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Energy Technology Department

Laboratory of Bio-energy

ECONOMICS OF COMBINED POWER PLANT AND PYROLYSIS BIO-OIL PRODUCTION

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Double Degree Program in Bio-energy Technology

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Economics of combined power plant and pyrolysis bio-oil production

Master’s thesis 2011

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Keywords: biomass, pyrolysis, RTP technology, ablative technology, bio-oil, economics, efficiency, profitability.

There are reasons of necessity in bio-fuel use and bio-energy fast development. It includes the material about bio-energy technologies, applications and methods. There are basic thermodynamics and economic theories. The economic calculation presents the comparison between two combinations. There are boiler plant below 20 MW in combination with ablative pyrolysis plant for bio-oil production and CHP plant below 100 MW in combination with the RTP pyrolysis bio-oil production technology.

It provides a material about wood chips and bio-oil characteristics and explains it nature, presents the situation around the bio-fuel market or bio-fuel trade. There is a description of pyrolysis technologies such as ablative and RTP. The liquid product of the pyrolysis processes is bio-oil. The bio-oil could be different even of the same production process, because of the raw material nature and characteristics.

The calculation shows advantages and weaknesses of combinations and obtained a proof of suppositions. The next thing, proven by this work is the fact that to get more efficiency from energy project it is good possibility to built plants in combinations.

My final thesis has been done at the Energy Technology Department, Laboratory of Bio-Energy in Lappeenranta University of Technology, Finland. Perhaps, this work would not be done without of many things coincidence, happened and got keep going myself to targets, through all of my life, to achieve the best I have today. I am greatly indebted to Pr. Esa Vakkilainen that he provides an opportunity to work under his control. I owe a great many thanks to him for his understanding and support. That was a great pleasure and honor to work together.

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I am sincerely grateful to my fiancee. Thank you darling for everything you have done to me during my absence. That was the hardest year ever, thank you that you let me go study here. We would be the happiest couple forever.

And of course I can’t help saying about my family. I bless my father and my mother for love and upbringing they gave me. Thank you dears for who I am. Thanks to my uncle and his advices. And impossible to forget my sister and cosine jokes and laugh. And I want to give thanks to my grandmother. I know she is watching me from the heavens and proud of me.

I am religious person and practice Orthodox Christianity. Therefore, I feel necessary to show gratitude to Almighty God, Jesus Christ and St. Maria, to all Saints and my Guardian Angel. This is a great miracle and happiness to live and realize that the God set you by His hands. I am still feeling during my prey that They are blessing me for what I want to do. I will try to keep going through my life with nobility, without sin and to do my best as I can. Thank You for everything I have.

The rest of material, not included in this list, might have elementary and logical translation.

Elucidation, expansion for abbreviations and symbols

CHP	Combined heat and power
GHG	Greenhouse gas
DC	Direct current
RTP	Rapid Thermal Processing
PRC	Pyrolysis Centrifuge Reactor
WBA	World Bio-energy Association
UNCTAD	United Nations Conference on Trade and Development
GDP	Gross Domestic Product
USD	United States Dollar
VTT	Technical Research Center of Finland
BTG	Biomass Technology Group
NREL	National Renewable Energy Laboratory
HHV	High Heating Value
SRF	Solid Recovered Fuels
BFB	Bubbling Fluidized-Bed
HVAC	Heating, Ventilating and Air Conditioning

1 INTRODUCTION

This final thesis work is about bio-energy and bio-fuel, about the reasons of necessity in bio-fuel use and bio-energy fast development. It includes the material about bio-energy technologies, applications and methods. There are basic thermodynamics and economic theories. The economic calculation presents the comparison between two combinations. There are boiler plant below 20 MW in combination with ablative pyrolysis plant for bio-oil production and CHP plant below 100 MW in combination with the RTP pyrolysis bio-oil production technology.

RTP (Rapid Thermal Processing) is biomass to liquid conversion technology. RTP theoretical fundamentals based on the fast pyrolysis process reactions. The mode of reaction in ablative pyrolysis is analogous to melting butter in a frying pan, when the rate of melting can be significantly enhanced by pressing down and moving the butter over the heated pan surface.

And of course it is very important to say that this work present the situation around the bio-fuel market or bio-fuel trade. It provides information about the country leaders in bio-energy sector. And this thesis includes detailed description of mentioned pyrolysis technologies, boiler plant and general equipment of typical CHP plant. It has detailed characteristics of wood chips and bio-oil. The calculation shows advantages and weaknesses of combinations and obtained a proof of suppositions. There is a description of plants location, which is about climate, society, geographic position and politics in the bio-energy industry.

The economic calculation, comparisons, basic economic data and assumptions were based on Jerkko Stark project “Nopeaan pyrolyysiin perustuvan biooljyn tuotantolaitoksen liiketoiminnallinen malli ja kannattavuuslaskenta Savonlinnan seudulla; 2011”.

2 BIOMASS TO ENERGY

2.1 CHALLENGES TODAY

Regular world population growth, follow developing and rise of many vitally important life segments. The steady increase in food and clothes production, variable social services, needs in comfort and elements of modern life, brings high demand for energy sector. It is even hard to imagine this century without cars, planes, military and cosmic equipment, cell phones, computers, TV sets, internet and thousands of variable goods. The proposal in many countries is different and limited. Several most efficient solutions could fix the situation. There are: research in the field of new energy sources and extension of renewable energy share, programs in energy efficiency, diversification of power nets with the construction of new power plants and other objects of energy industry.

The most cheap, efficient and common way to produce heat and electricity is heat and power plant (could be named as CHP). Cogeneration is a process or cycle, which using a heating engines to generate both heat and electricity. Nowadays, humanity has a lot of technologies and types of plant applications. The biggest and significant differences between plants are a working fuel and “working body”. Most of these applications uses fossil fuels, which are exhaustible fuels and exists irregular on the world’s surface. That means region or country specification and need in one or several fuel types. A great role plays geographical position, climate and landscape. For many countries these aspects are decisive in the fuel choice.

The fossil fuels formed inside the soil, this is the reason of “dirty” fossil nature. Soil feeds the inceptive and existent minerals, carried inside the mineral’s structure chemical elements and metals. Combustion of fossil fuels close connected with high level of flue heavy gases, dust, GHGs and other emissions. To decrease the emission’s level, energy industry uses a great number of combustion methods and efficient equipment. Electric filters, fly-ash collectors, water treatment, modern boilers and other device are help to reduce emissions. All these actions could minimize emission consequences, but couldn’t exclude environmental pollution.

Power capacity expansion leads aggravation of the environmental condition. One of the biggest pollutants is energy industry. Nowadays, the humanity is on the verge of the ecology system disaster. The situations around of Global Warming and Ozone Layer destruction are sorrowful and terrible facts. And, already, no one can say that this is a trifle or a myth. Actually, these are the serious reasons for rapid growth of the renewable energy sources. This impact could be a good promotion tool for renewable energy inventions, and, can bring cheap and environmental friendly energy for different countries. Solar, wind, hydro and thermal power, solid, gaseous, liquid bio-fuels are presented a great field to choose the most appropriate type of energy. Day by day, the developing of bio-fuel industry brings as new, more efficient methods and upgrades for production, as new types of fuel and energy.

Bio-fuels could replace fossils in the closest, but indefinite period of this century. At least, in some regions, bio-fuel production shows sustainable competitiveness. It happens because of the positive bio-fuel aspects. Bio-fuel is low emission and environmental friendly source of energy, the biggest part of bio-fuel assortment is cheaper than fossils or at the same price level, developing agricultural sector and energy efficiency in primary, domestic use. Pellets, wood chips, bio-oil, bio-diesel, bio-gas, bio-alcohols could constitute mutual category, named as bio-fuel. Bio-fuels produced from different nature with various parameters, but characteristics of these fuels are acceptable for invisible substitution of fossils, because of the same or similar properties and working equipment. Bio-fuel production is deep dependant of raw material availability and price. Raw material or biomass can be taken from numerous of agricultural, environmental, human life cycle segments. Various wood residues, fats from animal and food industry, straw, crops and corns, fermentation products and municipal solid waste are sources of bio-fuel. Humanity found a lot of methods of combustion and gasification, fermentation and upgrading, thus energy industry is coming to a new era of the twenty first century.

2.2 POWER PLANT AND BIOMASS WORLD MARKET

Probably, the first commercial, central power plant was the Pearl Street Station on Manhattan Island, New York, USA. It was generated electricity for the city, used the same business model of distribution and work structure as modern companies using today. It started to generate electricity in 1882 and increased the share of power capacity more than ten times in two years. Power plant had a great success, mostly because of it inventor, world known and very famous scientist Thomas Edison. He built and processed station business model and work effectiveness of the framework. Around two years before, he patented a system for electricity distribution and founded the Edison Illuminating Company. In the prehistory of all these changes and innovations was one of the most significant, common and well known invention. Mr. Edison improved investigations and idea of electrical light bulb, and patented his own project, and formed a new company, the Edison Electric Light company. But, it is hard not to say any word about the station, which Mr. Edison had switched on half of year earlier than Pearl Street Station. The steam generating station, at Holborn Viaduct in London, was provided electricity to street lamps and several private houses. The USA station regarded as the first one, because of it modern organizational model. But in fact, the London's station left it behind. At the very begging, both of the stations, were generated around 110 V of DC electricity. That period of time, the idea of electric light and electricity was rapidly spread around the world. Many of businessmen, companies and organizations were interested in electricity market occupation. It was incredibly profitable time for energy industry.

Figure 2.2.1: The Pearl Street Station sketch.

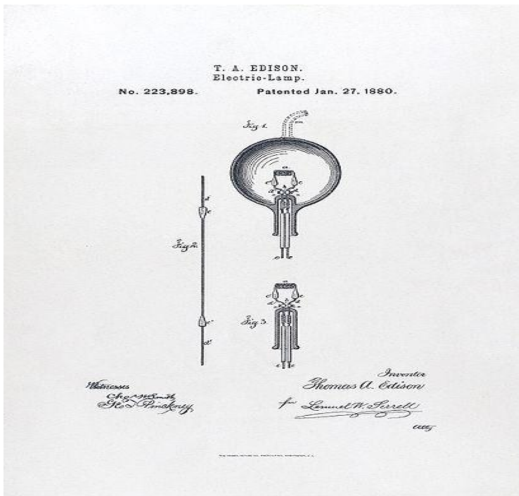


Figure 2.2.2: USA patent of Edison's electric lamp.

Thomas Alva Edison was truly a great man. He was born the 11^{-th} of February, 1847 and deceased, at the age of 84 years old, the 18^{-th} of October, 1931. He was an American scientist, businessman and inventor, who developed and improved many devices that are still using in various spheres and influencing on life around. Mr. Edison is one of the most prolific inventors in the world history. He is keeping more than 1 500 patents, registered around the world. He had two spouses and six children. Three of his sons, were the inventors. One of them, Charles Edison picked up the company upon father's funeral and later was elected Governor of New Jersey.

Today, possible to take for examination many types of power plants. To classify plants better to mark main categories. The basic differences between power stations are working fuel, type and sort of general equipment, theoretical and practical foundations of a plant processes. There are: thermal, nuclear, hydro, condensing and incineration stations, plants working on bio-fuel and using other renewable energy sources. In my mind these categories are mostly spread through the world, otherwise this list could be expanded by numerous of different plants. The energy industry presented diverse of application size and it power capacity.

