2	2.3	44.1	27.2	0.0
Cp3 and Cp15 = 1.21 1.01							
Turbine No.1:							
Manufacturer:Kawasaki							
Model No.: M1A -11A							
#4i	1,017.3	102.6	1,384.4	4.1	627.0	27.2	10.2
#5i	315.0	101.3	594.5	3.2	92.9	27.2	10.2
#6i	315.0	103.8	594.5	3.2	94.9	27.2	10.2
#8i	0.0	0.0	0.0	0.0	0.0	0.0	0.0
#9i	20.0	101.3	293.2	2.5	0.0	8.2	0.0
#10i	378.1	942.1	661.1	2.7	315.4	8.2	0.0
#11i	650.0	872.2	958.8	3.1	495.1	8.2	0.0
#12i	20.0	872.2				0.1	0.0
#13i	910.0	872.2	1,257.9	3.4	710.5	8.3	0.0
#14i	469.4	101.3	759.1	3.4	184.8	8.3	0.0
#16i	804.4	101.3	1,135.0	3.9	438.5	27.2	0.0
#17i	728.1	101.3	1,047.3	3.8	379.3	35.5	0.0

Cp4i and Cp5i = 1.20 1.05
Cp10i and Cp11i = 1.06 1.13
Cp16i = 1.16

POWER GENERATED (kW) and RATED OUTPUT POWER (kW)	= 1,114 1,235
ENERGY RELEASED IN COMBUSTOR (kW)	=37,033
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW)	= 3,85922,902
KILN HEAT AVAILABLE (kW)	=26,761
ENERGY REQUIRED IN DRYER (kW)	= 0
ENERGY INPUT FROM NATURAL GAS (kW)	= 2,839
HEAT EXCHANGER EFFECTIVENESS	=0.107
FIRST LAW EFFICIENCY	=69.9
SECOND LAW EFFICIENCY	=53.8

Turbine No.2:
Manufacturer:Kawasaki
Model No.: M1A - 23

#4ii	1,029.2	102.6	1,398.6	4.1	637.9	27.2	10.2
#5ii	315.0	101.3	594.5	3.2	92.9	27.2	10.2
#6ii	315.0	103.8	594.5	3.2	94.9	27.2	10.2
#8ii	0.0	0.0	0.0	0.0	0.0	0.0	0.0
#9ii	20.0	101.3	293.2	2.5	0.0	9.3	0.0
#10ii	449.0	1,134.6	737.0	2.7	374.8	9.3	0.0
#11ii	650.0	1,064.7	958.8	3.0	495.1	9.3	0.0
#12ii	20.0	1,064.7				0.1	0.0
#13ii	1,140.0	1,064.7	1,531.0	3.5	938.6	9.4	0.0
#14ii	586.4	101.3	887.7	3.6	266.2	9.4	0.0
#16ii	818.5	101.3	1,151.3	3.9	450.3	27.2	0.0
#17ii	759.8	101.3	1,083.6	3.8	403.1	36.6	0.0

Cp4ii and Cp5ii = 1.20 1.05
Cp10ii and Cp11ii = 1.08 1.13
Cp16ii = 1.16

POWER GENERATED (kW) AND RATED OUTPUT POWER (kW) = 1,915 2,043
ENERGY RELEASED IN COMBUSTOR (kW) =37,033
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW) = 5,58423,345
KILN HEAT AVAILABLE (kW) =28,929
ENERGY REQUIRED IN DRYER (kW) = 0
ENERGY INPUT FROM NATURAL GAS (kW) = 6,071
HEAT EXCHANGER EFFECTIVENESS =0.312
FIRST LAW EFFICIENCY =71.6
SECOND LAW EFFICIENCY =56.6

Turbine No.3:
Manufacturer:Kawasaki
Model No.: M1T - 23

#4iii	966.9	102.6	1,324.8	4.0	581.2	27.2	10.2
#5iii	315.0	101.3	594.5	3.2	92.9	27.2	10.2
#6iii	315.0	103.8	594.5	3.2	94.9	27.2	10.2
#8iii	0.0	0.0	0.0	0.0	0.0	0.0	0.0
#9iii	20.0	101.3	293.2	2.5	0.0	18.6	0.0
#10iii	453.2	1,124.4	741.5	2.8	370.3	18.6	0.0
#11iii	650.0	1,054.5	958.8	3.0	504.7	18.6	0.0
#12iii	20.0	1,054.5				0.2	0.0
#13iii	1,130.0	1,054.5	1,519.0	3.5	921.9	18.8	0.0
#14iii	581.9	101.3	882.7	3.6	256.5	18.8	0.0
#16iii	745.2	101.3	1,066.9	3.8	389.4	27.2	0.0
#17iii	679.2	101.3	991.7	3.7	335.2	46.0	0.0

Cp4iii and Cp5iii = 1.19 1.05
Cp10iii and Cp11iii = 1.08 1.13
Cp16iii = 1.15

POWER GENERATED (kW) AND RATED OUTPUT POWER (kW) = 3,615 3,981
ENERGY RELEASED IN COMBUSTOR (kW) =37,033
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW) =11,07421,051
KILN HEAT AVAILABLE (kW) =32,125
ENERGY REQUIRED IN DRYER (kW) = 0
ENERGY INPUT FROM NATURAL GAS (kW) =11,891
HEAT EXCHANGER EFFECTIVENESS =0.198
FIRST LAW EFFICIENCY =73.1
SECOND LAW EFFICIENCY =59.1

OPTION #1: METALLIC HEAT EXCHANGER

Ambient Temperature (C) = 20
Atmospheric Pressure (kPa) = 101.3
PLANT CONDITIONS:
Sawmill annual capacity (Mfbm) =150
Annual wood waste production (ODT) = 78,440
Initial wood waste moisture content (%) = 50
Target wood waste moisture content (%) = 50
Max compressed air temperature via HX (C) = 650

PROCESS FLOW CONDITIONS

FLOW	TEMP deg C	PRESSURE kPa	ENTHALPY kJ/kg	ENTROPY kJ/kgK	EXERGY kJ/kg	MASS kg/sec	MOISTURE %H2O
#1	20.0					5.5	50.0
#2	20.0					5.5	50.0
#3	1,094.1	103.1	1,476.0	4.1	698.8	27.2	10.2
#7	20.0	101.3	293.2	2.5	0.0	24.6	0.0
#15	20.0	171.2	293.2	2.3	44.1	27.2	0.0
Cp3 and Cp15 = 1.21 1.01							
Turbine No.1:							
Manufacturer:Kawasaki							
Model No.: 1 Unit of the M1T - 23							
#4i	966.9	102.6	1,324.8	4.0	581.2	27.2	10.2
#5i	315.0	101.3	594.5	3.2	92.9	27.2	10.2
#6i	315.0	103.8	594.5	3.2	94.9	27.2	10.2
#8i	0.0	0.0	0.0	0.0	0.0	0.0	0.0
#9i	20.0	101.3	293.2	2.5	0.0	18.6	0.0
#10i	453.2	1,124.4	741.5	2.7	376.7	18.6	0.0
#11i	650.0	1,054.5	958.8	3.0	511.0	18.6	0.0
#12i	20.0	1,054.5				0.2	0.0
#13i	1,130.0	1,054.5	1,519.0	3.5	928.2	18.8	0.0
#14i	581.9	101.3	882.7	3.6	262.9	18.8	0.0
#16i	745.2	101.3	1,066.9	3.8	389.4	27.2	0.0
#17i	679.2	101.3	991.7	3.7	337.7	46.0	0.0

Cp4i and Cp5i = 1.19 1.05
Cp10i and Cp11i = 1.08 1.13
Cp16i = 1.15

POWER GENERATED (kW) and RATED OUTPUT POWER (kW) = 3,615 3,981
ENERGY RELEASED IN COMBUSTOR (kW) =37,033
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW) =11,07421,051
KILN HEAT AVAILABLE (kW) =32,125
ENERGY REQUIRED IN DRYER (kW) = 0
ENERGY INPUT FROM NATURAL GAS (kW) =11,891
HEAT EXCHANGER EFFECTIVENESS =0.198
FIRST LAW EFFICIENCY =73.1
SECOND LAW EFFICIENCY =59.3

Turbine No.2:
Manufacturer:Kawasaki
Model No.: 2 Units of the M1T - 23

#4ii	839.7	102.6	1,175.9	3.9	469.4	27.2	10.2
#5ii	315.0	101.3	594.5	3.2	92.9	27.2	10.2
#6ii	315.0	103.8	594.5	3.2	94.9	27.2	10.2
#8ii	0.0	0.0	0.0	0.0	0.0	0.0	0.0
#9ii	20.0	101.3	293.2	2.5	0.0	37.2	0.0
#10ii	453.2	1,124.4	741.5	2.7	376.7	37.2	0.0
#11ii	650.0	1,054.5	958.8	3.0	511.0	37.2	0.0
#12ii	20.0	1,054.5				0.4	0.0
#13ii	1,130.0	1,054.5	1,519.0	3.5	928.2	37.6	0.0
#14ii	581.9	101.3	882.7	3.6	262.9	37.6	0.0
#16ii	597.6	101.3	900.1	3.6	274.5	27.2	0.0
#17ii	588.5	101.3	890.0	3.6	267.8	64.8	0.0

Cp4ii and Cp5ii = 1.16 1.05
Cp10ii and Cp11ii = 1.08 1.13
Cp16ii = 1.11

POWER GENERATED (kW) AND RATED OUTPUT POWER (kW) = 7,230 7,962
ENERGY RELEASED IN COMBUSTOR (kW) =37,033
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW) =22,14816,512
KILN HEAT AVAILABLE (kW) =38,660
ENERGY REQUIRED IN DRYER (kW) = 0
ENERGY INPUT FROM NATURAL GAS (kW) =23,782
HEAT EXCHANGER EFFECTIVENESS =0.397
FIRST LAW EFFICIENCY =75.5
SECOND LAW EFFICIENCY =63.2

Turbine No.3:
Manufacturer:Kawasaki
Model No.: 3 Units of the M1T - 23

#4iii	712.5	102.6	1,029.6	3.8	364.1	27.2	10.2
#5iii	315.0	101.3	594.5	3.2	92.9	27.2	10.2
#6iii	315.0	103.8	594.5	3.2	94.9	27.2	10.2
#8iii	0.0	0.0	0.0	0.0	0.0	0.0	0.0
#9iii	20.0	101.3	293.2	2.5	0.0	55.8	0.0
#10iii	453.2	1,124.4	741.5	2.8	370.3	55.8	0.0
#11iii	650.0	1,054.5	958.8	3.0	504.7	55.8	0.0
#12iii	20.0	1,054.5				0.6	0.0
#13iii	1,130.0	1,054.5	1,519.0	3.5	921.9	56.4	0.0
#14iii	581.9	101.3	882.7	3.6	256.5	56.4	0.0
#16iii	452.9	101.3	741.3	3.4	174.1	27.2	0.0
#17iii	540.3	101.3	836.6	3.6	229.7	83.6	0.0

Cp4iii and Cp5iii = 1.14 1.05
Cp10iii and Cp11iii = 1.08 1.13
Cp16iii = 1.08

POWER GENERATED (kW) AND RATED OUTPUT POWER (kW) =10,84511,943
ENERGY RELEASED IN COMBUSTOR (kW) =37,033
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW) =33,22212,191
KILN HEAT AVAILABLE (kW) =45,413
ENERGY REQUIRED IN DRYER (kW) = 0
ENERGY INPUT FROM NATURAL GAS (kW) =35,674
HEAT EXCHANGER EFFECTIVENESS =0.595
FIRST LAW EFFICIENCY =77.4
SECOND LAW EFFICIENCY =65.8

OPTION #1: METALLIC HEAT EXCHANGER

Ambient Temperature (C)	= 20
Atmospheric Pressure (kPa)	= 101.3
PLANT CONDITIONS:	
Sawmill annual capacity (Mfbm)	=250
Annual wood waste production (ODT)	=130,734
Initial wood waste moisture content (%)	= 50
Target wood waste moisture content (%)	= 50
Max compressed air temperature via HX (C)	= 650

PROCESS FLOW CONDITIONS

FLOW	TEMP deg C	PRESSURE kPa	ENTHALPY kJ/kg	ENTROPY kJ/kgK	EXERGY kJ/kg	MASS kg/sec	MOISTURE %H2O
#1	20.0					9.2	50.0
#2	20.0					9.2	50.0
#3	1,094.1	103.1	1,476.0	4.1	698.8	45.3	10.2
#7	20.0	101.3	293.2	2.5	0.0	40.9	0.0
#15	20.0	171.2	293.2	2.3	44.1	45.3	0.0

Cp3 and Cp15 = 1.21 1.01

Turbine No.1:

Manufacturer:Kawasaki

Model No.: M1A -11A

FLOW	TEMP deg C	PRESSURE kPa	ENTHALPY kJ/kg	ENTROPY kJ/kgK	EXERGY kJ/kg	MASS kg/sec	MOISTURE %H2O
#4i	1,048.0	102.6	1,421.0	4.1	655.4	45.3	10.2
#5i	315.0	101.3	594.5	3.2	92.9	45.3	10.2
#6i	315.0	103.8	594.5	3.2	94.9	45.3	10.2
#8i	0.0	0.0	0.0	0.0	0.0	0.0	0.0
#9i	20.0	101.3	293.2	2.5	0.0	8.2	0.0
#10i	378.1	942.1	661.1	2.7	315.4	8.2	0.0
#11i	650.0	872.2	958.8	3.1	495.1	8.2	0.0
#12i	20.0	872.2				0.1	0.0
#13i	910.0	872.2	1,257.9	3.4	710.5	8.3	0.0
#14i	469.4	101.3	759.1	3.4	184.8	8.3	0.0
#16i	840.8	101.3	1,177.1	3.9	469.3	45.3	0.0
#17i	784.9	101.3	1,112.5	3.8	425.3	53.6	0.0

Cp4i and Cp5i = 1.20 1.05

Cp10i and Cp11i = 1.06 1.13

Cp16i = 1.16

POWER GENERATED (kW) and RATED OUTPUT POWER (kW)	= 1,114 1,235
ENERGY RELEASED IN COMBUSTOR (kW)	=61,723
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW)	= 3,85940,079
KILN HEAT AVAILABLE (kW)	=43,938
ENERGY REQUIRED IN DRYER (kW)	= 0
ENERGY INPUT FROM NATURAL GAS (kW)	= 2,839
HEAT EXCHANGER EFFECTIVENESS	=0.064
FIRST LAW EFFICIENCY	=69.8
SECOND LAW EFFICIENCY	=53.8

Turbine No.2:
Manufacturer:Kawasaki
Model No.: M1A - 23

#4ii	1,055.2	102.6	1,429.5	4.1	662.0	45.3	10.2
#5ii	315.0	101.3	594.5	3.2	92.9	45.3	10.2
#6ii	315.0	103.8	594.5	3.2	94.9	45.3	10.2
#8ii	0.0	0.0	0.0	0.0	0.0	0.0	0.0
#9ii	20.0	101.3	293.2	2.5	0.0	9.3	0.0
#10ii	449.0	1,134.6	737.0	2.7	374.8	9.3	0.0
#11ii	650.0	1,064.7	958.8	3.0	495.1	9.3	0.0
#12ii	20.0	1,064.7				0.1	0.0
#13ii	1,140.0	1,064.7	1,531.0	3.5	938.6	9.4	0.0
#14ii	586.4	101.3	887.7	3.6	266.2	9.4	0.0
#16ii	849.2	101.3	1,186.9	3.9	476.6	45.3	0.0
#17ii	804.9	101.3	1,135.6	3.9	440.5	54.7	0.0

Cp4ii and Cp5ii = 1.20 1.05
Cp10ii and Cp11ii = 1.08 1.13
Cp16ii = 1.16

POWER GENERATED (kW) AND RATED OUTPUT POWER (kW)	= 1,915 2,043
ENERGY RELEASED IN COMBUSTOR (kW)	=61,723
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW)	= 5,58440,527
KILN HEAT AVAILABLE (kW)	=46,111
ENERGY REQUIRED IN DRYER (kW)	= 0
ENERGY INPUT FROM NATURAL GAS (kW)	= 6,071
HEAT EXCHANGER EFFECTIVENESS	=0.312
FIRST LAW EFFICIENCY	=70.8
SECOND LAW EFFICIENCY	=55.6

Turbine No.3:
Manufacturer:Kawasaki
Model No.: M1T - 23

#4iii	1,017.8	102.6	1,385.1	4.1	627.5	45.3	10.2
#5iii	315.0	101.3	594.5	3.2	92.9	45.3	10.2
#6iii	315.0	103.8	594.5	3.2	94.9	45.3	10.2
#8iii	0.0	0.0	0.0	0.0	0.0	0.0	0.0
#9iii	20.0	101.3	293.2	2.5	0.0	18.6	0.0
#10iii	453.2	1,124.4	741.5	2.8	370.3	18.6	0.0
#11iii	650.0	1,054.5	958.8	3.0	504.7	18.6	0.0
#12iii	20.0	1,054.5				0.2	0.0
#13iii	1,130.0	1,054.5	1,519.0	3.5	921.9	18.8	0.0
#14iii	581.9	101.3	882.7	3.6	256.5	18.8	0.0
#16iii	805.0	101.3	1,135.7	3.9	439.0	45.3	0.0
#17iii	740.6	101.3	1,061.6	3.8	385.5	64.1	0.0

Cp4iii and Cp5iii = 1.20 1.05
Cp10iii and Cp11iii = 1.08 1.13
Cp16iii = 1.16

POWER GENERATED (kW) AND RATED OUTPUT POWER (kW)	= 3,615 3,981
ENERGY RELEASED IN COMBUSTOR (kW)	=61,723
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW)	=11,07438,204
KILN HEAT AVAILABLE (kW)	=49,278
ENERGY REQUIRED IN DRYER (kW)	= 0
ENERGY INPUT FROM NATURAL GAS (kW)	=11,891
HEAT EXCHANGER EFFECTIVENESS	=0.119
FIRST LAW EFFICIENCY	=71.9
SECOND LAW EFFICIENCY	=57.2

OPTION #1: METALLIC HEAT EXCHANGER

Ambient Temperature (C)	= 20
Atmospheric Pressure (kPa)	= 101.3
PLANT CONDITIONS:	
Sawmill annual capacity (Mfbm)	=250
Annual wood waste production (ODT)	=130,734
Initial wood waste moisture content (%)	= 50
Target wood waste moisture content (%)	= 50
Max compressed air temperature via HX (C)	= 650

PROCESS FLOW CONDITIONS

FLOW	TEMP deg C	PRESSURE kPa	ENTHALPY kJ/kg	ENTROPY kJ/kgK	EXERGY kJ/kg	MASS kg/sec	MOISTURE %H2O
#1	20.0					9.2	50.0
#2	20.0					9.2	50.0
#3	1,094.1	103.1	1,476.0	4.1	698.8	45.3	10.2
#7	20.0	101.3	293.2	2.5	0.0	40.9	0.0
#15	20.0	171.2	293.2	2.3	44.1	45.3	0.0

Cp3 and Cp15 = 1.21 1.01
Turbine No.1:
Manufacturer:Kawasaki
Model No.: 1 Unit of the M1T - 23

FLOW	TEMP deg C	PRESSURE kPa	ENTHALPY kJ/kg	ENTROPY kJ/kgK	EXERGY kJ/kg	MASS kg/sec	MOISTURE %H2O
#4i	1,017.8	102.6	1,385.1	4.1	627.5	45.3	10.2
#5i	315.0	101.3	594.5	3.2	92.9	45.3	10.2
#6i	315.0	103.8	594.5	3.2	94.9	45.3	10.2
#8i	0.0	0.0	0.0	0.0	0.0	0.0	0.0
#9i	20.0	101.3	293.2	2.5	0.0	18.6	0.0
#10i	453.2	1,124.4	741.5	2.7	376.7	18.6	0.0
#11i	650.0	1,054.5	958.8	3.0	511.0	18.6	0.0
#12i	20.0	1,054.5				0.2	0.0
#13i	1,130.0	1,054.5	1,519.0	3.5	928.2	18.8	0.0
#14i	581.9	101.3	882.7	3.6	262.9	18.8	0.0
#16i	805.0	101.3	1,135.7	3.9	439.0	45.3	0.0
#17i	740.6	101.3	1,061.6	3.8	387.4	64.1	0.0

Cp4i and Cp5i = 1.20 1.05
Cp10i and Cp11i = 1.08 1.13
Cp16i = 1.16

POWER GENERATED (kW) and RATED OUTPUT POWER (kW)	= 3,615 3,981
ENERGY RELEASED IN COMBUSTOR (kW)	=61,723
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW)	=11,07438,204
KILN HEAT AVAILABLE (kW)	=49,278
ENERGY REQUIRED IN DRYER (kW)	= 0
ENERGY INPUT FROM NATURAL GAS (kW)	=11,891
HEAT EXCHANGER EFFECTIVENESS	=0.119
FIRST LAW EFFICIENCY	=71.9
SECOND LAW EFFICIENCY	=57.4

Turbine No.2:
Manufacturer:Kawasaki
Model No.: 2 Units of the M1T - 23

#4ii	941.5	102.6	1,294.9	4.0	558.4	45.3	10.2
#5ii	315.0	101.3	594.5	3.2	92.9	45.3	10.2
#6ii	315.0	103.8	594.5	3.2	94.9	45.3	10.2
#8ii	0.0	0.0	0.0	0.0	0.0	0.0	0.0
#9ii	20.0	101.3	293.2	2.5	0.0	37.2	0.0
#10ii	453.2	1,124.4	741.5	2.7	376.7	37.2	0.0
#11ii	650.0	1,054.5	958.8	3.0	511.0	37.2	0.0
#12ii	20.0	1,054.5				0.4	0.0
#13ii	1,130.0	1,054.5	1,519.0	3.5	928.2	37.6	0.0
#14ii	581.9	101.3	882.7	3.6	262.9	37.6	0.0
#16ii	715.5	101.3	1,033.0	3.8	365.4	45.3	0.0
#17ii	655.4	101.3	964.9	3.7	318.9	82.9	0.0

Cp4ii and Cp5ii = 1.18 1.05
Cp10ii and Cp11ii = 1.08 1.13
Cp16ii = 1.14

POWER GENERATED (kW) AND RATED OUTPUT POWER (kW) = 7,230 7,962
ENERGY RELEASED IN COMBUSTOR (kW) =61,723
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW) =22,14833,545
KILN HEAT AVAILABLE (kW) =55,693
ENERGY REQUIRED IN DRYER (kW) = 0
ENERGY INPUT FROM NATURAL GAS (kW) =23,782
HEAT EXCHANGER EFFECTIVENESS =0.307
FIRST LAW EFFICIENCY =73.6
SECOND LAW EFFICIENCY =60.2

Turbine No.3:
Manufacturer:Kawasaki
Model No.: 3 Units of the M1T - 23

#4iii	865.2	102.6	1,205.5	3.9	491.3	45.3	10.2
#5iii	315.0	101.3	594.5	3.2	92.9	45.3	10.2
#6iii	315.0	103.8	594.5	3.2	94.9	45.3	10.2
#8iii	0.0	0.0	0.0	0.0	0.0	0.0	0.0
#9iii	20.0	101.3	293.2	2.5	0.0	55.8	0.0
#10iii	453.2	1,124.4	741.5	2.8	370.3	55.8	0.0
#11iii	650.0	1,054.5	958.8	3.0	504.7	55.8	0.0
#12iii	20.0	1,054.5				0.6	0.0
#13iii	1,130.0	1,054.5	1,519.0	3.5	921.9	56.4	0.0
#14iii	581.9	101.3	882.7	3.6	256.5	56.4	0.0
#16iii	627.0	101.3	932.9	3.7	296.3	45.3	0.0
#17iii	602.0	101.3	905.1	3.6	274.3	101.7	0.0

Cp4iii and Cp5iii = 1.17 1.05
Cp10iii and Cp11iii = 1.08 1.13
Cp16iii = 1.12

POWER GENERATED (kW) AND RATED OUTPUT POWER (kW) =10,84511,943
ENERGY RELEASED IN COMBUSTOR (kW) =61,723
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW) =33,22229,007
KILN HEAT AVAILABLE (kW) =62,230
ENERGY REQUIRED IN DRYER (kW) = 0
ENERGY INPUT FROM NATURAL GAS (kW) =35,674
HEAT EXCHANGER EFFECTIVENESS =0.357
FIRST LAW EFFICIENCY =75.0
SECOND LAW EFFICIENCY =62.1

OPTION #2: CERAMIC HEAT EXCHANGER

Ambient Temperature (C) = 20
Atmospheric Pressure (kPa) = 101.3
PLANT CONDITIONS:
Sawmill annual capacity (Mfbm) = 50
Annual wood waste production (ODT) = 26,147
Initial wood waste moisture content (%) = 50
Target wood waste moisture content (%) = 50
Maximum Heat Exchanger Pressure (kPa) = 1200

PROCESS FLOW CONDITIONS

FLOW #	TEMP C	PRESS. kPa	ENTH. kJ/kg	ENTR. kJ/kgK	EXER. kJ/kg	MASS kg/sec	MOISTURE %H2O
#1	20.0					1.8	50.0
#2	20.0					1.8	50.0
#3	1,094.1	103.1	1,476.0	4.1	698.8	9.1	10.2
#7	20.0	101.3	293.2	2.5	0.0	8.2	0.0
#15	20.0	171.2	293.2	2.3	44.1	9.1	0.0

Cp3 and Cp15 = 1.21 1.01
Turbine No.1:
Manufacturer:Kawasaki
Model No.: M1A -11A

FLOW #	TEMP C	PRESS. kPa	ENTH. kJ/kg	ENTR. kJ/kgK	EXER. kJ/kg	MASS kg/sec	MOISTURE %H2O
#4i	620.1	102.6	925.3	3.6	292.3	9.1	10.2
#5i	315.0	101.3	594.5	3.2	92.9	9.1	10.2
#6i	315.0	103.8	594.5	3.2	94.9	9.1	10.2
#8i	0.0	0.0	0.0	0.0	0.0	0.0	0.0
#9i	20.0	101.3	293.2	2.5	0.0	8.2	0.0
#10i	378.1	942.1	661.1	2.7	315.4	8.2	0.0
#11i	910.0	872.2	1,257.9	3.4	710.5	8.2	0.0
#12i	20.0	872.2				0.0	0.0
#13i	910.0	872.2	1,257.9	3.4	710.5	8.3	0.0
#14i	469.4	101.3	759.1	3.4	184.8	8.3	0.0
#16i	349.4	101.3	630.6	3.3	111.6	9.1	0.0
#17i	407.1	101.3	692.0	3.4	146.5	17.4	0.0

Cp4i and Cp5i = 1.12 1.05
Cp10i and Cp11i = 1.06 1.18
Cp16i = 1.06

POWER GENERATED (kW) AND RATED OUTPUT POWER (kW) = 1,114 1,235
ENERGY RELEASED IN COMBUSTOR (kW) =12,345
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW) = 3,859 3,060
KILN HEAT AVAILABLE (kW) = 6,920
ENERGY REQUIRED IN DRYER (kW) = 0
ENERGY INPUT FROM NATURAL GAS (kW) = 0
HEAT EXCHANGER EFFECTIVENESS =0.743
FIRST LAW EFFICIENCY =65.1
SECOND LAW EFFICIENCY =45.1

Turbine No.2:
Manufacturer:Kawasaki
Model No.:   M1A - 23

#4ii	560.0	102.6	858.4	3.6	248.1	9.1	10.2
#5ii	315.0	101.3	594.5	3.2	92.9	9.1	10.2
#6ii	315.0	103.8	594.5	3.2	94.9	9.1	10.2
#8ii	0.0	0.0	0.0	0.0	0.0	0.0	0.0
#9ii	20.0	101.3	293.2	2.5	0.0	9.3	0.0
#10ii	449.0	1,134.6	737.0	2.7	374.8	9.3	0.0
#11ii	974.0	1,064.7	1,333.2	3.4	784.4	9.3	0.0
#12ii	20.0	1,064.7				0.0	0.0
#13ii	1,140.0	1,064.7	1,531.0	3.5	938.6	9.4	0.0
#14ii	586.4	101.3	887.7	3.6	266.2	9.4	0.0
#16ii	282.7	101.3	560.7	3.1	76.5	9.1	0.0
#17ii	439.8	101.3	727.1	3.4	173.0	18.5	0.0

Cp4ii and Cp5ii = 1.11 1.05
Cp10ii and Cp11ii = 1.08 1.22
Cp16ii = 1.04

POWER GENERATED (kW) AND RATED OUTPUT POWER (kW) = 1,915 2,043
ENERGY RELEASED IN COMBUSTOR (kW) =12,345
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW) = 5,584 2,426
KILN HEAT AVAILABLE (kW) = 8,011
ENERGY REQUIRED IN DRYER (kW) = 0
ENERGY INPUT FROM NATURAL GAS (kW) = 2,203
HEAT EXCHANGER EFFECTIVENESS =0.828
FIRST LAW EFFICIENCY =68.2
SECOND LAW EFFICIENCY =53.3

Turbine No.3:
Manufacturer:Kawasaki
Model No.:   M1T - 23

#4iii	564.2	102.6	863.0	3.6	251.1	9.1	10.2
#5iii	315.0	101.3	594.5	3.2	92.9	9.1	10.2
#6iii	315.0	103.8	594.5	3.2	94.9	9.1	10.2
#8iii	0.0	0.0	0.0	0.0	0.0	0.0	0.0
#9iii	20.0	101.3	293.2	2.5	0.0	18.6	0.0
#10iii	453.2	1,124.4	741.5	2.7	376.7	18.6	0.0
#11iii	713.8	1,054.5	1,031.0	3.1	561.0	18.6	0.0
#12iii	20.0	1,054.5				0.2	0.0
#13iii	1,130.0	1,054.5	1,519.0	3.5	928.2	18.8	0.0
#14iii	581.9	101.3	882.7	3.6	262.9	18.8	0.0
#16iii	287.3	101.3	565.5	3.2	78.8	9.1	0.0
#17iii	488.1	101.3	779.4	3.5	203.0	27.9	0.0

Cp4iii and Cp5iii = 1.11 1.05
Cp10iii and Cp11iii = 1.08 1.21
Cp16iii = 1.04

POWER GENERATED (kW) AND RATED OUTPUT POWER (kW) = 3,615 3,981
ENERGY RELEASED IN COMBUSTOR (kW) =12,345
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW) =11,074 2,470
KILN HEAT AVAILABLE (kW) =13,544
ENERGY REQUIRED IN DRYER (kW) = 0
ENERGY INPUT FROM NATURAL GAS (kW) =10,399
HEAT EXCHANGER EFFECTIVENESS =0.827
FIRST LAW EFFICIENCY =75.4
SECOND LAW EFFICIENCY =64.1

OPTION #2: CERAMIC HEAT EXCHANGER

Ambient Temperature (C)	= 20
Atmospheric Pressure (kPa)	= 101.3
PLANT CONDITIONS:	
Sawmill annual capacity (Mfbm)	= 50
Annual wood waste production (ODT)	= 26,147
Initial wood waste moisture content (%)	= 50
Target wood waste moisture content (%)	= 50
Maximum Heat Exchanger Pressure (kPa)	= 1200

PROCESS FLOW CONDITIONS

FLOW #	TEMP C	PRESS. kPa	ENTH. kJ/kg	ENTR. kJ/kgK	EXER. kJ/kg	MASS kg/sec	MOISTURE %H2O
#1	20.0					1.8	50.0
#2	20.0					1.8	50.0
#3	1,094.1	103.1	1,476.0	4.1	698.8	9.1	10.2
#7	20.0	101.3	293.2	2.5	0.0	8.2	0.0
#15	20.0	171.2	293.2	2.3	44.1	9.1	0.0

Cp3 and Cp15 = 1.21 1.01
Turbine No.1:
Manufacturer:Kawasaki
Model No.: 1 Unit of the M1T - 23

FLOW #	TEMP C	PRESS. kPa	ENTH. kJ/kg	ENTR. kJ/kgK	EXER. kJ/kg	MASS kg/sec	MOISTURE %H2O
#4i	564.2	102.6	863.0	3.6	251.1	9.1	10.2
#5i	315.0	101.3	594.5	3.2	92.9	9.1	10.2
#6i	315.0	103.8	594.5	3.2	94.9	9.1	10.2
#8i	0.0	0.0	0.0	0.0	0.0	0.0	0.0
#9i	20.0	101.3	293.2	2.5	0.0	18.6	0.0
#10i	453.2	1,124.4	741.5	2.7	376.7	18.6	0.0
#11i	713.8	1,054.5	1,031.0	3.1	561.0	18.6	0.0
#12i	20.0	1,054.5				0.2	0.0
#13i	1,130.0	1,054.5	1,519.0	3.5	928.2	18.8	0.0
#14i	581.9	101.3	882.7	3.6	262.9	18.8	0.0
#16i	287.3	101.3	565.5	3.2	78.8	9.1	0.0
#17i	488.1	101.3	779.4	3.5	203.0	27.9	0.0

Cp4i and Cp5i = 1.11 1.05
Cp10i and Cp11i = 1.08 1.21
Cp16i = 1.04

POWER GENERATED (kW) AND RATED OUTPUT POWER (kW)	= 3,615 3,981
ENERGY RELEASED IN COMBUSTOR (kW)	=12,345
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW)	=11,074 2,470
KILN HEAT AVAILABLE (kW)	=13,544
ENERGY REQUIRED IN DRYER (kW)	= 0
ENERGY INPUT FROM NATURAL GAS (kW)	=10,399
HEAT EXCHANGER EFFECTIVENESS	=0.827
FIRST LAW EFFICIENCY	=75.4
SECOND LAW EFFICIENCY	=64.1

Turbine No.2:
Manufacturer:Kawasaki
Model No.: 2 Units of the M1T - 23

#4ii	564.2	102.6	863.0	3.6	251.1	9.1	10.2
#5ii	315.0	101.3	594.5	3.2	92.9	9.1	10.2
#6ii	315.0	103.8	594.5	3.2	94.9	9.1	10.2
#8ii	0.0	0.0	0.0	0.0	0.0	0.0	0.0
#9ii	20.0	101.3	293.2	2.5	0.0	37.2	0.0
#10ii	453.2	1,124.4	741.5	2.7	376.7	37.2	0.0
#11ii	583.5	1,054.5	884.4	2.9	461.0	37.2	0.0
#12ii	20.0	1,054.5				0.5	0.0
#13ii	1,130.0	1,054.5	1,519.0	3.5	928.2	37.6	0.0
#14ii	581.9	101.3	882.7	3.6	262.9	37.6	0.0
#16ii	287.3	101.3	565.5	3.2	78.8	9.1	0.0
#17ii	526.1	101.3	821.0	3.5	227.1	46.6	0.0

Cp4ii and Cp5ii = 1.11 1.05
Cp10ii and Cp11ii = 1.08 1.21
Cp16ii = 1.04

POWER GENERATED (kW) AND RATED OUTPUT POWER (kW) = 7,230 7,962
ENERGY RELEASED IN COMBUSTOR (kW) =12,345
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW) =22,148 2,470
KILN HEAT AVAILABLE (kW) =24,618
ENERGY REQUIRED IN DRYER (kW) = 0
ENERGY INPUT FROM NATURAL GAS (kW) =26,859
HEAT EXCHANGER EFFECTIVENESS =0.827
FIRST LAW EFFICIENCY =81.2
SECOND LAW EFFICIENCY =73.6

Turbine No.3:
Manufacturer:Kawasaki
Model No.: 3 Units of the M1T - 23

#4iii	564.2	102.6	863.0	3.6	251.1	9.1	10.2
#5iii	315.0	101.3	594.5	3.2	92.9	9.1	10.2
#6iii	315.0	103.8	594.5	3.2	94.9	9.1	10.2
#8iii	0.0	0.0	0.0	0.0	0.0	0.0	0.0
#9iii	20.0	101.3	293.2	2.5	0.0	55.8	0.0
#10iii	453.2	1,124.4	741.5	2.7	376.7	55.8	0.0
#11iii	540.0	1,054.5	836.3	2.9	429.9	55.8	0.0
#12iii	20.0	1,054.5				0.8	0.0
#13iii	1,130.0	1,054.5	1,519.0	3.5	928.2	56.4	0.0
#14iii	581.9	101.3	882.7	3.6	262.9	56.4	0.0
#16iii	287.3	101.3	565.5	3.2	78.8	9.1	0.0
#17iii	542.2	101.3	838.7	3.5	237.4	65.4	0.0

Cp4iii and Cp5iii = 1.11 1.05
Cp10iii and Cp11iii = 1.08 1.21
Cp16iii = 1.04

POWER GENERATED (kW) AND RATED OUTPUT POWER (kW) =10,84511,943
ENERGY RELEASED IN COMBUSTOR (kW) =12,345
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW) =33,222 2,470
KILN HEAT AVAILABLE (kW) =35,692
ENERGY REQUIRED IN DRYER (kW) = 0
ENERGY INPUT FROM NATURAL GAS (kW) =43,268
HEAT EXCHANGER EFFECTIVENESS =0.827
FIRST LAW EFFICIENCY =83.7
SECOND LAW EFFICIENCY =77.7

OPTION #2: CERAMIC HEAT EXCHANGER

Ambient Temperature (C) = 20
Atmospheric Pressure (kPa) = 101.3
PLANT CONDITIONS:
Sawmill annual capacity (Mfbm) =100
Annual wood waste production (ODT) = 52,294
Initial wood waste moisture content (%) = 50
Target wood waste moisture content (%) = 50
Maximum Heat Exchanger Pressure (kPa) = 1200

PROCESS FLOW CONDITIONS

FLOW #	TEMP C	PRESS. kPa	ENTH. kJ/kg	ENTR. kJ/kgK	EXER. kJ/kg	MASS kg/sec	MOISTURE %H2O
#1	20.0					3.7	50.0
#2	20.0					3.7	50.0
#3	1,094.1	103.1	1,476.0	4.1	698.8	18.1	10.2
#7	20.0	101.3	293.2	2.5	0.0	16.4	0.0
#15	20.0	171.2	293.2	2.3	44.1	18.1	0.0

Cp3 and Cp15 = 1.21 1.01
Turbine No.1:
Manufacturer:Kawasaki
Model No.: M1A -11A

#4i	857.1	102.6	1,196.1	3.9	484.4	18.1	10.2
#5i	315.0	101.3	594.5	3.2	92.9	18.1	10.2
#6i	315.0	103.8	594.5	3.2	94.9	18.1	10.2
#8i	0.0	0.0	0.0	0.0	0.0	0.0	0.0
#9i	20.0	101.3	293.2	2.5	0.0	8.2	0.0
#10i	378.1	942.1	661.1	2.7	315.4	8.2	0.0
#11i	910.0	872.2	1,257.9	3.4	710.5	8.2	0.0
#12i	20.0	872.2				0.0	0.0
#13i	910.0	872.2	1,257.9	3.4	710.5	8.3	0.0
#14i	469.4	101.3	759.1	3.4	184.8	8.3	0.0
#16i	617.7	101.3	922.5	3.6	289.4	18.1	0.0
#17i	571.7	101.3	871.3	3.6	256.6	26.4	0.0

Cp4i and Cp5i = 1.17 1.05
Cp10i and Cp11i = 1.06 1.18
Cp16i = 1.12
POWER GENERATED (kW) AND RATED OUTPUT POWER (kW) = 1,114 1,235
ENERGY RELEASED IN COMBUSTOR (kW) =24,689
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW) = 3,85911,415
KILN HEAT AVAILABLE (kW) =15,274
ENERGY REQUIRED IN DRYER (kW) = 0
ENERGY INPUT FROM NATURAL GAS (kW) = 0
HEAT EXCHANGER EFFECTIVENESS =0.743
FIRST LAW EFFICIENCY =66.4
SECOND LAW EFFICIENCY =47.6

Turbine No.2:
Manufacturer:Kawasaki
Model No.: M1A - 23

#4ii	738.7	102.6	1,059.4	3.8	385.1	18.1	10.2
#5ii	315.0	101.3	594.5	3.2	92.9	18.1	10.2
#6ii	315.0	103.8	594.5	3.2	94.9	18.1	10.2
#8ii	0.0	0.0	0.0	0.0	0.0	0.0	0.0
#9ii	20.0	101.3	293.2	2.5	0.0	9.3	0.0
#10ii	449.0	1,134.6	737.0	2.7	374.8	9.3	0.0
#11ii	1,140.0	1,064.7	1,531.0	3.5	938.6	9.3	0.0
#12ii	20.0	1,064.7				0.0	0.0
#13ii	1,140.0	1,064.7	1,531.0	3.5	938.6	9.4	0.0
#14ii	586.4	101.3	887.7	3.6	266.2	9.4	0.0
#16ii	482.4	101.3	773.2	3.5	193.3	18.1	0.0
#17ii	518.1	101.3	812.3	3.5	218.2	27.5	0.0

Cp4ii and Cp5ii = 1.14 1.05
Cp10ii and Cp11ii = 1.08 1.22
Cp16ii = 1.09

POWER GENERATED (kW) AND RATED OUTPUT POWER (kW) = 1,915 2,043
ENERGY RELEASED IN COMBUSTOR (kW) =24,689
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW) = 5,584 8,706
KILN HEAT AVAILABLE (kW) =14,291
ENERGY REQUIRED IN DRYER (kW) = 0
ENERGY INPUT FROM NATURAL GAS (kW) = 0
HEAT EXCHANGER EFFECTIVENESS =1.071
FIRST LAW EFFICIENCY =65.6
SECOND LAW EFFICIENCY =47.8

Turbine No.3:
Manufacturer:Kawasaki
Model No.: M1T - 23

#4iii	564.2	102.6	863.0	3.6	251.1	18.1	10.2
#5iii	315.0	101.3	594.5	3.2	92.9	18.1	10.2
#6iii	315.0	103.8	594.5	3.2	94.9	18.1	10.2
#8iii	0.0	0.0	0.0	0.0	0.0	0.0	0.0
#9iii	20.0	101.3	293.2	2.5	0.0	18.6	0.0
#10iii	453.2	1,124.4	741.5	2.7	376.7	18.6	0.0
#11iii	974.5	1,054.5	1,333.7	3.4	784.0	18.6	0.0
#12iii	20.0	1,054.5				0.1	0.0
#13iii	1,130.0	1,054.5	1,519.0	3.5	928.2	18.8	0.0
#14iii	581.9	101.3	882.7	3.6	262.9	18.8	0.0
#16iii	287.3	101.3	565.5	3.2	78.8	18.1	0.0
#17iii	439.6	101.3	726.9	3.4	172.5	36.9	0.0

Cp4iii and Cp5iii = 1.11 1.05
Cp10iii and Cp11iii = 1.08 1.21
Cp16iii = 1.04

POWER GENERATED (kW) AND RATED OUTPUT POWER (kW) = 3,615 3,981
ENERGY RELEASED IN COMBUSTOR (kW) =24,689
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW) =11,074 4,940
KILN HEAT AVAILABLE (kW) =16,014
ENERGY REQUIRED IN DRYER (kW) = 0
ENERGY INPUT FROM NATURAL GAS (kW) = 4,143
HEAT EXCHANGER EFFECTIVENESS =0.827
FIRST LAW EFFICIENCY =68.1
SECOND LAW EFFICIENCY =52.7

OPTION #2: CERAMIC HEAT EXCHANGER

Ambient Temperature (C)	= 20
Atmospheric Pressure (kPa)	= 101.3
PLANT CONDITIONS:	
Sawmill annual capacity (Mfbm)	=100
Annual wood waste production (ODT)	= 52,294
Initial wood waste moisture content (%)	= 50
Target wood waste moisture content (%)	= 50
Maximum Heat Exchanger Pressure (kPa)	= 1200

PROCESS FLOW CONDITIONS

FLOW #	TEMP C	PRESS. kPa	ENTH. kJ/kg	ENTR. kJ/kgK	EXER. kJ/kg	MASS kg/sec	MOISTURE %H2O
#1	20.0					3.7	50.0
#2	20.0					3.7	50.0
#3	1,094.1	103.1	1,476.0	4.1	698.8	18.1	10.2
#7	20.0	101.3	293.2	2.5	0.0	16.4	0.0
#15	20.0	171.2	293.2	2.3	44.1	18.1	0.0

Cp3 and Cp15 = 1.21 1.01

Turbine No.1:

Manufacturer:Kawasaki

Model No.: 1 Unit of the M1T - 23

FLOW #	TEMP C	PRESS. kPa	ENTH. kJ/kg	ENTR. kJ/kgK	EXER. kJ/kg	MASS kg/sec	MOISTURE %H2O
#4i	564.2	102.6	863.0	3.6	251.1	18.1	10.2
#5i	315.0	101.3	594.5	3.2	92.9	18.1	10.2
#6i	315.0	103.8	594.5	3.2	94.9	18.1	10.2
#8i	0.0	0.0	0.0	0.0	0.0	0.0	0.0
#9i	20.0	101.3	293.2	2.5	0.0	18.6	0.0
#10i	453.2	1,124.4	741.5	2.7	376.7	18.6	0.0
#11i	974.5	1,054.5	1,333.7	3.4	784.0	18.6	0.0
#12i	20.0	1,054.5				0.1	0.0
#13i	1,130.0	1,054.5	1,519.0	3.5	928.2	18.8	0.0
#14i	581.9	101.3	882.7	3.6	262.9	18.8	0.0
#16i	287.3	101.3	565.5	3.2	78.8	18.1	0.0
#17i	439.6	101.3	726.9	3.4	172.5	36.9	0.0

Cp4i and Cp5i = 1.11 1.05

Cp10i and Cp11i = 1.08 1.21

Cp16i = 1.04

POWER GENERATED (kW) AND RATED OUTPUT POWER (kW)	= 3,615 3,981
ENERGY RELEASED IN COMBUSTOR (kW)	=24,689
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW)	=11,074 4,940
KILN HEAT AVAILABLE (kW)	=16,014
ENERGY REQUIRED IN DRYER (kW)	= 0
ENERGY INPUT FROM NATURAL GAS (kW)	= 4,143
HEAT EXCHANGER EFFECTIVENESS	=0.827
FIRST LAW EFFICIENCY	=68.1
SECOND LAW EFFICIENCY	=52.7

Turbine No.2:
Manufacturer:Kawasaki
Model No.: 2 Units of the M1T - 23

#4ii	564.2	102.6	863.0	3.6	251.1	18.1	10.2
#5ii	315.0	101.3	594.5	3.2	92.9	18.1	10.2
#6ii	315.0	103.8	594.5	3.2	94.9	18.1	10.2
#8ii	0.0	0.0	0.0	0.0	0.0	0.0	0.0
#9ii	20.0	101.3	293.2	2.5	0.0	37.2	0.0
#10ii	453.2	1,124.4	741.5	2.7	376.7	37.2	0.0
#11ii	713.8	1,054.5	1,031.0	3.1	561.0	37.2	0.0
#12ii	20.0	1,054.5				0.4	0.0
#13ii	1,130.0	1,054.5	1,519.0	3.5	928.2	37.6	0.0
#14ii	581.9	101.3	882.7	3.6	262.9	37.6	0.0
#16ii	287.3	101.3	565.5	3.2	78.8	18.1	0.0
#17ii	488.1	101.3	779.4	3.5	203.0	55.7	0.0

Cp4ii and Cp5ii = 1.11 1.05
Cp10ii and Cp11ii = 1.08 1.21
Cp16ii = 1.04

POWER GENERATED (kW) AND RATED OUTPUT POWER (kW) = 7,230 7,962
ENERGY RELEASED IN COMBUSTOR (kW) =24,689
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW) =22,148 4,940
KILN HEAT AVAILABLE (kW) =27,088
ENERGY REQUIRED IN DRYER (kW) = 0
ENERGY INPUT FROM NATURAL GAS (kW) =20,797
HEAT EXCHANGER EFFECTIVENESS =0.827
FIRST LAW EFFICIENCY =75.4
SECOND LAW EFFICIENCY =64.2

Turbine No.3:
Manufacturer:Kawasaki
Model No.: 3 Units of the M1T - 23

#4iii	564.2	102.6	863.0	3.6	251.1	18.1	10.2
#5iii	315.0	101.3	594.5	3.2	92.9	18.1	10.2
#6iii	315.0	103.8	594.5	3.2	94.9	18.1	10.2
#8iii	0.0	0.0	0.0	0.0	0.0	0.0	0.0
#9iii	20.0	101.3	293.2	2.5	0.0	55.8	0.0
#10iii	453.2	1,124.4	741.5	2.7	376.7	55.8	0.0
#11iii	626.9	1,054.5	932.9	3.0	493.3	55.8	0.0
#12iii	20.0	1,054.5				0.7	0.0
#13iii	1,130.0	1,054.5	1,519.0	3.5	928.2	56.4	0.0
#14iii	581.9	101.3	882.7	3.6	262.9	56.4	0.0
#16iii	287.3	101.3	565.5	3.2	78.8	18.1	0.0
#17iii	511.9	101.3	805.4	3.5	218.1	74.5	0.0

Cp4iii and Cp5iii = 1.11 1.05
Cp10iii and Cp11iii = 1.08 1.21
Cp16iii = 1.04

POWER GENERATED (kW) AND RATED OUTPUT POWER (kW) =10,84511,943
ENERGY RELEASED IN COMBUSTOR (kW) =24,689
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW) =33,222 4,940
KILN HEAT AVAILABLE (kW) =38,162
ENERGY REQUIRED IN DRYER (kW) = 0
ENERGY INPUT FROM NATURAL GAS (kW) =37,284
HEAT EXCHANGER EFFECTIVENESS =0.827
FIRST LAW EFFICIENCY =79.1
SECOND LAW EFFICIENCY =70.1

OPTION #2: CERAMIC HEAT EXCHANGER

Ambient Temperature (C)	= 20
Atmospheric Pressure (kPa)	= 101.3
PLANT CONDITIONS:	
Sawmill annual capacity (Mfbm)	=150
Annual wood waste production (ODT)	= 78,440
Initial wood waste moisture content (%)	= 50
Target wood waste moisture content (%)	= 50
Maximum Heat Exchanger Pressure (kPa)	= 1200

PROCESS FLOW CONDITIONS

FLOW #	TEMP C	PRESS. kPa	ENTH. kJ/kg	ENTR. kJ/kgK	EXER. kJ/kg	MASS kg/sec	MOISTURE %H2O
#1	20.0					5.5	50.0
#2	20.0					5.5	50.0
#3	1,094.1	103.1	1,476.0	4.1	698.8	27.2	10.2
#7	20.0	101.3	293.2	2.5	0.0	24.6	0.0
#15	20.0	171.2	293.2	2.3	44.1	27.2	0.0

Cp3 and Cp15 = 1.21 1.01

Turbine No.1:
Manufacturer:Kawasaki
Model No.: M1A -11A

FLOW #	TEMP C	PRESS. kPa	ENTH. kJ/kg	ENTR. kJ/kgK	EXER. kJ/kg	MASS kg/sec	MOISTURE %H2O
#4i	936.1	102.6	1,288.5	4.0	553.6	27.2	10.2
5i	315.0	101.3	594.5	3.2	92.9	27.2	10.2
6i	315.0	103.8	594.5	3.2	94.9	27.2	10.2
#8i	0.0	0.0	0.0	0.0	0.0	0.0	0.0
#9i	20.0	101.3	293.2	2.5	0.0	8.2	0.0
#10i	378.1	942.1	661.1	2.7	315.4	8.2	0.0
#11i	910.0	872.2	1,257.9	3.4	710.5	8.2	0.0
#12i	20.0	872.2				0.0	0.0
#13i	910.0	872.2	1,257.9	3.4	710.5	8.3	0.0
#14i	469.4	101.3	759.1	3.4	184.8	8.3	0.0
#16i	709.3	101.3	1,025.9	3.8	360.4	27.2	0.0
#17i	654.3	101.3	963.6	3.7	319.4	35.5	0.0

Cp4i and Cp5i = 1.18 1.05
Cp10i and Cp11i = 1.06 1.18
Cp16i = 1.14

POWER GENERATED (kW) AND RATED OUTPUT POWER (kW)	= 1,114 1,235
ENERGY RELEASED IN COMBUSTOR (kW)	=37,033
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW)	= 3,85919,934
KILN HEAT AVAILABLE (kW)	=23,793
ENERGY REQUIRED IN DRYER (kW)	= 0
ENERGY INPUT FROM NATURAL GAS (kW)	= 0
HEAT EXCHANGER EFFECTIVENESS	=0.743
FIRST LAW EFFICIENCY	=67.3
SECOND LAW EFFICIENCY	=49.3

Turbine No.2:
Manufacturer:Kawasaki
Model No.: M1A - 23

#4ii	857.1	102.6	1,196.1	3.9	484.4	27.2	10.2
#5ii	315.0	101.3	594.5	3.2	92.9	27.2	10.2
#6ii	315.0	103.8	594.5	3.2	94.9	27.2	10.2
#8ii	0.0	0.0	0.0	0.0	0.0	0.0	0.0
#9ii	20.0	101.3	293.2	2.5	0.0	9.3	0.0
#10ii	449.0	1,134.6	737.0	2.7	374.8	9.3	0.0
#11ii	1,140.0	1,064.7	1,531.0	3.5	938.6	9.3	0.0
#12ii	20.0	1,064.7				0.0	0.0
#13ii	1,140.0	1,064.7	1,531.0	3.5	938.6	9.4	0.0
#14ii	586.4	101.3	887.7	3.6	266.2	9.4	0.0
#16ii	617.7	101.3	922.5	3.7	289.4	27.2	0.0
#17ii	609.7	101.3	913.6	3.6	283.5	36.6	0.0

Cp4ii and Cp5ii = 1.17 1.05
Cp10ii and Cp11ii = 1.08 1.22
Cp16ii = 1.12

POWER GENERATED (kW) AND RATED OUTPUT POWER (kW) = 1,915 2,043
ENERGY RELEASED IN COMBUSTOR (kW) =37,033
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW) = 5,58417,123
KILN HEAT AVAILABLE (kW) =22,707
ENERGY REQUIRED IN DRYER (kW) = 0
ENERGY INPUT FROM NATURAL GAS (kW) = 0
HEAT EXCHANGER EFFECTIVENESS =1.071
FIRST LAW EFFICIENCY =66.5
SECOND LAW EFFICIENCY =48.9

Turbine No.3:
Manufacturer:Kawasaki
Model No.: M1T - 23

#4iii	630.2	102.6	936.6	3.7	299.8	27.2	10.2
#5iii	315.0	101.3	594.5	3.2	92.9	27.2	10.2
#6iii	315.0	103.8	594.5	3.2	94.9	27.2	10.2
#8iii	0.0	0.0	0.0	0.0	0.0	0.0	0.0
#9iii	20.0	101.3	293.2	2.5	0.0	18.6	0.0
#10iii	453.2	1,124.4	741.5	2.7	376.7	18.6	0.0
#11iii	1,130.0	1,054.5	1,519.0	3.5	928.2	18.6	0.0
#12iii	20.0	1,054.5				0.0	0.0
#13iii	1,130.0	1,054.5	1,519.0	3.5	928.2	18.8	0.0
#14iii	581.9	101.3	882.7	3.6	262.9	18.8	0.0
#16iii	360.6	101.3	642.5	3.3	118.0	27.2	0.0
#17iii	452.3	101.3	740.6	3.4	177.2	46.0	0.0

Cp4iii and Cp5iii = 1.12 1.05
Cp10iii and Cp11iii = 1.08 1.21
Cp16iii = 1.06

POWER GENERATED (kW) AND RATED OUTPUT POWER (kW) = 3,615 3,981
ENERGY RELEASED IN COMBUSTOR (kW) =37,033
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW) =11,074 9,504
KILN HEAT AVAILABLE (kW) =20,578
ENERGY REQUIRED IN DRYER (kW) = 0
ENERGY INPUT FROM NATURAL GAS (kW) = 0
HEAT EXCHANGER EFFECTIVENESS =1.056
FIRST LAW EFFICIENCY =65.3
SECOND LAW EFFICIENCY =47.3

OPTION #2: CERAMIC HEAT EXCHANGER

Ambient Temperature (C)	= 20
Atmospheric Pressure (kPa)	= 101.3
PLANT CONDITIONS:	
Sawmill annual capacity (Mfbm)	=150
Annual wood waste production (ODT)	= 78,440
Initial wood waste moisture content (%)	= 50
Target wood waste moisture content (%)	= 50
Maximum Heat Exchanger Pressure (kPa)	= 1200

PROCESS FLOW CONDITIONS

FLOW #	TEMP C	PRESS. kPa	ENTH. kJ/kg	ENTR. kJ/kgK	EXER. kJ/kg	MASS kg/sec	MOISTURE %H2O
#1	20.0					5.5	50.0
#2	20.0					5.5	50.0
#3	1,094.1	103.1	1,476.0	4.1	698.8	27.2	10.2
#7	20.0	101.3	293.2	2.5	0.0	24.6	0.0
#15	20.0	171.2	293.2	2.3	44.1	27.2	0.0

Cp3 and Cp15 = 1.21 1.01

Turbine No.1:

Manufacturer:Kawasaki

Model No.: 1 Unit of the M1T - 23

FLOW #	TEMP C	PRESS. kPa	ENTH. kJ/kg	ENTR. kJ/kgK	EXER. kJ/kg	MASS kg/sec	MOISTURE %H2O
#4i	630.2	102.6	936.6	3.7	299.8	27.2	10.2
5i	315.0	101.3	594.5	3.2	92.9	27.2	10.2
6i	315.0	103.8	594.5	3.2	94.9	27.2	10.2
#8i	0.0	0.0	0.0	0.0	0.0	0.0	0.0
#9i	20.0	101.3	293.2	2.5	0.0	18.6	0.0
#10i	453.2	1,124.4	741.5	2.7	376.7	18.6	0.0
#11i	1,130.0	1,054.5	1,519.0	3.5	928.2	18.6	0.0
#12i	20.0	1,054.5				0.0	0.0
#13i	1,130.0	1,054.5	1,519.0	3.5	928.2	18.8	0.0
#14i	581.9	101.3	882.7	3.6	262.9	18.8	0.0
#16i	360.6	101.3	642.5	3.3	118.0	27.2	0.0
#17i	452.3	101.3	740.6	3.4	177.2	46.0	0.0

Cp4i and Cp5i = 1.12 1.05

Cp10i and Cp11i = 1.08 1.21

Cp16i = 1.06

POWER GENERATED (kW) AND RATED OUTPUT POWER (kW)	= 3,615 3,981
ENERGY RELEASED IN COMBUSTOR (kW)	=37,033
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW)	=11,074 9,504
KILN HEAT AVAILABLE (kW)	=20,578
ENERGY REQUIRED IN DRYER (kW)	= 0
ENERGY INPUT FROM NATURAL GAS (kW)	= 0
HEAT EXCHANGER EFFECTIVENESS	=1.056
FIRST LAW EFFICIENCY	=65.3
SECOND LAW EFFICIENCY	=47.3

Turbine No.2:
Manufacturer:Kawasaki
Model No.: 2 Units of the M1T - 23

#4ii	564.2	102.6	863.0	3.6	251.1	27.2	10.2
#5ii	315.0	101.3	594.5	3.2	92.9	27.2	10.2
#6ii	315.0	103.8	594.5	3.2	94.9	27.2	10.2
#8ii	0.0	0.0	0.0	0.0	0.0	0.0	0.0
#9ii	20.0	101.3	293.2	2.5	0.0	37.2	0.0
#10ii	453.2	1,124.4	741.5	2.7	376.7	37.2	0.0
#11ii	844.1	1,054.5	1,181.0	3.2	669.2	37.2	0.0
#12ii	20.0	1,054.5				0.3	0.0
#13ii	1,130.0	1,054.5	1,519.0	3.5	928.2	37.6	0.0
#14ii	581.9	101.3	882.7	3.6	262.9	37.6	0.0
#16ii	287.3	101.3	565.5	3.2	78.8	27.2	0.0
#17ii	460.5	101.3	749.5	3.4	185.6	64.8	0.0

Cp4ii and Cp5ii = 1.11 1.05
Cp10ii and Cp11ii = 1.08 1.21
Cp16ii = 1.04

POWER GENERATED (kW) AND RATED OUTPUT POWER (kW) = 7,230 7,962
ENERGY RELEASED IN COMBUSTOR (kW) =37,033
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW) =22,148 7,410
KILN HEAT AVAILABLE (kW) =29,558
ENERGY REQUIRED IN DRYER (kW) = 0
ENERGY INPUT FROM NATURAL GAS (kW) =14,599
HEAT EXCHANGER EFFECTIVENESS =0.827
FIRST LAW EFFICIENCY =71.2
SECOND LAW EFFICIENCY =57.6

Turbine No.3:
Manufacturer:Kawasaki
Model No.: 3 Units of the M1T - 23

#4iii	564.2	102.6	863.0	3.6	251.1	27.2	10.2
#5iii	315.0	101.3	594.5	3.2	92.9	27.2	10.2
#6iii	315.0	103.8	594.5	3.2	94.9	27.2	10.2
#8iii	0.0	0.0	0.0	0.0	0.0	0.0	0.0
#9iii	20.0	101.3	293.2	2.5	0.0	55.8	0.0
#10iii	453.2	1,124.4	741.5	2.7	376.7	55.8	0.0
#11iii	713.8	1,054.5	1,031.0	3.1	561.0	55.8	0.0
#12iii	20.0	1,054.5				0.6	0.0
#13iii	1,130.0	1,054.5	1,519.0	3.5	928.2	56.4	0.0
#14iii	581.9	101.3	882.7	3.6	262.9	56.4	0.0
#16iii	287.3	101.3	565.5	3.2	78.8	27.2	0.0
#17iii	488.1	101.3	779.4	3.5	203.0	83.6	0.0

Cp4iii and Cp5iii = 1.11 1.05
Cp10iii and Cp11iii = 1.08 1.21
Cp16iii = 1.04

POWER GENERATED (kW) AND RATED OUTPUT POWER (kW) =10,84511,943
ENERGY RELEASED IN COMBUSTOR (kW) =37,033
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW) =33,222 7,410
KILN HEAT AVAILABLE (kW) =40,632
ENERGY REQUIRED IN DRYER (kW) = 0
ENERGY INPUT FROM NATURAL GAS (kW) =31,196
HEAT EXCHANGER EFFECTIVENESS =0.827
FIRST LAW EFFICIENCY =75.4
SECOND LAW EFFICIENCY =64.3

OPTION #2: CERAMIC HEAT EXCHANGER

Ambient Temperature (C)	= 20
Atmospheric Pressure (kPa)	= 101.3
PLANT CONDITIONS:	
Sawmill annual capacity (Mfbm)	=250
Annual wood waste production (ODT)	=130,734
Initial wood waste moisture content (%)	= 50
Target wood waste moisture content (%)	= 50
Maximum Heat Exchanger Pressure (kPa)	= 1200