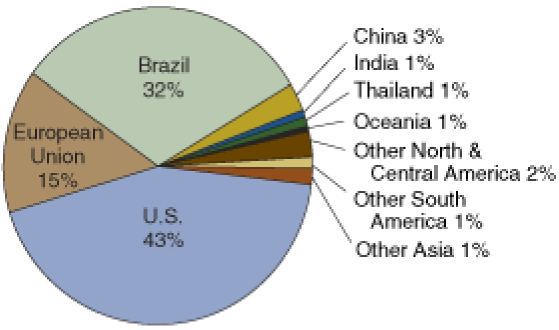
Small size and power capacity plants are usually make a demand for private and domestic use, constituted a range from less than 1 MW, till around 15 MW. Huge plants are almost for industrial sector, to fulfill resident proposal and sometimes reach around 1000 MW. Last years, small scale plants are high essential among the applications using a bio-fuel. Bio-fuel properties and prices, convenience features, combustion methods and environmental requirements, practically could achieve very high level of the cycle efficiency. Anyway, like all other projects, bio-fuel power plants have a row of disadvantages. Biomass is high dependent of climate change and sudden incidents, because of it nature origin. Other big drawbacks are high transportation cost, storing, still low demand and under developing equipment. Fortunately, these drawbacks are well known, and use of successful projects experience and solutions leads to it minimization. By the way, the profitability of bio-fuel production is directly depended of gasoline and diesel prices, which are fluctuate because of the high fossil's cost mutability.

Against all the odds, bio-fuel proposal increases every day and follows developing of bio-energy industry and diversification of this sector. As a result of aforesaid and of my authentic interest, chosen topic of final thesis is about bio-energy and bio-fuel production. The short thesis description is economics of pyrolysis bio-fuel production combined with power plant working on bio-fuel. The idea of this bio-fuel production type is to get other fuel from initial, the fuel with different properties and physical condition, getting liquid bio-oil from solid wood chips. It is in connection with thermal and economic foundations, kind of “symbiosis” between different applications in energy production.

The country climate plays a great role in development of bio-fuel industry. Hot climate countries will always show a great bio-fuel share growth, because of the longer growing season and higher quantity of coming per acre yield. It decreases fuel and other input costs. Several of northern countries, show very good opportunities. These are industrialized countries, reach and full of different raw materials. Besides, the northern countries are taking a part in development of the world biomass market trade. Provide the supply of extra biomass and replenish own lack of certain reserves.

The global bio-fuel production increased around four times from 4.7 billion gallons in 2000 to about 18.5 in 2010, but still averages a small share compare to the world total energy consumption. One more consequence of increased bio-fuel demand has contributed by world food and feed growing prices. There are: EU, USA and Brazil concentrated around 90 percent of the world bio-fuel production. Fortunately, the Asian market is coming bigger every day. Malaysia, Indonesia, China and Japan have been done a lot of successful projects [International Energy Agency, FO Licht].

Table 2.2.3: The world bio-fuel industry shares.



2.3 SCENARIOS OF BIO-FUEL MARKET DEVELOPMENT

To achieve maximum efficient country biomass trade usage and logistic model, it is necessary to invent in mechanism of biomass market an instrument which could be called as a scenario of bio-fuel development. The scenario is a theoretical and predictive kind of “forecasting” and approximate “business plan” for bio-fuel development. This was not an official determination of scenario conception, but hopefully easy to descript and understand it. The scenario character could be very different. Sometimes it includes many of bio-fuel standards and properties and sometimes includes just a forecasting models and a conclusion of researched information, it could be a short and a long term scenario and finally possible based on pessimistic and optimistic predictive schemes. The scenario conception is deep developed and for it examination truly needs another final thesis work, so this chapter is providing general and basic information of the scenario phenomena.

The bio-fuel scenarios and forecasting are created by different countries, organizations and universities by using of different information resources, options and models. But almost all of them conclude the same future for the bio-energy sector and the bio-fuel market. Scenario is an official document with formulating requirements and usually consisted of technical and theoretical bio-energy data. But, still any of interested persons could make it own scenario and it follows an attention necessity to references and basic scenario information, name of organization presented the document.

The World Bioenergy Association (WBA) recently released a position paper on the global potentials of biomass energy. The position paper (based on the report by the Department of Energy and Technology at the Swedish University of Agricultural Sciences) says that "the potential to produce biomass for energy in a sustainable way is sufficient to meet global demand. Among the highlights of the position paper are: the total global bio-energy production potential by 2050 (based on a scenario applying "best available technologies") is estimated at 1,548 Exajoules (1 Exajoule is equal to 10^{18} Joules). On the other hand, global primary energy consumption (on a high end consumption scenario) is lesser and is estimated at 1,041 Exajoules, there are no technical problems seen with respect to shifting the energy mix from fossil fuels to bio-energy; however, efforts to improve overall efficiency must be in place,

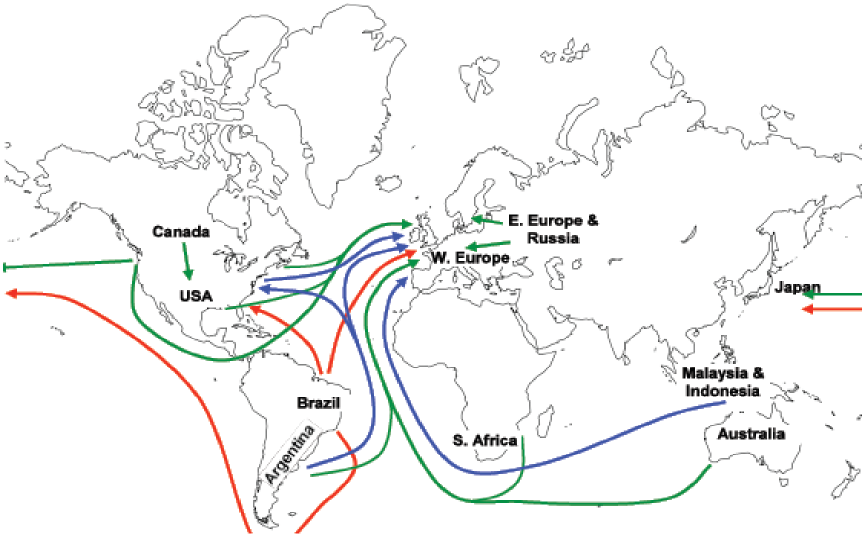


Figure 2.3.1: Current main shipping lanes for biomass and bio-fuel (Red line – ethanol, green line – wood pellets, blue line – vegetable oils & biodiesel) [IEA Bio-energy, Sustainable International Bio-energy trade].

the next is only about 0.19 percent of the total global land area is devoted to bio-fuels, while 0.5 percent of total global land area is agricultural land, there is little public awareness on potential of bio-energy, and the establishment of an information/education campaign will be helpful to promote bio-energy, "sustainable development of biomass and bio-fuel is a major challenge" in increasing biomass production for bio-energy; international efforts to establish "sustainability criteria" to regulate the production and trade of bio-energy are underway [WBA, http://www.worldbioenergy.org].

In general, developing countries have a larger potential to produce biomass than industrialized countries due to better climate conditions and lower labor costs. Under this assumption, international trade in bio-fuels or feedstocks from developing to developed countries is expected to increase with significant positive implications for development [UNCTAD, The bio-fuel market: current situation and alternative scenarios].

The most well known, positive and common scenario is the Blue Map scenario. Reducing CO_2 emissions by 50% by 2050 represents a tough challenge. This scenario implies a very rapid change of direction. Costs are not only substantially higher, but much more uncertain, because the BLUE scenarios demand deployment of technologies still under development, whose progress and ultimate success are hard to predict. While the present scenarios are demanding, the BLUE scenarios require urgent implementation of unprecedented and far-reaching new policies in the energy sector.

Based on optimistic assumptions about the progress of key technologies, the BLUE Map scenario requires deployment of all technologies involving costs of up to USD 200 per ton of CO_2 saved when fully commercialized. If the progress of these technologies fails to reach expectations, costs may rise to as much as USD 500 per ton. At the margin, therefore, the BLUE Map scenario requires technologies at least four times as costly as the most expensive technology options needed for existing map scenarios. However, the average cost of the technologies needed for BLUE Map is much lower than the marginal, in the range of USD 38 to USD 117 per ton of CO_2 saved.

Additional investment needs in the BLUE Map scenario are USD 45 trillion over the period up to 2050. They cover larger deployment investment in technologies not yet market-competitive (even with CO_2 reduction incentives), and commercial investment in low-carbon options (stimulated by CO_2 reduction incentives). The total is about USD 1.1 trillion per year. This is roughly equivalent to the current GDP of Italy [www.greenfacts.org].

Table 2.3.2: Overview of the global potential bio-energy supply on the long term for a number ofcategories and the main pre-conditions and assumptions that determine these potentials [INTERNATIONAL BIOENERGY TRADE, Scenario study on international biomass market in 2020; Jussi Heinimö, Virpi Pakarinen, Ville Ojanen, Tuomo Kässi, 2007; Faaij et a., 2006].

Biomass category	Main assumptions and remarks	Potential bioenergy supply up to 2050, [EJ/yr].
Energy farming on current agricultural land	Potential land surplus: 0-4 Gha (more average: 1-2 Gha). A large surplus requires structural adaptation of intensive agricultural production systems. When this is not feasible, the bio-energy potential could be reduced to zero as well. On average, higher yields are likely because of better soil quality: 8-12 dry ton/ha*yr is assumed.	0 – 700 (more average development: 100 – 300)
Biomass production on marginal lands	On a global scale a maximum land surface of 1.7 Gha could be involved. Low productivity of 2-5 dry ton/ha*yr. The supply could below or zero due to poor economics or competition with food production.	(0) 60 – 150
Bio-materials	Range of the land area required to meet the additional global demand for bio-materials: 0.2-0.8 Gha. (Average productivity: 5 dry ton/ha*yr). This demand should come from categories I and II in case the world's forests are unable to meet the additional demand. If they are, however, the claim on (agricultural) land could be zero.	Minus (0) 40 –150
Residues from agriculture	Estimates from various studies. Potential depends on yield/product ratios and the total agricultural land area as well as type of production system: Extensive production systems require re-use of residues for maintaining soil fertility. Intensive systems allow for higher utilization rates of residues.	15 – 70
Forest residues	The (sustainable) energy potential of the world's forests is unclear. Part is natural forest (reserves). Range is based on literature data. Low value: figure for sustainable forest management. High value: technical potential. Figures include processing residues.	(0) 30 – 150
Dung	Use of dried dung. Low estimate based on global current use. High estimate: technical potential. Longer-term utilisation (collection) is uncertain.	(0) 5 – 55
Organic wastes	Estimate on basis of literature values. Strongly dependent on economic development, consumption and the use of bio-materials. Figures include the organic fraction of municipal solid waste and waste wood. Higher values possible by more intensive use of bio-materials.	5 – 50
Total	Most pessimistic scenario: no land available for energy farming; only utilization of residues. Most optimistic scenario: intensive agriculture concentrated on the better quality soils.	40 – 1 100 (250 – 500)

3 PYROLYSIS

3.1 PYROLYSIS AND BIOFUEL

Historical facts show that pyrolysis has been used a long time ago. The pyrolysis was the main and common process to produce charcoal and coke using clay beehive ovens. Other great revelation was done by Abraham Pineo Genser (May 2, 1797 – April 29, 1864). He was a Canadian physician and geologist. In 1854, he used the coal pyrolysis at 427 ^{0}C to produce kerosene. This was an efficient alternative to whale oil and helped a lot for saving the whale population.

Pyrolysis is thermochemical process of organic material decomposition at increased temperatures and in the absence of oxygen. The customary pyrolysis process proceeded under a pressure at the temperature around 430 ^{0}C. Practically, it is almost impossible to achieve absolutely oxygen-free atmosphere. The reason is the fact that biomass always contains small oxygen and air seeping presence in fuel particles. There are many types of pyrolysis, used in a large scale of industry sectors and other purposes. The pyrolysis processes occurs in cooking, chemical industry, fire-equipment production, bio-fuel production, carbon fiber and coke manufacturing. Even plastic waste disposal uses anhydrous pyrolysis to produce liquid fuel from plastic waste. This fuel's properties are similar to diesel. The pyrolysis temperature difference shows a diversity of the processes. The cooking temperature around 100 ^{0}C, seemed to be negligibly small compare to carbon fiber production process, occurring between 1500 ^{0}C and 3000 ^{0}C.