PROCESS FLOW CONDITIONS

FLOW #	TEMP C	PRESS. kPa	ENTH. kJ/kg	ENTR. kJ/kgK	EXER. kJ/kg	MASS kg/sec	MOISTURE %H2O
#1	20.0					9.2	50.0
#2	20.0					9.2	50.0
#3	1,094.1	103.1	1,476.0	4.1	698.8	45.3	10.2
#7	20.0	101.3	293.2	2.5	0.0	40.9	0.0
#15	20.0	171.2	293.2	2.3	44.1	45.3	0.0

Cp3 and Cp15 = 1.21 1.01

Turbine No.1:

Manufacturer:Kawasaki

Model No.: M1A -11A

FLOW #	TEMP C	PRESS. kPa	ENTH. kJ/kg	ENTR. kJ/kgK	EXER. kJ/kg	MASS kg/sec	MOISTURE %H2O
#4i	999.3	102.6	1,363.2	4.1	610.6	45.3	10.2
#5i	315.0	101.3	594.5	3.2	92.9	45.3	10.2
#6i	315.0	103.8	594.5	3.2	94.9	45.3	10.2
#8i	0.0	0.0	0.0	0.0	0.0	0.0	0.0
#9i	20.0	101.3	293.2	2.5	0.0	8.2	0.0
#10i	378.1	942.1	661.1	2.7	315.4	8.2	0.0
#11i	910.0	872.2	1,257.9	3.4	710.5	8.2	0.0
#12i	20.0	872.2				8.2	0.0
						0.0	0.0
#13i	910.0	872.2	1,257.9	3.4	710.5	8.3	0.0
#14i	469.4	101.3	759.1	3.4	184.8	8.3	0.0
#16i	783.3	101.3	1,110.6	3.8	420.7	45.3	0.0
#17i	736.0	101.3	1,056.3	3.8	384.3	53.6	0.0

Cp4i and Cp5i = 1.19 1.05

Cp10i and Cp11i = 1.06 1.18

Cp16i = 1.15

POWER GENERATED (kW) AND RATED OUTPUT POWER (kW)	= 1,114 1,235
ENERGY RELEASED IN COMBUSTOR (kW)	=61,723
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW)	= 3,85937,064
KILN HEAT AVAILABLE (kW)	=40,923
ENERGY REQUIRED IN DRYER (kW)	= 0
ENERGY INPUT FROM NATURAL GAS (kW)	= 0
HEAT EXCHANGER EFFECTIVENESS	=0.743
FIRST LAW EFFICIENCY	=68.1
SECOND LAW EFFICIENCY	=50.9

Turbine No.2:
Manufacturer:Kawasaki
Model No.: M1A - 23

#4ii	951.9	102.6	1,307.2	4.0	567.8	45.3	10.2
#5ii	315.0	101.3	594.5	3.2	92.9	45.3	10.2
#6ii	315.0	103.8	594.5	3.2	94.9	45.3	10.2
#8ii	0.0	0.0	0.0	0.0	0.0	0.0	0.0
#9ii	20.0	101.3	293.2	2.5	0.0	9.3	0.0
#10ii	449.0	1,134.6	737.0	2.7	374.8	9.3	0.0
#11ii	1,140.0	1,064.7	1,531.0	3.5	938.6	9.3	0.0
#12ii	20.0	1,064.7				0.0	0.0
#13ii	1,140.0	1,064.7	1,531.0	3.5	938.6	9.4	0.0
#14ii	586.4	101.3	887.7	3.6	266.2	9.4	0.0
#16ii	727.7	101.3	1,046.8	3.8	375.1	45.3	0.0
#17ii	703.7	101.3	1,019.5	3.8	356.4	54.7	0.0

Cp4ii and Cp5ii = 1.18 1.05
Cp10ii and Cp11ii = 1.08 1.22
Cp16ii = 1.14

POWER GENERATED (kW) AND RATED OUTPUT POWER (kW) = 1,915 2,043
ENERGY RELEASED IN COMBUSTOR (kW) =61,723
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW) = 5,58434,174
KILN HEAT AVAILABLE (kW) =39,758
ENERGY REQUIRED IN DRYER (kW) = 0
ENERGY INPUT FROM NATURAL GAS (kW) = 0
HEAT EXCHANGER EFFECTIVENESS =1.071
FIRST LAW EFFICIENCY =67.5
SECOND LAW EFFICIENCY =50.5

Turbine No.3:
Manufacturer:Kawasaki
Model No.: M1T - 23

#4iii	815.8	102.6	1,148.1	3.9	449.0	45.3	10.2
#5iii	315.0	101.3	594.5	3.2	92.9	45.3	10.2
#6iii	315.0	103.8	594.5	3.2	94.9	45.3	10.2
#8iii	0.0	0.0	0.0	0.0	0.0	0.0	0.0
#9iii	20.0	101.3	293.2	2.5	0.0	18.6	0.0
#10iii	453.2	1,124.4	741.5	2.7	376.7	18.6	0.0
#11iii	1,130.0	1,054.5	1,519.0	3.5	928.2	18.6	0.0
#12iii	20.0	1,054.5				0.0	0.0
#13iii	1,130.0	1,054.5	1,519.0	3.5	928.2	18.8	0.0
#14iii	581.9	101.3	882.7	3.6	262.9	18.8	0.0
#16iii	570.1	101.3	869.5	3.6	254.3	45.3	0.0
#17iii	573.6	101.3	873.4	3.6	256.8	64.1	0.0

Cp4iii and Cp5iii = 1.16 1.05
Cp10iii and Cp11iii = 1.08 1.21
Cp16iii = 1.11

POWER GENERATED (kW) AND RATED OUTPUT POWER (kW) = 3,615 3,981
ENERGY RELEASED IN COMBUSTOR (kW) =61,723
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW) =11,07426,133
KILN HEAT AVAILABLE (kW) =37,207
ENERGY REQUIRED IN DRYER (kW) = 0
ENERGY INPUT FROM NATURAL GAS (kW) = 0
HEAT EXCHANGER EFFECTIVENESS =1.056
FIRST LAW EFFICIENCY =66.1
SECOND LAW EFFICIENCY =48.2

OPTION #2: CERAMIC HEAT EXCHANGER

Ambient Temperature (C)	= 20
Atmospheric Pressure (kPa)	= 101.3
PLANT CONDITIONS:	
Sawmill annual capacity (Mfbm)	=250
Annual wood waste production (ODT)	=130,734
Initial wood waste moisture content (%)	= 50
Target wood waste moisture content (%)	= 50
Maximum Heat Exchanger Pressure (kPa)	= 1200

PROCESS FLOW CONDITIONS

FLOW #	TEMP C	PRESS. kPa	ENTH. kJ/kg	ENTR. kJ/kgK	EXER. kJ/kg	MASS kg/sec	MOISTURE %H2O
#1	20.0					9.2	50.0
#2	20.0					9.2	50.0
#3	1,094.1	103.1	1,476.0	4.1	698.8	45.3	10.2
#7	20.0	101.3	293.2	2.5	0.0	40.9	0.0
#15	20.0	171.2	293.2	2.3	44.1	45.3	0.0

Cp3 and Cp15 = 1.21 1.01

Turbine No.1:
Manufacturer:Kawasaki
Model No.: 1 Unit of the M1T - 23

FLOW #	TEMP C	PRESS. kPa	ENTH. kJ/kg	ENTR. kJ/kgK	EXER. kJ/kg	MASS kg/sec	MOISTURE %H2O
#4i	815.8	102.6	1,148.1	3.9	449.0	45.3	10.2
#5i	315.0	101.3	594.5	3.2	92.9	45.3	10.2
#6i	315.0	103.8	594.5	3.2	94.9	45.3	10.2
#8i	0.0	0.0	0.0	0.0	0.0	0.0	0.0
#9i	20.0	101.3	293.2	2.5	0.0	18.6	0.0
#10i	453.2	1,124.4	741.5	2.7	376.7	18.6	0.0
#11i	1,130.0	1,054.5	1,519.0	3.5	928.2	18.6	0.0
#12i	20.0	1,054.5				0.0	0.0
#13i	1,130.0	1,054.5	1,519.0	3.5	928.2	18.8	0.0
#14i	581.9	101.3	882.7	3.6	262.9	18.8	0.0
#16i	570.1	101.3	869.5	3.6	254.3	45.3	0.0
#17i	573.6	101.3	873.4	3.6	256.8	64.1	0.0

Cp4i and Cp5i = 1.16 1.05
Cp10i and Cp11i = 1.08 1.21
Cp16i = 1.11

POWER GENERATED (kW) AND RATED OUTPUT POWER (kW)	= 3,615 3,981
ENERGY RELEASED IN COMBUSTOR (kW)	=61,723
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW)	=11,07426,133
KILN HEAT AVAILABLE (kW)	=37,207
ENERGY REQUIRED IN DRYER (kW)	= 0
ENERGY INPUT FROM NATURAL GAS (kW)	= 0
HEAT EXCHANGER EFFECTIVENESS	=1.056
FIRST LAW EFFICIENCY	=66.1
SECOND LAW EFFICIENCY	=48.2

Turbine No.2:
Manufacturer:Kawasaki
Model No.: 2 Units of the M1T - 23

#4ii	564.2	102.6	863.0	3.6	251.1	45.3	10.2
#5ii	315.0	101.3	594.5	3.2	92.9	45.3	10.2
#6ii	315.0	103.8	594.5	3.2	94.9	45.3	10.2
#8ii	0.0	0.0	0.0	0.0	0.0	0.0	0.0
#9ii	20.0	101.3	293.2	2.5	0.0	37.2	0.0
#10ii	453.2	1,124.4	741.5	2.7	376.7	37.2	0.0
#11ii	1,104.8	1,054.5	1,488.8	3.5	904.4	37.2	0.0
#12ii	20.0	1,054.5				0.0	0.0
#13ii	1,130.0	1,054.5	1,519.0	3.5	928.2	37.6	0.0
#14ii	581.9	101.3	882.7	3.6	262.9	37.6	0.0
#16ii	287.3	101.3	565.5	3.2	78.8	45.3	0.0
#17ii	423.2	101.3	709.2	3.4	162.2	82.9	0.0

Cp4ii and Cp5ii = 1.11 1.05
Cp10ii and Cp11ii = 1.08 1.21
Cp16ii = 1.04

POWER GENERATED (kW) AND RATED OUTPUT POWER (kW) = 7,230 7,962
ENERGY RELEASED IN COMBUSTOR (kW) =61,723
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW) =22,14812,349
KILN HEAT AVAILABLE (kW) =34,497
ENERGY REQUIRED IN DRYER (kW) = 0
ENERGY INPUT FROM NATURAL GAS (kW) = 1,876
HEAT EXCHANGER EFFECTIVENESS =1.017
FIRST LAW EFFICIENCY =65.6
SECOND LAW EFFICIENCY =49.0

Turbine No.3:
Manufacturer:Kawasaki
Model No.: 3 Units of the M1T - 23

#4iii	564.2	102.6	863.0	3.6	251.1	45.3	10.2
#5iii	315.0	101.3	594.5	3.2	92.9	45.3	10.2
#6iii	315.0	103.8	594.5	3.2	94.9	45.3	10.2
#8iii	0.0	0.0	0.0	0.0	0.0	0.0	0.0
#9iii	20.0	101.3	293.2	2.5	0.0	55.8	0.0
#10iii	453.2	1,124.4	741.5	2.7	376.7	55.8	0.0
#11iii	887.6	1,054.5	1,231.6	3.3	706.7	55.8	0.0
#12iii	20.0	1,054.5				0.3	0.0
#13iii	1,130.0	1,054.5	1,519.0	3.5	928.2	56.4	0.0
#14iii	581.9	101.3	882.7	3.6	262.9	56.4	0.0
#16iii	287.3	101.3	565.5	3.2	78.8	45.3	0.0
#17iii	452.9	101.3	741.3	3.4	180.8	101.7	0.0

Cp4iii and Cp5iii = 1.11 1.05
Cp10iii and Cp11iii = 1.08 1.21
Cp16iii = 1.04

POWER GENERATED (kW) AND RATED OUTPUT POWER (kW) =10,84511,943
ENERGY RELEASED IN COMBUSTOR (kW) =61,723
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW) =33,22212,349
KILN HEAT AVAILABLE (kW) =45,571
ENERGY REQUIRED IN DRYER (kW) = 0
ENERGY INPUT FROM NATURAL GAS (kW) =18,761
HEAT EXCHANGER EFFECTIVENESS =0.827
FIRST LAW EFFICIENCY =70.1
SECOND LAW EFFICIENCY =55.9

OPTION #3: ATMOSPHERIC FLUIDIZED BED AIR HEATER

Ambient Temperature (C)	= 20
Atmospheric Pressure (kPa)	= 101.3

PLANT CONDITIONS:

Sawmill annual capacity (Mfbm)	= 50
Annual wood waste production (ODT)	= 26,147
Initial wood waste moisture content (%)	= 50
Target wood waste moisture content (%)	= 50
Maximum Air Tube Temperature (C)	= 815

PROCESS FLOW CONDITIONS

FLOW #	TEMP deg C	PRESSURE kPa	ENTHALPY kJ/kg	ENTROPY kJ/kgK	EXERGY kJ/kg	MASS FLOW kg/sec	MOISTURE %H2O
#1	20.0					1.8	50.0
#2	20.0					1.8	50.0
#3	1,000.0	103.1	1,364.0	4.1	610.4	9.1	10.2
#7	20.0	187.5	293.2	2.5	5.2	8.2	0.0
#8	315.0	117.6	594.5	3.2	94.1	8.2	0.0
#15	20.0	171.2	293.2	2.3	44.1	9.1	0.0
Cp7, Cp8 and Cp15 = 1.01 1.05 1.01							
Turbine No.1:							
Manufacturer:Kawasaki							
Model No.: M1A -11A							
#4ai	1,000.0	103.1	1,364.0	4.1	610.4	9.1	10.2
#4i	497.9	102.6	790.1	3.5	203.6	9.1	10.2
#5i	232.0	101.3	508.2	3.0	51.7	9.1	10.2
#6i	232.0	101.3	508.2	3.1	50.7	9.1	10.2
#9i	20.0	101.3	293.2	2.5	0.0	9.1	10.2
#10i	378.1	942.1	661.1	2.7	315.4	8.2	0.0
#11ai	815.0						
#11i	815.0	802.3	1,147.2	3.3	621.4	8.2	0.0
#12i	20.0	802.3				0.0	0.0
#13i	910.0	802.3	1,257.9	3.4	703.5	8.3	0.0
#14i	482.0	101.3	772.7	3.5	193.0	8.3	0.0
#16i	566.8	101.3	865.9	3.6	251.9	9.1	0.0
#17i	526.5	101.3	821.4	3.5	223.8	17.4	0.0
Cp4ai and Cp4 = 1.19 1.09							
Cp5 and Cp16i = 1.03 1.11							

POWER GENERATED (kW) AND RATED OUTPUT POWER (KW)	= 1,001 1,235
ENERGY RELEASED IN COMBUSTOR (kW)	=12,345
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW)	= 3,972 5,194
KILN HEAT AVAILABLE (kW)	= 9,165
ENERGY REQUIRED IN DRYER (kW)	= 0
ENERGY INPUT FROM NATURAL GAS (kW)	= 1,123
FIRST LAW EFFICIENCY	=75.5
SECOND LAW EFFICIENCY	=35.9

Turbine No.2:
Manufacturer:Kawasaki
Model No.: M1A - 23

#4aii	1,000.0	103.1	1,364.0	4.1	610.4	9.1	10.2
#4ii	497.9	102.6	790.1	3.5	203.6	9.1	10.2
#5ii	232.0	101.3	508.2	3.0	51.7	9.1	10.2
#6ii	232.0	101.3	508.2	3.1	50.7	9.1	10.2
#9ii	20.0	101.3	293.2	2.5	0.0	9.3	0.0
#10ii	449.0	1,134.6	737.0	2.7	374.8	9.3	0.0
#11aii	815.0						
#11ii	815.0	994.8	1,147.2	3.2	639.5	9.3	0.0
#12ii	20.0	994.8				0.1	0.0
#13ii	1,140.0	994.8	1,531.0	3.5	932.9	9.4	0.0
#14ii	597.8	101.3	900.3	3.6	274.6	9.4	0.0
#16ii	566.8	101.3	865.9	3.6	251.9	9.1	0.0
#17ii	582.6	101.3	883.4	3.6	263.5	18.5	0.0

Cp4aii and Cp4 = 1.19 1.09
Cp5 and Cp16ii = 1.03 1.11

POWER GENERATED (kW) AND RATED OUTPUT POWER (kW) = 1,797 2,043
ENERGY RELEASED IN COMBUSTOR (kW) =12,345
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW) = 5,703 5,194
KILN HEAT AVAILABLE (kW) =10,896
ENERGY REQUIRED IN DRYER (kW) = 0
ENERGY INPUT FROM NATURAL GAS (kW) = 4,124
FIRST LAW EFFICIENCY =77.1
SECOND LAW EFFICIENCY =45.8

Turbine No.3:
Manufacturer:Kawasaki
Model No.: M1T - 23

#4aiii	744.5	103.1	1,066.0	3.8	389.0	9.1	10.2
#4iii	497.9	102.6	790.1	3.5	203.6	9.1	10.2
#5iii	232.0	101.3	508.2	3.0	51.7	9.1	10.2
#6iii	232.0	101.3	508.2	3.1	50.7	9.1	10.2
#9iii	20.0	101.3	293.2	2.5	0.0	18.6	0.0
#10iii	453.2	1,124.4	741.5	2.7	384.4	18.6	0.0
#11aiii	688.2						
#11iii	815.0	984.6	1,147.2	3.2	646.4	18.6	0.0
#12iii	20.0	984.6				0.1	0.0
#13iii	1,130.0	984.6	1,519.0	3.5	930.2	18.8	0.0
#14iii	593.3	101.3	895.3	3.6	279.1	18.8	0.0
#16iii	283.0	101.3	561.0	3.1	76.6	9.1	0.0
#17iii	494.6	101.3	786.5	3.4	213.2	27.9	0.0

Cp4aiii and Cp4 = 1.14 1.09
Cp5 and Cp16iii = 1.03 1.04

POWER GENERATED (kW) AND RATED OUTPUT POWER (kW) = 3,377 3,981
ENERGY RELEASED IN COMBUSTOR (kW) =12,345
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW) =11,312 2,429
KILN HEAT AVAILABLE (kW) =13,741
ENERGY REQUIRED IN DRYER (kW) = 0
ENERGY INPUT FROM NATURAL GAS (kW) = 7,998
FIRST LAW EFFICIENCY =84.1
SECOND LAW EFFICIENCY =55.9

OPTION #3: ATMOSPHERIC FLUIDIZED BED AIR HEATER

Ambient Temperature (C)	= 20
Atmospheric Pressure (kPa)	= 101.3

PLANT CONDITIONS:

Sawmill annual capacity (Mfbm)	= 50
Annual wood waste production (ODT)	= 26,147
Initial wood waste moisture content (%)	= 50
Target wood waste moisture content (%)	= 50
Maximum Air Tube Temperature (C)	= 815

PROCESS FLOW CONDITIONS

FLOW #	TEMP deg C	PRESSURE kPa	ENTHALPY kJ/kg	ENTROPY kJ/kgK	EXERGY kJ/kg	MASS FLOW kg/sec	MOISTURE %H2O
#1	20.0					1.8	50.0
#2	20.0					1.8	50.0
#3	1,000.0	103.1	1,364.0	4.1	610.4	9.1	10.2
#7	20.0	187.5	293.2	2.5	5.2	8.2	0.0
#8	315.0	117.6	594.5	3.2	94.1	8.2	0.0
#15	20.0	171.2	293.2	2.3	44.1	9.1	0.0

Cp7, Cp8 and Cp15 = 1.01 1.05 1.01

Turbine No.1:

Manufacturer:Kawasaki

Model No.: 1 Unit of the M1T - 23

FLOW #	TEMP deg C	PRESSURE kPa	ENTHALPY kJ/kg	ENTROPY kJ/kgK	EXERGY kJ/kg	MASS FLOW kg/sec	MOISTURE %H2O
#4ai	744.5	103.1	1,066.0	3.8	389.0	9.1	10.2
#4i	497.9	102.6	790.1	3.5	203.6	9.1	10.2
#5i	232.0	101.3	508.2	3.0	51.7	9.1	10.2
#6i	232.0	101.3	508.2	3.1	50.7	9.1	10.2
#9i	20.0	101.3	293.2	2.5	0.0	18.6	0.0
#10i	453.2	1,124.4	741.5	2.7	376.7	18.6	0.0
#11ai	688.2						
#11i	815.0	984.6	1,147.2	3.2	638.6	18.6	0.0
#12i	20.0	984.6				0.1	0.0
#13i	1,130.0	984.6	1,519.0	3.5	922.5	18.8	0.0
#14i	593.3	101.3	895.3	3.6	271.3	18.8	0.0
#16i	283.0	101.3	561.0	3.1	76.6	9.1	0.0
#17i	494.6	101.3	786.5	3.5	207.9	27.9	0.0

Cp4ai and Cp4 = 1.14 1.09

Cp5 and Cp16i = 1.03 1.04

POWER GENERATED (kW) AND RATED OUTPUT POWER (KW)	= 3,377 3,981
ENERGY RELEASED IN COMBUSTOR (kW)	=12,345
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW)	=11,312 2,429
KILN HEAT AVAILABLE (kW)	= 13,741
ENERGY REQUIRED IN DRYER (kW)	= 0
ENERGY INPUT FROM NATURAL GAS (kW)	= 7,998
FIRST LAW EFFICIENCY	=84.1
SECOND LAW EFFICIENCY	=55.2

Turbine No.2:
Manufacturer:Kawasaki
Model No.: 2 Units of the M1T - 23

#4aii	572.1	103.1	871.7	3.6	255.9	9.1	10.2
#4ii	497.9	102.6	790.1	3.5	203.6	9.1	10.2
#5ii	232.0	101.3	508.2	3.0	51.7	9.1	10.2
#6ii	232.0	101.3	508.2	3.1	50.7	9.1	10.2
#9ii	20.0	101.3	293.2	2.5	0.0	37.2	0.0
#10ii	453.2	1,124.4	741.5	2.7	376.7	37.2	0.0
#11aii	572.1						
#11ii	679.2	984.6	991.7	2.8	606.2	37.2	0.0
#12ii	20.0	984.6				0.4	0.0
#13ii	1,130.0	984.6	1,519.0	3.3	1,000.8	37.6	0.0
#14ii	593.3	101.3	895.3	3.4	349.7	37.6	0.0
#16ii	97.8	101.3	371.5	2.7	9.0	9.1	0.0
#17ii	501.0	101.3	793.5	3.2	283.4	46.6	0.0

Cp4aii and Cp4 = 1.11 1.09
Cp5 and Cp16ii = 1.03 1.01

POWER GENERATED (kW) AND RATED OUTPUT POWER (kW) = 6,753 7,962
ENERGY RELEASED IN COMBUSTOR (kW) =12,345
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW) =22,625 711
KILN HEAT AVAILABLE (kW) =23,336
ENERGY REQUIRED IN DRYER (kW) = 0
ENERGY INPUT FROM NATURAL GAS (kW) =22,422
FIRST LAW EFFICIENCY =86.5
SECOND LAW EFFICIENCY =76.9

Turbine No.3:
Manufacturer:Kawasaki
Model No.: 3 Units of the M1T - 23

#4aiii	532.8	103.1	828.3	3.5	227.9	9.1	10.2
#4iii	497.9	102.6	790.1	3.5	203.6	9.1	10.2
#5iii	232.0	101.3	508.2	3.0	51.7	9.1	10.2
#6iii	232.0	101.3	508.2	3.1	50.7	9.1	10.2
#9iii	20.0	101.3	293.2	2.5	0.0	55.8	0.0
#10iii	453.2	1,124.4	741.5	2.7	384.4	55.8	0.0
#11aiii	532.8						
#11iii	611.3	984.6	915.4	2.8	543.9	55.8	0.0
#12iii	20.0	984.6				0.7	0.0
#13iii	1,130.0	984.6	1,519.0	3.3	990.5	56.4	0.0
#14iii	593.3	101.3	895.3	3.4	339.4	56.4	0.0
#16iii	56.5	101.3	329.8	2.6	2.4	9.1	0.0
#17iii	522.4	101.3	817.0	3.3	292.7	65.4	0.0

Cp4aiii and Cp4 = 1.10 1.09
Cp5 and Cp16iii = 1.03 1.01

POWER GENERATED (kW) AND RATED OUTPUT POWER (kW) =10,13011,943
ENERGY RELEASED IN COMBUSTOR (kW) =12,345
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW) =33,937 332
KILN HEAT AVAILABLE (kW) =34,270
ENERGY REQUIRED IN DRYER (kW) = 0
ENERGY INPUT FROM NATURAL GAS (kW) =38,366
FIRST LAW EFFICIENCY =87.6
SECOND LAW EFFICIENCY =81.8

OPTION #3: ATMOSPHERIC FLUIDIZED BED AIR HEATER

Ambient Temperature (C)	= 20
Atmospheric Pressure (kPa)	= 101.3

PLANT CONDITIONS:

Sawmill annual capacity (Mfbm)	=150
Annual wood waste production (ODT)	= 78,440
Initial wood waste moisture content (%)	= 50
Target wood waste moisture content (%)	= 50
Maximum Air Tube Temperature (C)	= 815

PROCESS FLOW CONDITIONS

FLOW #	TEMP deg C	PRESSURE kPa	ENTHALPY kJ/kg	ENTROPY kJ/kgK	EXERGY kJ/kg	MASS FLOW kg/sec	MOISTURE %H2O
#1	20.0					5.5	50.0
#2	20.0					5.5	50.0
#3	1,000.0	103.1	1,364.0	4.1	610.4	27.2	10.2
#7	20.0	187.5	293.2	2.5	5.2	24.6	0.0
#8	315.0	117.6	594.5	3.2	94.1	24.6	0.0
#15	20.0	171.2	293.2	2.3	44.1	27.2	0.0

Cp7, Cp8 and Cp15 = 1.01 1.05 1.01

Turbine No.1:
Manufacturer:Kawasaki
Model No.: M1A -11A

FLOW #	TEMP deg C	PRESSURE kPa	ENTHALPY kJ/kg	ENTROPY kJ/kgK	EXERGY kJ/kg	MASS FLOW kg/sec	MOISTURE %H2O
#4ai	1,000.0	103.1	1,364.0	4.1	610.4	27.2	10.2
#4i	497.9	102.6	790.1	3.5	203.6	27.2	10.2
#5i	232.0	101.3	508.2	3.0	51.7	27.2	10.2
#6i	232.0	101.3	508.2	3.1	50.7	27.2	10.2
#9i	20.0	101.3	293.2	2.5	0.0	8.2	0.0
#10i	378.1	942.1	661.1	2.7	315.4	8.2	0.0
#11ai	815.0						
#11i	815.0	802.3	1,147.2	3.3	621.4	8.2	0.0
#12i	20.0	802.3				0.0	0.0
#13i	910.0	802.3	1,257.9	3.4	703.5	8.3	0.0
#14i	482.0	101.3	772.7	3.5	193.0	8.3	0.0
#16i	566.8	101.3	865.9	3.6	251.9	27.2	0.0
#17i	547.1	101.3	844.1	3.6	238.2	35.5	0.0

Cp4ai and Cp4 = 1.19 1.09
Cp5 and Cp16i = 1.03 1.11

POWER GENERATED (kW) AND RATED OUTPUT POWER (KW)	= 1,001 1,235
ENERGY RELEASED IN COMBUSTOR (kW)	=37,033
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW)	= 3,97215,581
KILN HEAT AVAILABLE (kW)	= 19,552
ENERGY REQUIRED IN DRYER (kW)	= 0
ENERGY INPUT FROM NATURAL GAS (kW)	= 1,123
FIRST LAW EFFICIENCY	=53.9
SECOND LAW EFFICIENCY	=22.4

Turbine No.2:
Manufacturer:Kawasaki
Model No.: M1A - 23

#4aii	1,000.0	103.1	1,364.0	4.1	610.4	27.2	10.2
#4ii	497.9	102.6	790.1	3.5	203.6	27.2	10.2
#5ii	232.0	101.3	508.2	3.0	51.7	27.2	10.2
#6ii	232.0	101.3	508.2	3.1	50.7	27.2	10.2
#9ii	20.0	101.3	293.2	2.5	0.0	9.3	0.0
#10ii	449.0	1,134.6	737.0	2.7	374.8	9.3	0.0
#11aii	815.0						
#11ii	815.0	994.8	1,147.2	3.2	639.5	9.3	0.0
#12ii	20.0	994.8				0.1	0.0
#13ii	1,140.0	994.8	1,531.0	3.5	932.9	9.4	0.0
#14ii	597.8	101.3	900.3	3.6	274.6	9.4	0.0
#16ii	566.8	101.3	865.9	3.6	251.9	27.2	0.0
#17ii	574.8	101.3	874.7	3.6	257.8	36.6	0.0

Cp4aii and Cp4 = 1.19 1.09
Cp5 and Cp16ii = 1.03 1.11

POWER GENERATED (kW) AND RATED OUTPUT POWER (kW) = 1,797 2,043
ENERGY RELEASED IN COMBUSTOR (kW) =37,033
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW) = 5,70315,581
KILN HEAT AVAILABLE (kW) =21,284
ENERGY REQUIRED IN DRYER (kW) = 0
ENERGY INPUT FROM NATURAL GAS (kW) = 4,124
FIRST LAW EFFICIENCY =56.1
SECOND LAW EFFICIENCY =27.3

Turbine No.3:
Manufacturer:Kawasaki
Model No.: M1T - 23

#4aiii	1,000.0	103.1	1,364.0	4.1	610.4	27.2	10.2
#4iii	497.9	102.6	790.1	3.5	203.6	27.2	10.2
#5iii	232.0	101.3	508.2	3.0	51.7	27.2	10.2
#6iii	232.0	101.3	508.2	3.1	50.7	27.2	10.2
#9iii	20.0	101.3	293.2	2.5	0.0	18.6	0.0
#10iii	453.2	1,124.4	741.5	2.7	384.4	18.6	0.0
#11aiii	815.0						
#11iii	815.0	984.6	1,147.2	3.2	646.4	18.6	0.0
#12iii	20.0	984.6				0.1	0.0
#13iii	1,130.0	984.6	1,519.0	3.5	930.2	18.8	0.0
#14iii	593.3	101.3	895.3	3.6	279.1	18.8	0.0
#16iii	566.8	101.3	865.9	3.6	251.9	27.2	0.0
#17iii	577.7	101.3	877.9	3.6	263.0	46.0	0.0

Cp4aiii and Cp4 = 1.19 1.09
Cp5 and Cp16iii = 1.03 1.11

POWER GENERATED (kW) AND RATED OUTPUT POWER (kW) = 3,377 3,981
ENERGY RELEASED IN COMBUSTOR (kW) =37,033
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW) =11,31215,581
KILN HEAT AVAILABLE (kW) =26,893
ENERGY REQUIRED IN DRYER (kW) = 0
ENERGY INPUT FROM NATURAL GAS (kW) = 7,998
FIRST LAW EFFICIENCY =67.2
SECOND LAW EFFICIENCY =37.1

OPTION #3: ATMOSPHERIC FLUIDIZED BED AIR HEATER

Ambient Temperature (C)	= 20
Atmospheric Pressure (kPa)	= 101.3

PLANT CONDITIONS:

Sawmill annual capacity (Mfbm)	=150
Annual wood waste production (ODT)	= 78,440
Initial wood waste moisture content (%)	= 50
Target wood waste moisture content (%)	= 50
Maximum Air Tube Temperature (C)	= 815

PROCESS FLOW CONDITIONS

FLOW #	TEMP deg C	PRESSURE kPa	ENTHALPY kJ/kg	ENTROPY kJ/kgK	EXERGY kJ/kg	MASS FLOW kg/sec	MOISTURE %H2O
#1	20.0					5.5	50.0
#2	20.0					5.5	50.0
#3	1,000.0	103.1	1,364.0	4.1	610.4	27.2	10.2
#7	20.0	187.5	293.2	2.5	5.2	24.6	0.0
#8	315.0	117.6	594.5	3.2	94.1	24.6	0.0
#15	20.0	171.2	293.2	2.3	44.1	27.2	0.0
Cp7, Cp8 and Cp15 = 1.01 1.05 1.01							
Turbine No.1:							
Manufacturer:Kawasaki							
Model No.: 1 Unit of the M1T - 23							
#4ai	1,000.0	103.1	1,364.0	4.1	610.4	27.2	10.2
#4i	497.9	102.6	790.1	3.5	203.6	27.2	10.2
#5i	232.0	101.3	508.2	3.0	51.7	27.2	10.2
#6i	232.0	101.3	508.2	3.1	50.7	27.2	10.2
#9i	20.0	101.3	293.2	2.5	0.0	18.6	10.2
#10i	453.2	1,124.4	741.5	2.7	376.7	18.6	0.0
#11ai	815.0						0.0
#11i	815.0	984.6	1,147.2	3.2	638.6	18.6	0.0
#12i	20.0	984.6				0.1	0.0
#13i	1,130.0	984.6	1,519.0	3.5	922.5	18.8	0.0
#14i	593.3	101.3	895.3	3.6	271.3	18.8	0.0
#16i	566.8	101.3	865.9	3.6	251.9	27.2	0.0
#17i	577.7	101.3	877.9	3.6	259.9	46.0	0.0
Cp4ai and Cp4 = 1.19 1.09							
Cp5 and Cp16i = 1.03 1.11							

POWER GENERATED (kW) AND RATED OUTPUT POWER (KW)	= 3,377 3,981
ENERGY RELEASED IN COMBUSTOR (kW)	=37,033
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW)	=11,31215,581
KILN HEAT AVAILABLE (kW)	= 26,893
ENERGY REQUIRED IN DRYER (kW)	= 0
ENERGY INPUT FROM NATURAL GAS (kW)	= 7,998
FIRST LAW EFFICIENCY	=67.2
SECOND LAW EFFICIENCY	=36.8

Turbine No.2:
Manufacturer:Kawasaki
Model No.: 2 Units of the M1T - 23

#4aii	982.6	103.1	1,343.4	4.0	594.5	27.2	10.2
#4ii	497.9	102.6	790.1	3.5	203.6	27.2	10.2
#5ii	232.0	101.3	508.2	3.0	51.7	27.2	10.2
#6ii	232.0	101.3	508.2	3.1	50.7	27.2	10.2
#9ii	20.0	101.3	293.2	2.5	0.0	37.2	0.0
#10ii	453.2	1,124.4	741.5	2.7	376.7	37.2	0.0
#11aii	802.0						
#11ii	815.0	984.6	1,147.2	3.2	638.6	37.2	0.0
#12ii	20.0	984.6				0.3	0.0
#13ii	1,130.0	984.6	1,519.0	3.5	922.5	37.6	0.0
#14ii	593.3	101.3	895.3	3.6	271.3	37.6	0.0
#16ii	547.1	101.3	844.2	3.6	238.0	27.2	0.0
#17ii	574.0	101.3	873.9	3.6	257.3	64.8	0.0

Cp4aii and Cp4 = 1.19 1.09
Cp5 and Cp16ii = 1.03 1.10

POWER GENERATED (kW) AND RATED OUTPUT POWER (kW) = 6,753 7,962
ENERGY RELEASED IN COMBUSTOR (kW) =37,033
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW) =22,62514,991
KILN HEAT AVAILABLE (kW) =37,615
ENERGY REQUIRED IN DRYER (kW) = 0
ENERGY INPUT FROM NATURAL GAS (kW) =15,996
FIRST LAW EFFICIENCY =83.7
SECOND LAW EFFICIENCY =51.3

Turbine No.3:
Manufacturer:Kawasaki
Model No.: 3 Units of the M1T - 23

#4aiii	744.4	103.1	1,066.0	3.8	388.9	27.2	10.2
#4iii	497.9	102.6	790.1	3.5	203.6	27.2	10.2
#5iii	232.0	101.3	508.2	3.0	51.7	27.2	10.2
#6iii	232.0	101.3	508.2	3.1	50.7	27.2	10.2
#9iii	20.0	101.3	293.2	2.5	0.0	55.8	0.0
#10iii	453.2	1,124.4	741.5	2.7	384.4	55.8	0.0
#11aiii	688.2						
#11iii	815.0	984.6	1,147.2	3.2	646.4	55.8	0.0
#12iii	20.0	984.6				0.4	0.0
#13iii	1,130.0	984.6	1,519.0	3.5	930.2	56.4	0.0
#14iii	593.3	101.3	895.3	3.6	279.1	56.4	0.0
#16iii	282.9	101.3	561.0	3.1	76.6	27.2	0.0
#17iii	494.6	101.3	786.5	3.4	213.2	83.6	0.0

Cp4aiii and Cp4 = 1.14 1.09
Cp5 and Cp16iii = 1.03 1.04

POWER GENERATED (kW) AND RATED OUTPUT POWER (kW) =10,13011,943
ENERGY RELEASED IN COMBUSTOR (kW) =37,033
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW) =33,937 7,285
KILN HEAT AVAILABLE (kW) =41,223
ENERGY REQUIRED IN DRYER (kW) = 0
ENERGY INPUT FROM NATURAL GAS (kW) =23,993
FIRST LAW EFFICIENCY =84.1
SECOND LAW EFFICIENCY =56.1

OPTION #3: ATMOSPHERIC FLUIDIZED BED AIR HEATER

Ambient Temperature (C) = 20
Atmospheric Pressure (kPa) = 101.3

PLANT CONDITIONS:
Sawmill annual capacity (Mfbm) =250
Annual wood waste production (ODT) =130,734
Initial wood waste moisture content (%) = 50
Target wood waste moisture content (%) = 50
Maximum Air Tube Temperature (C) = 815

PROCESS FLOW CONDITIONS

FLOW #	TEMP deg C	PRESSURE kPa	ENTHALPY kJ/kg	ENTROPY kJ/kgK	EXERGY kJ/kg	MASS FLOW kg/sec	MOISTURE %H2O
#1	20.0					9.2	50.0
#2	20.0					9.2	50.0
#3	1,000.0	103.1	1,364.0	4.1	610.4	45.3	10.2
#7	20.0	187.5	293.2	2.5	5.2	40.9	0.0
#8	315.0	117.6	594.5	3.2	94.1	40.9	0.0
#15	20.0	171.2	293.2	2.3	44.1	45.3	0.0

Cp7, Cp8 and Cp15 = 1.01 1.05 1.01
Turbine No.1:
Manufacturer:Kawasaki
Model No.: M1A -11A

FLOW #	TEMP deg C	PRESSURE kPa	ENTHALPY kJ/kg	ENTROPY kJ/kgK	EXERGY kJ/kg	MASS FLOW kg/sec	MOISTURE %H2O
#4ai	1,000.0	103.1	1,364.0	4.1	610.4	45.3	10.2
#4i	497.9	102.6	790.1	3.5	203.6	45.3	10.2
#5i	232.0	101.3	508.2	3.0	51.7	45.3	10.2
#6i	232.0	101.3	508.2	3.1	50.7	45.3	10.2
#9i	20.0	101.3	293.2	2.5	0.0	8.2	0.0
#10i	378.1	942.1	661.1	2.7	315.4	8.2	0.0
#11ai	815.0						
#11i	815.0	802.3	1,147.2	3.3	621.4	8.2	0.0
#12i	20.0	802.3				0.0	0.0
#13i	910.0	802.3	1,257.9	3.4	703.5	8.3	0.0
#14i	482.0	101.3	772.7	3.5	193.0	8.3	0.0
#16i	566.8	101.3	865.9	3.6	251.9	45.3	0.0
#17i	553.8	101.3	851.5	3.6	242.8	53.6	0.0

Cp4ai and Cp4 = 1.19 1.09
Cp5 and Cp16i = 1.03 1.11

POWER GENERATED (kW) AND RATED OUTPUT POWER (KW) = 1,001 1,235
ENERGY RELEASED IN COMBUSTOR (kW) =61,723
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW) = 3,97225,968
KILN HEAT AVAILABLE (kW) = 29,940
ENERGY REQUIRED IN DRYER (kW) = 0
ENERGY INPUT FROM NATURAL GAS (kW) = 1,123
FIRST LAW EFFICIENCY =49.2
SECOND LAW EFFICIENCY =19.5

Turbine No.2:
Manufacturer:Kawasaki
Model No.: M1A - 23

#4aii	1,000.0	103.1	1,364.0	4.1	610.4	45.3	10.2
#4ii	497.9	102.6	790.1	3.5	203.6	45.3	10.2
#5ii	232.0	101.3	508.2	3.0	51.7	45.3	10.2
#6ii	232.0	101.3	508.2	3.1	50.7	45.3	10.2
#9ii	20.0	101.3	293.2	2.5	0.0	9.3	0.0
#10ii	449.0	1,134.6	737.0	2.7	374.8	9.3	0.0
#11aii	815.0						
#11ii	815.0	994.8	1,147.2	3.2	639.5	9.3	0.0
#12ii	20.0	994.8				0.1	0.0
#13ii	1,140.0	994.8	1,531.0	3.5	932.9	9.4	0.0
#14ii	597.8	101.3	900.3	3.6	274.6	9.4	0.0
#16ii	566.8	101.3	865.9	3.6	251.9	45.3	0.0
#17ii	572.1	101.3	871.8	3.6	255.8	54.7	0.0

Cp4aii and Cp4 = 1.19 1.09
Cp5 and Cp16ii = 1.03 1.11

POWER GENERATED (kW) AND RATED OUTPUT POWER (kW) = 1,797 2,043
ENERGY RELEASED IN COMBUSTOR (kW) =61,723
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW) = 5,70325,968
KILN HEAT AVAILABLE (kW) =31,671
ENERGY REQUIRED IN DRYER (kW) = 0
ENERGY INPUT FROM NATURAL GAS (kW) = 4,124
FIRST LAW EFFICIENCY =50.8
SECOND LAW EFFICIENCY =22.7

Turbine No.3:
Manufacturer:Kawasaki
Model No.: M1T - 23

#4aiii	1,000.0	103.1	1,364.0	4.1	610.4	45.3	10.2
#4iii	497.9	102.6	790.1	3.5	203.6	45.3	10.2
#5iii	232.0	101.3	508.2	3.0	51.7	45.3	10.2
#6iii	232.0	101.3	508.2	3.1	50.7	45.3	10.2
#9iii	20.0	101.3	293.2	2.5	0.0	18.6	0.0
#10iii	453.2	1,124.4	741.5	2.7	384.4	18.6	0.0
#11aiii	815.0						
#11iii	815.0	984.6	1,147.2	3.2	646.4	18.6	0.0
#12iii	20.0	984.6				0.1	0.0
#13iii	1,130.0	984.6	1,519.0	3.5	930.2	18.8	0.0
#14iii	593.3	101.3	895.3	3.6	279.1	18.8	0.0
#16iii	566.8	101.3	865.9	3.6	251.9	45.3	0.0
#17iii	574.6	101.3	874.5	3.6	259.9	64.1	0.0

Cp4aiii and Cp4 = 1.19 1.09
Cp5 and Cp16iii = 1.03 1.11

POWER GENERATED (kW) AND RATED OUTPUT POWER (kW) = 3,377 3,981
ENERGY RELEASED IN COMBUSTOR (kW) =61,723
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW) =11,31225,968
KILN HEAT AVAILABLE (kW) =37,280
ENERGY REQUIRED IN DRYER (kW) = 0
ENERGY INPUT FROM NATURAL GAS (kW) = 7,998
FIRST LAW EFFICIENCY =58.3
SECOND LAW EFFICIENCY =29.3

OPTION #3: ATMOSPHERIC FLUIDIZED BED AIR HEATER

Ambient Temperature (C)	= 20
Atmospheric Pressure (kPa)	= 101.3

PLANT CONDITIONS:

Sawmill annual capacity (Mfbm)	=250
Annual wood waste production (ODT)	=130,734
Initial wood waste moisture content (%)	= 50
Target wood waste moisture content (%)	= 50
Maximum Air Tube Temperature (C)	= 815

PROCESS FLOW CONDITIONS

FLOW #	TEMP deg C	PRESSURE kPa	ENTHALPY kJ/kg	ENTROPY kJ/kgK	EXERGY kJ/kg	MASS FLOW kg/sec	MOISTURE %H2O
#1	20.0					9.2	50.0
#2	20.0					9.2	50.0
#3	1,000.0	103.1	1,364.0	4.1	610.4	45.3	10.2
#7	20.0	187.5	293.2	2.5	5.2	40.9	0.0
#8	315.0	117.6	594.5	3.2	94.1	40.9	0.0
#15	20.0	171.2	293.2	2.3	44.1	45.3	0.0

Cp7, Cp8 and Cp15 = 1.01 1.05 1.01

Turbine No.1:
Manufacturer:Kawasaki
Model No.: 1 Unit of the M1T - 23

FLOW #	TEMP deg C	PRESSURE kPa	ENTHALPY kJ/kg	ENTROPY kJ/kgK	EXERGY kJ/kg	MASS FLOW kg/sec	MOISTURE %H2O
#4ai	1,000.0	103.1	1,364.0	4.1	610.4	45.3	10.2
#4i	497.9	102.6	790.1	3.5	203.6	45.3	10.2
#5i	232.0	101.3	508.2	3.0	51.7	45.3	10.2
#6i	232.0	101.3	508.2	3.1	50.7	45.3	10.2
#9i	20.0	101.3	293.2	2.5	0.0	18.6	0.0
#10i	453.2	1,124.4	741.5	2.7	376.7	18.6	0.0
#11ai	815.0						
#11i	815.0	984.6	1,147.2	3.2	638.6	18.6	0.0
#12i	20.0	984.6				0.1	0.0
#13i	1,130.0	984.6	1,519.0	3.5	922.5	18.8	0.0
#14i	593.3	101.3	895.3	3.6	271.3	18.8	0.0
#16i	566.8	101.3	865.9	3.6	251.9	45.3	0.0
#17i	574.6	101.3	874.5	3.6	257.6	64.1	0.0

Cp4ai and Cp4 = 1.19 1.09
Cp5 and Cp16i = 1.03 1.11

POWER GENERATED (kW) AND RATED OUTPUT POWER (KW)	= 3,377 3,981
ENERGY RELEASED IN COMBUSTOR (kW)	=61,723
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW)	=11,31225,968
KILN HEAT AVAILABLE (kW)	= 37,280
ENERGY REQUIRED IN DRYER (kW)	= 0
ENERGY INPUT FROM NATURAL GAS (kW)	= 7,998
FIRST LAW EFFICIENCY	=58.3
SECOND LAW EFFICIENCY	=29.1

Turbine No.2:
Manufacturer:Kawasaki
Model No.: 2 Units of the M1T - 23

#4aii	1,000.0	103.1	1,364.0	4.1	610.4	45.3	10.2
#4ii	497.9	102.6	790.1	3.5	203.6	45.3	10.2
#5ii	232.0	101.3	508.2	3.0	51.7	45.3	10.2
#6ii	232.0	101.3	508.2	3.1	50.7	45.3	10.2
#9ii	20.0	101.3	293.2	2.5	0.0	37.2	0.0
#10ii	453.2	1,124.4	741.5	2.7	376.7	37.2	0.0
#11aii	815.0						
#11ii	815.0	984.6	1,147.2	3.2	638.6	37.2	0.0
#12ii	20.0	984.6				0.3	0.0
#13ii	1,130.0	984.6	1,519.0	3.5	922.5	37.6	0.0
#14ii	593.3	101.3	895.3	3.6	271.3	37.6	0.0
#16ii	566.8	101.3	865.9	3.6	251.9	45.3	0.0
#17ii	578.9	101.3	879.2	3.6	260.7	82.9	0.0

Cp4aii and Cp4 = 1.19 1.09
Cp5 and Cp16ii = 1.03 1.11

POWER GENERATED (kW) AND RATED OUTPUT POWER (kW) = 6,753 7,962
ENERGY RELEASED IN COMBUSTOR (kW) =61,723
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW) =22,62525,968
KILN HEAT AVAILABLE (kW) =48,593
ENERGY REQUIRED IN DRYER (kW) = 0
ENERGY INPUT FROM NATURAL GAS (kW) =15,996
FIRST LAW EFFICIENCY =71.2
SECOND LAW EFFICIENCY =40.3

Turbine No.3:
Manufacturer:Kawasaki
Model No.: 3 Units of the M1T - 23

#4aiii	1,000.0	103.1	1,364.0	4.1	610.4	45.3	10.2
#4iii	497.9	102.6	790.1	3.5	203.6	45.3	10.2
#5iii	232.0	101.3	508.2	3.0	51.7	45.3	10.2
#6iii	232.0	101.3	508.2	3.1	50.7	45.3	10.2
#9iii	20.0	101.3	293.2	2.5	0.0	55.8	0.0
#10iii	453.2	1,124.4	741.5	2.7	384.4	55.8	0.0
#11aiii	815.0						
#11iii	815.0	984.6	1,147.2	3.2	646.4	55.8	0.0
#12iii	20.0	984.6				0.4	0.0
#13iii	1,130.0	984.6	1,519.0	3.5	930.2	56.4	0.0
#14iii	593.3	101.3	895.3	3.6	279.1	56.4	0.0
#16iii	566.8	101.3	865.9	3.6	251.9	45.3	0.0
#17iii	581.5	101.3	882.2	3.6	267.0	101.7	0.0

Cp4aiii and Cp4 = 1.19 1.09
Cp5 and Cp16iii = 1.03 1.11

POWER GENERATED (kW) AND RATED OUTPUT POWER (kW) =10,13011,943
ENERGY RELEASED IN COMBUSTOR (kW) =61,723
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW) =33,93725,968
KILN HEAT AVAILABLE (kW) =59,905
ENERGY REQUIRED IN DRYER (kW) = 0
ENERGY INPUT FROM NATURAL GAS (kW) =23,993
FIRST LAW EFFICIENCY =81.7
SECOND LAW EFFICIENCY =49.9

Appendix B:

Linear Programming Models for Options #1, #2, #3

```
! OPTION #1 - METALLIC HEAT EXCHANGER
!
!
constraints 58;
! BEGINNING OF PARAMETER LIST
parameters 45
                      ! Discount Factors over 20 years
i = 0.08;             ! i = real discount rate (%)
f = 0.04;             ! f = inflation rate (%)
ir =(1+i)*(1+f)-1;    ! ir = nominal discount rate (%)
B1 = 1/(1+ir);        ! Discount - year 1
B2 = 1/(1+ir)^2;      ! Discount - year 2
B3 = 1/(1+ir)^3;      ! Discount - year 3
B4 = 1/(1+ir)^4;      ! Discount - year 4
B5 = 1/(1+ir)^5;      ! Discount - year 5
B6 = 1/(1+ir)^6;      ! Discount - year 6
B7 = 1/(1+ir)^7;      ! Discount - year 7
B8 = 1/(1+ir)^8;      ! Discount - year 8
B9 = 1/(1+ir)^9;      ! Discount - year 9
B10 = 1/(1+ir)^10;! Discount - year 10
B11 = 1/(1+ir)^11;! Discount - year 11
B12 = 1/(1+ir)^12;! Discount - year 12
B13 = 1/(1+ir)^13;! Discount - year 13
B14 = 1/(1+ir)^14;! Discount - year 14
B15 = 1/(1+ir)^15;! Discount - year 15
B16 = 1/(1+ir)^16;! Discount - year 16
B17 = 1/(1+ir)^17;! Discount - year 17
B18 = 1/(1+ir)^18;! Discount - year 18
B19 = 1/(1+ir)^19;! Discount - year 19
B20 = 1/(1+ir)^20;! Discount - year 20

dispcredit = 39.42; ! Wood waste Disposal Credit ($-hrs/kg-yr)
                    ! 5$/green tonne= 39.42 $-hrs/kg-yr
                    ! Hours of Operation per year
hours1 = 4160;      ! Sawmill operating hours/yr
                    ! 2 shifts/day @ 260days/yr @ 8hrs/shift
hours2 = 7884;      ! Hours of electricity production/yr
                    ! 90% of 365 days/yr @ 24 hrs/day

hours3 = hours2-hours1;  ! Hours over which maximum excess
                         ! electricity is produced
hours4 = 292;       ! Standby hours = 10%*365 days*8 hrs/day

dc = 76.44;         ! Rate Schedule 1200's:
                    ! Demand charge = $6.37/kW/month =
                    ! $76.44/kW/yr
dcstand = 0.00665; ! Standby demand charge

ec = 0.0312;        ! Rate Schedule 1200's:
                    ! Energy Charge = 0.0312 $/kWh
ecstand = 0.02599; ! Standby energy charge

exc1 = 0.0343;   ! Firm electricity purchase price
                 ! including energy & capacity 0.0343 $/kWh
exc2 = 0.015;  ! Secondary electricity purchase price 0.015 $/kWh
```

```
pf = 0.90;         ! Plant power factor

gascost1w = 3.35; ! Gas cost $/GJ for process heat in winter(3.35)
gascost1s = 2.75; ! Gas cost $/GJ for process heat in summer(2.75)
gascost2w = 2.50; ! Gas cost $/GJ for cogen in winter(2.50)
gascost2s = 1.95; ! Gas cost $/GJ for cogen in summer(1.95)

woodwaste = 19908;     ! Maximum available wood waste (kg/hr)
proheat = 20000;       ! Plant heating required (kW)
avdemand = 3000;       ! Average demand (kW)
pkdemand = 4000;       ! Peak demand (kw)

corptax = 0.43;        ! Corporate Tax rate (%)

mathand = 600000;      ! Allowance for a material handling system
! END OF PARAMETER LIST
!
! VARIABLE LIST:
! Mf = flow rate of wood fuel (kg/hr)
! Exwood = wood not consumed as fuel = Woodwaste - Mf (kg/hr)
! peakdemand = peak electricity demand (kw)
! averagedemand = average electricity demand (kw)
! demandsave = savings in demand charge ($)
! demandchge = cost of supplying peak demand ($)
! energycharge = cost of continuous energy supply ($)
! totalcharge = demandcharge + energycharge ($)
! electricsave = electricity savings ($)
! genelec = amount of electricity being generated (kw)
! exelec1 = amount of electricity in excess of average demand
!         = netelec - averagedemand
! exelec2 = netelec
! netelec = net electricity output (kW)
! standbypower = amount of standby power demanded (kW)
! standbycost = cost of standby power ($)
! idfan = electricity required to run id fan (kW)
! dryercost = cost of wood waste dryer ($)
! dryersize = size of wood waste dryer (kg/hr)
! furnacecost = cost of wood combustor ($)
! furnacesize = size of wood combustor (kg/hr)
! turbcost = cost of gas turbine ($)
! turbsize = size of gas turbine (kw)
! mthxcost = cost of the metal gas/air heat exchanger ($)
! mthxsize = size of gas/air heat exchanger
! hxcost = cost of the kiln/air heat exchanger ($)
! hxsize = size of kiln/air heat exchanger (kg/hr)
! multicost = cost of multiclone ($)
! multisize = size of multiclone
! totalcap1 = equipment capital cost ($)
! install = cost of installation & delivery ($)
! totalcap2 = totalcap1 + install ($)
! ductwork = cost of ductwork ($)
! electrical = cost of electrical ($)
! instrument = cost of instrumentation ($)
! piping = cost of piping ($)
! structural = cost of structural/civil ($)
```

```
! totalcap3 = totalcap2 + duct.+elec.+instr.+pip.+struc ($)
! engineering = cost of engineering ($)
! constructm = cost of construction management ($)
! totalcap4 = totalcap3 + eng.+constrm ($)
! contingency = % of totalcap4 ($)
! total = project total capital cost ($)
! gas = amount of gas energy consumed (kw)
! gasenergy = cost of gas consumed ($)
! kilnheat = kiln heat required (kw)
! processheat = total plant thermal requirements (kw)
! heatenergy = cost of providing the process heat ($)
! benefits = project benefits over life of project ($)
! costs = project costs over life of project ($)
! OM = yearly operating and maintenanace costs
! class34_1 = class 34 tax credit in year of purchase
! class34_2 = class 34 tax credit in year 1
! class34_3 = class 34 tax credit in year 2
! IT = yearly insurance and property tax

variables 54 Mf Exwood demandsave demandchge energycharge
totalcharge genelec exelec1 exelec2 dryercost dryersize furnacecost
furnacesize turbcost turbsize mthxcost mthxsize hxcost hxsize
totalcap1 install totalcap2 ductwork peakdemand averagedemand
processheat electrical instrument piping structural totalcap3
engineering constructm totalcap4 contingency total gas gasenergy
electricsave kilnheat heatenergy benefits costs standbypower
standbycost multicost multisize
OM class34_1 class34_2 class34_3 IT netelec idfan;
! ------------------------------------------------------------
! OBJECTIVE FUNCTION:
maximize
benefits - costs [cashflow];

! ------------------------------------------------------------
! ------------------------------------------------------------
! SUBJECT TO THE FOLLOWING CONSTRAINTS:
!
! BENEFITS (savings):
Benefits =dispcredit*B1*Mf+
dispcredit*B2*Mf+dispcredit*B3*Mf+dispcredit*B4*Mf+
dispcredit*B5*Mf+dispcredit*B6*Mf+dispcredit*B7*Mf+
dispcredit*B8*Mf+dispcredit*B9*Mf+dispcredit*B10*Mf+
dispcredit*B11*Mf+dispcredit*B12*Mf+dispcredit*B13*Mf+
dispcredit*B14*Mf+dispcredit*B15*Mf+dispcredit*B16*Mf+
dispcredit*B17*Mf+dispcredit*B18*Mf+dispcredit*B19*Mf+
dispcredit*B20*Mf+
B1*electricsave+ B2*electricsave +
B3*electricsave + B4*electricsave + B5*electricsave +
B6*electricsave + B7*electricsave + B8*electricsave+
B9*electricsave+B10*electricsave+ B11*electricsave+
B12*electricsave+B13*electricsave+B14*electricsave+
B15*electricsave+B16*electricsave+B17*electricsave+
B18*electricsave+B19*electricsave+B20*electricsave+
excl*hours1*B1*exelec1 + excl*hours1*B2*exelec1+
excl*hours1*B3*exelec1 + excl*hours1*B4*exelec1 +
```

```
excl*hours1*B5*exelec1 + excl*hours1*B6*exelec1 +
excl*hours1*B7*exelec1 + excl*hours1*B8*exelec1 +
excl*hours1*B9*exelec1 + excl*hours1*B10*exelec1 +
excl*hours1*B11*exelec1 + excl*hours1*B12*exelec1 +
excl*hours1*B13*exelec1 + excl*hours1*B14*exelec1 +
excl*hours1*B15*exelec1 + excl*hours1*B16*exelec1 +
excl*hours1*B17*exelec1 + excl*hours1*B18*exelec1 +
excl*hours1*B19*exelec1 + excl*hours1*B20*exelec1 +
exc2*hours3*B1*exelec2 + exc2*hours3*B2*exelec2+
exc2*hours3*B3*exelec2 + exc2*hours3*B4*exelec2 +
exc2*hours3*B5*exelec2 + exc2*hours3*B6*exelec2 +
exc2*hours3*B7*exelec2 + exc2*hours3*B8*exelec2 +
exc2*hours3*B9*exelec2 + exc2*hours3*B10*exelec2 +
exc2*hours3*B11*exelec2 + exc2*hours3*B12*exelec2 +
exc2*hours3*B13*exelec2 + exc2*hours3*B14*exelec2 +
exc2*hours3*B15*exelec2 + exc2*hours3*B16*exelec2 +
exc2*hours3*B17*exelec2 + exc2*hours3*B18*exelec2 +
exc2*hours3*B19*exelec2 + exc2*hours3*B20*exelec2 +
B1*heatenergy + B2*heatenergy +
B3*heatenergy + B4*heatenergy + B5*heatenergy +
B6*heatenergy + B7*heatenergy + B8*heatenergy +
B9*heatenergy + B10*heatenergy + B11*heatenergy +
B12*heatenergy + B13*heatenergy + B14*heatenergy +
B15*heatenergy + B16*heatenergy + B17*heatenergy +
B18*heatenergy + B19*heatenergy + B20*heatenergy +
class34_1 + B1*class34_2 + B2*class34_3 [benefit];
! ------------------------------------------------------
! COSTS:
! ------------------------------------------------------
costs = total + B1*gasenergy + B2*gasenergy +
B3*gasenergy + B4*gasenergy + B5*gasenergy + B6*gasenergy +
B7*gasenergy + B8*gasenergy + B9*gasenergy + B10*gasenergy +
B11*gasenergy + B12*gasenergy + B13*gasenergy + B14*gasenergy +
B15*gasenergy + B16*gasenergy + B17*gasenergy + B18*gasenergy +
B19*gasenergy + B20*gasenergy +
B1*IT + B2*IT + B3*IT +
B4*IT + B5*IT + B6*IT +
B7*IT + B8*IT + B9*IT +
B10*IT + B11*IT + B12*IT +
B13*IT + B14*IT + B15*IT +
B16*IT + B17*IT + B18*IT +
B19*IT + B20*IT +
B1*OM + B2*OM + B3*OM + B4*OM + B5*OM +
B6*OM + B7*OM + B8*OM + B9*OM + B10*OM + B11*OM +
B12*OM + B13*OM + B14*OM + B15*OM + B16*OM + B17*OM +
B18*OM + B19*OM + B20*OM +
B1*standbycost+B2*standbycost+B3*standbycost+B4*standbycost+
B5*standbycost+B6*standbycost+B7*standbycost+B8*standbycost+
B9*standbycost+B10*standbycost+B11*standbycost+B12*standbycost+
B13*standbycost+B14*standbycost+B15*standbycost+B16*standbycost+
B17*standbycost+B18*standbycost+B19*standbycost+B20*standbycost
[cost];
! ------------------------------------------------------
! ELECTRICITY DEMANDS AND CHARGES:
! ------------------------------------------------------
```

```
averagedemand =avdemand;
peakdemand =pkdemand;


! CASE 1: averagedemand <= netelec <= peakdemand
!netelec <= peakdemand [power];
!netelec >= averagedemand;
!netelec = 0.9*genelec-idfan;
!demandsave = dc*netelec;
!demandchge = dc*peakdemand;
!energycharge = ec*hours1*averagedemand;
!totalcharge = demandchge + energycharge;
!electricsave = energycharge + demandsave;
!standbypower = 0;
!standbycost=hours4*pf*dcstand*standbypower+
!hours4*ecstand*standbypower;

! CASE 2: netelec <= avergedemand
netelec <= averagedemand [power];
netelec >= 660;
netelec = 0.9*genelec-idfan;
demandsave = dc*netelec;
demandchge = dc*peakdemand;
energycharge = ec*hours1*averagedemand;
totalcharge = demandchge + energycharge;
electricsave = ec*hours1*netelec + demandsave;
standbypower = 0;
standbycost = hours4*pf*dcstand*standbypower +
hours4*ecstand*standbypower;

! CASE 3: netelec >= peakdemand
!netelec >= peakdemand [power];
!netelec <= 12000;
!netelec = 0.9*genelec-idfan;
!demandsave = demandchge;
!demandchge = dc*peakdemand;
!energycharge = ec*hours1*averagedemand;
!totalcharge = demandchge + energycharge;
!electricsave = totalcharge;
!standbypower = 0;
!standbycost = hours4*pf*dcstand*standbypower +
!hours4*ecstand*standbypower;
! -----------------------------------------------------------
! EXCESS ELECTRICITY PRODUCED
! -----------------------------------------------------------
! CASE 1:
!exelec1 = netelec - averagedemand;  ! During sawmill operation
!exelec2 = netelec;                  ! Sawmill shutdown
! CASE 2:
exelec1 = 0;
exelec2 = netelec;
! CASE 3:
!exelec1 = netelec - averagedemand;
!exelec2 = netelec;
! -----------------------------------------------------------
```

```
! CAPITAL COSTS:
! -------------------------------------------------------
                ! Hog fuel dryer
dryercost = 0; ! No hog fuel dryer is required for metal HX
dryersize = 0;
furnacecost = 73.7 Mf + 1023583; ! Wood waste combustor (Furnace):
furnacesize = Mf;
                ! Gas Turbine: Kawasaki
turbcost = 883 genelec + 514975;
turbsize = genelec;
                ! Metal Kiln/Air Heat Exchanger:
hxcost = 14.76Mf + 88074;
hxsize = Mf;
                ! Metal Gas/Air Heat Exchanger:
mthxcost = 14.76Mf + 88074;
mthxsize = Mf;
multicost = 0;
multisize = 0;
                ! Option Direct Firing
!mthxcost = 0;
!mthxsize = 0;
!multicost = 3.39*Mf + 11600;
!multisize = Mf;
                ! Total Capital No.1:
totalcap1 = mathand + dryercost + furnacecost + turbcost +
mthxcost + hxcost + multicost;
                ! Installation and Labour = 10% of totalcap1:
install = 0.10 totalcap1;
                ! Total Capital No.2:
totalcap2 = install + totalcap1;
                ! Ductwork = 10% of totalcap2:
ductwork = 0.10 totalcap2;
                ! Electrical = 14% of totalcap2:
electrical = 0.14 totalcap2;
                ! Instrumentation = 5% of totalcap2:
instrument = 0.05 totalcap2;
                ! Piping = 5% of totalcap2:
piping = 0.05 totalcap2;
                ! Structural = 15% of totalcap2:
structural = 0.15*totalcap2;
                ! New Capital, totalcap3:
totalcap3 = totalcap2 + ductwork + electrical + instrument
+ piping + structural;
                ! Engineering costs = 7% of totalcap3:
engineering = 0.07 totalcap3;
                ! Construction Management = 5% of totalcap3:
constructm = 0.05 totalcap3;
                ! New total, totalcap4:
totalcap4 = totalcap3 + engineering + constructm;
                ! Contingency = 10%:
contingency = 0.10 totalcap4;
! ----------------------------------------------------------
! PROJECT TOTAL CAPITAL COST:
! ----------------------------------------------------------
total = totalcap4 + contingency;
```

```
! ------------------------------------------------------------
! PHYSICAL RELATIONSHIPS AND CONSTRAINTS:
! ------------------------------------------------------------
! Gas energy required:

! Case 1 wood flow:
!gas = 2.81 genelec;            ! When 6624 <= Mf <= 19908 kg/hr
!genelec <= 11943;!7962;

! Case 2 wood flow:
gas = 2.85 genelec;           ! When 19908 <= Mf <= 33,156 kg/hr
genelec <= 11943;

gasenergy = 7/12*0.0036*hours2*gascost2s*gas
 + 5/12*0.0036*hours2*gascost2w*gas; ! cost of gas for cogen
! ----------------------------------------
! Kiln Heating: Made available from process
! ----------------------------------------
processheat = 1.926*genelec + 1.26*Mf;  ! This includes heat from
                                        ! both the turbine exhaust
                                        ! and the excess flue gas
! ---------------------------
! Plant thermal requirements:
! ---------------------------
kilnheat = proheat;
processheat >= kilnheat [heat];
! OR
!processheat <= kilnheat [heat];
! ---------------------------------------------
! Heatenergy savings assuming gas is displaced:
! ---------------------------------------------
heatenergy = (7/12)*0.0036*hours2*gascost1s*kilnheat
 + (5/12)*0.0036*hours2*gascost1w*kilnheat; ! for process heat
! OR
!heatenergy = (7/12)*0.0036*hours2*gascost1s*processheat
! + (5/12)*0.0036*hours2*gascost1w*processheat; ! for process heat

! ---------------------------------
! Maximum Availabe wood waste (kg/hr):
! ---------------------------------
6624 <= Mf;   ! Minimum feasible flow required
Mf <= WoodWaste;
Exwood = Woodwaste - Mf;
! ---------------------------------------------
! ID FAN POWER REQUIREMENTS
! ---------------------------------------------
idfan = 0.013*Mf;  ! ID fan power in kW for standard combustor
! ---------------------------------------------
! OPERATING AND MAINTENANCE
! ---------------------------------------------
OM = 0.025 totalcap3;  ! 2.5% of Totalcap3
! ---------------------------------------------
!  INSURANCE AND PROPERTY TAX
! ---------------------------------------------
IT = 0.015 totalcap3;  ! 1.5% of Totalcap3
```

```
! -------------------------------------------------------
! CLASS 34 INCOME TAX CREDIT
! --------------------------------------------------------
class34_1 = 0.25*corptax*turbcost+0.25*corptax*furnacecost;
class34_2 = 0.50*corptax*turbcost+0.50*corptax*furnacecost;
class34_3 = 0.25*corptax*turbcost+0.25*corptax*furnacecost;
end
```

```
! OPTION #2 - CERAMIC HEAT EXCHANGER
!
!
constraints 58;
! BEGINNING OF PARAMETER LIST
parameters 45
                  ! Discount Factors over 20 years
i = 0.08;         ! i = real discount rate (%)
f = 0.04;         ! f = inflation rate (%)
ir =(1+i)*(1+f)-1;  ! ir = nominal discount rate (%)
B1 = 1/(1+ir);     ! Discount - year 1
B2 = 1/(1+ir)^2;   ! Discount - year 2
B3 = 1/(1+ir)^3;   ! Discount - year 3
B4 = 1/(1+ir)^4;   ! Discount - year 4
B5 = 1/(1+ir)^5;   ! Discount - year 5
B6 = 1/(1+ir)^6;   ! Discount - year 6
B7 = 1/(1+ir)^7;   ! Discount - year 7
B8 = 1/(1+ir)^8;   ! Discount - year 8
B9 = 1/(1+ir)^9;   ! Discount - year 9
B10 = 1/(1+ir)^10;! Discount - year 10
B11 = 1/(1+ir)^11;! Discount - year 11
B12 = 1/(1+ir)^12;! Discount - year 12
B13 = 1/(1+ir)^13;! Discount - year 13
B14 = 1/(1+ir)^14;! Discount - year 14
B15 = 1/(1+ir)^15;! Discount - year 15
B16 = 1/(1+ir)^16;! Discount - year 16
B17 = 1/(1+ir)^17;! Discount - year 17
B18 = 1/(1+ir)^18;! Discount - year 18
B19 = 1/(1+ir)^19;! Discount - year 19
B20 = 1/(1+ir)^20;! Discount - year 20

dispcredit = 39.42; ! Wood waste Disposal Credit ($-hrs/kg-yr)
                    ! 5$/green tonne= 39.42 $-hrs/kg-yr
                    ! Hours of Operation per year
hours1 = 4160;      ! Sawmill operating hours/yr
                    ! 2 shifts/day @ 260days/yr @ 8hrs/shift
hours2 = 7884;      ! Hours of electricity production/yr
                    ! 90% of 365 days/yr @ 24 hrs/day

hours3 = hours2-hours1;  ! Hours over which maximum excess
                         ! electricity is produced
hours4 = 292;       ! Standby hours = 10%*365 days*8 hrs/day

dc = 76.44;         ! Rate Schedule 1200's:
                    ! Demand charge = $6.37/kW/month =
                    ! $76.44/kW/yr
dcstand = 0.00665; ! Standby demand charge

ec = 0.0312;        ! Rate Schedule 1200's:
                    ! Energy Charge = 0.0312 $/kWh
ecstand = 0.02599; ! Standby energy charge

exc1 = 0.0343;    ! Firm electricity purchase price
                  ! including energy & capacity 0.0343 $/kWh
exc2 = 0.015;  ! Secondary electricity purchase price 0.015 $/kWh
```

```
pf = 0.90;         ! Plant power factor

gascost1w = 3.35;  ! Gas cost $/GJ for process heat in winter(3.35)
gascost1s = 2.75;  ! Gas cost $/GJ for process heat in summer(2.75)
gascost2w = 2.50;   ! Gas cost $/GJ for cogen in winter(2.50)
gascost2s = 1.95;   ! Gas cost $/GJ for cogen in summer(1.95)

woodwaste = 19908;     ! Maximum available wood waste (kg/hr)
proheat = 20000;       ! Plant heating required (kW)
avdemand = 3000;       ! Average demand (kW)
pkdemand = 4000;       ! Peak demand (kw)

corptax = 0.43;        ! Corporate Tax rate (%)

mathand = 600000;      ! Allowance for a material handling system
! END OF PARAMETER LIST
!
! VARIABLE LIST:
! Mf = flow rate of wood fuel (kg/hr)
! Exwood = wood not consumed as fuel = Woodwaste - Mf (kg/hr)
! peakdemand = peak electricity demand (kw)
! averagedemand = average electricity demand (kw)
! demandsave = savings in demand charge ($)
! demandchge = cost of supplying peak demand ($)
! energycharge = cost of continuous energy supply ($)
! totalcharge = demandcharge + energycharge ($)
! electricsave = electricity savings ($)
! genelec = amount of electricity being generated (kw)
! exelec1 = amount of electricity in excess of average demand
!         = netelec - averagedemand
! exelec2 = netelec
! netelec = net electricity output (kW)
! standbypower = amount of standby power demanded (kW)
! standbycost = cost of standby power ($)
! idfan = electricity required to run id fan (kW)
! dryercost = cost of wood waste dryer ($)
! dryersize = size of wood waste dryer (kg/hr)
! furnacecost = cost of wood combustor ($)
! furnacesize = size of wood combustor (kg/hr)
! turbcost = cost of gas turbine ($)
! turbsize = size of gas turbine (kw)
! cehxcost = cost of the ceramic gas/air heat exchanger ($)
! cehxsize = size of gas/air heat exchanger
! hxcost = cost of the kiln/air heat exchanger ($)
! hxsize = size of kiln/air heat exchanger (kg/hr)
! multicost = cost of multiclone ($)
! multisize = size of multiclone
! totalcap1 = equipment capital cost ($)
! install = cost of installation & delivery ($)
! totalcap2 = totalcap1 + install ($)
! ductwork = cost of ductwork ($)
! electrical = cost of electrical ($)
! instrument = cost of instrumentation ($)
! piping = cost of piping ($)
! structural = cost of structural/civil ($)
```

```
! totalcap3 = totalcap2 + duct.+elec.+instr.+pip.+struc ($)
! engineering = cost of engineering ($)
! constructm = cost of construction management ($)
! totalcap4 = totalcap3 + eng.+constrm ($)
! contingency = % of totalcap4 ($)
! total = project total capital cost ($)
! gas = amount of gas energy consumed (kw)
! gasenergy = cost of gas consumed ($)
! kilnheat = kiln heat required (kw)
! processheat = total plant thermal requirements (kw)
! heatenergy = cost of providing the process heat ($)
! benefits = project benefits over life of project ($)
! costs = project costs over life of project ($)
! OM = yearly operating and maintenanace costs
! class34_1 = class 34 tax credit in year of purchase
! class34_2 = class 34 tax credit in year 1
! class34_3 = class 34 tax credit in year 2
! IT = yearly insurance and property tax

variables 54 Mf Exwood demandsave demandchge energycharge
totalcharge genelec exelec1 exelec2 dryercost dryersize furnacecost
furnacesize turbcost turbsize cehxcost cehxsize hxcost hxsize
totalcap1 install totalcap2 ductwork peakdemand averagedemand
processheat electrical instrument piping structural totalcap3
engineering constructm totalcap4 contingency total gas gasenergy
electricsave kilnheat heatenergy benefits costs standbypower
standbycost multicost multisize
OM class34_1 class34_2 class34_3 IT netelec idfan;
! -------------------------------------------------------------
! OBJECTIVE FUNCTION:
maximize
benefits - costs [cashflow];

! -------------------------------------------------------------
! -------------------------------------------------------------
! SUBJECT TO THE FOLLOWING CONSTRAINTS:
!
! BENEFITS (savings):
Benefits =dispcredit*B1*Mf+
dispcredit*B2*Mf+dispcredit*B3*Mf+dispcredit*B4*Mf+
dispcredit*B5*Mf+dispcredit*B6*Mf+dispcredit*B7*Mf+
dispcredit*B8*Mf+dispcredit*B9*Mf+dispcredit*B10*Mf+
dispcredit*B11*Mf+dispcredit*B12*Mf+dispcredit*B13*Mf+
dispcredit*B14*Mf+dispcredit*B15*Mf+dispcredit*B16*Mf+
dispcredit*B17*Mf+dispcredit*B18*Mf+dispcredit*B19*Mf+
dispcredit*B20*Mf+
B1*electricsave+ B2*electricsave +
B3*electricsave + B4*electricsave + B5*electricsave +
B6*electricsave + B7*electricsave + B8*electricsave+
B9*electricsave+B10*electricsave+ B11*electricsave+
B12*electricsave+B13*electricsave+B14*electricsave+
B15*electricsave+B16*electricsave+B17*electricsave+
B18*electricsave+B19*electricsave+B20*electricsave+
exc1*hours1*B1*exelec1 + exc1*hours1*B2*exelec1+
exc1*hours1*B3*exelec1 + exc1*hours1*B4*exelec1 +
```

```
excl*hours1*B5*exelec1 + excl*hours1*B6*exelec1 +
excl*hours1*B7*exelec1 + excl*hours1*B8*exelec1 +
excl*hours1*B9*exelec1 + excl*hours1*B10*exelec1 +
excl*hours1*B11*exelec1 + excl*hours1*B12*exelec1 +
excl*hours1*B13*exelec1 + excl*hours1*B14*exelec1 +
excl*hours1*B15*exelec1 + excl*hours1*B16*exelec1 +
excl*hours1*B17*exelec1 + excl*hours1*B18*exelec1 +
excl*hours1*B19*exelec1 + excl*hours1*B20*exelec1 +
exc2*hours3*B1*exelec2 + exc2*hours3*B2*exelec2+
exc2*hours3*B3*exelec2 + exc2*hours3*B4*exelec2 +
exc2*hours3*B5*exelec2 + exc2*hours3*B6*exelec2 +
exc2*hours3*B7*exelec2 + exc2*hours3*B8*exelec2 +
exc2*hours3*B9*exelec2 + exc2*hours3*B10*exelec2 +
exc2*hours3*B11*exelec2 + exc2*hours3*B12*exelec2 +
exc2*hours3*B13*exelec2 + exc2*hours3*B14*exelec2 +
exc2*hours3*B15*exelec2 + exc2*hours3*B16*exelec2 +
exc2*hours3*B17*exelec2 + exc2*hours3*B18*exelec2 +
exc2*hours3*B19*exelec2 + exc2*hours3*B20*exelec2 +
B1*heatenergy + B2*heatenergy +
B3*heatenergy + B4*heatenergy + B5*heatenergy +
B6*heatenergy + B7*heatenergy + B8*heatenergy +
B9*heatenergy + B10*heatenergy + B11*heatenergy +
B12*heatenergy + B13*heatenergy + B14*heatenergy +
B15*heatenergy + B16*heatenergy + B17*heatenergy +
B18*heatenergy + B19*heatenergy + B20*heatenergy +
class34_1 + B1*class34_2 + B2*class34_3 [benefit];
! ------------------------------------------------------------
! COSTS:
! ------------------------------------------------------------
costs = total + B1*gasenergy + B2*gasenergy +
B3*gasenergy + B4*gasenergy + B5*gasenergy + B6*gasenergy +
B7*gasenergy + B8*gasenergy + B9*gasenergy + B10*gasenergy +
B11*gasenergy + B12*gasenergy + B13*gasenergy + B14*gasenergy +
B15*gasenergy + B16*gasenergy + B17*gasenergy + B18*gasenergy +
B19*gasenergy + B20*gasenergy +
B1*IT + B2*IT + B3*IT +
B4*IT + B5*IT + B6*IT +
B7*IT + B8*IT + B9*IT +
B10*IT + B11*IT + B12*IT +
B13*IT + B14*IT + B15*IT +
B16*IT + B17*IT + B18*IT +
B19*IT + B20*IT +
B1*OM + B2*OM + B3*OM + B4*OM + B5*OM +
B6*OM + B7*OM + B8*OM + B9*OM + B10*OM + B11*OM +
B12*OM + B13*OM + B14*OM + B15*OM + B16*OM + B17*OM +
B18*OM + B19*OM + B20*OM +
B1*standbycost+B2*standbycost+B3*standbycost+B4*standbycost+
B5*standbycost+B6*standbycost+B7*standbycost+B8*standbycost+
B9*standbycost+B10*standbycost+B11*standbycost+B12*standbycost+
B13*standbycost+B14*standbycost+B15*standbycost+B16*standbycost+
B17*standbycost+B18*standbycost+B19*standbycost+B20*standbycost
[cost];
! ------------------------------------------------------------
! ELECTRICITY DEMANDS AND CHARGES:
! ------------------------------------------------------------
```

```
averagedemand =avdemand;
peakdemand =pkdemand;


! CASE 1: averagedemand <= netelec <= peakdemand
!netelec <= peakdemand [power];
!netelec >= averagedemand;
!netelec = 0.9*genelec-idfan;
!demandsave = dc*netelec;
!demandchge = dc*peakdemand;
!energycharge = ec*hours1*averagedemand;
!totalcharge = demandchge + energycharge;
!electricsave = energycharge + demandsave;
!standbypower = 0;
!standbycost=hours4*pf*dcstand*standbypower+
!hours4*ecstand*standbypower;

! CASE 2: netelec <= avergedemand
netelec <= averagedemand [power];
netelec >= 660;
netelec = 0.9*genelec-idfan;
demandsave = dc*netelec;
demandchge = dc*peakdemand;
energycharge = ec*hours1*averagedemand;
totalcharge = demandchge + energycharge;
electricsave = ec*hours1*netelec + demandsave;
standbypower = 0;
standbycost = hours4*pf*dcstand*standbypower +
hours4*ecstand*standbypower;

! CASE 3: netelec >= peakdemand
!netelec >= peakdemand [power];
!netelec <= 12000;
!netelec = 0.9*genelec-idfan;
!demandsave = demandchge;
!demandchge = dc*peakdemand;
!energycharge = ec*hours1*averagedemand;
!totalcharge = demandchge + energycharge;
!electricsave = totalcharge;
!standbypower = 0;
!standbycost = hours4*pf*dcstand*standbypower +
!hours4*ecstand*standbypower;
! ----------------------------------------------------------
! EXCESS ELECTRICITY PRODUCED
! ----------------------------------------------------------
! CASE 1:
!exelec1 = netelec - averagedemand;  ! During sawmill operation
!exelec2 = netelec;                  ! Sawmill shutdown
! CASE 2:
exelec1 = 0;
exelec2 = netelec;
! CASE 3:
!exelec1 = netelec - averagedemand;
!exelec2 = netelec;
! ----------------------------------------------------------
```

```
! CAPITAL COSTS:
! ------------------------------------------------------------
                  ! Hog fuel dryer
dryercost = 0; ! No hog fuel dryer is required for metal HX
dryersize = 0;
furnacecost = 73.7 Mf + 1023583; ! Wood waste combustor (Furnace):
furnacesize = Mf;
                  ! Gas Turbine: Kawasaki
turbcost = 883 genelec + 514975;
turbsize = genelec;
                  ! Ceramic Gas/Air Heat Exchanger:
cehxcost = 103*Mf + 4433914;
cehxsize = Mf;
                  ! Metal Kiln/Air Heat Exchanger:
hxcost = 14.76Mf + 88074;
hxsize = Mf;
multicost = 0;
multisize = 0;
                  ! Option Direct Firing
!hxcost = 0;
!hxsize = 0;
!multicost = 3.39*Mf + 11600;
!multisize = Mf;
                  ! Total Capital No.1:
totalcap1 = mathand + dryercost + furnacecost + turbcost +
cehxcost + hxcost + multicost;
                  ! Installation and Labour = 10% of totalcap1:
install = 0.10 totalcap1;
                  ! Total Capital No.2:
totalcap2 = install + totalcap1;
                  ! Ductwork = 10% of totalcap2:
ductwork = 0.10 totalcap2;
                  ! Electrical = 14% of totalcap2:
electrical = 0.14 totalcap2;
                  ! Instrumentation = 5% of totalcap2:
instrument = 0.05 totalcap2;
                  ! Piping = 5% of totalcap2:
piping = 0.05 totalcap2;
                  ! Structural = 15% of totalcap2:
structural = 0.15*totalcap2;
                  ! New Capital, totalcap3:
totalcap3 = totalcap2 + ductwork + electrical + instrument
+ piping + structural;
                  ! Engineering costs = 7% of totalcap3:
engineering = 0.07 totalcap3;
                  ! Construction Management = 5% of totalcap3:
constructm = 0.05 totalcap3;

                  ! New total, totalcap4:
totalcap4 = totalcap3 + engineering + constructm;
                  ! Contingency = 10%:
contingency = 0.10 totalcap4;
! ---------------------------------------------------------------
! PROJECT TOTAL CAPITAL COST:
! ---------------------------------------------------------------
```

```
total = totalcap4 + contingency;
! -------------------------------------------------------------
! PHYSICAL RELATIONSHIPS AND CONSTRAINTS:
! -------------------------------------------------------------
! Gas energy required:

! Case 1 wood flow:              ! Mf <= 13248 kg/hr
!gas = 0;
!genelec <= 2043;

! Case 2 wood flow:              ! 13248 < Mf <= 19,908 kg/hr
gas = 0;
genelec <= 3981;

! Case 3 wood flow:              ! 19,908 < Mf <= 33,156 kg/hr
!gas = 0;
!genelec <= 7962;

gasenergy = 7/12*0.0036*hours2*gascost2s*gas
 + 5/12*0.0036*hours2*gascost2w*gas; ! cost of gas for cogen
! ----------------------------------------
! Kiln Heating: Made available from process
! ----------------------------------------
processheat = -1.11*genelec + 1.26*Mf;

! --------------------------
! Plant thermal requirements:
! --------------------------
kilnheat = proheat;

!processheat <= kilnheat [heat];
! OR
processheat >= kilnheat [heat];

! ---------------------------------------------
! Heatenergy savings assuming gas is displaced:
! ---------------------------------------------

!heatenergy = (7/12)*0.0036*hours2*gascost1s*processheat
! + (5/12)*0.0036*hours2*gascost1w*processheat;
! OR
heatenergy = (7/12)*0.0036*hours2*gascost1s*kilnheat+
 (5/12)*0.0036*hours2*gascost1w*kilnheat;

! ------------------------------------
! Maximum Availabe wood waste (kg/hr):
! ------------------------------------
13248 <= Mf;   ! Minimum feasible flow required
Mf <= WoodWaste;
Exwood = Woodwaste - Mf;
! --------------------------------------------
! ID FAN POWER REQUIREMENTS
! --------------------------------------------
idfan = 0.013*Mf;  ! ID fan power in kW for standard combustor
! --------------------------------------------
```

Turbine No.2:
Manufacturer:Kawasaki
Model No.: M1A - 23

#4ii	951.9	102.6	1,307.2	4.0	567.8	45.3	10.2
#5ii	315.0	101.3	594.5	3.2	92.9	45.3	10.2
#6ii	315.0	103.8	594.5	3.2	94.9	45.3	10.2
#8ii	0.0	0.0	0.0	0.0	0.0	0.0	0.0
#9ii	20.0	101.3	293.2	2.5	0.0	9.3	0.0
#10ii	449.0	1,134.6	737.0	2.7	374.8	9.3	0.0
#11ii	1,140.0	1,064.7	1,531.0	3.5	938.6	9.3	0.0
#12ii	20.0	1,064.7				0.0	0.0
#13ii	1,140.0	1,064.7	1,531.0	3.5	938.6	9.4	0.0
#14ii	586.4	101.3	887.7	3.6	266.2	9.4	0.0
#16ii	727.7	101.3	1,046.8	3.8	375.1	45.3	0.0
#17ii	703.7	101.3	1,019.5	3.8	356.4	54.7	0.0

Cp4ii and Cp5ii = 1.18 1.05
Cp10ii and Cp11ii = 1.08 1.22
Cp16ii = 1.14

POWER GENERATED (kW) AND RATED OUTPUT POWER (kW) = 1,915 2,043
ENERGY RELEASED IN COMBUSTOR (kW) =61,723
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW) = 5,58434,174
KILN HEAT AVAILABLE (kW) =39,758
ENERGY REQUIRED IN DRYER (kW) = 0
ENERGY INPUT FROM NATURAL GAS (kW) = 0
HEAT EXCHANGER EFFECTIVENESS =1.071
FIRST LAW EFFICIENCY =67.5
SECOND LAW EFFICIENCY =50.5

Turbine No.3:
Manufacturer:Kawasaki
Model No.: M1T - 23

#4iii	815.8	102.6	1,148.1	3.9	449.0	45.3	10.2
#5iii	315.0	101.3	594.5	3.2	92.9	45.3	10.2
#6iii	315.0	103.8	594.5	3.2	94.9	45.3	10.2
#8iii	0.0	0.0	0.0	0.0	0.0	0.0	0.0
#9iii	20.0	101.3	293.2	2.5	0.0	18.6	0.0
#10iii	453.2	1,124.4	741.5	2.7	376.7	18.6	0.0
#11iii	1,130.0	1,054.5	1,519.0	3.5	928.2	18.6	0.0
#12iii	20.0	1,054.5				0.0	0.0
#13iii	1,130.0	1,054.5	1,519.0	3.5	928.2	18.8	0.0
#14iii	581.9	101.3	882.7	3.6	262.9	18.8	0.0
#16iii	570.1	101.3	869.5	3.6	254.3	45.3	0.0
#17iii	573.6	101.3	873.4	3.6	256.8	64.1	0.0

Cp4iii and Cp5iii = 1.16 1.05
Cp10iii and Cp11iii = 1.08 1.21
Cp16iii = 1.11

POWER GENERATED (kW) AND RATED OUTPUT POWER (kW) = 3,615 3,981
ENERGY RELEASED IN COMBUSTOR (kW) =61,723
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW) =11,07426,133
KILN HEAT AVAILABLE (kW) =37,207
ENERGY REQUIRED IN DRYER (kW) = 0
ENERGY INPUT FROM NATURAL GAS (kW) = 0
HEAT EXCHANGER EFFECTIVENESS =1.056
FIRST LAW EFFICIENCY =66.1
SECOND LAW EFFICIENCY =48.2

OPTION #2: CERAMIC HEAT EXCHANGER

Ambient Temperature (C)	= 20
Atmospheric Pressure (kPa)	= 101.3
PLANT CONDITIONS:	
Sawmill annual capacity (Mfbm)	=250
Annual wood waste production (ODT)	=130,734
Initial wood waste moisture content (%)	= 50
Target wood waste moisture content (%)	= 50
Maximum Heat Exchanger Pressure (kPa)	= 1200

PROCESS FLOW CONDITIONS

FLOW #	TEMP C	PRESS. kPa	ENTH. kJ/kg	ENTR. kJ/kgK	EXER. kJ/kg	MASS kg/sec	MOISTURE %H2O
#1	20.0					9.2	50.0
#2	20.0					9.2	50.0
#3	1,094.1	103.1	1,476.0	4.1	698.8	45.3	10.2
#7	20.0	101.3	293.2	2.5	0.0	40.9	0.0
#15	20.0	171.2	293.2	2.3	44.1	45.3	0.0

Cp3 and Cp15 = 1.21 1.01

Turbine No.1:
Manufacturer:Kawasaki
Model No.: 1 Unit of the M1T - 23

FLOW #	TEMP C	PRESS. kPa	ENTH. kJ/kg	ENTR. kJ/kgK	EXER. kJ/kg	MASS kg/sec	MOISTURE %H2O
#4i	815.8	102.6	1,148.1	3.9	449.0	45.3	10.2
#5i	315.0	101.3	594.5	3.2	92.9	45.3	10.2
#6i	315.0	103.8	594.5	3.2	94.9	45.3	10.2
#8i	0.0	0.0	0.0	0.0	0.0	0.0	0.0
#9i	20.0	101.3	293.2	2.5	0.0	18.6	0.0
#10i	453.2	1,124.4	741.5	2.7	376.7	18.6	0.0
#11i	1,130.0	1,054.5	1,519.0	3.5	928.2	18.6	0.0
#12i	20.0	1,054.5				0.0	0.0
#13i	1,130.0	1,054.5	1,519.0	3.5	928.2	18.8	0.0
#14i	581.9	101.3	882.7	3.6	262.9	18.8	0.0
#16i	570.1	101.3	869.5	3.6	254.3	45.3	0.0
#17i	573.6	101.3	873.4	3.6	256.8	64.1	0.0

Cp4i and Cp5i = 1.16 1.05
Cp10i and Cp11i = 1.08 1.21
Cp16i = 1.11

POWER GENERATED (kW) AND RATED OUTPUT POWER (kW)	= 3,615 3,981
ENERGY RELEASED IN COMBUSTOR (kW)	=61,723
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW)	=11,07426,133
KILN HEAT AVAILABLE (kW)	=37,207
ENERGY REQUIRED IN DRYER (kW)	= 0
ENERGY INPUT FROM NATURAL GAS (kW)	= 0
HEAT EXCHANGER EFFECTIVENESS	=1.056
FIRST LAW EFFICIENCY	=66.1
SECOND LAW EFFICIENCY	=48.2

Turbine No.2:
Manufacturer:Kawasaki
Model No.: 2 Units of the M1T - 23

#4ii	564.2	102.6	863.0	3.6	251.1	45.3	10.2
#5ii	315.0	101.3	594.5	3.2	92.9	45.3	10.2
#6ii	315.0	103.8	594.5	3.2	94.9	45.3	10.2
#8ii	0.0	0.0	0.0	0.0	0.0	0.0	0.0
#9ii	20.0	101.3	293.2	2.5	0.0	37.2	0.0
#10ii	453.2	1,124.4	741.5	2.7	376.7	37.2	0.0
#11ii	1,104.8	1,054.5	1,488.8	3.5	904.4	37.2	0.0
#12ii	20.0	1,054.5				0.0	0.0
#13ii	1,130.0	1,054.5	1,519.0	3.5	928.2	37.6	0.0
#14ii	581.9	101.3	882.7	3.6	262.9	37.6	0.0
#16ii	287.3	101.3	565.5	3.2	78.8	45.3	0.0
#17ii	423.2	101.3	709.2	3.4	162.2	82.9	0.0

Cp4ii and Cp5ii = 1.11 1.05
Cp10ii and Cp11ii = 1.08 1.21
Cp16ii = 1.04

POWER GENERATED (kW) AND RATED OUTPUT POWER (kW) = 7,230 7,962
ENERGY RELEASED IN COMBUSTOR (kW) =61,723
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW) =22,14812,349
KILN HEAT AVAILABLE (kW) =34,497
ENERGY REQUIRED IN DRYER (kW) = 0
ENERGY INPUT FROM NATURAL GAS (kW) = 1,876
HEAT EXCHANGER EFFECTIVENESS =1.017
FIRST LAW EFFICIENCY =65.6
SECOND LAW EFFICIENCY =49.0