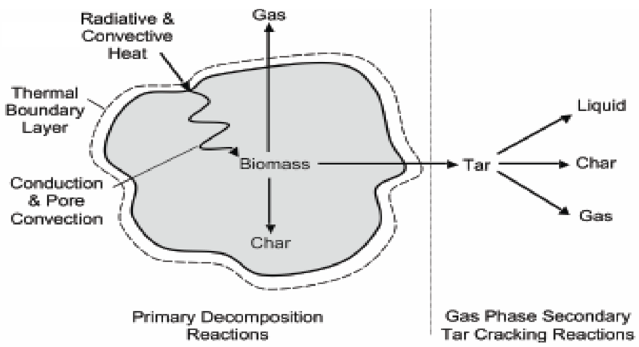


Figure 3.1.1: The biomass pyrolysis process.

The pyrolysis processes widely applicable in bio-fuel industry. The bio-fuel pyrolisis production has a several advantages, which are refers to all bio-fuel technologies such as low prices of raw material, environmental friendly processes, equipment control. The raw material, plant location, transportation, type of application and processes directly influences to the complete fuel cost.

Table 3.1.2: Bio-fuel production products and stages.

BY-PRODUCTS	•ELECTRICITY •THERMAL ENERGY
INTERMEDIATE PRODUCTS	•SYNGAS •CHARCOAL
FINAL PRODUCTS	•BIO-OIL •CHARCOAL

There are several main types of pyrolysis for biomass conversion into next generation fuels: slow, flash, rapid or fast and catalytic processes. Each of these categories could include several methods and technologies. It is a little, negligible doubt about flash and fast pyrolysis determination. Some scientist are trying to prove categories identity, others are persisting on moderate small difference and proposing to define the flash pyrolysis as a sort of the fast process.

It is possible to separate the biomass pyrolysis process into three constituent yields. There are solid, liquid and gaseous yields. The solid yield could be a char or carbon. The liquid are tar, heavy hydrocarbons and water. And finally the gaseous yields mostly are CO_2, CO, C_2H_2, C_2H_4, C_2H_6. More practical and simple explanation of pyrolysis production model is on the table below.

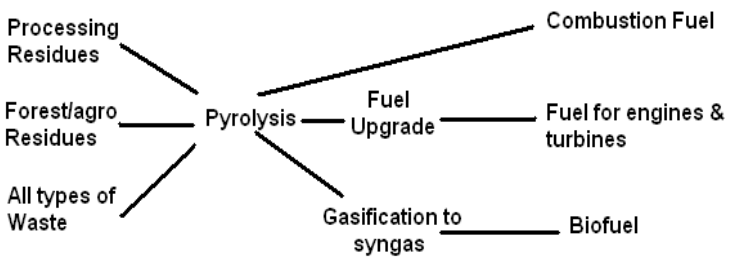


Figure 3.1.3: The bio-fuel pyrolysis framework.

To build clear and effective explanatory comparison and achieve thesis goals, RTP and ablative pyrolysis types were chosen. Attentive examination of these applications, accordingly with thesis topic, directed to decision of two combined plants. The first project is combination of boiler plant around 20 MW with ablative pyrolysis bio-oil production. And the second one is combined 100 MW power plant and pyrolysis bio-oil formation by RTP method.

3.2 FAST PYROLYSIS

The fast pyrolysis was chosen, because of it high efficient parameters in bio-oil production. As was written before, fast pyrolysis is a determination, which includes several production technologies, such as RTP and ablative pyrolysis . Compare to all other bio-oil pyrolysis processes, the fast pyrolysis has numbers of advantages: gives the maximum output of completed fuel, easy and developed to operate, quite cheap, has a short cycle time.

Apart from the pyrolysis determination it is necessary to add that pyrolysis is the first step in all combustion and gasification processes where it is followed by total or partial oxidation of the working fuel. A condition of lower process temperature and longer vapour residence times supports the production mostly of char coal. High temperature and longer vapour residence time increases the biomass transformation to gas, and moderate temperature and short vapour residence time are the most efficient parameters for liquid fuel production.

Table 3.2.1: Typical product yields (dry wood basis) obtained by different modes of pyrolysis of wood [Bridgwater, A. V.: Biomass Fast Pyrolysis; Thermal Science: Vol. 8 (2004), No. 2].

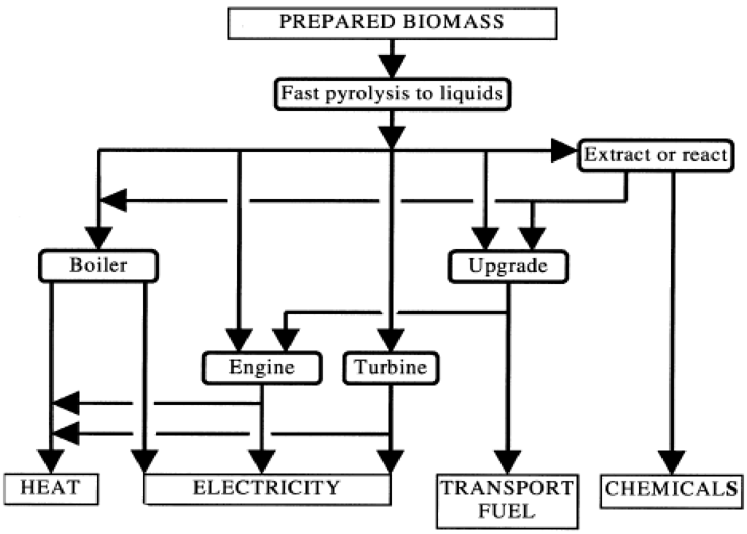
PROCESS	CONDITIONS	LIQUID	CHAR	GAS
Fast pyrolysis	Moderate temperature, short residence time particularly vapour	75%	12%	13%
Carbonization	Low temperature, very long residence time	30%	35%	35%
Gasification	High temperature, long residence times	5%	10%	85%

Duration of the fast pyrolysis process takes around of few seconds. The pyrolysis cycle includes several very important, basic processes: kinetics of chemical reaction, phase transition, heat & mass transfer processes. The main cycle issue is to handle the reacting biomass particles at effective parameters and minimize the opportunity for the charcoal formation. There are several available methods to achieve the optimum cycle model. One way is the fluidized bed process, used small particles of biomass to increase heat & mass media effect. Another way is very rapid, directed heat only to the particle surface that contacts the heat surface, biomass is under the pressure called ablative process. Available similar to fluidized bed process – circulating fluidized bed, bubbling fluidized bed and transported bed processes. Others are rotating cone, entrained flow, ablative and auger processes.

The biomass, decomposed during the fast pyrolysis process and generates mostly vapours and aerosols, precipitates some charcoal. After cooling and condensation, formed dark liquid has a heating value around half of typical oil fuel. Compare to the traditional pyrolysis processes that making charcoal, the fast pyrolysis is an advance, because of chosen, high efficient and controlled parameters. These criteria increases yields of liquid. The most significant features of the fast pyrolysis process:

- ✓ very high heating and mass media effect rates during the fast pyrolysis reaction
- ✓ carefully operated pyrolysis process temperature of around 500 ºC and vapour process temperature of 400-450 ºC
- ✓ short vapour residence time, which takes approximately a few seconds
- ✓ final phase rapid cooling of the pyrolysis vapour, completed the bio-oil production

Table 3.2.2: Applications of pyrolysis liquids. [A.V. Bridgewater, D. Meier, D. Radlein: An overview of fast pyrolysis of biomass; Organic Geochemistry 30 (1999) 1479±1493].



The bio-oil, gathered from the biomass sources and obtaines up to 75% share of income feed. By the way pyrolysis bio-oil production, almost exclude the quantity of ash, flue gases and other wastes. The first phases of fast pyrolysis process are drying of biomass to approximately 10% of water, in order to minimize it particles in the bio-oil (moisture standard is up to 15%), grinding the feed (at the limits from 2 mm till 6 mm, a few applications are skip this phase). Making of sufficiently small particles ensures almost all the cycle: rapid and pyrolysis reactions, separation of solids (char), and bio-oil gathering. The fast pyrolysis process is available for any sort of biomass.

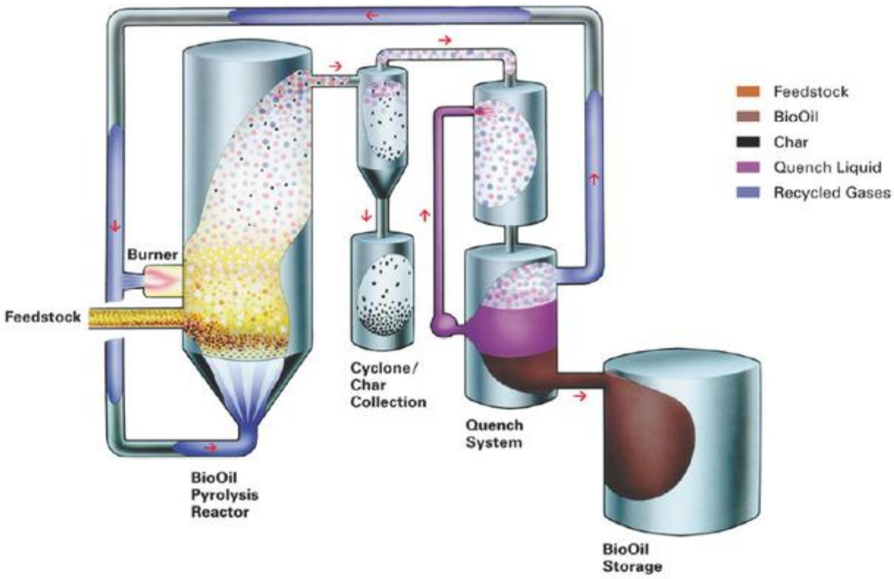


Figure 3.2.3: Non principled scheme of the fast pyrolysis process [Dynamotive's technologies, dynamotive.com].

It is more need for detailed examination of basic pyrolysis phases and processes, because of many doubts and innovations. By the way, many of the doubts are coming, because of still not well developed stream of pyrolysis process and competitiveness between energy companies. Well, to begin with examination of basic determination, presents the heat & mass media process (heat transfer process). To achieve the efficient cycle work, the pyrolysis reactor has to satisfy heat & mass media requirements. The basic requirements are belong to the reactor heat transfer medium (solid reactor wall in ablative reactors, gas and solid in fluid and transport bed reactors, gas in entrained flow reactors), and to the fast pyrolysis phase where is heat exchange between transfer medium and pyrolysing biomass. Low heating rate tin the heat transfer reaction and expand time of pyrolysis process. The same reason lead to one more essential requirement.

Char removal is very important part of the process. Big char particles hinder and change the pyrolysis reaction, because it brings to the process low thermal conductivity of biomass and low heating rates. This effect increases char temperature and it formation. It cracks organic vapours to secondary char in the rector gas environment and during the primary vapour formation of water and gas. Thus, it is a significant need in rapid char removal from the hot reactor environment and exclusion of interaction with the pyrolysis vapour product.

Since the thermal conductivity of biomass is very poor (0.1 W/mK along the grain, ca 0.05 W/mK cross grain), reliance on gas-solid heat transfer means that biomass particles have to be very small to fulfill the requirements of rapid heating to achieve high liquid yields. Claimed temperature increases of 10,000 C/s may be achieved at the thin reaction layer but the low thermal conductivity of wood will prevent such temperature gradients throughout the whole particle. As particle size increases, liquid yields reduce as secondary reactions within the particle become increasingly significant [Scott D.S., Piskorz J., 1984. The Continuous Flash Pyrolysis of Biomass. Can. J. Chem. Eng. 62 (3), 404±412.].

The heat supply of pyrolysis process has to fulfill requirement for the high heat transfer rate. Theoretically, to achieve efficient fast pyrolysis condition it is required heat fluxes of 50 W/cm^2. This value is not necessary and could be various in different applications. There are two fundamental principles for heat & mass media in the fast pyrolysis technologies: conductive and convective. Each of the method has own benefits and disadvantages, brings special limitation to the fast pyrolysis reactor design.

As was written before, the feed preparation is being an important part of the cycle. The ablative pyrolysis could almost exclude this part, because it can work with big particles of biomass, but anyway it needs a drying step. After the drying, the moisture of biomass should be less, than 15% of water. Because of evaporation, the bio-oil always includes water content. It is not possible to remove water particles by typical method of distillation. Water content could influence to cycle properties of pH, viscosity, corrosiveness, stability and controllability of the process. A solution of selective condensation could reduce not only the water content, but the cycle efficiency, because of the operating complications and losses of the low molecular weight volatile component.

It is hard to overemphasize the process temperature importance. The lower limit for the fast pyrolysis process temperature is approximately 435 ^{0}C, for gathering liguid yields at the share of at least 50% within condition of low time process reactions. The most efficient cycle temperature is 500 – 520 ^{0}C, mostly for all types of woody biomass, because of the highest liquid yield production possibility at this temperature. Fortunately, the temperature effect is not well developed in the field of the product fuel quality. An achievement of high efficient cycle, deep depended of interconnected actions: reactor design and temperature control.

The secondary vapour cracking is very significant effect in the cycle. Long vapour residence times and high temperatures (more than 500 ^{0}C) cause secondary cracking of primary products reducing yields of specific products and organic liquids. Lower temperatures (less than 400 ^{0}C) lead to condensation reactions and the subsequent formation of lower molecular weight liquids which can probably react. [A.V. Bridgewater, D. Meier, D. Radlein: An overview of fast pyrolysis of biomass; Organic Geochemistry 30 (1999) 1479±1493].

Small particles of char and ash are coming from the cyclones and pyrolysis process to the completed bio-fuel. Separation and removal of ash metals and solid particles is underdevelopment, but still available several complicated and expensive methods. There are ceramic cloth bag house filter, used a hot gas filtration (Diebold et al., 1993) and candle filters for short run durations. But unfortunately, these methods are not applicable to the char separation. These are the reasons of need in high quality feed preparation. [A.V. Bridgewater, D. Meier, D. Radlein: An overview of fast pyrolysis of biomass; Organic Geochemistry 30 (1999) 1479±1493].

3.3 RTP PROCESS AND TECHNOLOGIES

RTP (Rapid Thermal Processing) is biomass to liquid conversion technology. RTP theoretical fundamentals based on the fast pyrolysis process reactions. RTP is used to convert cellulosic biomass feedstock, usually forestry or agricultural residuals, into pyrolysis oil - a light, pourable, clean-burning liquid. Pyrolysis oil provides a sustainable, cost effective and virtually carbon-neutral alternative for process heat, power generation and, with further refining, transportation fuels. [RTP™, rapid thermal processing report from Envergent Technologies].

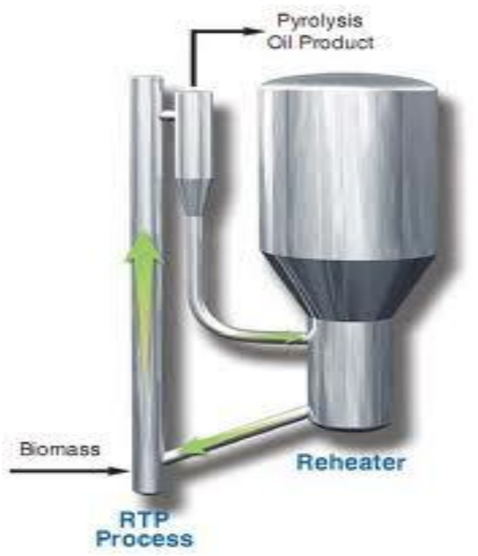


Figure 3.3.1: The primary model of RTP process [1].

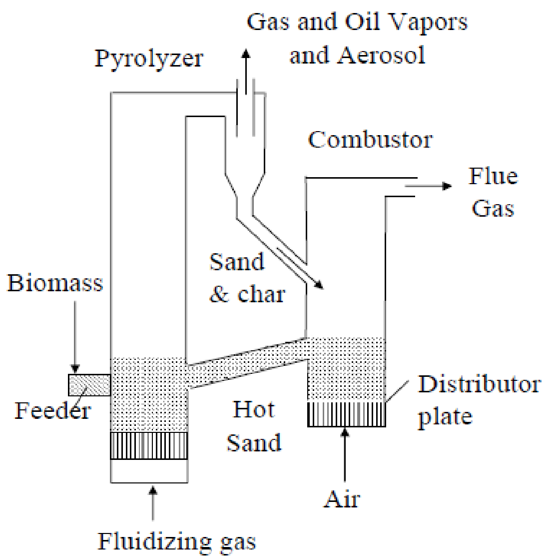


Figure 3.3.2: Circulating transported fluidized bed reactor scheme [2].

1- Overview of RTP process by UOP's company.
2- Robert C. Brown and Jennifer Holmgren; Fast pyrolysis and bio-oil upgrading; UOP and Iowa State University presentation.

RTP is a fast thermal process in which biomass rapidly heated to approximately 500°C in the absence of oxygen. A circulating transported fluidized bed reactor system is at the heart of the process. A turbulent stream of hot sand flashes the biomass into a vapour. The vapour is then rapidly condensed into a liquid. This process occurs in less than two seconds, yielding high quantities of bio-oil. In addition to pyrolysis oil, RTP produces char and a non-condensable gas, both of which can be used to provide process energy in the reheater to maintain the RTP process and/or in the dryer to condition the biomass. [RTP report of Ensyn Technologies Inc.; RTP™, rapid thermal processing report from Envergent Technologies].

More detailed process could be presented as simple as next explanation. The biomass source is coming to the feed preparation system, where it is become in conformability with required parameters, become threaded and dried. Acceptable biomass moisture content is 10% and the feed size is 3 mm, approximately, it depends of technology. After the preparation the feed is going to reactor. The feed is heated in the absence of oxygen at the reactor system, separates to the char, vapour and flue gas content. The quantity of not combusted char left on the reactor bottom side and injects from reheater. The hot mix of vapour and flue gases is come to the cyclone. There, the solid and heavy particles are settled and clean content of vapour is coming to the final cycle processes. The vapour is cooling and condensing, bio-oil is licking into the oil tank. Non-condensable and reheated gases are coming back to the cycle.

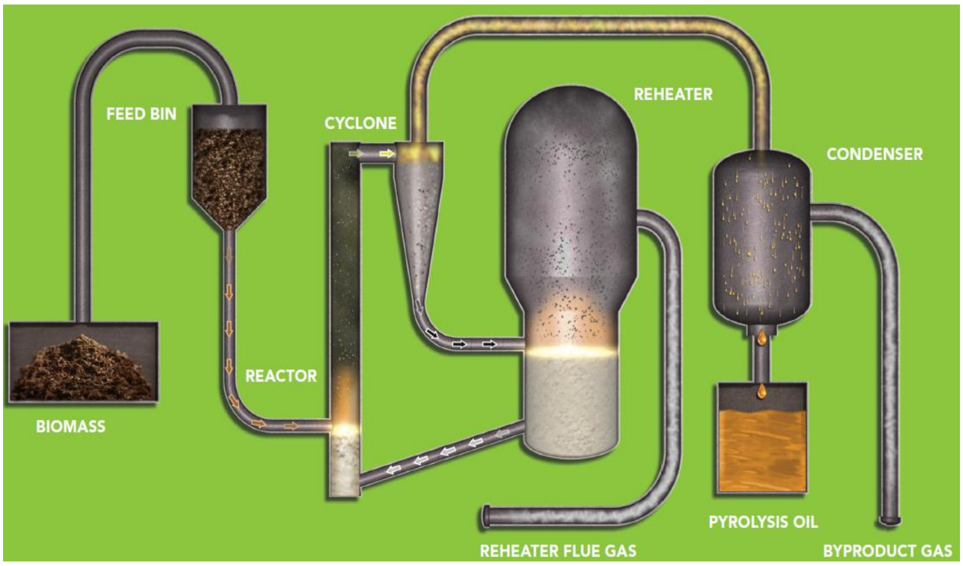


Figure 3.3.3: RTP bio-oil production process [RTP™, rapid thermal processing report from Envergent Technologies].

Pyrolysis oil created by rapid thermal processing contains almost no sulfur and is virtually carbon-neutral. It can be easily adapted for use in a wide variety of industries including pulp and paper, refining and petrochemicals, electrical generation and most energy intensive heavy industry These features are a distinct benefit for companies looking to reduce their greenhouse gas emissions [RTP™, rapid thermal processing report from Envergent Technologies].

There are many companies and universities around the world developing fast pyrolysis processes and RTP particularly. This development started more than twenty years ago and now the company leaders such as Honeywell UOP, VTT, Envergent, Ensyn, BTG, few Swedish and Dutch universities are presented different variations of the same technology. All these companies provide own methods and equipment. The difference could be found in application scheme using reheater or not, several types of reactor (the same processes and temperatures, but it is more about appearance), equipment such as cyclones raw material.

RTP technology of the bio-oil production has a large list of benefits compare to other methods such as gasification, pelletization and it own several disadvantages. To begin with the list, it is right to say that RTP technology is the most efficient, developed and commercial successful application today. Already, with a use of big experience, were invented and improved many of RTP's processes, technologies, management methods, ways of application and equipment installation. Well, in summary, it is definitely the most reliable fast pyrolysis process technology.

First of all about RTP process weaknesses. It is possible to say that almost all minuses of RTP process, and belongs to the renewable energy industry and biomass source. Here is the RTP process most important advantages:

- ✓ big source of applicable biomass
- ✓ fast thermal processes, fast cycle time
- ✓ high percentage of outcome liquid and
- ✓ moderate process parameters, easy to handle and operate (compare to big plants)
- ✓ various technologies, applicable for different plants and joint use
- ✓ environmental friendly (low GHG and etc., waste and residue utilization)
- ✓ compact installation

3.4 ABLATIVE PYROLYSIS

The process of ablative fast-pyrolysis follows a simple principle that demands a low energy input. The wood feed material can enter the reactor without being hackled or milled. During the thermal reaction, only the wood is subjected to the heating process. Neither a heat carrier nor a transport gas needed, so that the loss of input energy is minimized. (These properties mark the difference between the ablative flash-pyrolysis and other conventional fast-pyrolysis processes which are generally realized in a fluidized sand bed reactor. Utilizing the conventional method, biomass first has to be milled into fine particles, what demands for a high input of energy [PYTEC press release].

Ablative pyrolysis is substantially different in concept compared to the other methods of fast pyrolysis. In all these other methods, the rate of reaction is limited by the rate of heat transfer through a biomass particle, which is why small particles are required. The mode of reaction in ablative pyrolysis is analogous to melting butter in a frying pan, when the rate of melting can be significantly enhanced by pressing down and moving the butter over the heated pan surface. In ablative pyrolysis heat is transferred from the hot reactor wall to “melt” wood that is in contact with it under pressure. The pyrolysis front thus moves unidirectionally through the biomass particle. As the wood is mechanically passed away, the residual oil film both provides lubrication for successive biomass particles and rapidly evaporates to give pyrolysis vapours for collection in the same way as other processes. The rate of reaction is strongly influenced by pressure, the relative velocity of wood on the heat exchange surface and the reactor surface temperature [Progress in thermochemical biomass conversion, Volume 2, IEA Bioenergy, A.V. Bridgwater].

The ablative fast pyrolysis process is still underdevelopment and looks like more theoretical method. This assertion is a bit incorrectly. Nowadays, the development brings a lot of innovative reactors and equipment. Many companies provide various application modes used different parameters and raw material. Here are several most efficient and common technologies. The first one is the fast ablative pyrolysis performed by Aston University. The second technology is developed by NREL’s company and third one is an ablative pyrolysis application named as PRC.