Turbine No.3:
Manufacturer:Kawasaki
Model No.: 3 Units of the M1T - 23

#4iii	564.2	102.6	863.0	3.6	251.1	45.3	10.2
#5iii	315.0	101.3	594.5	3.2	92.9	45.3	10.2
#6iii	315.0	103.8	594.5	3.2	94.9	45.3	10.2
#8iii	0.0	0.0	0.0	0.0	0.0	0.0	0.0
#9iii	20.0	101.3	293.2	2.5	0.0	55.8	0.0
#10iii	453.2	1,124.4	741.5	2.7	376.7	55.8	0.0
#11iii	887.6	1,054.5	1,231.6	3.3	706.7	55.8	0.0
#12iii	20.0	1,054.5				0.3	0.0
#13iii	1,130.0	1,054.5	1,519.0	3.5	928.2	56.4	0.0
#14iii	581.9	101.3	882.7	3.6	262.9	56.4	0.0
#16iii	287.3	101.3	565.5	3.2	78.8	45.3	0.0
#17iii	452.9	101.3	741.3	3.4	180.8	101.7	0.0

Cp4iii and Cp5iii = 1.11 1.05
Cp10iii and Cp11iii = 1.08 1.21
Cp16iii = 1.04

POWER GENERATED (kW) AND RATED OUTPUT POWER (kW) =10,84511,943
ENERGY RELEASED IN COMBUSTOR (kW) =61,723
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW) =33,22212,349
KILN HEAT AVAILABLE (kW) =45,571
ENERGY REQUIRED IN DRYER (kW) = 0
ENERGY INPUT FROM NATURAL GAS (kW) =18,761
HEAT EXCHANGER EFFECTIVENESS =0.827
FIRST LAW EFFICIENCY =70.1
SECOND LAW EFFICIENCY =55.9

OPTION #3: ATMOSPHERIC FLUIDIZED BED AIR HEATER

Ambient Temperature (C)	= 20
Atmospheric Pressure (kPa)	= 101.3

PLANT CONDITIONS:

Sawmill annual capacity (Mfbm)	= 50
Annual wood waste production (ODT)	= 26,147
Initial wood waste moisture content (%)	= 50
Target wood waste moisture content (%)	= 50
Maximum Air Tube Temperature (C)	= 815

PROCESS FLOW CONDITIONS

FLOW #	TEMP deg C	PRESSURE kPa	ENTHALPY kJ/kg	ENTROPY kJ/kgK	EXERGY kJ/kg	MASS FLOW kg/sec	MOISTURE %H2O
#1	20.0					1.8	50.0
#2	20.0					1.8	50.0
#3	1,000.0	103.1	1,364.0	4.1	610.4	9.1	10.2
#7	20.0	187.5	293.2	2.5	5.2	8.2	0.0
#8	315.0	117.6	594.5	3.2	94.1	8.2	0.0
#15	20.0	171.2	293.2	2.3	44.1	9.1	0.0
Cp7, Cp8 and Cp15 = 1.01 1.05 1.01							
Turbine No.1:							
Manufacturer:Kawasaki							
Model No.: M1A -11A							
#4ai	1,000.0	103.1	1,364.0	4.1	610.4	9.1	10.2
#4i	497.9	102.6	790.1	3.5	203.6	9.1	10.2
#5i	232.0	101.3	508.2	3.0	51.7	9.1	10.2
#6i	232.0	101.3	508.2	3.1	50.7	9.1	10.2
#9i	20.0	101.3	293.2	2.5	0.0	8.2	0.0
#10i	378.1	942.1	661.1	2.7	315.4	8.2	0.0
#11ai	815.0						
#11i	815.0	802.3	1,147.2	3.3	621.4	8.2	0.0
#12i	20.0	802.3				0.0	0.0
#13i	910.0	802.3	1,257.9	3.4	703.5	8.3	0.0
#14i	482.0	101.3	772.7	3.5	193.0	8.3	0.0
#16i	566.8	101.3	865.9	3.6	251.9	9.1	0.0
#17i	526.5	101.3	821.4	3.5	223.8	17.4	0.0
Cp4ai and Cp4 = 1.19 1.09							
Cp5 and Cp16i = 1.03 1.11							

POWER GENERATED (kW) AND RATED OUTPUT POWER (KW)	= 1,001 1,235
ENERGY RELEASED IN COMBUSTOR (kW)	=12,345
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW)	= 3,972 5,194
KILN HEAT AVAILABLE (kW)	= 9,165
ENERGY REQUIRED IN DRYER (kW)	= 0
ENERGY INPUT FROM NATURAL GAS (kW)	= 1,123
FIRST LAW EFFICIENCY	=75.5
SECOND LAW EFFICIENCY	=35.9

Turbine No.2:
Manufacturer:Kawasaki
Model No.: M1A - 23

#4aii	1,000.0	103.1	1,364.0	4.1	610.4	9.1	10.2
#4ii	497.9	102.6	790.1	3.5	203.6	9.1	10.2
#5ii	232.0	101.3	508.2	3.0	51.7	9.1	10.2
#6ii	232.0	101.3	508.2	3.1	50.7	9.1	10.2
#9ii	20.0	101.3	293.2	2.5	0.0	9.3	0.0
#10ii	449.0	1,134.6	737.0	2.7	374.8	9.3	0.0
#11aii	815.0						
#11ii	815.0	994.8	1,147.2	3.2	639.5	9.3	0.0
#12ii	20.0	994.8				0.1	0.0
#13ii	1,140.0	994.8	1,531.0	3.5	932.9	9.4	0.0
#14ii	597.8	101.3	900.3	3.6	274.6	9.4	0.0
#16ii	566.8	101.3	865.9	3.6	251.9	9.1	0.0
#17ii	582.6	101.3	883.4	3.6	263.5	18.5	0.0

Cp4aii and Cp4 = 1.19 1.09
Cp5 and Cp16ii = 1.03 1.11

POWER GENERATED (kW) AND RATED OUTPUT POWER (kW) = 1,797 2,043
ENERGY RELEASED IN COMBUSTOR (kW) =12,345
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW) = 5,703 5,194
KILN HEAT AVAILABLE (kW) =10,896
ENERGY REQUIRED IN DRYER (kW) = 0
ENERGY INPUT FROM NATURAL GAS (kW) = 4,124
FIRST LAW EFFICIENCY =77.1
SECOND LAW EFFICIENCY =45.8

Turbine No.3:
Manufacturer:Kawasaki
Model No.: M1T - 23

#4aiii	744.5	103.1	1,066.0	3.8	389.0	9.1	10.2
#4iii	497.9	102.6	790.1	3.5	203.6	9.1	10.2
#5iii	232.0	101.3	508.2	3.0	51.7	9.1	10.2
#6iii	232.0	101.3	508.2	3.1	50.7	9.1	10.2
#9iii	20.0	101.3	293.2	2.5	0.0	18.6	0.0
#10iii	453.2	1,124.4	741.5	2.7	384.4	18.6	0.0
#11aiii	688.2						
#11iii	815.0	984.6	1,147.2	3.2	646.4	18.6	0.0
#12iii	20.0	984.6				0.1	0.0
#13iii	1,130.0	984.6	1,519.0	3.5	930.2	18.8	0.0
#14iii	593.3	101.3	895.3	3.6	279.1	18.8	0.0
#16iii	283.0	101.3	561.0	3.1	76.6	9.1	0.0
#17iii	494.6	101.3	786.5	3.4	213.2	27.9	0.0

Cp4aiii and Cp4 = 1.14 1.09
Cp5 and Cp16iii = 1.03 1.04

POWER GENERATED (kW) AND RATED OUTPUT POWER (kW) = 3,377 3,981
ENERGY RELEASED IN COMBUSTOR (kW) =12,345
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW) =11,312 2,429
KILN HEAT AVAILABLE (kW) =13,741
ENERGY REQUIRED IN DRYER (kW) = 0
ENERGY INPUT FROM NATURAL GAS (kW) = 7,998
FIRST LAW EFFICIENCY =84.1
SECOND LAW EFFICIENCY =55.9

OPTION #3: ATMOSPHERIC FLUIDIZED BED AIR HEATER

Ambient Temperature (C)	=	20
Atmospheric Pressure (kPa)	=	101.3

PLANT CONDITIONS:

Sawmill annual capacity (Mfbm)	=	50
Annual wood waste production (ODT)	=	26,147
Initial wood waste moisture content (%)	=	50
Target wood waste moisture content (%)	=	50
Maximum Air Tube Temperature (C)	=	815

PROCESS FLOW CONDITIONS

FLOW #	TEMP deg C	PRESSURE kPa	ENTHALPY kJ/kg	ENTROPY kJ/kgK	EXERGY kJ/kg	MASS FLOW kg/sec	MOISTURE %H2O
#1	20.0					1.8	50.0
#2	20.0					1.8	50.0
#3	1,000.0	103.1	1,364.0	4.1	610.4	9.1	10.2
#7	20.0	187.5	293.2	2.5	5.2	8.2	0.0
#8	315.0	117.6	594.5	3.2	94.1	8.2	0.0
#15	20.0	171.2	293.2	2.3	44.1	9.1	0.0
Cp7, Cp8 and Cp15 = 1.01 1.05 1.01							
Turbine No.1:							
Manufacturer:Kawasaki							
Model No.: 1 Unit of the M1T - 23							
#4ai	744.5	103.1	1,066.0	3.8	389.0	9.1	10.2
#4i	497.9	102.6	790.1	3.5	203.6	9.1	10.2
#5i	232.0	101.3	508.2	3.0	51.7	9.1	10.2
#6i	232.0	101.3	508.2	3.1	50.7	9.1	10.2
#9i	20.0	101.3	293.2	2.5	0.0	18.6	0.0
#10i	453.2	1,124.4	741.5	2.7	376.7	18.6	0.0
#11ai	688.2						
#11i	815.0	984.6	1,147.2	3.2	638.6	18.6	0.0
#12i	20.0	984.6				0.1	0.0
#13i	1,130.0	984.6	1,519.0	3.5	922.5	18.8	0.0
#14i	593.3	101.3	895.3	3.6	271.3	18.8	0.0
#16i	283.0	101.3	561.0	3.1	76.6	9.1	0.0
#17i	494.6	101.3	786.5	3.5	207.9	27.9	0.0
Cp4ai and Cp4 = 1.14 1.09							
Cp5 and Cp16i = 1.03 1.04							

POWER GENERATED (kW) AND RATED OUTPUT POWER (KW)	= 3,377 3,981
ENERGY RELEASED IN COMBUSTOR (kW)	=12,345
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW)	=11,312 2,429
KILN HEAT AVAILABLE (kW)	= 13,741
ENERGY REQUIRED IN DRYER (kW)	= 0
ENERGY INPUT FROM NATURAL GAS (kW)	= 7,998
FIRST LAW EFFICIENCY	=84.1
SECOND LAW EFFICIENCY	=55.2

Turbine No.2:
Manufacturer:Kawasaki
Model No.: 2 Units of the M1T - 23

#4aii	572.1	103.1	871.7	3.6	255.9	9.1	10.2
#4ii	497.9	102.6	790.1	3.5	203.6	9.1	10.2
#5ii	232.0	101.3	508.2	3.0	51.7	9.1	10.2
#6ii	232.0	101.3	508.2	3.1	50.7	9.1	10.2
#9ii	20.0	101.3	293.2	2.5	0.0	37.2	0.0
#10ii	453.2	1,124.4	741.5	2.7	376.7	37.2	0.0
#11aii	572.1						
#11ii	679.2	984.6	991.7	2.8	606.2	37.2	0.0
#12ii	20.0	984.6				0.4	0.0
#13ii	1,130.0	984.6	1,519.0	3.3	1,000.8	37.6	0.0
#14ii	593.3	101.3	895.3	3.4	349.7	37.6	0.0
#16ii	97.8	101.3	371.5	2.7	9.0	9.1	0.0
#17ii	501.0	101.3	793.5	3.2	283.4	46.6	0.0

Cp4aii and Cp4 = 1.11 1.09
Cp5 and Cp16ii = 1.03 1.01

POWER GENERATED (kW) AND RATED OUTPUT POWER (kW) = 6,753 7,962
ENERGY RELEASED IN COMBUSTOR (kW) =12,345
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW) =22,625 711
KILN HEAT AVAILABLE (kW) =23,336
ENERGY REQUIRED IN DRYER (kW) = 0
ENERGY INPUT FROM NATURAL GAS (kW) =22,422
FIRST LAW EFFICIENCY =86.5
SECOND LAW EFFICIENCY =76.9

Turbine No.3:
Manufacturer:Kawasaki
Model No.: 3 Units of the M1T - 23

#4aiii	532.8	103.1	828.3	3.5	227.9	9.1	10.2
#4iii	497.9	102.6	790.1	3.5	203.6	9.1	10.2
#5iii	232.0	101.3	508.2	3.0	51.7	9.1	10.2
#6iii	232.0	101.3	508.2	3.1	50.7	9.1	10.2
#9iii	20.0	101.3	293.2	2.5	0.0	55.8	0.0
#10iii	453.2	1,124.4	741.5	2.7	384.4	55.8	0.0
#11aiii	532.8						
#11iii	611.3	984.6	915.4	2.8	543.9	55.8	0.0
#12iii	20.0	984.6				0.7	0.0
#13iii	1,130.0	984.6	1,519.0	3.3	990.5	56.4	0.0
#14iii	593.3	101.3	895.3	3.4	339.4	56.4	0.0
#16iii	56.5	101.3	329.8	2.6	2.4	9.1	0.0
#17iii	522.4	101.3	817.0	3.3	292.7	65.4	0.0

Cp4aiii and Cp4 = 1.10 1.09
Cp5 and Cp16iii = 1.03 1.01

POWER GENERATED (kW) AND RATED OUTPUT POWER (kW) =10,13011,943
ENERGY RELEASED IN COMBUSTOR (kW) =12,345
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW) =33,937 332
KILN HEAT AVAILABLE (kW) =34,270
ENERGY REQUIRED IN DRYER (kW) = 0
ENERGY INPUT FROM NATURAL GAS (kW) =38,366
FIRST LAW EFFICIENCY =87.6
SECOND LAW EFFICIENCY =81.8

OPTION #3: ATMOSPHERIC FLUIDIZED BED AIR HEATER

Ambient Temperature (C) = 20
Atmospheric Pressure (kPa) = 101.3

PLANT CONDITIONS:
Sawmill annual capacity (Mfbm) =150
Annual wood waste production (ODT) = 78,440
Initial wood waste moisture content (%) = 50
Target wood waste moisture content (%) = 50
Maximum Air Tube Temperature (C) = 815

PROCESS FLOW CONDITIONS

FLOW #	TEMP deg C	PRESSURE kPa	ENTHALPY kJ/kg	ENTROPY kJ/kgK	EXERGY kJ/kg	MASS FLOW kg/sec	MOISTURE %H2O
#1	20.0					5.5	50.0
#2	20.0					5.5	50.0
#3	1,000.0	103.1	1,364.0	4.1	610.4	27.2	10.2
#7	20.0	187.5	293.2	2.5	5.2	24.6	0.0
#8	315.0	117.6	594.5	3.2	94.1	24.6	0.0
#15	20.0	171.2	293.2	2.3	44.1	27.2	0.0
Cp7, Cp8 and Cp15 = 1.01 1.05 1.01							
Turbine No.1:							
Manufacturer:Kawasaki							
Model No.: M1A -11A							
#4ai	1,000.0	103.1	1,364.0	4.1	610.4	27.2	10.2
#4i	497.9	102.6	790.1	3.5	203.6	27.2	10.2
#5i	232.0	101.3	508.2	3.0	51.7	27.2	10.2
#6i	232.0	101.3	508.2	3.1	50.7	27.2	10.2
#9i	20.0	101.3	293.2	2.5	0.0	8.2	0.0
#10i	378.1	942.1	661.1	2.7	315.4	8.2	0.0
#11ai	815.0						
#11i	815.0	802.3	1,147.2	3.3	621.4	8.2	0.0
#12i	20.0	802.3				0.0	0.0
#13i	910.0	802.3	1,257.9	3.4	703.5	8.3	0.0
#14i	482.0	101.3	772.7	3.5	193.0	8.3	0.0
#16i	566.8	101.3	865.9	3.6	251.9	27.2	0.0
#17i	547.1	101.3	844.1	3.6	238.2	35.5	0.0

Cp4ai and Cp4 = 1.19 1.09
Cp5 and Cp16i = 1.03 1.11

POWER GENERATED (kW) AND RATED OUTPUT POWER (KW) = 1,001 1,235
ENERGY RELEASED IN COMBUSTOR (kW) =37,033
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW) = 3,97215,581
KILN HEAT AVAILABLE (kW) = 19,552
ENERGY REQUIRED IN DRYER (kW) = 0
ENERGY INPUT FROM NATURAL GAS (kW) = 1,123
FIRST LAW EFFICIENCY =53.9
SECOND LAW EFFICIENCY =22.4

Turbine No.2:
Manufacturer:Kawasaki
Model No.: M1A - 23

#4aii	1,000.0	103.1	1,364.0	4.1	610.4	27.2	10.2
#4ii	497.9	102.6	790.1	3.5	203.6	27.2	10.2
#5ii	232.0	101.3	508.2	3.0	51.7	27.2	10.2
#6ii	232.0	101.3	508.2	3.1	50.7	27.2	10.2
#9ii	20.0	101.3	293.2	2.5	0.0	9.3	0.0
#10ii	449.0	1,134.6	737.0	2.7	374.8	9.3	0.0
#11aii	815.0						
#11ii	815.0	994.8	1,147.2	3.2	639.5	9.3	0.0
#12ii	20.0	994.8				0.1	0.0
#13ii	1,140.0	994.8	1,531.0	3.5	932.9	9.4	0.0
#14ii	597.8	101.3	900.3	3.6	274.6	9.4	0.0
#16ii	566.8	101.3	865.9	3.6	251.9	27.2	0.0
#17ii	574.8	101.3	874.7	3.6	257.8	36.6	0.0

Cp4aii and Cp4 = 1.19 1.09
Cp5 and Cp16ii = 1.03 1.11

POWER GENERATED (kW) AND RATED OUTPUT POWER (kW) = 1,797 2,043
ENERGY RELEASED IN COMBUSTOR (kW) =37,033
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW) = 5,70315,581
KILN HEAT AVAILABLE (kW) =21,284
ENERGY REQUIRED IN DRYER (kW) = 0
ENERGY INPUT FROM NATURAL GAS (kW) = 4,124
FIRST LAW EFFICIENCY =56.1
SECOND LAW EFFICIENCY =27.3

Turbine No.3:
Manufacturer:Kawasaki
Model No.: M1T - 23

#4aiii	1,000.0	103.1	1,364.0	4.1	610.4	27.2	10.2
#4iii	497.9	102.6	790.1	3.5	203.6	27.2	10.2
#5iii	232.0	101.3	508.2	3.0	51.7	27.2	10.2
#6iii	232.0	101.3	508.2	3.1	50.7	27.2	10.2
#9iii	20.0	101.3	293.2	2.5	0.0	18.6	0.0
#10iii	453.2	1,124.4	741.5	2.7	384.4	18.6	0.0
#11aiii	815.0						
#11iii	815.0	984.6	1,147.2	3.2	646.4	18.6	0.0
#12iii	20.0	984.6				0.1	0.0
#13iii	1,130.0	984.6	1,519.0	3.5	930.2	18.8	0.0
#14iii	593.3	101.3	895.3	3.6	279.1	18.8	0.0
#16iii	566.8	101.3	865.9	3.6	251.9	27.2	0.0
#17iii	577.7	101.3	877.9	3.6	263.0	46.0	0.0

Cp4aiii and Cp4 = 1.19 1.09
Cp5 and Cp16iii = 1.03 1.11

POWER GENERATED (kW) AND RATED OUTPUT POWER (kW) = 3,377 3,981
ENERGY RELEASED IN COMBUSTOR (kW) =37,033
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW) =11,31215,581
KILN HEAT AVAILABLE (kW) =26,893
ENERGY REQUIRED IN DRYER (kW) = 0
ENERGY INPUT FROM NATURAL GAS (kW) = 7,998
FIRST LAW EFFICIENCY =67.2
SECOND LAW EFFICIENCY =37.1

OPTION #3: ATMOSPHERIC FLUIDIZED BED AIR HEATER

Ambient Temperature (C)	= 20
Atmospheric Pressure (kPa)	= 101.3

PLANT CONDITIONS:

Sawmill annual capacity (Mfbm)	=150
Annual wood waste production (ODT)	= 78,440
Initial wood waste moisture content (%)	= 50
Target wood waste moisture content (%)	= 50
Maximum Air Tube Temperature (C)	= 815

PROCESS FLOW CONDITIONS

FLOW #	TEMP deg C	PRESSURE kPa	ENTHALPY kJ/kg	ENTROPY kJ/kgK	EXERGY kJ/kg	MASS FLOW kg/sec	MOISTURE %H2O
#1	20.0					5.5	50.0
#2	20.0					5.5	50.0
#3	1,000.0	103.1	1,364.0	4.1	610.4	27.2	10.2
#7	20.0	187.5	293.2	2.5	5.2	24.6	0.0
#8	315.0	117.6	594.5	3.2	94.1	24.6	0.0
#15	20.0	171.2	293.2	2.3	44.1	27.2	0.0
Cp7, Cp8 and Cp15 = 1.01 1.05 1.01							
Turbine No.1:							
Manufacturer:Kawasaki							
Model No.: 1 Unit of the M1T - 23							
#4ai	1,000.0	103.1	1,364.0	4.1	610.4	27.2	10.2
#4i	497.9	102.6	790.1	3.5	203.6	27.2	10.2
#5i	232.0	101.3	508.2	3.0	51.7	27.2	10.2
#6i	232.0	101.3	508.2	3.1	50.7	27.2	10.2
#9i	20.0	101.3	293.2	2.5	0.0	18.6	0.0
#10i	453.2	1,124.4	741.5	2.7	376.7	18.6	0.0
#11ai	815.0						
#11i	815.0	984.6	1,147.2	3.2	638.6	18.6	0.0
#12i	20.0	984.6				0.1	0.0
#13i	1,130.0	984.6	1,519.0	3.5	922.5	18.8	0.0
#14i	593.3	101.3	895.3	3.6	271.3	18.8	0.0
#16i	566.8	101.3	865.9	3.6	251.9	27.2	0.0
#17i	577.7	101.3	877.9	3.6	259.9	46.0	0.0
Cp4ai and Cp4 = 1.19 1.09							
Cp5 and Cp16i = 1.03 1.11							

POWER GENERATED (kW) AND RATED OUTPUT POWER (KW)	= 3,377 3,981
ENERGY RELEASED IN COMBUSTOR (kW)	=37,033
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW)	=11,31215,581
KILN HEAT AVAILABLE (kW)	= 26,893
ENERGY REQUIRED IN DRYER (kW)	= 0
ENERGY INPUT FROM NATURAL GAS (kW)	= 7,998
FIRST LAW EFFICIENCY	=67.2
SECOND LAW EFFICIENCY	=36.8

Turbine No.2:
Manufacturer:Kawasaki
Model No.: 2 Units of the M1T - 23

#4aii	982.6	103.1	1,343.4	4.0	594.5	27.2	10.2
#4ii	497.9	102.6	790.1	3.5	203.6	27.2	10.2
#5ii	232.0	101.3	508.2	3.0	51.7	27.2	10.2
#6ii	232.0	101.3	508.2	3.1	50.7	27.2	10.2
#9ii	20.0	101.3	293.2	2.5	0.0	37.2	0.0
#10ii	453.2	1,124.4	741.5	2.7	376.7	37.2	0.0
#11aii	802.0						
#11ii	815.0	984.6	1,147.2	3.2	638.6	37.2	0.0
#12ii	20.0	984.6				0.3	0.0
#13ii	1,130.0	984.6	1,519.0	3.5	922.5	37.6	0.0
#14ii	593.3	101.3	895.3	3.6	271.3	37.6	0.0
#16ii	547.1	101.3	844.2	3.6	238.0	27.2	0.0
#17ii	574.0	101.3	873.9	3.6	257.3	64.8	0.0

Cp4aii and Cp4 = 1.19 1.09
Cp5 and Cp16ii = 1.03 1.10

POWER GENERATED (kW) AND RATED OUTPUT POWER (kW) = 6,753 7,962
ENERGY RELEASED IN COMBUSTOR (kW) =37,033
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW) =22,62514,991
KILN HEAT AVAILABLE (kW) =37,615
ENERGY REQUIRED IN DRYER (kW) = 0
ENERGY INPUT FROM NATURAL GAS (kW) =15,996
FIRST LAW EFFICIENCY =83.7
SECOND LAW EFFICIENCY =51.3

Turbine No.3:
Manufacturer:Kawasaki
Model No.: 3 Units of the M1T - 23

#4aiii	744.4	103.1	1,066.0	3.8	388.9	27.2	10.2
#4iii	497.9	102.6	790.1	3.5	203.6	27.2	10.2
#5iii	232.0	101.3	508.2	3.0	51.7	27.2	10.2
#6iii	232.0	101.3	508.2	3.1	50.7	27.2	10.2
#9iii	20.0	101.3	293.2	2.5	0.0	55.8	0.0
#10iii	453.2	1,124.4	741.5	2.7	384.4	55.8	0.0
#11aiii	688.2						
#11iii	815.0	984.6	1,147.2	3.2	646.4	55.8	0.0
#12iii	20.0	984.6				0.4	0.0
#13iii	1,130.0	984.6	1,519.0	3.5	930.2	56.4	0.0
#14iii	593.3	101.3	895.3	3.6	279.1	56.4	0.0
#16iii	282.9	101.3	561.0	3.1	76.6	27.2	0.0
#17iii	494.6	101.3	786.5	3.4	213.2	83.6	0.0

Cp4aiii and Cp4 = 1.14 1.09
Cp5 and Cp16iii = 1.03 1.04

POWER GENERATED (kW) AND RATED OUTPUT POWER (kW) =10,13011,943
ENERGY RELEASED IN COMBUSTOR (kW) =37,033
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW) =33,937 7,285
KILN HEAT AVAILABLE (kW) =41,223
ENERGY REQUIRED IN DRYER (kW) = 0
ENERGY INPUT FROM NATURAL GAS (kW) =23,993
FIRST LAW EFFICIENCY =84.1
SECOND LAW EFFICIENCY =56.1

OPTION #3: ATMOSPHERIC FLUIDIZED BED AIR HEATER

Ambient Temperature (C)	= 20
Atmospheric Pressure (kPa)	= 101.3

PLANT CONDITIONS:

Sawmill annual capacity (Mfbm)	=250
Annual wood waste production (ODT)	=130,734
Initial wood waste moisture content (%)	= 50
Target wood waste moisture content (%)	= 50
Maximum Air Tube Temperature (C)	= 815

PROCESS FLOW CONDITIONS

FLOW #	TEMP deg C	PRESSURE kPa	ENTHALPY kJ/kg	ENTROPY kJ/kgK	EXERGY kJ/kg	MASS FLOW kg/sec	MOISTURE %H2O
#1	20.0					9.2	50.0
#2	20.0					9.2	50.0
#3	1,000.0	103.1	1,364.0	4.1	610.4	45.3	10.2
#7	20.0	187.5	293.2	2.5	5.2	40.9	0.0
#8	315.0	117.6	594.5	3.2	94.1	40.9	0.0
#15	20.0	171.2	293.2	2.3	44.1	45.3	0.0

Cp7, Cp8 and Cp15 = 1.01 1.05 1.01

Turbine No.1:
Manufacturer:Kawasaki
Model No.: M1A -11A

FLOW #	TEMP deg C	PRESSURE kPa	ENTHALPY kJ/kg	ENTROPY kJ/kgK	EXERGY kJ/kg	MASS FLOW kg/sec	MOISTURE %H2O
#4ai	1,000.0	103.1	1,364.0	4.1	610.4	45.3	10.2
#4i	497.9	102.6	790.1	3.5	203.6	45.3	10.2
#5i	232.0	101.3	508.2	3.0	51.7	45.3	10.2
#6i	232.0	101.3	508.2	3.1	50.7	45.3	10.2
#9i	20.0	101.3	293.2	2.5	0.0	8.2	0.0
#10i	378.1	942.1	661.1	2.7	315.4	8.2	0.0
#11ai	815.0						
#11i	815.0	802.3	1,147.2	3.3	621.4	8.2	0.0
#12i	20.0	802.3				0.0	0.0
#13i	910.0	802.3	1,257.9	3.4	703.5	8.3	0.0
#14i	482.0	101.3	772.7	3.5	193.0	8.3	0.0
#16i	566.8	101.3	865.9	3.6	251.9	45.3	0.0
#17i	553.8	101.3	851.5	3.6	242.8	53.6	0.0

Cp4ai and Cp4 = 1.19 1.09
Cp5 and Cp16i = 1.03 1.11

POWER GENERATED (kW) AND RATED OUTPUT POWER (KW)	= 1,001 1,235
ENERGY RELEASED IN COMBUSTOR (kW)	=61,723
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW)	= 3,97225,968
KILN HEAT AVAILABLE (kW)	= 29,940
ENERGY REQUIRED IN DRYER (kW)	= 0
ENERGY INPUT FROM NATURAL GAS (kW)	= 1,123
FIRST LAW EFFICIENCY	=49.2
SECOND LAW EFFICIENCY	=19.5

Turbine No.2:
Manufacturer:Kawasaki
Model No.: M1A - 23

#4aii	1,000.0	103.1	1,364.0	4.1	610.4	45.3	10.2
#4ii	497.9	102.6	790.1	3.5	203.6	45.3	10.2
#5ii	232.0	101.3	508.2	3.0	51.7	45.3	10.2
#6ii	232.0	101.3	508.2	3.1	50.7	45.3	10.2
#9ii	20.0	101.3	293.2	2.5	0.0	9.3	0.0
#10ii	449.0	1,134.6	737.0	2.7	374.8	9.3	0.0
#11aii	815.0						
#11ii	815.0	994.8	1,147.2	3.2	639.5	9.3	0.0
#12ii	20.0	994.8				0.1	0.0
#13ii	1,140.0	994.8	1,531.0	3.5	932.9	9.4	0.0
#14ii	597.8	101.3	900.3	3.6	274.6	9.4	0.0
#16ii	566.8	101.3	865.9	3.6	251.9	45.3	0.0
#17ii	572.1	101.3	871.8	3.6	255.8	54.7	0.0

Cp4aii and Cp4 = 1.19 1.09
Cp5 and Cp16ii = 1.03 1.11

POWER GENERATED (kW) AND RATED OUTPUT POWER (kW) = 1,797 2,043
ENERGY RELEASED IN COMBUSTOR (kW) =61,723
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW) = 5,70325,968
KILN HEAT AVAILABLE (kW) =31,671
ENERGY REQUIRED IN DRYER (kW) = 0
ENERGY INPUT FROM NATURAL GAS (kW) = 4,124
FIRST LAW EFFICIENCY =50.8
SECOND LAW EFFICIENCY =22.7