The key features of ablative pyrolysis process are: high pressure of particle on hot reactor wall, achieved due to centrifugal force (NREL) or mechanically (Aston), high relative motion between particle and reactor wall, reactor wall temperature around 600 ^{0}C. And important to list the ablative pyrolysis process particular features and basic advantages:

- ✓ use of large feed sizes
- ✓ insert gas is not required, so the processing equipment is smaller (in the case of mechanically applied pressure)
- ✓ the reaction system is more intensive
- ✓ the process is limited by the rate of heat supply to the reactor rather than the rate of heat absorption by the pyrolysing biomass as in other reactors
- ✓ reaction rates are limited by heat transfer to the reactor, not to the biomass
- ✓ the process is surface area controlled so scaling is more costly
- ✓ the process is mechanically driven so the reactor is more complex [Progress in thermochemical biomass conversion, Volume 2, IEA Bioenergy; A.V. Bridgwater].

Well, the ablative pyrolysis process is interesting as much larger particle sizes can be employed than in other systems and there is no requirement for inert gas. Both lead to a potentially lower cost system. Previous scientific research of the ablative pyrolysis phenomena was concentrated to relationships between pressure, temperature and motion. NREL developed an ablative vortex reactor, where the biomass accelerated to supersonic velocities to derive high tangential pressures inside a heated cylinder. Unreacted particles are recycled and the vapours and char fines leave the reactor axially for collection. Liquid yields of 60-65% on dry feed basis are typically obtained [Progress in thermochemical biomass conversion, Volume 2, IEA Bioenergy; A.V. Bridgwater].

This design approach had the potential to use particle sizes up to 20 mm in contrast to the 2 mm particle size required for fluidized bed designs. Biomass particles were accelerated to very high velocities by an inert carrier gas (steam or nitrogen) and then introduced tangentially to the vortex (tubular) reactor. Under these conditions the particle was forced to slide across the inside surface of the reactor at high velocities. Centrifugal force at the high velocities applied a normal force to the particle against the reactor wall. The reactor wall temperature was maintained at 625°C. Vapors generated at the surface were quickly swept out of the reactor by the carrier gases to result in vapor residence times of 50-100 milliseconds. So this design was able to meet the requirements for fast pyrolysis and demonstrated yields of 65% liquids [M. Ringer, V. Putsche, J. Scahill; Large-scale pyrolysis oil production: a technology assessment and economic analysis; Technical report NREL/TP-510-37779, November 2006].

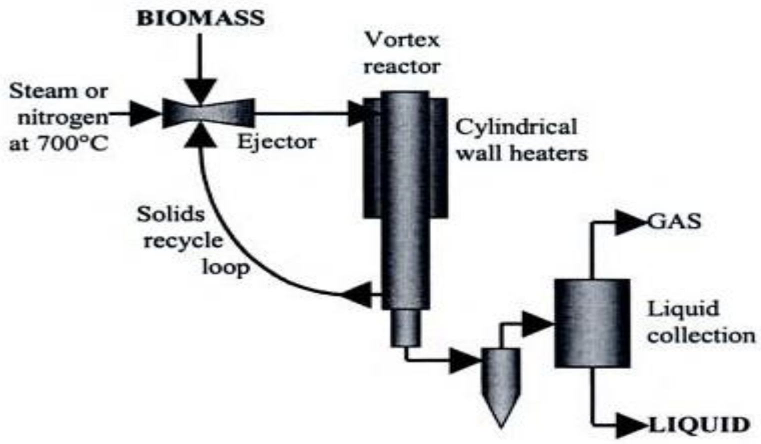


Figure 3.4.1: NREL Vortex ablative reactor [Progress in thermochemical biomass conversion, Volume 2, IEA Bioenergy; A.V. Bridgwater].

In practice it was necessary to incorporate a solids recycle loop close to the exit of the reactor to re-direct larger incompletely pyrolyzed particles back to the entrance to insure complete pyrolysis of the biomass. Particles could escape the reactor only when they were small enough to become re-entrained with the vapor and gases leaving the reactor. While the solids recycle loop was able to effectively address the issue of insuring all particles would be completely pyrolyzed it resulted in a small portion of the product vapors being recycled into the high temperature zone of the reactor. This portion of vapors effectively had a longer residence time at the pyrolysis reactor temperature and most likely resulted in cracking of the product to gases thus resulting in slightly lower yields compared to other fluidized bed designs [M. Ringer, V. Putsche, J. Scahill; Large-scale pyrolysis oil production: a technology assessment and economic analysis; Technical report NREL/TP-510-37779, November 2006].

Other design issues with the vortex reactor were: high entering velocities of particles into the reactor caused erosion at the transition from linear to angular momentum, excessive wear was realized in the recycle loop (both wear problems were exacerbated when inert tramp material (stones, etc.) were introduced with the feed), uncertainties about the scalability of the design related to maintaining high particle velocities throughout the length of the reactor. The high velocities are necessary for centrifugal force to maintain particle pressure against the reactor wall. The high sliding velocity and constant pressure of the particle against the 600°C reactor wall are necessary to achieve the high heat transfer requirements for fast pyrolysis. Because of all these weaknesses a development of the ablative vortex reactor was abandoned, approximately in 1997 [M. Ringer, V. Putsche, J. Scahill; Large-scale pyrolysis oil production: a technology assessment and economic analysis; Technical report NREL/TP-510-37779, November 2006].

Scientists at Aston University have developed a thermolysis reactor for the conversion of solid biomass into bio-oil, for use in power and heat generation, as a precursor for biofuels, and as a raw material for chemicals and other speciality products. Aston’s ablative pyrolysis reactor offers the potential for very high specific throughputs with reduced equipment size, lower energy usage, and a corresponding drop in reactor, liquid collection and char removal costs. This technique involves the ‘melting’ or ‘thermal erosion’ of biomass that comes into contact with a hot surface (above 430°C) by applying high mechanical pressure (more than $1*10^5$ Pa) to the particles as they traverse the surface. Over 85% of the biomass “melts” initially, then vaporises off the hot surface. Vapours are then cooled and collected to form a liquid bio-oil product. This process has several other advantages over existing fast pyrolysis techniques [Aston University, Business Partnership Unit report, Commercial opportunity].

- ✓ Bio-oil output that is comparable to the best fast pyrolysis reactors
- ✓ Higher specific throughputs
- ✓ Lower reactor and system volume
- ✓ Lower capital and running costs
- ✓ Much larger particles of biomass [Aston University, Business Partnership Unit report, Commercial opportunity].

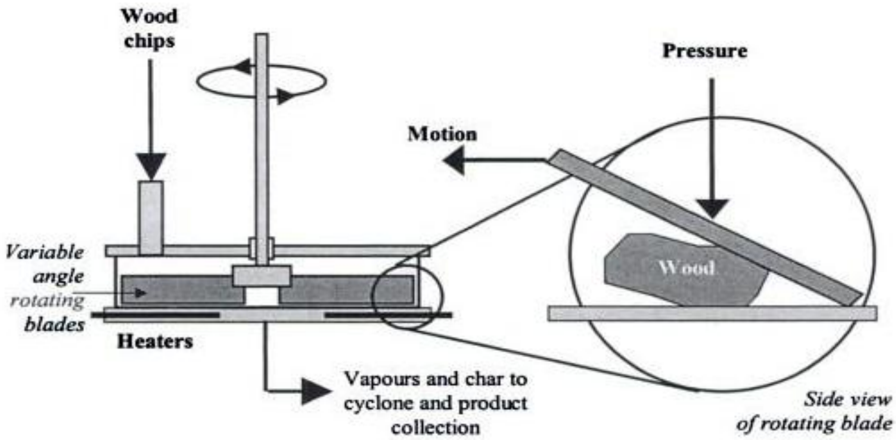


Figure 3.4.2: Aston University rotating blade ablative reactor [Aston University, Business Partnership Unit report, Commercial opportunity].

A variable rate screw feeder carried the feed material to the tangential inlet on the horizontally oriented tubular reactor (ø 82 x 200 mm). Within the reactor a solid rotor with three radial wings having a wing-to-wall clearance of 2 mm turned at a fixed speed between 10 000 and 20 000 rpm creating a centrifugal force at the pipe wall of nominally 4 900 to 17 000 G. At the inlet, the wing-towall clearance was increased by 6 mm to form an acceleration zone in order to minimize the damage to the particles by collision with the wings upon entry. Heat was supplied to the reactor wall by a single electric resistance heater coiled around the pipe. A temperature deviation from the set-point of less than 5 °C was generally achieved for the controlling thermocouple.

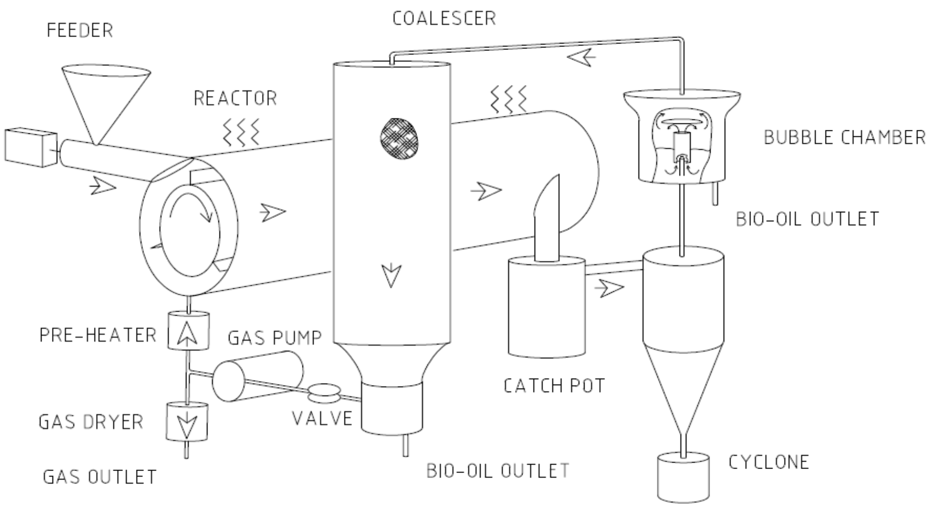


Figure 3.4.3: Experimental ablative Pyrolysis Centrifuge Reactor System [Bech, N.; Jensen, P.A.; Dam-Johansen, K.; Department of Chemical Engineering, CHEC Research Centre, Technical University of Denmark].

4 BIO-OIL

4.1 GENERAL ABOUT BIO-OIL

The liquid product of the pyrolysis processes is bio-oil. The bio-oil could be different even of the same production process, because of the raw material nature and characteristics. Pyrolysis liquid is referred to by many names including pyrolysis liquid, pyrolysis oil, bio-oil, bio-crude-oil, bio-fuel-oil, wood liquids, wood oil, liquid smoke, wood distillates, pyroligneous tar, pyroligneous acid, and liquid wood. It is combustible and renewable hence the use of the term 'bio'. Pyrolysis liquid has a heating value of nearly half that of a conventional fuel oil – typically 16–18 MJ/kg [Prof. T. Bridgewater; Aston University; A guide to fast pyrolysis of biomass for fuels and chemicals; PyNe Guide 1; March, 1999].

4.1.1 BIO-OIL APPEARANCE

Pyrolysis liquid typically is a dark brown free flowing liquid. Depending upon the initial feedstock and the mode of fast pyrolysis, the color can be almost black through dark red-brown to dark green, being influenced by the presence of micro-carbon in the liquid and by the chemical composition. Hot vapour filtration gives a more translucent red-brown appearance due to the absence of char. High nitrogen contents in the liquid can give it a dark green tinge. The liquid has a distinctive odour - an acid smoky smell, which can irritate the eyes if exposed for a prolonged period to the liquids. This is a thick liquid which looks the same with the common oil. [Prof. T. Bridgewater; Aston University; A guide to fast pyrolysis of biomass for fuels and chemicals; PyNe Guide 1; March, 1999].