Turbine No.3:
Manufacturer:Kawasaki
Model No.: M1T - 23

#4aiii	1,000.0	103.1	1,364.0	4.1	610.4	45.3	10.2
#4iii	497.9	102.6	790.1	3.5	203.6	45.3	10.2
#5iii	232.0	101.3	508.2	3.0	51.7	45.3	10.2
#6iii	232.0	101.3	508.2	3.1	50.7	45.3	10.2
#9iii	20.0	101.3	293.2	2.5	0.0	18.6	0.0
#10iii	453.2	1,124.4	741.5	2.7	384.4	18.6	0.0
#11aiii	815.0						
#11iii	815.0	984.6	1,147.2	3.2	646.4	18.6	0.0
#12iii	20.0	984.6				0.1	0.0
#13iii	1,130.0	984.6	1,519.0	3.5	930.2	18.8	0.0
#14iii	593.3	101.3	895.3	3.6	279.1	18.8	0.0
#16iii	566.8	101.3	865.9	3.6	251.9	45.3	0.0
#17iii	574.6	101.3	874.5	3.6	259.9	64.1	0.0

Cp4aiii and Cp4 = 1.19 1.09
Cp5 and Cp16iii = 1.03 1.11

POWER GENERATED (kW) AND RATED OUTPUT POWER (kW) = 3,377 3,981
ENERGY RELEASED IN COMBUSTOR (kW) =61,723
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW) =11,31225,968
KILN HEAT AVAILABLE (kW) =37,280
ENERGY REQUIRED IN DRYER (kW) = 0
ENERGY INPUT FROM NATURAL GAS (kW) = 7,998
FIRST LAW EFFICIENCY =58.3
SECOND LAW EFFICIENCY =29.3

OPTION #3: ATMOSPHERIC FLUIDIZED BED AIR HEATER

Ambient Temperature (C)	= 20
Atmospheric Pressure (kPa)	= 101.3

PLANT CONDITIONS:

Sawmill annual capacity (Mfbm)	=250
Annual wood waste production (ODT)	=130,734
Initial wood waste moisture content (%)	= 50
Target wood waste moisture content (%)	= 50
Maximum Air Tube Temperature (C)	= 815

PROCESS FLOW CONDITIONS

FLOW #	TEMP deg C	PRESSURE kPa	ENTHALPY kJ/kg	ENTROPY kJ/kgK	EXERGY kJ/kg	MASS FLOW kg/sec	MOISTURE %H2O
#1	20.0					9.2	50.0
#2	20.0					9.2	50.0
#3	1,000.0	103.1	1,364.0	4.1	610.4	45.3	10.2
#7	20.0	187.5	293.2	2.5	5.2	40.9	0.0
#8	315.0	117.6	594.5	3.2	94.1	40.9	0.0
#15	20.0	171.2	293.2	2.3	44.1	45.3	0.0

Cp7, Cp8 and Cp15 = 1.01 1.05 1.01

Turbine No.1:

Manufacturer:Kawasaki

Model No.: 1 Unit of the M1T - 23

FLOW #	TEMP deg C	PRESSURE kPa	ENTHALPY kJ/kg	ENTROPY kJ/kgK	EXERGY kJ/kg	MASS FLOW kg/sec	MOISTURE %H2O
#4ai	1,000.0	103.1	1,364.0	4.1	610.4	45.3	10.2
#4i	497.9	102.6	790.1	3.5	203.6	45.3	10.2
#5i	232.0	101.3	508.2	3.0	51.7	45.3	10.2
#6i	232.0	101.3	508.2	3.1	50.7	45.3	10.2
#9i	20.0	101.3	293.2	2.5	0.0	18.6	0.0
#10i	453.2	1,124.4	741.5	2.7	376.7	18.6	0.0
#11ai	815.0						
#11i	815.0	984.6	1,147.2	3.2	638.6	18.6	0.0
#12i	20.0	984.6				0.1	0.0
#13i	1,130.0	984.6	1,519.0	3.5	922.5	18.8	0.0
#14i	593.3	101.3	895.3	3.6	271.3	18.8	0.0
#16i	566.8	101.3	865.9	3.6	251.9	45.3	0.0
#17i	574.6	101.3	874.5	3.6	257.6	64.1	0.0

Cp4ai and Cp4 = 1.19 1.09

Cp5 and Cp16i = 1.03 1.11

POWER GENERATED (kW) AND RATED OUTPUT POWER (KW)	= 3,377 3,981
ENERGY RELEASED IN COMBUSTOR (kW)	=61,723
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW)	=11,31225,968
KILN HEAT AVAILABLE (kW)	= 37,280
ENERGY REQUIRED IN DRYER (kW)	= 0
ENERGY INPUT FROM NATURAL GAS (kW)	= 7,998
FIRST LAW EFFICIENCY	=58.3
SECOND LAW EFFICIENCY	=29.1

Turbine No.2:
Manufacturer:Kawasaki
Model No.: 2 Units of the M1T - 23

#4aii	1,000.0	103.1	1,364.0	4.1	610.4	45.3	10.2
#4ii	497.9	102.6	790.1	3.5	203.6	45.3	10.2
#5ii	232.0	101.3	508.2	3.0	51.7	45.3	10.2
#6ii	232.0	101.3	508.2	3.1	50.7	45.3	10.2
#9ii	20.0	101.3	293.2	2.5	0.0	37.2	0.0
#10ii	453.2	1,124.4	741.5	2.7	376.7	37.2	0.0
#11aii	815.0						
#11ii	815.0	984.6	1,147.2	3.2	638.6	37.2	0.0
#12ii	20.0	984.6				0.3	0.0
#13ii	1,130.0	984.6	1,519.0	3.5	922.5	37.6	0.0
#14ii	593.3	101.3	895.3	3.6	271.3	37.6	0.0
#16ii	566.8	101.3	865.9	3.6	251.9	45.3	0.0
#17ii	578.9	101.3	879.2	3.6	260.7	82.9	0.0

Cp4aii and Cp4 = 1.19 1.09
Cp5 and Cp16ii = 1.03 1.11

POWER GENERATED (kW) AND RATED OUTPUT POWER (kW) = 6,753 7,962
ENERGY RELEASED IN COMBUSTOR (kW) =61,723
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW) =22,62525,968
KILN HEAT AVAILABLE (kW) =48,593
ENERGY REQUIRED IN DRYER (kW) = 0
ENERGY INPUT FROM NATURAL GAS (kW) =15,996
FIRST LAW EFFICIENCY =71.2
SECOND LAW EFFICIENCY =40.3

Turbine No.3:
Manufacturer:Kawasaki
Model No.: 3 Units of the M1T - 23

#4aiii	1,000.0	103.1	1,364.0	4.1	610.4	45.3	10.2
#4iii	497.9	102.6	790.1	3.5	203.6	45.3	10.2
#5iii	232.0	101.3	508.2	3.0	51.7	45.3	10.2
#6iii	232.0	101.3	508.2	3.1	50.7	45.3	10.2
#9iii	20.0	101.3	293.2	2.5	0.0	55.8	0.0
#10iii	453.2	1,124.4	741.5	2.7	384.4	55.8	0.0
#11aiii	815.0						
#11iii	815.0	984.6	1,147.2	3.2	646.4	55.8	0.0
#12iii	20.0	984.6				0.4	0.0
#13iii	1,130.0	984.6	1,519.0	3.5	930.2	56.4	0.0
#14iii	593.3	101.3	895.3	3.6	279.1	56.4	0.0
#16iii	566.8	101.3	865.9	3.6	251.9	45.3	0.0
#17iii	581.5	101.3	882.2	3.6	267.0	101.7	0.0

Cp4aiii and Cp4 = 1.19 1.09
Cp5 and Cp16iii = 1.03 1.11

POWER GENERATED (kW) AND RATED OUTPUT POWER (kW) =10,13011,943
ENERGY RELEASED IN COMBUSTOR (kW) =61,723
TURBINE EXHAUST HEAT (kW) AND EXCESS FLUE GAS HEAT (kW) =33,93725,968
KILN HEAT AVAILABLE (kW) =59,905
ENERGY REQUIRED IN DRYER (kW) = 0
ENERGY INPUT FROM NATURAL GAS (kW) =23,993
FIRST LAW EFFICIENCY =81.7
SECOND LAW EFFICIENCY =49.9

Appendix B:

Linear Programming Models for Options #1, #2, #3

```
! OPTION #1 - METALLIC HEAT EXCHANGER
!
!
constraints 58;
! BEGINNING OF PARAMETER LIST
parameters 45
                    ! Discount Factors over 20 years
i = 0.08;           ! i = real discount rate (%)
f = 0.04;           ! f = inflation rate (%)
ir =(1+i)*(1+f)-1;  ! ir = nominal discount rate (%)
B1 = 1/(1+ir);       ! Discount - year 1
B2 = 1/(1+ir)^2;     ! Discount - year 2
B3 = 1/(1+ir)^3;     ! Discount - year 3
B4 = 1/(1+ir)^4;     ! Discount - year 4
B5 = 1/(1+ir)^5;     ! Discount - year 5
B6 = 1/(1+ir)^6;     ! Discount - year 6
B7 = 1/(1+ir)^7;     ! Discount - year 7
B8 = 1/(1+ir)^8;     ! Discount - year 8
B9 = 1/(1+ir)^9;     ! Discount - year 9
B10 = 1/(1+ir)^10;! Discount - year 10
B11 = 1/(1+ir)^11;! Discount - year 11
B12 = 1/(1+ir)^12;! Discount - year 12
B13 = 1/(1+ir)^13;! Discount - year 13
B14 = 1/(1+ir)^14;! Discount - year 14
B15 = 1/(1+ir)^15;! Discount - year 15
B16 = 1/(1+ir)^16;! Discount - year 16
B17 = 1/(1+ir)^17;! Discount - year 17
B18 = 1/(1+ir)^18;! Discount - year 18
B19 = 1/(1+ir)^19;! Discount - year 19
B20 = 1/(1+ir)^20;! Discount - year 20

dispcredit = 39.42; ! Wood waste Disposal Credit ($-hrs/kg-yr)
                    ! 5$/green tonne= 39.42 $-hrs/kg-yr
                    ! Hours of Operation per year
hours1 = 4160;      ! Sawmill operating hours/yr
                    ! 2 shifts/day @ 260days/yr @ 8hrs/shift
hours2 = 7884;      ! Hours of electricity production/yr
                    ! 90% of 365 days/yr @ 24 hrs/day

hours3 = hours2-hours1;  ! Hours over which maximum excess
                         ! electricity is produced
hours4 = 292;       ! Standby hours = 10%*365 days*8 hrs/day

dc = 76.44;         ! Rate Schedule 1200's:
                    ! Demand charge = $6.37/kW/month =
                    ! $76.44/kW/yr
dcstand = 0.00665; ! Standby demand charge

ec = 0.0312;        ! Rate Schedule 1200's:
                    ! Energy Charge = 0.0312 $/kWh
ecstand = 0.02599; ! Standby energy charge

excl = 0.0343;   ! Firm electricity purchase price
                 ! including energy & capacity 0.0343 $/kWh
exc2 = 0.015;  ! Secondary electricity purchase price 0.015 $/kWh
```

```
pf = 0.90;        ! Plant power factor

gascost1w = 3.35; ! Gas cost $/GJ for process heat in winter(3.35)
gascost1s = 2.75; ! Gas cost $/GJ for process heat in summer(2.75)
gascost2w = 2.50; ! Gas cost $/GJ for cogen in winter(2.50)
gascost2s = 1.95; ! Gas cost $/GJ for cogen in summer(1.95)

woodwaste = 19908;     ! Maximum available wood waste (kg/hr)
proheat = 20000;       ! Plant heating required (kW)
avdemand = 3000;       ! Average demand (kW)
pkdemand = 4000;       ! Peak demand (kw)

corptax = 0.43;        ! Corporate Tax rate (%)

mathand = 600000;      ! Allowance for a material handling system
! END OF PARAMETER LIST
!
! VARIABLE LIST:
! Mf = flow rate of wood fuel (kg/hr)
! Exwood = wood not consumed as fuel = Woodwaste - Mf (kg/hr)
! peakdemand = peak electricity demand (kw)
! averagedemand = average electricity demand (kw)
! demandsave = savings in demand charge ($)
! demandchge = cost of supplying peak demand ($)
! energycharge = cost of continuous energy supply ($)
! totalcharge = demandcharge + energycharge ($)
! electricsave = electricity savings ($)
! genelec = amount of electricity being generated (kw)
! exelec1 = amount of electricity in excess of average demand
!         = netelec - averagedemand
! exelec2 = netelec
! netelec = net electricity output (kW)
! standbypower = amount of standby power demanded (kW)
! standbycost = cost of standby power ($)
! idfan = electricity required to run id fan (kW)
! dryercost = cost of wood waste dryer ($)
! dryersize = size of wood waste dryer (kg/hr)
! furnacecost = cost of wood combustor ($)
! furnacesize = size of wood combustor (kg/hr)
! turbcost = cost of gas turbine ($)
! turbsize = size of gas turbine (kw)
! mthxcost = cost of the metal gas/air heat exchanger ($)
! mthxsize = size of gas/air heat exchanger
! hxcost = cost of the kiln/air heat exchanger ($)
! hxsize = size of kiln/air heat exchanger (kg/hr)
! multicost = cost of multiclone ($)
! multisize = size of multiclone
! totalcap1 = equipment capital cost ($)
! install = cost of installation & delivery ($)
! totalcap2 = totalcap1 + install ($)
! ductwork = cost of ductwork ($)
! electrical = cost of electrical ($)
! instrument = cost of instrumentation ($)
! piping = cost of piping ($)
! structural = cost of structural/civil ($)
```

```
! totalcap3 = totalcap2 + duct.+elec.+instr.+pip.+struc ($)
! engineering = cost of engineering ($)
! constructm = cost of construction management ($)
! totalcap4 = totalcap3 + eng.+constrm ($)
! contingency = % of totalcap4 ($)
! total = project total capital cost ($)
! gas = amount of gas energy consumed (kw)
! gasenergy = cost of gas consumed ($)
! kilnheat = kiln heat required (kw)
! processheat = total plant thermal requirements (kw)
! heatenergy = cost of providing the process heat ($)
! benefits = project benefits over life of project ($)
! costs = project costs over life of project ($)
! OM = yearly operating and maintenanace costs
! class34_1 = class 34 tax credit in year of purchase
! class34_2 = class 34 tax credit in year 1
! class34_3 = class 34 tax credit in year 2
! IT = yearly insurance and property tax

variables 54 Mf Exwood demandsave demandchge energycharge
totalcharge genelec exelec1 exelec2 dryercost dryersize furnacecost
furnacesize turbcost turbsize mthxcost mthxsize hxcost hxsize
totalcap1 install totalcap2 ductwork peakdemand averagedemand
processheat electrical instrument piping structural totalcap3
engineering constructm totalcap4 contingency total gas gasenergy
electricsave kilnheat heatenergy benefits costs standbypower
standbycost multicost multisize
OM class34_1 class34_2 class34_3 IT netelec idfan;
! ------------------------------------------------------
! OBJECTIVE FUNCTION:
maximize
benefits - costs [cashflow];

! ------------------------------------------------------
! ------------------------------------------------------
! SUBJECT TO THE FOLLOWING CONSTRAINTS:
!
! BENEFITS (savings):
Benefits =dispcredit*B1*Mf+
dispcredit*B2*Mf+dispcredit*B3*Mf+dispcredit*B4*Mf+
dispcredit*B5*Mf+dispcredit*B6*Mf+dispcredit*B7*Mf+
dispcredit*B8*Mf+dispcredit*B9*Mf+dispcredit*B10*Mf+
dispcredit*B11*Mf+dispcredit*B12*Mf+dispcredit*B13*Mf+
dispcredit*B14*Mf+dispcredit*B15*Mf+dispcredit*B16*Mf+
dispcredit*B17*Mf+dispcredit*B18*Mf+dispcredit*B19*Mf+
dispcredit*B20*Mf+
B1*electricsave+ B2*electricsave +
B3*electricsave + B4*electricsave + B5*electricsave +
B6*electricsave + B7*electricsave + B8*electricsave+
B9*electricsave+B10*electricsave+ B11*electricsave+
B12*electricsave+B13*electricsave+B14*electricsave+
B15*electricsave+B16*electricsave+B17*electricsave+
B18*electricsave+B19*electricsave+B20*electricsave+
excl*hours1*B1*exelec1 + excl*hours1*B2*exelec1+
excl*hours1*B3*exelec1 + excl*hours1*B4*exelec1 +
```

```
exc1*hours1*B5*exelec1 + exc1*hours1*B6*exelec1 +
exc1*hours1*B7*exelec1 + exc1*hours1*B8*exelec1 +
exc1*hours1*B9*exelec1 + exc1*hours1*B10*exelec1 +
exc1*hours1*B11*exelec1 + exc1*hours1*B12*exelec1 +
exc1*hours1*B13*exelec1 + exc1*hours1*B14*exelec1 +
exc1*hours1*B15*exelec1 + exc1*hours1*B16*exelec1 +
exc1*hours1*B17*exelec1 + exc1*hours1*B18*exelec1 +
exc1*hours1*B19*exelec1 + exc1*hours1*B20*exelec1 +
exc2*hours3*B1*exelec2 + exc2*hours3*B2*exelec2+
exc2*hours3*B3*exelec2 + exc2*hours3*B4*exelec2 +
exc2*hours3*B5*exelec2 + exc2*hours3*B6*exelec2 +
exc2*hours3*B7*exelec2 + exc2*hours3*B8*exelec2 +
exc2*hours3*B9*exelec2 + exc2*hours3*B10*exelec2 +
exc2*hours3*B11*exelec2 + exc2*hours3*B12*exelec2 +
exc2*hours3*B13*exelec2 + exc2*hours3*B14*exelec2 +
exc2*hours3*B15*exelec2 + exc2*hours3*B16*exelec2 +
exc2*hours3*B17*exelec2 + exc2*hours3*B18*exelec2 +
exc2*hours3*B19*exelec2 + exc2*hours3*B20*exelec2 +
B1*heatenergy + B2*heatenergy +
B3*heatenergy + B4*heatenergy + B5*heatenergy +
B6*heatenergy + B7*heatenergy + B8*heatenergy +
B9*heatenergy + B10*heatenergy + B11*heatenergy +
B12*heatenergy + B13*heatenergy + B14*heatenergy +
B15*heatenergy + B16*heatenergy + B17*heatenergy +
B18*heatenergy + B19*heatenergy + B20*heatenergy +
class34_1 + B1*class34_2 + B2*class34_3 [benefit];
! ------------------------------------------------------------
! COSTS:
! ------------------------------------------------------------
costs = total + B1*gasenergy + B2*gasenergy +
B3*gasenergy + B4*gasenergy + B5*gasenergy + B6*gasenergy +
B7*gasenergy + B8*gasenergy + B9*gasenergy + B10*gasenergy +
B11*gasenergy + B12*gasenergy + B13*gasenergy + B14*gasenergy +
B15*gasenergy + B16*gasenergy + B17*gasenergy + B18*gasenergy +
B19*gasenergy + B20*gasenergy +
B1*IT + B2*IT + B3*IT +
B4*IT + B5*IT + B6*IT +
B7*IT + B8*IT + B9*IT +
B10*IT + B11*IT + B12*IT +
B13*IT + B14*IT + B15*IT +
B16*IT + B17*IT + B18*IT +
B19*IT + B20*IT +
B1*OM + B2*OM + B3*OM + B4*OM + B5*OM +
B6*OM + B7*OM + B8*OM + B9*OM + B10*OM + B11*OM +
B12*OM + B13*OM + B14*OM + B15*OM + B16*OM + B17*OM +
B18*OM + B19*OM + B20*OM +
B1*standbycost+B2*standbycost+B3*standbycost+B4*standbycost+
B5*standbycost+B6*standbycost+B7*standbycost+B8*standbycost+
B9*standbycost+B10*standbycost+B11*standbycost+B12*standbycost+
B13*standbycost+B14*standbycost+B15*standbycost+B16*standbycost+
B17*standbycost+B18*standbycost+B19*standbycost+B20*standbycost
[cost];
! ------------------------------------------------------------
! ELECTRICITY DEMANDS AND CHARGES:
! ------------------------------------------------------------
```

```
averagedemand =avdemand;
peakdemand =pkdemand;


! CASE 1: averagedemand <= netelec <= peakdemand
!netelec <= peakdemand [power];
!netelec >= averagedemand;
!netelec = 0.9*genelec-idfan;
!demandsave = dc*netelec;
!demandchge = dc*peakdemand;
!energycharge = ec*hours1*averagedemand;
!totalcharge = demandchge + energycharge;
!electricsave = energycharge + demandsave;
!standbypower = 0;
!standbycost=hours4*pf*dcstand*standbypower+
!hours4*ecstand*standbypower;

! CASE 2: netelec <= avergedemand
netelec <= averagedemand [power];
netelec >= 660;
netelec = 0.9*genelec-idfan;
demandsave = dc*netelec;
demandchge = dc*peakdemand;
energycharge = ec*hours1*averagedemand;
totalcharge = demandchge + energycharge;
electricsave = ec*hours1*netelec + demandsave;
standbypower = 0;
standbycost = hours4*pf*dcstand*standbypower +
hours4*ecstand*standbypower;

! CASE 3: netelec >= peakdemand
!netelec >= peakdemand [power];
!netelec <= 12000;
!netelec = 0.9*genelec-idfan;
!demandsave = demandchge;
!demandchge = dc*peakdemand;
!energycharge = ec*hours1*averagedemand;
!totalcharge = demandchge + energycharge;
!electricsave = totalcharge;
!standbypower = 0;
!standbycost = hours4*pf*dcstand*standbypower +
!hours4*ecstand*standbypower;
! ----------------------------------------------------------
! EXCESS ELECTRICITY PRODUCED
! ----------------------------------------------------------
! CASE 1:
!exelec1 = netelec - averagedemand;  ! During sawmill operation
!exelec2 = netelec;                  ! Sawmill shutdown
! CASE 2:
exelec1 = 0;
exelec2 = netelec;
! CASE 3:
!exelec1 = netelec - averagedemand;
!exelec2 = netelec;
! ----------------------------------------------------------
```

```
! CAPITAL COSTS:
! ----------------------------------------------------------
                    ! Hog fuel dryer
dryercost = 0; ! No hog fuel dryer is required for metal HX
dryersize = 0;
furnacecost = 73.7 Mf + 1023583; ! Wood waste combustor (Furnace):
furnacesize = Mf;
                    ! Gas Turbine: Kawasaki
turbcost = 883 genelec + 514975;
turbsize = genelec;
                    ! Metal Kiln/Air Heat Exchanger:
hxcost = 14.76Mf + 88074;
hxsize = Mf;
                    ! Metal Gas/Air Heat Exchanger:
mthxcost = 14.76Mf + 88074;
mthxsize = Mf;
multicost = 0;
multisize = 0;
                    ! Option Direct Firing
!mthxcost = 0;
!mthxsize = 0;
!multicost = 3.39*Mf + 11600;
!multisize = Mf;
                    ! Total Capital No.1:
totalcap1 = mathand + dryercost + furnacecost + turbcost +
mthxcost + hxcost + multicost;
                    ! Installation and Labour = 10% of totalcap1:
install = 0.10 totalcap1;
                    ! Total Capital No.2:
totalcap2 = install + totalcap1;
                    ! Ductwork = 10% of totalcap2:
ductwork = 0.10 totalcap2;
                    ! Electrical = 14% of totalcap2:
electrical = 0.14 totalcap2;
                    ! Instrumentation = 5% of totalcap2:
instrument = 0.05 totalcap2;
                    ! Piping = 5% of totalcap2:
piping = 0.05 totalcap2;
                    ! Structural = 15% of totalcap2:
structural = 0.15*totalcap2;
                    ! New Capital, totalcap3:
totalcap3 = totalcap2 + ductwork + electrical + instrument
+ piping + structural;
                    ! Engineering costs = 7% of totalcap3:
engineering = 0.07 totalcap3;
                    ! Construction Management = 5% of totalcap3:
constructm = 0.05 totalcap3;
                    ! New total, totalcap4:
totalcap4 = totalcap3 + engineering + constructm;
                    ! Contingency = 10%:
contingency = 0.10 totalcap4;
! -------------------------------------------------------------
! PROJECT TOTAL CAPITAL COST:
! -------------------------------------------------------------
total = totalcap4 + contingency;
```

```
! -------------------------------------------------------------
! PHYSICAL RELATIONSHIPS AND CONSTRAINTS:
! -------------------------------------------------------------
! Gas energy required:

! Case 1 wood flow:
!gas = 2.81 genelec;            ! When 6624 <= Mf <= 19908 kg/hr
!genelec <= 11943;!7962;

! Case 2 wood flow:
gas = 2.85 genelec;           ! When 19908 <= Mf <= 33,156 kg/hr
genelec <= 11943;

gasenergy = 7/12*0.0036*hours2*gascost2s*gas
 + 5/12*0.0036*hours2*gascost2w*gas; ! cost of gas for cogen
! ----------------------------------------
! Kiln Heating: Made available from process
! ----------------------------------------
processheat = 1.926*genelec + 1.26*Mf;  ! This includes heat from
                                        ! both the turbine exhaust
                                        ! and the excess flue gas
! ------------------------
! Plant thermal requirements:
! ------------------------
kilnheat = proheat;
processheat >= kilnheat [heat];
! OR
!processheat <= kilnheat [heat];
! --------------------------------------------
! Heatenergy savings assuming gas is displaced:
! --------------------------------------------
heatenergy = (7/12)*0.0036*hours2*gascost1s*kilnheat
 + (5/12)*0.0036*hours2*gascost1w*kilnheat; ! for process heat
! OR
!heatenergy = (7/12)*0.0036*hours2*gascost1s*processheat
! + (5/12)*0.0036*hours2*gascost1w*processheat; ! for process heat

! ----------------------------------
! Maximum Availabe wood waste (kg/hr):
! ----------------------------------
6624 <= Mf;   ! Minimum feasible flow required
Mf <= WoodWaste;
Exwood = Woodwaste - Mf;
! -------------------------------------------
! ID FAN POWER REQUIREMENTS
! -------------------------------------------
idfan = 0.013*Mf;  ! ID fan power in kW for standard combustor
! -------------------------------------------
! OPERATING AND MAINTENANCE
! -------------------------------------------
OM = 0.025 totalcap3;  ! 2.5% of Totalcap3
! -------------------------------------------
!  INSURANCE AND PROPERTY TAX
! -------------------------------------------
IT = 0.015 totalcap3;  ! 1.5% of Totalcap3
```

```
! -----------------------------------------------------
! CLASS 34 INCOME TAX CREDIT
! ------------------------------------------------------
class34_1 = 0.25*corptax*turbcost+0.25*corptax*furnacecost;
class34_2 = 0.50*corptax*turbcost+0.50*corptax*furnacecost;
class34_3 = 0.25*corptax*turbcost+0.25*corptax*furnacecost;
end
```

```
! OPTION #2 - CERAMIC HEAT EXCHANGER
!
!
constraints 58;
! BEGINNING OF PARAMETER LIST
parameters 45
                    ! Discount Factors over 20 years
i = 0.08;           ! i = real discount rate (%)
f = 0.04;           ! f = inflation rate (%)
ir =(1+i)*(1+f)-1;  ! ir = nominal discount rate (%)
B1 = 1/(1+ir);      ! Discount - year 1
B2 = 1/(1+ir)^2;    ! Discount - year 2
B3 = 1/(1+ir)^3;    ! Discount - year 3
B4 = 1/(1+ir)^4;    ! Discount - year 4
B5 = 1/(1+ir)^5;    ! Discount - year 5
B6 = 1/(1+ir)^6;    ! Discount - year 6
B7 = 1/(1+ir)^7;    ! Discount - year 7
B8 = 1/(1+ir)^8;    ! Discount - year 8
B9 = 1/(1+ir)^9;    ! Discount - year 9
B10 = 1/(1+ir)^10;! Discount - year 10
B11 = 1/(1+ir)^11;! Discount - year 11
B12 = 1/(1+ir)^12;! Discount - year 12
B13 = 1/(1+ir)^13;! Discount - year 13
B14 = 1/(1+ir)^14;! Discount - year 14
B15 = 1/(1+ir)^15;! Discount - year 15
B16 = 1/(1+ir)^16;! Discount - year 16
B17 = 1/(1+ir)^17;! Discount - year 17
B18 = 1/(1+ir)^18;! Discount - year 18
B19 = 1/(1+ir)^19;! Discount - year 19
B20 = 1/(1+ir)^20;! Discount - year 20

dispcredit = 39.42; ! Wood waste Disposal Credit ($-hrs/kg-yr)
                    ! 5$/green tonne= 39.42 $-hrs/kg-yr
                    ! Hours of Operation per year
hours1 = 4160;      ! Sawmill operating hours/yr
                    ! 2 shifts/day @ 260days/yr @ 8hrs/shift
hours2 = 7884;      ! Hours of electricity production/yr
                    ! 90% of 365 days/yr @ 24 hrs/day

hours3 = hours2-hours1;  ! Hours over which maximum excess
                         ! electricity is produced
hours4 = 292;       ! Standby hours = 10%*365 days*8 hrs/day

dc = 76.44;         ! Rate Schedule 1200's:
                    ! Demand charge = $6.37/kW/month =
                    ! $76.44/kW/yr
dcstand = 0.00665; ! Standby demand charge

ec = 0.0312;        ! Rate Schedule 1200's:
                    ! Energy Charge = 0.0312 $/kWh
ecstand = 0.02599; ! Standby energy charge

excl = 0.0343;    ! Firm electricity purchase price
                  ! including energy & capacity 0.0343 $/kWh
exc2 = 0.015;  ! Secondary electricity purchase price 0.015 $/kWh
```

```
pf = 0.90;          ! Plant power factor

gascost1w = 3.35;  ! Gas cost $/GJ for process heat in winter(3.35)
gascost1s = 2.75;  ! Gas cost $/GJ for process heat in summer(2.75)
gascost2w = 2.50;   ! Gas cost $/GJ for cogen in winter(2.50)
gascost2s = 1.95;   ! Gas cost $/GJ for cogen in summer(1.95)

woodwaste = 19908;     ! Maximum available wood waste (kg/hr)
proheat = 20000;       ! Plant heating required (kW)
avdemand = 3000;       ! Average demand (kW)
pkdemand = 4000;       ! Peak demand (kw)

corptax = 0.43;        ! Corporate Tax rate (%)

mathand = 600000;      ! Allowance for a material handling system
! END OF PARAMETER LIST
!
! VARIABLE LIST:
! Mf = flow rate of wood fuel (kg/hr)
! Exwood = wood not consumed as fuel = Woodwaste - Mf (kg/hr)
! peakdemand = peak electricity demand (kw)
! averagedemand = average electricity demand (kw)
! demandsave = savings in demand charge ($)
! demandchge = cost of supplying peak demand ($)
! energycharge = cost of continuous energy supply ($)
! totalcharge = demandcharge + energycharge ($)
! electricsave = electricity savings ($)
! genelec = amount of electricity being generated (kw)
! exelec1 = amount of electricity in excess of average demand
!         = netelec - averagedemand
! exelec2 = netelec
! netelec = net electricity output (kW)
! standbypower = amount of standby power demanded (kW)
! standbycost = cost of standby power ($)
! idfan = electricity required to run id fan (kW)
! dryercost = cost of wood waste dryer ($)
! dryersize = size of wood waste dryer (kg/hr)
! furnacecost = cost of wood combustor ($)
! furnacesize = size of wood combustor (kg/hr)
! turbcost = cost of gas turbine ($)
! turbsize = size of gas turbine (kw)
! cehxcost = cost of the ceramic gas/air heat exchanger ($)
! cehxsize = size of gas/air heat exchanger
! hxcost = cost of the kiln/air heat exchanger ($)
! hxsize = size of kiln/air heat exchanger (kg/hr)
! multicost = cost of multiclone ($)
! multisize = size of multiclone
! totalcap1 = equipment capital cost ($)
! install = cost of installation & delivery ($)
! totalcap2 = totalcap1 + install ($)
! ductwork = cost of ductwork ($)
! electrical = cost of electrical ($)
! instrument = cost of instrumentation ($)
! piping = cost of piping ($)
! structural = cost of structural/civil ($)
```

```
! totalcap3 = totalcap2 + duct.+elec.+instr.+pip.+struc ($)
! engineering = cost of engineering ($)
! constructm = cost of construction management ($)
! totalcap4 = totalcap3 + eng.+constrm ($)
! contingency = % of totalcap4 ($)
! total = project total capital cost ($)
! gas = amount of gas energy consumed (kw)
! gasenergy = cost of gas consumed ($)
! kilnheat = kiln heat required (kw)
! processheat = total plant thermal requirements (kw)
! heatenergy = cost of providing the process heat ($)
! benefits = project benefits over life of project ($)
! costs = project costs over life of project ($)
! OM = yearly operating and maintenanace costs
! class34_1 = class 34 tax credit in year of purchase
! class34_2 = class 34 tax credit in year 1
! class34_3 = class 34 tax credit in year 2
! IT = yearly insurance and property tax

variables 54 Mf Exwood demandsave demandchge energycharge
totalcharge genelec exelec1 exelec2 dryercost dryersize furnacecost
furnacesize turbcost turbsize cehxcost cehxsize hxcost hxsize
totalcap1 install totalcap2 ductwork peakdemand averagedemand
processheat electrical instrument piping structural totalcap3
engineering constructm totalcap4 contingency total gas gasenergy
electricsave kilnheat heatenergy benefits costs standbypower
standbycost multicost multisize
OM class34_1 class34_2 class34_3 IT netelec idfan;
! -------------------------------------------------------------
! OBJECTIVE FUNCTION:
maximize
benefits - costs [cashflow];

! -------------------------------------------------------------
! -------------------------------------------------------------
! SUBJECT TO THE FOLLOWING CONSTRAINTS:
!
! BENEFITS (savings):
Benefits =dispcredit*B1*Mf+
dispcredit*B2*Mf+dispcredit*B3*Mf+dispcredit*B4*Mf+
dispcredit*B5*Mf+dispcredit*B6*Mf+dispcredit*B7*Mf+
dispcredit*B8*Mf+dispcredit*B9*Mf+dispcredit*B10*Mf+
dispcredit*B11*Mf+dispcredit*B12*Mf+dispcredit*B13*Mf+
dispcredit*B14*Mf+dispcredit*B15*Mf+dispcredit*B16*Mf+
dispcredit*B17*Mf+dispcredit*B18*Mf+dispcredit*B19*Mf+
dispcredit*B20*Mf+
B1*electricsave+ B2*electricsave +
B3*electricsave + B4*electricsave + B5*electricsave +
B6*electricsave + B7*electricsave + B8*electricsave+
B9*electricsave+B10*electricsave+ B11*electricsave+
B12*electricsave+B13*electricsave+B14*electricsave+
B15*electricsave+B16*electricsave+B17*electricsave+
B18*electricsave+B19*electricsave+B20*electricsave+
exc1*hours1*B1*exelec1 + exc1*hours1*B2*exelec1+
exc1*hours1*B3*exelec1 + exc1*hours1*B4*exelec1 +
```

```
excl*hours1*B5*exelec1 + excl*hours1*B6*exelec1 +
excl*hours1*B7*exelec1 + excl*hours1*B8*exelec1 +
excl*hours1*B9*exelec1 + excl*hours1*B10*exelec1 +
excl*hours1*B11*exelec1 + excl*hours1*B12*exelec1 +
excl*hours1*B13*exelec1 + excl*hours1*B14*exelec1 +
excl*hours1*B15*exelec1 + excl*hours1*B16*exelec1 +
excl*hours1*B17*exelec1 + excl*hours1*B18*exelec1 +
excl*hours1*B19*exelec1 + excl*hours1*B20*exelec1 +
exc2*hours3*B1*exelec2 + exc2*hours3*B2*exelec2+
exc2*hours3*B3*exelec2 + exc2*hours3*B4*exelec2 +
exc2*hours3*B5*exelec2 + exc2*hours3*B6*exelec2 +
exc2*hours3*B7*exelec2 + exc2*hours3*B8*exelec2 +
exc2*hours3*B9*exelec2 + exc2*hours3*B10*exelec2 +
exc2*hours3*B11*exelec2 + exc2*hours3*B12*exelec2 +
exc2*hours3*B13*exelec2 + exc2*hours3*B14*exelec2 +
exc2*hours3*B15*exelec2 + exc2*hours3*B16*exelec2 +
exc2*hours3*B17*exelec2 + exc2*hours3*B18*exelec2 +
exc2*hours3*B19*exelec2 + exc2*hours3*B20*exelec2 +
B1*heatenergy + B2*heatenergy +
B3*heatenergy + B4*heatenergy + B5*heatenergy +
B6*heatenergy + B7*heatenergy + B8*heatenergy +
B9*heatenergy + B10*heatenergy + B11*heatenergy +
B12*heatenergy + B13*heatenergy + B14*heatenergy +
B15*heatenergy + B16*heatenergy + B17*heatenergy +
B18*heatenergy + B19*heatenergy + B20*heatenergy +
class34_1 + B1*class34_2 + B2*class34_3 [benefit];
! ----------------------------------------------------------
! COSTS:
! ----------------------------------------------------------
costs = total + B1*gasenergy + B2*gasenergy +
B3*gasenergy + B4*gasenergy + B5*gasenergy + B6*gasenergy +
B7*gasenergy + B8*gasenergy + B9*gasenergy + B10*gasenergy +
B11*gasenergy + B12*gasenergy + B13*gasenergy + B14*gasenergy +
B15*gasenergy + B16*gasenergy + B17*gasenergy + B18*gasenergy +
B19*gasenergy + B20*gasenergy +
B1*IT + B2*IT + B3*IT +
B4*IT + B5*IT + B6*IT +
B7*IT + B8*IT + B9*IT +
B10*IT + B11*IT + B12*IT +
B13*IT + B14*IT + B15*IT +
B16*IT + B17*IT + B18*IT +
B19*IT + B20*IT +
B1*OM + B2*OM + B3*OM + B4*OM + B5*OM +
B6*OM + B7*OM + B8*OM + B9*OM + B10*OM + B11*OM +
B12*OM + B13*OM + B14*OM + B15*OM + B16*OM + B17*OM +
B18*OM + B19*OM + B20*OM +
B1*standbycost+B2*standbycost+B3*standbycost+B4*standbycost+
B5*standbycost+B6*standbycost+B7*standbycost+B8*standbycost+
B9*standbycost+B10*standbycost+B11*standbycost+B12*standbycost+
B13*standbycost+B14*standbycost+B15*standbycost+B16*standbycost+
B17*standbycost+B18*standbycost+B19*standbycost+B20*standbycost
[cost];
! ----------------------------------------------------------
! ELECTRICITY DEMANDS AND CHARGES:
! ----------------------------------------------------------
```

```
averagedemand =avdemand;
peakdemand =pkdemand;


! CASE 1: averagedemand <= netelec <= peakdemand
!netelec <= peakdemand [power];
!netelec >= averagedemand;
!netelec = 0.9*genelec-idfan;
!demandsave = dc*netelec;
!demandchge = dc*peakdemand;
!energycharge = ec*hours1*averagedemand;
!totalcharge = demandchge + energycharge;
!electricsave = energycharge + demandsave;
!standbypower = 0;
!standbycost=hours4*pf*dcstand*standbypower+
!hours4*ecstand*standbypower;

! CASE 2: netelec <= avergedemand
netelec <= averagedemand [power];
netelec >= 660;
netelec = 0.9*genelec-idfan;
demandsave = dc*netelec;
demandchge = dc*peakdemand;
energycharge = ec*hours1*averagedemand;
totalcharge = demandchge + energycharge;
electricsave = ec*hours1*netelec + demandsave;
standbypower = 0;
standbycost = hours4*pf*dcstand*standbypower +
hours4*ecstand*standbypower;

! CASE 3: netelec >= peakdemand
!netelec >= peakdemand [power];
!netelec <= 12000;
!netelec = 0.9*genelec-idfan;
!demandsave = demandchge;
!demandchge = dc*peakdemand;
!energycharge = ec*hours1*averagedemand;
!totalcharge = demandchge + energycharge;
!electricsave = totalcharge;
!standbypower = 0;
!standbycost = hours4*pf*dcstand*standbypower +
!hours4*ecstand*standbypower;
! ------------------------------------------------------------
! EXCESS ELECTRICITY PRODUCED
! ------------------------------------------------------------
! CASE 1:
!exelec1 = netelec - averagedemand;  ! During sawmill operation
!exelec2 = netelec;                  ! Sawmill shutdown
! CASE 2:
exelec1 = 0;
exelec2 = netelec;
! CASE 3:
!exelec1 = netelec - averagedemand;
!exelec2 = netelec;
! ------------------------------------------------------------
```

```
! CAPITAL COSTS:
! ------------------------------------------------------------
                   ! Hog fuel dryer
dryercost = 0; ! No hog fuel dryer is required for metal HX
dryersize = 0;
furnacecost = 73.7 Mf + 1023583; ! Wood waste combustor (Furnace):
furnacesize = Mf;
                   ! Gas Turbine: Kawasaki
turbcost = 883 genelec + 514975;
turbsize = genelec;
                   ! Ceramic Gas/Air Heat Exchanger:
cehxcost = 103*Mf + 4433914;
cehxsize = Mf;
                   ! Metal Kiln/Air Heat Exchanger:
hxcost = 14.76Mf + 88074;
hxsize = Mf;
multicost = 0;
multisize = 0;
                   ! Option Direct Firing
!hxcost = 0;
!hxsize = 0;
!multicost = 3.39*Mf + 11600;
!multisize = Mf;
                   ! Total Capital No.1:
totalcap1 = mathand + dryercost + furnacecost + turbcost +
cehxcost + hxcost + multicost;
                   ! Installation and Labour = 10% of totalcap1:
install = 0.10 totalcap1;
                   ! Total Capital No.2:
totalcap2 = install + totalcap1;
                   ! Ductwork = 10% of totalcap2:
ductwork = 0.10 totalcap2;
                   ! Electrical = 14% of totalcap2:
electrical = 0.14 totalcap2;
                   ! Instrumentation = 5% of totalcap2:
instrument = 0.05 totalcap2;
                   ! Piping = 5% of totalcap2:
piping = 0.05 totalcap2;
                   ! Structural = 15% of totalcap2:
structural = 0.15*totalcap2;
                   ! New Capital, totalcap3:
totalcap3 = totalcap2 + ductwork + electrical + instrument
+ piping + structural;
                   ! Engineering costs = 7% of totalcap3:
engineering = 0.07 totalcap3;
                   ! Construction Management = 5% of totalcap3:
constructm = 0.05 totalcap3;

                   ! New total, totalcap4:
totalcap4 = totalcap3 + engineering + constructm;
                   ! Contingency = 10%:
contingency = 0.10 totalcap4;
! ---------------------------------------------------------------
! PROJECT TOTAL CAPITAL COST:
! ---------------------------------------------------------------
```

```
total = totalcap4 + contingency;
! ---------------------------------------------------------------
! PHYSICAL RELATIONSHIPS AND CONSTRAINTS:
! ---------------------------------------------------------------
! Gas energy required:

! Case 1 wood flow:              ! Mf <= 13248 kg/hr
!gas = 0;
!genelec <= 2043;

! Case 2 wood flow:              ! 13248 < Mf <= 19,908 kg/hr
gas = 0;
genelec <= 3981;

! Case 3 wood flow:              ! 19,908 < Mf <= 33,156 kg/hr
!gas = 0;
!genelec <= 7962;

gasenergy = 7/12*0.0036*hours2*gascost2s*gas
 + 5/12*0.0036*hours2*gascost2w*gas; ! cost of gas for cogen
! ---------------------------------------
! Kiln Heating: Made available from process
! ---------------------------------------
processheat = -1.11*genelec + 1.26*Mf;

! --------------------------
! Plant thermal requirements:
! --------------------------
kilnheat = proheat;

!processheat <= kilnheat [heat];
! OR
processheat >= kilnheat [heat];

! --------------------------------------------
! Heatenergy savings assuming gas is displaced:
! --------------------------------------------

!heatenergy = (7/12)*0.0036*hours2*gascost1s*processheat
! + (5/12)*0.0036*hours2*gascost1w*processheat;
! OR
heatenergy = (7/12)*0.0036*hours2*gascost1s*kilnheat+
 (5/12)*0.0036*hours2*gascost1w*kilnheat;

! -----------------------------------
! Maximum Availabe wood waste (kg/hr):
! -----------------------------------
13248 <= Mf;   ! Minimum feasible flow required
Mf <= WoodWaste;
Exwood = Woodwaste - Mf;
! -------------------------------------------
! ID FAN POWER REQUIREMENTS
! -------------------------------------------
idfan = 0.013*Mf;  ! ID fan power in kW for standard combustor
! -------------------------------------------
```

```
! OPERATING AND MAINTENANCE
! ----------------------------------------------
OM = 0.025 totalcap3;  ! 2.5% of Totalcap3
! ----------------------------------------------
!  INSURANCE AND PROPERTY TAX
! ----------------------------------------------
IT = 0.015 totalcap3;  ! 1.5% of Totalcap3
! -----------------------------------------------------
! CLASS 34 INCOME TAX CREDIT
! ------------------------------------------------------
class34_1 = 0.25*corptax*turbcost+0.25*corptax*furnacecost;
class34_2 = 0.50*corptax*turbcost+0.50*corptax*furnacecost;
class34_3 = 0.25*corptax*turbcost+0.25*corptax*furnacecost;
end
```

```
! OPTION #3 - ATMOSPHERIC FLUIDIZED BED SYSTEM
!
!
constraints 52;
! BEGINNING OF PARAMETER LIST
parameters 45
                     ! Discount Factors over 20 years
i = 0.08;            ! i = real discount rate (%)
f = 0.04;            ! f = inflation rate (%)
ir =(1+i)*(1+f)-1;   ! ir = nominal discount rate (%)
B1 = 1/(1+ir);       ! Discount - year 1
B2 = 1/(1+ir)^2;     ! Discount - year 2
B3 = 1/(1+ir)^3;     ! Discount - year 3
B4 = 1/(1+ir)^4;     ! Discount - year 4
B5 = 1/(1+ir)^5;     ! Discount - year 5
B6 = 1/(1+ir)^6;     ! Discount - year 6
B7 = 1/(1+ir)^7;     ! Discount - year 7
B8 = 1/(1+ir)^8;     ! Discount - year 8
B9 = 1/(1+ir)^9;     ! Discount - year 9
B10 = 1/(1+ir)^10;! Discount - year 10
B11 = 1/(1+ir)^11;! Discount - year 11
B12 = 1/(1+ir)^12;! Discount - year 12
B13 = 1/(1+ir)^13;! Discount - year 13
B14 = 1/(1+ir)^14;! Discount - year 14
B15 = 1/(1+ir)^15;! Discount - year 15
B16 = 1/(1+ir)^16;! Discount - year 16
B17 = 1/(1+ir)^17;! Discount - year 17
B18 = 1/(1+ir)^18;! Discount - year 18
B19 = 1/(1+ir)^19;! Discount - year 19
B20 = 1/(1+ir)^20;! Discount - year 20

dispcredit = 39.42; ! Wood waste Disposal Credit ($-hrs/kg-yr)
                    ! 5$/green tonne= 39.42 $-hrs/kg-yr
                    ! Hours of Operation per year
hours1 = 4160;      ! Sawmill operating hours/yr
                    ! 2 shifts/day @ 260days/yr @ 8hrs/shift
hours2 = 7884;      ! Hours of electricity production/yr
                    ! 90% of 365 days/yr @ 24 hrs/day

hours3 = hours2-hours1;  ! Hours over which maximum excess
                         ! electricity is produced
hours4 = 292;       ! Standby hours = 10%*365 days*8 hrs/day

dc = 76.44;         ! Rate Schedule 1200's:
                    ! Demand charge = $6.37/kW/month =
                    ! $76.44/kW/yr
dcstand = 0.00665; ! Standby demand charge

ec = 0.0312;        ! Rate Schedule 1200's:
                    ! Energy Charge = 0.0312 $/kWh
ecstand = 0.02599; ! Standby energy charge

excl = 0.0343;    ! Firm electricity purchase price
                  ! including energy & capacity 0.0343 $/kWh
exc2 = 0.015;  ! Secondary electricity purchase price 0.015 $/kWh
```

```
pf = 0.90;         ! Plant power factor

gascost1w = 3.35; ! Gas cost $/GJ for process heat in winter(3.35)
gascost1s = 2.75; ! Gas cost $/GJ for process heat in summer(2.75)
gascost2w = 2.50; ! Gas cost $/GJ for cogen in winter(2.50)
gascost2s = 1.95; ! Gas cost $/GJ for cogen in summer(1.95)

woodwaste = 19908;     ! Maximum available wood waste (kg/hr)
proheat = 20000;       ! Plant heating required (kW)
avdemand = 3000;       ! Average demand (kW)
pkdemand = 4000;       ! Peak demand (kw)

corptax = 0.43;        ! Corporate Tax rate (%)

mathand = 800000;      ! Allowance for a material handling system
! END OF PARAMETER LIST
!
! VARIABLE LIST:
! Mf = flow rate of wood fuel (kg/hr)
! Exwood = wood not consumed as fuel = Woodwaste - Mf (kg/hr)
! peakdemand = peak electricity demand (kw)
! averagedemand = average electricity demand (kw)
! demandsave = savings in demand charge ($)
! demandchge = cost of supplying peak demand ($)
! energycharge = cost of continuous energy supply ($)
! totalcharge = demandcharge + energycharge ($)
! electricsave = electricity savings ($)
! genelec = amount of electricity being generated (kw)
! exelec1 = amount of electricity in excess of average demand
!         = netelec - averagedemand
! exelec2 = netelec
! netelec = net electricity output (kW)
! standbypower = amount of standby power demanded (kW)
! standbycost = cost of standby power ($)
! idfan = electricity required to run id fan (kW)
! dryercost = cost of wood waste dryer ($)
! dryersize = size of wood waste dryer (kg/hr)
! fluidbedcost = cost of fluid bed system ($)
! fluidbedsize = size of fluid bed system (kg/hr)
! turbcost = cost of gas turbine ($)
! turbsize = size of gas turbine (kw)
! totalcap1 = equipment capital cost, excluding fluid bed ($)
! install = cost of installation & delivery ($)
! totalcap2 = totalcap1 + install ($)
! ductwork = cost of ductwork ($)
! electrical = cost of electrical ($)
! instrument = cost of instrumentation ($)
! piping = cost of piping ($)
! structural = cost of structural/civil ($)
! totalcap3 = totalcap2 + duct.+elec.+instr.+pip.+struc ($)
! engineering = cost of engineering ($)
! constructm = cost of construction management ($)
! totalcap4 = totalcap3 + eng.+constrm ($)
! contingency = % of totalcap4 ($)
! total = project total capital cost ($)
```

```
! gas = amount of gas energy consumed (kw)
! gasenergy = cost of gas consumed ($)
! kilnheat = kiln heat required (kw)
! processheat = total plant thermal requirements (kw)
! heatenergy = cost of providing the process heat ($)
! benefits = project benefits over life of project ($)
! costs = project costs over life of project ($)
! OM = yearly operating and maintenanace costs
! class34_1 = class 34 tax credit in year of purchase
! class34_2 = class 34 tax credit in year 1
! class34_3 = class 34 tax credit in year 2
! IT = yearly insurance and property tax

variables 50 Mf Exwood demandsave demandchge energycharge
totalcharge genelec exelec1 exelec2 dryercost dryersize
fluidbedcost fluidbedsize turbcost turbsize
totalcap1 install totalcap2 ductwork peakdemand averagedemand
processheat electrical instrument piping structural totalcap3
engineering constructm totalcap4 contingency total gas gasenergy
electricsave kilnheat heatenergy benefits costs standbypower
standbycost multicost multisize
OM class34_1 class34_2 class34_3 IT netelec idfan;
! ------------------------------------------------------------
! OBJECTIVE FUNCTION:
maximize
benefits - costs [cashflow];

! ------------------------------------------------------------
! ------------------------------------------------------------
! SUBJECT TO THE FOLLOWING CONSTRAINTS:
!
! BENEFITS (savings):
Benefits =dispcredit*B1*Mf+
dispcredit*B2*Mf+dispcredit*B3*Mf+dispcredit*B4*Mf+
dispcredit*B5*Mf+dispcredit*B6*Mf+dispcredit*B7*Mf+
dispcredit*B8*Mf+dispcredit*B9*Mf+dispcredit*B10*Mf+
dispcredit*B11*Mf+dispcredit*B12*Mf+dispcredit*B13*Mf+
dispcredit*B14*Mf+dispcredit*B15*Mf+dispcredit*B16*Mf+
dispcredit*B17*Mf+dispcredit*B18*Mf+dispcredit*B19*Mf+
dispcredit*B20*Mf+
B1*electricsave+ B2*electricsave +
B3*electricsave + B4*electricsave + B5*electricsave +
B6*electricsave + B7*electricsave + B8*electricsave+
B9*electricsave+B10*electricsave+ B11*electricsave+
B12*electricsave+B13*electricsave+B14*electricsave+
B15*electricsave+B16*electricsave+B17*electricsave+
B18*electricsave+B19*electricsave+B20*electricsave+
exc1*hours1*B1*exelec1 + exc1*hours1*B2*exelec1+
exc1*hours1*B3*exelec1 + exc1*hours1*B4*exelec1 +
exc1*hours1*B5*exelec1 + exc1*hours1*B6*exelec1 +
exc1*hours1*B7*exelec1 + exc1*hours1*B8*exelec1 +
exc1*hours1*B9*exelec1 + exc1*hours1*B10*exelec1 +
exc1*hours1*B11*exelec1 + exc1*hours1*B12*exelec1 +
exc1*hours1*B13*exelec1 + exc1*hours1*B14*exelec1 +
exc1*hours1*B15*exelec1 + exc1*hours1*B16*exelec1 +
```

```
excl*hours1*B17*exelec1 + excl*hours1*B18*exelec1 +
excl*hours1*B19*exelec1 + excl*hours1*B20*exelec1 +
exc2*hours3*B1*exelec2 + exc2*hours3*B2*exelec2+
exc2*hours3*B3*exelec2 + exc2*hours3*B4*exelec2 +
exc2*hours3*B5*exelec2 + exc2*hours3*B6*exelec2 +
exc2*hours3*B7*exelec2 + exc2*hours3*B8*exelec2 +
exc2*hours3*B9*exelec2 + exc2*hours3*B10*exelec2 +
exc2*hours3*B11*exelec2 + exc2*hours3*B12*exelec2 +
exc2*hours3*B13*exelec2 + exc2*hours3*B14*exelec2 +
exc2*hours3*B15*exelec2 + exc2*hours3*B16*exelec2 +
exc2*hours3*B17*exelec2 + exc2*hours3*B18*exelec2 +
exc2*hours3*B19*exelec2 + exc2*hours3*B20*exelec2 +
B1*heatenergy + B2*heatenergy +
B3*heatenergy + B4*heatenergy + B5*heatenergy +
B6*heatenergy + B7*heatenergy + B8*heatenergy +
B9*heatenergy + B10*heatenergy + B11*heatenergy +
B12*heatenergy + B13*heatenergy + B14*heatenergy +
B15*heatenergy + B16*heatenergy + B17*heatenergy +
B18*heatenergy + B19*heatenergy + B20*heatenergy +
class34_1 + B1*class34_2 + B2*class34_3 [benefit];
! ---------------------------------------------------------
! COSTS:
! ---------------------------------------------------------
costs = total + B1*gasenergy + B2*gasenergy +
B3*gasenergy + B4*gasenergy + B5*gasenergy + B6*gasenergy +
B7*gasenergy + B8*gasenergy + B9*gasenergy + B10*gasenergy +
B11*gasenergy + B12*gasenergy + B13*gasenergy + B14*gasenergy +
B15*gasenergy + B16*gasenergy + B17*gasenergy + B18*gasenergy +
B19*gasenergy + B20*gasenergy +
B1*IT + B2*IT + B3*IT +
B4*IT + B5*IT + B6*IT +
B7*IT + B8*IT + B9*IT +
B10*IT + B11*IT + B12*IT +
B13*IT + B14*IT + B15*IT +
B16*IT + B17*IT + B18*IT +
B19*IT + B20*IT +
B1*OM + B2*OM + B3*OM + B4*OM + B5*OM +
B6*OM + B7*OM + B8*OM + B9*OM + B10*OM + B11*OM +
B12*OM + B13*OM + B14*OM + B15*OM + B16*OM + B17*OM +
B18*OM + B19*OM + B20*OM +
B1*standbycost+B2*standbycost+B3*standbycost+B4*standbycost+
B5*standbycost+B6*standbycost+B7*standbycost+B8*standbycost+
B9*standbycost+B10*standbycost+B11*standbycost+B12*standbycost+
B13*standbycost+B14*standbycost+B15*standbycost+B16*standbycost+
B17*standbycost+B18*standbycost+B19*standbycost+B20*standbycost
[cost];
! ---------------------------------------------------------
! ELECTRICITY DEMANDS AND CHARGES:
! ---------------------------------------------------------
averagedemand =avdemand;
peakdemand =pkdemand;


! CASE 1: averagedemand <= netelec <= peakdemand
netelec <= peakdemand [power];
```

```
netelec >= averagedemand;
netelec = 0.9*genelec-idfan;
demandsave = dc*netelec;
demandchge = dc*peakdemand;
energycharge = ec*hours1*averagedemand;
totalcharge = demandchge + energycharge;
electricsave = energycharge + demandsave;
standbypower = 0;
standbycost=hours4*pf*dcstand*standbypower+
hours4*ecstand*standbypower;

! CASE 2: netelec <= avergedemand
!netelec <= averagedemand [power];
!netelec >= 660;
!netelec = 0.9*genelec-idfan;
!demandsave = dc*netelec;
!demandchge = dc*peakdemand;
!energycharge = ec*hours1*averagedemand;
!totalcharge = demandchge + energycharge;
!electricsave = ec*hours1*netelec + demandsave;
!standbypower = 0;
!standbycost = hours4*pf*dcstand*standbypower +
!hours4*ecstand*standbypower;

! CASE 3: netelec >= peakdemand
!netelec >= peakdemand [power];
!netelec <= 12000;
!netelec = 0.9*genelec-idfan;
!demandsave = demandchge;
!demandchge = dc*peakdemand;
!energycharge = ec*hours1*averagedemand;
!totalcharge = demandchge + energycharge;
!electricsave = totalcharge;
!standbypower = 0;
!standbycost = hours4*pf*dcstand*standbypower +
!hours4*ecstand*standbypower;
! ------------------------------------------------------------
! EXCESS ELECTRICITY PRODUCED
! ------------------------------------------------------------
! CASE 1:
exelec1 = netelec - averagedemand;  ! During sawmill operation
exelec2 = netelec;                  ! Sawmill shutdown
! CASE 2:
!exelec1 = 0;
!exelec2 = netelec;
! CASE 3:
!exelec1 = netelec - averagedemand;
!exelec2 = netelec;

! ------------------------------------------------------------
! CAPITAL COSTS:
! ------------------------------------------------------------
                 ! Hog fuel dryer
dryercost = 0;  ! No hog fuel dryer is required for metal HX
dryersize = 0;
```

```
                ! Complete Fluid Bed System
fluidbedcost = 551 Mf - 800000;
fluidbedsize = Mf;
                ! Gas Turbine: Kawasaki
turbcost = 883 genelec + 514975;
turbsize = genelec;
                ! Total Capital No.1:
totalcap1 = dryercost + turbcost;
                ! Installation and Labour = 10% of totalcap1:
install = 0.10 totalcap1;
                ! Total Capital No.2:
totalcap2 = install + totalcap1;
                ! Ductwork = 10% of totalcap2:
ductwork = 0.10 totalcap2;
                ! Electrical = 14% of totalcap2:
electrical = 0.14 totalcap2;
                ! Instrumentation = 5% of totalcap2:
instrument = 0.05 totalcap2;
                ! Piping = 5% of totalcap2:
piping = 0.05 totalcap2;
                ! Structural = 15% of totalcap2:
structural = 0.15*totalcap2;
                ! New Capital, totalcap3:
totalcap3 = totalcap2 + ductwork + electrical + instrument
+ piping + structural;
                ! Engineering costs = 7% of totalcap3:
engineering = 0.07 totalcap3;
                ! Construction Management = 5% of totalcap3:
constructm = 0.05 totalcap3;
                ! New total, totalcap4:
totalcap4 = totalcap3 + engineering + constructm +
            fluidbedcost + mathand;
                ! Contingency = 10%:
contingency = 0.10*totalcap4;
! ---------------------------------------------------------------
! PROJECT TOTAL CAPITAL COST:
! ---------------------------------------------------------------
total = totalcap4 + contingency;
! ---------------------------------------------------------------
! PHYSICAL RELATIONSHIPS AND CONSTRAINTS:
! ---------------------------------------------------------------
! Gas energy required:

! Case 1 wood flow:
gas = 1.75 genelec;           ! When 6624 <= Mf <= 19908 kg/hr
genelec <= 7962;
6624 <= Mf;

! Case 2 wood flow:
!gas = 1.80 genelec;          ! When 19908 <= Mf <= 33,156 kg/hr
!genelec <= 11943;
!19908 <= Mf;

gasenergy = 7/12*0.0036*hours2*gascost2s*gas
 + 5/12*0.0036*hours2*gascost2w*gas; ! cost of gas for cogen
```

```
! ------------------------------------------
! Kiln Heating: Made available from process
! ------------------------------------------
processheat = 2.428*genelec + 0.892*Mf;  ! This includes heat from
                                         ! both the turbine exhaust
                                         ! and the excess flue gas
! ---------------------------
! Plant thermal requirements:
! ---------------------------
kilnheat = proheat;
!processheat >= kilnheat [heat];
! OR
processheat <= kilnheat [heat];
! -----------------------------------------------
! Heatenergy savings assuming gas is displaced:
! -----------------------------------------------
!heatenergy = (7/12)*0.0036*hours2*gascost1s*kilnheat
! + (5/12)*0.0036*hours2*gascost1w*kilnheat; ! for process heat
! OR
heatenergy = (7/12)*0.0036*hours2*gascost1s*processheat
 + (5/12)*0.0036*hours2*gascost1w*processheat; ! for process heat

! -------------------------------------
! Maximum Availabe wood waste (kg/hr):
! -------------------------------------
Mf <= WoodWaste;
Exwood = Woodwaste - Mf;
! ----------------------------------------------
! ID FAN POWER REQUIREMENTS
! ----------------------------------------------
idfan = 0.029*Mf;  ! ID fan power in kW for standard combustor
! ----------------------------------------------
! OPERATING AND MAINTENANCE
! ----------------------------------------------
OM = 0.025 totalcap3 + 0.025*fluidbedcost;! 2.5% of material costs
! ----------------------------------------------
!  INSURANCE AND PROPERTY TAX
! ----------------------------------------------
IT = 0.015 totalcap3 + 0.015*fluidbedcost;! 1.5% of material costs
! -----------------------------------------------------
! CLASS 34 INCOME TAX CREDIT
! -----------------------------------------------------
class34_1 = 0.25*corptax*turbcost+0.25*corptax*0.3*fluidbedcost;
class34_2 = 0.50*corptax*turbcost+0.50*corptax*0.3*fluidbedcost;
class34_3 = 0.25*corptax*turbcost+0.25*corptax*0.3*fluidbedcost;
end
```