4.1.2 BASIC CHEMICAL DESCRIPTION

Bio-Oil is made up of the following constituents: 20-25% water, 25-30% water insoluble pyrolytic lignin, 5-12% organic acids, 5-10%non-polar hydrocarbons, 5-10% anhydrosugars and 10-25% of other oxygenated compounds [DynaMotive Bio-Oil overview]. The liquid contains several hundred different chemicals in widely varying proportions, ranging from low molecular weight and volatile formaldehyde and acetic acid to complex high molecular weight phenols and anhydrosugars. The liquid contains varying quantities of water which forms a stable single phase mixture, ranging from about 15% to an upper limit of about 40% water, depending on how it was produced and subsequently collected. Pyrolysis liquids can tolerate the addition of some water, but there is a limit to the amount of water which can be added to the liquid before phase separation occurs, in other words the liquid cannot be dissolved in water. It is immiscible with petroleum-derived fuels [Prof. T. Bridgewater; Aston University; A guide to fast pyrolysis of biomass for fuels and chemicals; PyNe Guide 1; March, 1999].

4.1.3 WATER CONTENT

Bio-oil has a content of water derived from the original moisture in the feedstock and the product of dehydration during the pyrolysis reaction and storage. The presence of water lowers the heating value and flame temperature, but on the other hand, water reduces the viscosity and enhances the fluidity, which is good for the atomization and combustion of bio-oil in the engine. Shihadeh and Hochgreb compared the bio-oils of NREL (National Renewable Energy Laboratory, US) to those of ENSYN (Ensyn Technologies, Inc., CA) and found that additional thermal cracking improved its chemical and vaporization characteristics. The better performance and better ignition of NREL oil derived from its lower water content and lower molecular weight [Zhang Qi, Chang Jie, Wang Tiejun, Xu Ying; Review of biomass pyrolysis oil properties and upgrading research; Energy Conversion and Management; 22 June, 2006].

4.1.4 BIO-OIL DENSITY & VISCOSITY

The density of the liquid is very high at around 1.2 kg/l compared to light fuel oil at around 0.85 kg/l. This means that the liquid has about 42% of the energy content of fuel oil on a weight basis, but 61% on a volumetric basis. This has implications on the design and specification of equipment such as pumps. The viscosity of the bio-oil as produced can vary from as low as 25 cS to as high as 1000 cS or more depending on the water content, the amount of light ends that have been collected and the extent to which the oil has aged. Viscosity is important in many fuel applications. Bio-oil cannot be completely vapourised once they have been recovered from the vapour phase. If the liquid is heated to 100 ^{0}C or more to try to remove water or distil off lighter fractions, it rapidly reacts and produces a char residue of around 50% of the original liquid and some distillate containing primary and secondary products and water. The liquid is, therefore, chemically unstable, and this effect increases with heating, so it is preferable to store the liquid at room temperature. These changes do occur at room temperature, but much more slowly and can be accommodated in a commercial application [Prof. T. Bridgewater; Aston University; A guide to fast pyrolysis of biomass for fuels and chemicals; PyNe Guide 1; March, 1999].

Depending on the biomass feedstocks and pyrolytic processes, the viscosities of bio-oils vary in a large range. Bio-oils produced from Pterocarpus indicus and Fraxinus mandshurica had a kinetic viscosity of 70–350 mPa s and 10–70 mPa s, respectively, and that from rice straw had a minimum kinetic viscosity of about 5–10 mPa s for its high water content [Luo ZY, Wang SR, Liao YF, et al. Research on biomass fast pyrolysis for liquid fuel. Biomass Bioenergy 2004;26:455–62]. Sipilae` et al. investigated the bio-oils from hardwood, softwood and straw by flash pyrolysis in an atmospheric fluidized bed [Sipilae` K, Kuoppala E, Fagernae`s L, et al. Characterization of biomass–based flash pyrolysis oils. Biomass Bioenergy 1998;14(2): 103–13]. It was found that the viscosities were reduced in the bio-oils with higher water content and less water insoluble components. Viscosity was affected by alcohols: an addition of 5 wt% methanol into hardwood pyrolysis oil with low methanol content decreased its viscosity by 35%. The straw oil is less viscous and had the highest methanol content of 4 wt%. The research of NREL showed that the viscosity increased only from 20 to 22 cP over a 4 month period when stored at 20 ^{0}C with 10% methanol addition to the bio-oil. This would extrapolate to a viscosity of 30 cP after storage for 12 months. Ethanol at 20% had a similar stabilizing effect. With 10 viscosity at 40 ^{0}C rose from about 13 cP to an interpolated 15 cP after preheating for 12 h at 90 ^{0}C, e.g. to reduce the viscosity for ease of atomization [Diebold JP. A review of the chemical and physical mechanisms of the storage stability of fast pyrolysis bio-oil. Available from: http:// webdev.its.iastate.edu/webnews/data/site_biorenew_reading/19/webnewsfilefield_ file/ReviewOfMechanisms.pdf]. Boucher et al. tested bio-oil performance with the addition of methanol regarding its use as a fuel for gas turbine applications. The methanol reduced the density and viscosity and increased the stability with the limitation of a lowered flash point in the blend [Boucher ME, Chaala A, Roy C. Bio-oils obtained by vacuum pyrolysis of softwood bark as a liquid fuel for gas turbines.

Part I: Properties of bio-oil and its blends with methanol and a pyrolytic aqueous phase. Biomass Bioenergy 2000;19:337–50].

4.1.5 OXYGEN CONTENT

The oxygen content of bio-oils is usually 45-50%. This oxygen is present in most of the more than 300 compounds that have been identified in the oils. The distribution of these compounds mostly depends on the type of bio mass used and on the process severity (temperature, residence time, and heating rate profiles). An increase in pyrolysis severity reduces the organic liquid yield due to cracking of the vapours and formation of gases but leaves the organic liquid with less oxygen. The single most abundant bio-oil component is water. The other major groups of compounds identified are hydroxyaldehydes, hydroxyketones, sugars, carboxylic acids, and phenolics. Most of the phenolic compounds are present as oligomers having a molecular weight ranging from 900 to 2500. The presence of oxygen in many oil components is the primary reason for differences in the properties and behavior seen between hydro carbon fuels and biomass pyrolysis oils. The high oxygen content results in a low energy density (heating value) that is less than 50% of that for conventional fuel oils and immiscibility with hydro carbon fuels [Bridgwater, A. V.: Biomass Fast Pyrolysis; Thermal Science: Vol. 8 (2004), No. 2].

4.1.6 BIO-OIL ACIDITY

Bio-oils comprise substantial amounts of carboxylic acids, such as acetic and formic acids, which leads to low pH values of 2–3. The bio-oil of pine had a pH of 2.6, while that of hardwood was 2.8 [Sipilae` K, Kuoppala E, Fagernae`s L, et al. Characterization of biomass–based flash pyrolysis oils. Biomass Bioenergy 1998;14(2): 103–13]. Acidity makes bio-oil very corrosive and extremely severe at elevated temperature, which imposes more requirements on construction materials of the vessels and the upgrading process before using bio-oil in transport fuels.

4.1.7 BIO-OIL HEATING VALUE

The properties of bio-oils depend on factors, such as biomass feedstocks, production processes, reaction conditions and collecting efficiency. Usually the bio-oils of oil plants have a higher heating value compared with those of straw, wood or agricultural residues. Beis et al. conducted pyrolysis experiments on a sample of safflower seed and obtained bio-oil with a heating value of 41.0 MJ/kg and a maximum yield of 44% [Beis SH, Onay O, Kockar OM. Fixed-bed pyrolysis of safflower seed: influence of pyrolysis parameters on product yields and compositions. Renew Energy 2002; 26:21–32]. Ozcimen and Karaosmanoglu produced bio-oil from rapeseed cake in a fixed bed with a heating value of 36.4 MJ/kg and a yield of 59.7%. However, taking wood and agricultural residues as raw materials, the bio-oils have a heating value of about 20 MJ/kg and a yield up to 70–80% [Ozcimen D, Karaosmanoglu F. Production and characterization of bio-oil and biochar from rapeseed cake. Renew Energy 2004;29: 779–87].

4.1.8 COMBUSTION PROCESS & ASH CONTENT

All these properties have an important impact on the behavior of bio-oils during combustion and consequently on the applications for energy production in standard equipment. Bio-oils are combustible but not flammable; because of the high content of non-volatile components bio-oil requires significant energy for ignition but once ignited, it burns with a stable self-sustaining flame. Combustion tests performed on single droplets demonstrated a very unique, multi-step process comprised of the following phases: ignition, quiescent burning (blue), droplet micro-explosion, disruptive sooty burning of droplet fragments (bright yellow), and formation and burnout of cenosphere particles. In contrast, petroleum distillate fuel oil demonstrated in the same conditions only quiescent, sooty burning from ignition through burnout. These properties of bio-oil could be used in comparison with fossil fuel combustion [Bridgwater, A. V.: Biomass Fast Pyrolysis; Thermal Science: Vol. 8 (2004), No. 2].

The presence of ash in bio-oil can cause erosion, corrosion and kicking problems in the engines and the valves and even deterioration when the ash content is higher than 0.1 wt%. However, alkali metals are problematic components of the ash. More specifically, sodium, potassium and vanadium are responsible for high temperature corrosion and deposition, while calcium is responsible for hard deposits [Zhang Qi, Chang Jie, Wang Tiejun, Xu Ying; Review of biomass pyrolysis oil properties and upgrading research; Energy Conversion and Management; 22 June, 2006].

4.1.9 BIO-OIL PREFERENCES AND WAYS OF UTILIZATION

Bio-oil could be used in many ways such as direct combustion, hydrocracking, gasification, fermentation. Various methods of bio-oil use follows development of applications and equipment. Bio-oil brings a lot of positive moments to the biomass market industry. It increase customer's interest and call, makes biomass market more sustainable and competitive compare to fossil fuels, because of bio-oil properties and ways of utilization. Many biomass sources are suitable for upgrading methods, convertible into opposite conditions. Bio-oil is applicable and effective in cogeneration and second generation transport fuel production. Bio-oil properties are making this fuel comfortable in use. It can be easy transported and utilized, it can be used in existing applications without any changes, environmental friendly and equipment safety. Bio-oil co-products are almost invisible or trace, there are: group of gases (CO, H_2, light hydrocarbons) and char or ash. These products could be very useful for energy production cycle (could be used as additional heat) and environment (soil fertilizer). Well, now it is possible to make a conclusion depended on summary of bio-oil production processes, fuel properties and characteristics. There are major bio-oil advantages:

- ✓ Compare to other bio-fuel, bio-oil is easy storable and transportable
- ✓ Successful applied to all existing equipment
- ✓ Wide range of use (bio-diesel production, chemicals, etc.)
- ✓ Great commercial and economic development potential (shows sustainable competitiveness against fossil fuels)
- ✓ Includes other bio-fuel advantages (cost, energy sector development, environmental friendly production, low emission combustion and etc.)

4.2 BIO-OIL AVERAGE CHARACTERISTICS

Table 4.1.1: Summary of typical properties and characteristics of wood bio-oil [Bridgwater, A. V.: Biomass Fast Pyrolysis; Thermal Science: Vol. 8 (2004), No. 2].

Physical property	Typical value	Notes
Moisture content	25%	Water comes from moisture in the feed and reaction water and cannot be separated. Values can range from 15 to 35%
pH	2.5	The low pH comes from organic acids
Density	1.20	Very high at around 1.2 kg/l compared to light fuel oil at around 0.85 kg/l. Bio-oil has about 40% of the energy content of fuel oil on a weight basis, but 60% on a volumetric basis
Elemental analysis		Typically: C: 57%, H: 6.0%, O: 37%, N: trace; Ash;trace depending on char content
Ash	0%	All ash is associated with the char
HHV as produced (depends on water)	18 MJ/kg	Bio-oil has a higher heating value of about 18 MJ/kg as produced with about 25% wt. water that cannot be separated
Viscosity (at 40 °C and 25% water)	50 cp	Viscosity as produced can vary from 20 cSt to as high as 1000 cSt (measured at 40 °C) depending on feedstock, water content, light and ageing
Solids (char)	0.2%	0.1% is a good level and 1% is often encountered
Vacuum distillation residue	50%	Cannot be completely vaporised. Heating to 100 ºC causes production of a solid residue of around 50% of the original liquid and distillate containing volatile organics and water
Appearance		Typically a dark brown free flowing liquid
Odour		A distinctive smoky smell
Miscibility		Water addition can be tolerated up to about 35%. Bio-oil is miscible with polar solvents such as methanol, but totally immiscible with petroleum-derived fuels

5 PROJECT PERFOMANCE

This chapter is a kind of introduction to the final thesis work. It will perform general assumptions and information, will introduce the problem, solutions and examples of the final thesis task. It is very important part of work, because it contains the idea of thesis development. The thesis name is economics of combined power plant and pyrolysis bio-oil application. The main topic idea is to make economic comparison between two combinations and use it as a basis in conclusion economic efficiency research. Well, here is another possible work explanation. It is a research to develop economic part of new stream of bio-fuel production by several different methods. More detailed example description would be performed further.

The biggest problems of all bio-energy projects are low level of experience and low development of project parts. Many of bio-energy projects are still under developing or performed it segment as experimental or pilot plants. And of course aspects like these could not cooperate to bio-energy project development, because a business vague profitability decreases investor's interest and confines investments.

The main investor of bio-energy projects is a country government and country energy corporations. Well, anyway a country government the biggest supporter for bio-energy development. It creates different projects, promoted actions, makes donations and taxes, obliges energy companies to fulfill it requirements. Correct government politics could encourage and stimulate the development of bio-energy sector. That is why a country government not only the most important investor but and a great regulation instrument. Not industrialized and developed, poor countries are not interested in the bio-energy development because of money lack. All energy projects are very expensive with a long term payback, costs sometimes tens and hundreds of millions euro. It follows a necessity of project risk minimization. Each business plan basis is economics. Project good theoretic economy makes it attractive in reality

This final thesis is a "drop", a part of common bio-energy development, maybe one day would help someone to build successful and efficient project. It will provide an information about which plant more efficient (combined or stand alone), which of pyrolysis bio-oil production processes is more reliable and cheap, which of two combinations is more logic and profitable.

5.1 PROJECT FORMULATION AND ASSUMPTIONS

5.1.1 LOCATION

This part will perform the basic information about the final thesis project. It will describe a plants location, size, equipment, processes; location characteristics; provide a data of bio-oil raw material. And it will include the information about several energy companies and organizations.

Chosen plant location seems to be, as a right decision. Nordic region is high developed in bio-energy. By the way, the final thesis has been done at the Finnish university. Today, Finland is developing many researches and projects to build a competitive structure of bio-fuel against fossils. Finish government create a great support for renewable energy share increase. Finnish population is solicitous about healthy way of life and about problems around environmental pollution. All these measures, deep invented in the life of typical resident, are giving a great result and good example for the rest of the world society.

Figure 5.1.1: Map of Finland [europa.eu].

Finland is a Nordic country situated in the Fennoscandian region of Nothern Europpe. It is bordered by Sweden in the west, Norway in the north and Russia in the east, while Estonia lies to its south across the Gulf of Finland [The free encyclopedia, Wikipedia]. Finland is in northern Europe, low-lying in the south and center with mountains in the north. One quarter of its territory lies north of the Arctic Circle, and the country experiences long, harsh winters. Most of the population is concentrated in the triangle formed by the cities of Helsinki (the capital), Tampere, and Turku. Coniferous forests and more than 180,000 lakes grace Finland, which maintains a fleet of icebreakers to keep ports open during the long winters. Despite a short growing season Finland is self-sufficient in meat, grains, and dairy products. For years, the wood and paper industry dominated Finland's exports; but now the metal and engineering aspects of industry have surpassed forest products [National Geographic].

The main idea of location description is a presentation of it climatic conditions. As was written before, one quarter of the Finnish territory is lying north of the Arctic Circle. Finland has a humid and cool semi continental climate, characterized by warm summers and freezing winters. The climate type in southern Finland is north temperate climate. Winters of southern Finland (average day time temperature is below 0 ^{0}C) are usually four months long, and the snow typically covers the land from middle of December to early April. In the southern coast, it can melt many times during early winter, and then come again. The coldest winter days of southern Finland are usually under −20 °C, and the warmest days of July and early August can be as high as 30 °C, although this is relatively rare. In northern Finland, particularly in Lapland, a subarctic climate dominates, characterized by cold – occasionally severe – winters and relatively warm, short summers. The main factor influencing Finland's climate is the country's geographical position between the 60th and 70th northern parallels in the Eurasian continent's coastal zone, which shows characteristics of both a maritime and a continental climate, depending on the direction of air flow. Finland is near enough to the Atlantic Ocean to be continuously warmed by the Gulf Stream, which explains the unusually warm climate considering the absolute latitude [The free encyclopedia, Wikipedia].

The climatic conditions are very significant for project development and further forecast in bio-energy industry. Cold and harsh climate brings necessity in increased heat and electricity input to control and operate heat and mass media processes at required parameters. Hot and dry climate brings an opposite opportunity. For example, high temperature could bring several changes into fermentation process and quicken it digestion. So, climatic conditions should be definitely considered.

5.1.2 RAW MATERIAL

The Finnish territory is reach of wood. Forest covers 86% of the country's area, the largest forested area in Europe. The forest consists of pine, spruce, birch, larch and other species. Finland is the largest producer of wood in Europe and among the largest in the world. The landscape is covered mostly (seventy-five percent of land area) by coniferous taiga forests and fens, with little arable land [The free encyclopedia, Wikipedia]. This abundance of wood resource makes the Finnish bio-energy based on wood and paper residue. Actually is a major fact of the Finnish world leader position in the wood energy production.

For the final thesis pyrolysis applications research was chosen wood chips raw material. This decision is logic in many project aspects. Wood chips which had been gathered and produced inside the Finnish territory are very cheap. It could be easy storage and transported, preparation and utilization equipment are high developed and easy in use. Wood chips material has a good characteristics for pyrolysis bio-oil production. Wood chips as a fuel resource has a numbers of collection residue methods and numbers of production processes. For example, it starts from the harvesting in the forest and ends in the drying machine after a woodchipper. This is one of the most common ways of wood chips production. Other popular way is woodworking industry, where chips or residues are harvested for further bio-fuel production and utilization. Possible chips harvesting and production comes from other industrial residues and demolition wood.

Wood chips are the most abundant bio-fuel but at the same time the least well-defined. Hence, standardization of wood chips is complicated and there are several standards already in effect or upcoming. The most relevant are EN 14961-4 for general classification and EN 15234-4 for the quality assurance [Linnaeus University FOREST-Handbook, chapter 00-10 1 Wood chips – Properties].

The biggest weakness of wood biomass used as bio-fuel is the fact of the wood “dirty” nature. It means that wood consist of many heavy elements. Mostly it comes to the roots like a feed from the soil. Wood combustion typically is high emission process. Wood combustion damages a plant equipment. It is full of CO_2, NO_x, metals and etc. Corrosion and erosion, fouling and slagging of boiler furnace

Table 5.1b.1: Low heating value of the most common tree types dry mass, MJ/kg [Tallinn Technical University; Villu Vares, Julo Kask, Peeter Mujste, Tynu Pihu, Sulev Soosaar; Bio-fuel guide, 2005].

TREE	TRUNK WITHOUT BARK	BARK	WHOLE TRUNK	TWIGS & CROWNS	WHOLE TREE
Pine	19.31	19.53	19.33	20.23	19.52
Spruce	19.05	18.80	19.02	19.17	19.29
White birch	18.68	22.75	19.19	19.94	19.30
White European birch	18.61	22.52	19.15	19.53	19.29
White alder	18.67	21.57	19.00	20.03	19.18
Black alder	18.89	21.48	19.31	19.37	19.31
Aspen	18.67	18.57	18.65	18.61	18.65

and surface are making wood fuel non attractive. It is one of the major reasons of the wood conversion development, it upgrading and gathering new sources. By the way, Finland is implementing the Kyoto Protocol and several other documents, such as Green Paper, based on environmental protection and emission reduce. The Finnish government is looking forward to replace fossil fuels with renewable sources.And it has social and national programs for renewable energy industry support. One of the programs is every year donation. Finnish residents are paying taxes per year for development of bio-energy sector.

6 CASE DESCRIPTIONS

6.1 PLANT COMBINATION №1

As was written before, the thesis name is economics of combined power plant and pyrolysis bio-oil application. The given task is to make an economic comparison between two different applications. There are: boiler plant below 20 MW in combination with ablative pyrolysis plant for bio-oil production and quite big co-generation cycle plant below 100 MW in combination with the RTP pyrolysis bio-oil production technology.

The working cycle till the scheduled maintenance period is 330 days per year, because of the Finnish climate and long term necessity in heat. The raw material for the boiler plant and ablative pyrolysis is wood chips. The quantity of raw material, which is going to the ablative pyrolysis plant for bio-oil production is 100 tons of dry biomass per day. The average high heating value of wood chips is about 15-18 MJ/kg.

Probably, it is not very important to give a completely detailed description of heating plant, combined with the ablative pyrolysis bio-oil production cycle. The reason is the fact that the thesis task is the economic efficiency of previously selected combinations, and the ablative pyrolysis process was descripted and explained in previous parts. Well nevertheless, to exclude several of description moments in the second case and prevent it expansion, better to show the basic energy production processes, using practical description of more simple boiler plant cycle. For the first case of the thesis development was chosen the application, well performed by "Komforts", Latvian energetic company.

The heating plant includes four vertical boilers with a capacity of 5 MW each. Boilers are working with furnace extensions with slanted active furnace-bar. With the work of hydraulic tappet, fuel from the storage is coming on the scapular conveyor and further to the conveyor belt. The conveyor belt is working in reversing regime. In the furnace extension fuel came by the hydraulic tappet. The combustion process takes place on the slanted active furnace-bar. On the upper part of the furnace-bar fuel is getting drying and on the bottom part fired. The rest of ash, which not came out with emission gases through the funnel, left at the bottom of the furnace and by hydraulic tappet come to the special tank or on the ash removal conveyor.

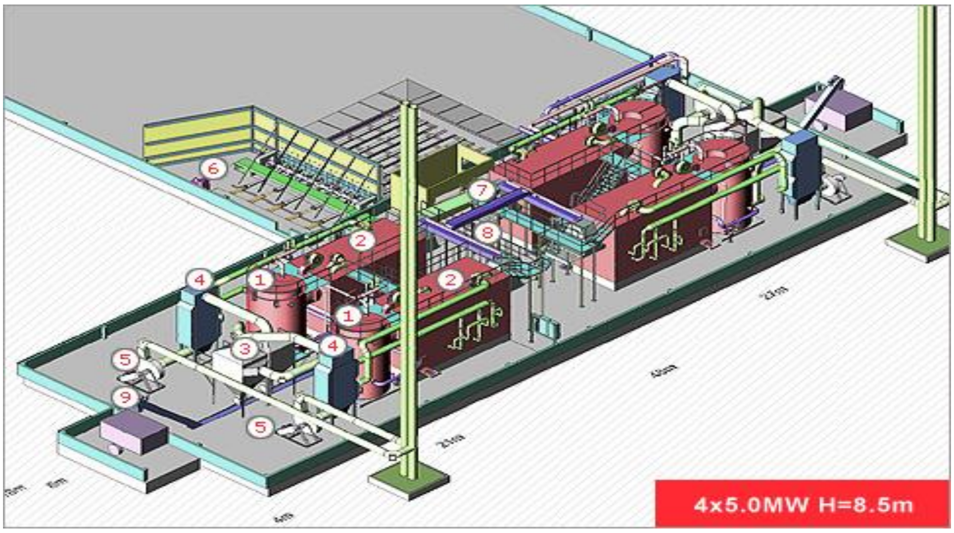


Figure 5.2a.1: Wood chip heating plant, 20 MW [“Komforts”].

Prime air sets under the furnace-bar, secondary air sets above the furnace-bar and tertiary sets to after burning camera of the furnace extension. Quantity of coming air, regulates by choke and depends on the fuel quantity and quality. Quantity of the oxygen in a smoke gases, controlled by an oxygen sonde, which is situated in the flue behind the boiler. Temperature in the furnace is regulated by temperature detector, which is installed inside the furnace (after 1100 ^{0}C it is an ash fusion). When the temperature in the furnace is reaching the critical point, coming fuel is decreasing. Essentials exhaustion in the furnace is regulated by smoke exhaust, which consists of frequency converter and exhaustion detector. A rotor rotation of the smoke exhaust are regulated automatically, depends on the furnace exhaustion. The combustion process in the furnace extension is regulated in according to essential water temperature in the boiler way out. With the water temperature is reaching the required point, follows decreasing of fuel and air supply. The process of combustion is controlling and handling in the scale of around 2 ^{0}C, of required water temperature in the boiler way out. The work of the heat-and-power engineering equipment is fully under automation. It is possible to connect a control panel with computer and Internet and control the process from other continent. The ash removal could be done by several ways. The ash could be removal from the heating plant by screw conveyor or by feed scapular chain transporter.

Picture keys:

1. Heating boiler.
2. Furnace extension.
3. Multicyclone.
4. Heater of primary air.
5. Smoke exhaust.
6. Fuel storage with active floor and hydraulic tappet.
7. Feed scapular chain transporter.
8. Control conveyor belt.
9. Fly-ash system.

After the boiler plant cycle, a part of heated water is going to the ablative pyrolysis application to heat the reactor. This is the main reason of combination to save energy and money loses and to increase the bio-oil production efficiency. The water temperature is around 110 ^{0}C. To minimize temperature loses, it is necessary to make water line system as shorter as possible. That means that the boiler plant and ablative pyrolysis application should be situated close to each other. That will reduce the water line system length, it follows reduction of constructed costs and heat transfer loses. By the way, heating plant is one of the cheapest energy generated applications, the most thermal efficient and easy to operate and control. It is one of the most common technologies for district heat supply, especially for small, distant and nook communities or regions.

5.2.2 PLANT COMBINATION №2

As was written before, the second combination is the RTP pyrolysis bio-oil production technology with CHP plant. And this chapter equipment description is going to be shorter than the previous one. The decision is logic because there is a great amount of power plant working equipment. The reason of the final thesis is economic comparison, but not a technical characterization. It is necessary to provide a basic, technical data for general items, such as turbine and boiler. The chosen items are a steam turbine and a high efficiency bubbling fluidized bed boiler.

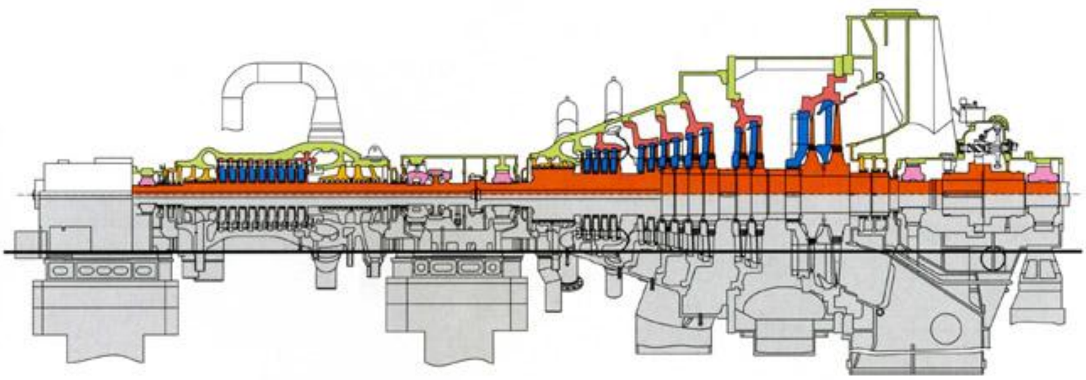


Figure 5.2b.1: "T" type steam turbine [The Ural Turbine Works, http://utz.ru].

The turbine is produced by Russian company the Ural Turbine Works. The model of turbine is T- 113/145-12.4. This is very popular and universal model of cogeneration or extraction turbine's "family", with keeping of basic design depending from steam parameters can have marking from T-100/130-12.0 up to T-125/150-12.6. On the base of this turbine there can be condensing steam turbines with capacity 130-150 MW produced. The starting parameters of the chosen turbine are: 12.4 MPa, 557.6 ^{0}C and 316.7 t/h [The Ural Turbine Works, http://utz.ru].

Theoretical working scheme of "T" type turbine could be presented as next phases description. Hot steam from the boiler unit comes to the vapor line and further to the working blades of the steam turbine high pressure part. With the expansion, the kinetic energy of the steam is converted into rotation mechanical energy of the turbine rotor, which is connected with a shaft of electric generator. During the steam expanding process, from the average pressure cylinder the extracting bleeding are done and the steam is going to the delivery water heaters. Exhaust steam from the last turbine stage enters the condenser, where it condensates and then through the pipeline is returned to the boiler unit by a pump. The biggest part of the heat, produced in the boiler, is using to heat the delivery water [The Ural Turbine Works, http://utz.ru].

The bubbling fluidized bed boiler will be provided by Vapor, Finnish company. Some of the basic parameters are identical with the turbine, and it is not necessary to provide the complete information about the item, so it is enough to prefer the boiler theoretical processes and several important properties. The boiler will be designed especially to the project and will use a different of shown parameters. Here is the basic characteristics and information about the BFB boiler technologies, presented on official web-page of the company.

The boiler technology is based on a modern membrane wall, natural circulation boiler with a patented Vapor Steamtec bubbling fluidizing bed grate. The BFB grate has no moving parts and can accept impurities like metal, stones and concrete in the biomass. The impurities are removed during the operation though the grate openings. The bubbling fluidizing bed is an 800–900 ^{0}C and 300–500 mm high layer of natural sand or other ceramic material, which is fluidized with primary air flow through air nozzles at the bottom of the grate [VAPOR, http://www.vapor.fi].

The biomass is fed through a fire safe fuel feeding system and chute into the boiler. There is a possibility to have a side feeding system for wood residues and Solid Recovered Fuels (SRF). This requires continuous monitoring of the flue gases. The bubbling hot sand effectively dries and gasifies the biomass fuel. The secondary air and tertiary air are fed to the combustion chamber for clean and efficient multistage combustion of the biomass. The air flows are controlled by the automation system to achieve high efficiency and low emissions. The bed temperature, usually about 850 ^{0}C is cooled, when necessary by diluting the primary air with recycled flue gas, containing less oxygen than air [VAPOR, http://www.vapor.fi].

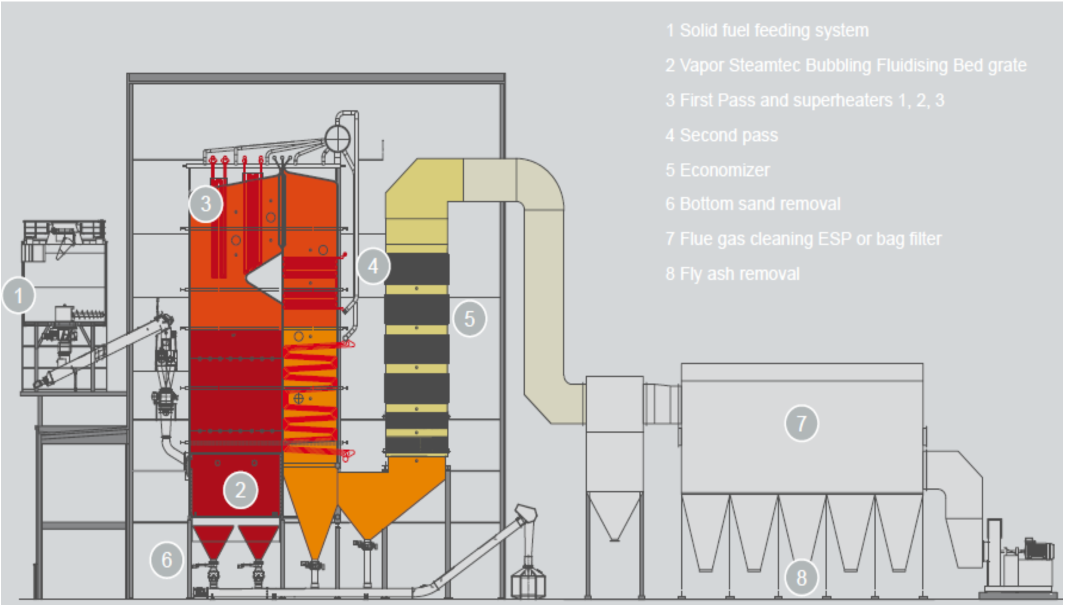


Figure 5.2b.2: BFB boiler scheme [VAPOR, http://www.vapor.fi].

The BFB boiler is high efficient and environmental friendly. It has low emission level and maintenance cost, because of the absence of the moving parts. The high coefficient of efficiency around 88%, and long time between schedule maintenance over 8500 h/y. These boiler and turbine parameters are sufficient in the project on the Finnish territory. The process of the efficient combination between power generated plant and pyrolysis bio-oil production application, was fully described in the first case. As possible to see after both cases examinations, the combination idea is the same, but with a difference of working equipment.

After the CHP plant cycle, a parts of heated water and exhausted steam are going to the RTP pyrolysis bio-oil application to heat the reactor. This is the main reason of combination to save energy and money loses and to increase the bio-oil production efficiency. To minimize temperature loses, it is necessary to make water line system as shorter as possible. That means that the boiler plant and the RTP pyrolysis application should be situated close to each other. That will reduce the water line system length, it follows reduction of constructed costs and heat transfer loses. With the CHP plant size around 100 MW it is possible to increase the bio-oil production through the RTP method. The RTP process is faster than the ablative and with the bigger heat supply it is possible to expand the application or to build several applications.

7 ECONOMIC COMPARISONS

7.1 ABLATIVE PLANT & BOILER PLANT APPLICATION

This part of thesis is economic evaluation of projects cost and it comparisons. It will include all segments of project designing such as project development, building costs, equipment prices, different loses, total cost, operating cost, production price and profitability of the application. The fundamental idea of this comparison is to find and prove the most efficient plant combination. Other thing is to face the efficiency of stand-alone plants in comparison of done combinations. All evaluations, economic assumptions, basic material and facts are based on the final thesis work of Jerkko Stark "Nopeaan pyrolyysiin perustuvan bioöljyn tuotantolaitoksen liiketoiminnallinen malli ja kannattavuuslaskenta Savonlinnan seudulla".

Of course, our works are very different, searching and achievements had been done by different ways and in different sides, but still has some of contacted points. The biggest differ between our works is the plant cycle. Jerkko Stark is developing a stand-alone RTP bio-oil plant. It is relevant to pick from that thesis the Finnish electricity and biomass prices, the RTP technology equipment cost, evaluation construction, fundamental of balances and other information. Well, probably, it is possible to say that a part of Starck's work will have a simple change, development and use in several directions here. By the way, one more important thing is inaccuracy and rough estimate of project combinations and it equipment. This is the consequence of the energy market sustainability and competitiveness. All the companies are interested in a careful security of new technologies. The creation of patents and long term technology hiding are helping to win the market innovative competition. These are the reasons of cost information lack.

7.1.1 CAPITAL COST

Based on Stark's project and information provided by Aston University, it is possible to make a logic conclusion about the cost of the ablative pyrolysis bio-oil equipment. Ablative equipment is chipper than the RTP technology equipment. These are different technologies and ablative cycle not includes a biomass preparation process such as drier, chipper and etc. Only this fact brings around of 5 M€ savings. The ablative cycle consists of simple handling system, conveyor, pyrolysis equipment, bio-oil tank, pump and oil line to access the transportation item. Besides, it is necessary to put in the account a water line, which is connected with the boiler plant and provides the transportation of hot water to heat the ablative pyrolysis reactor. And of course all these capital costs of ablative pyrolysis bio-oil production are in summary with total cost of the "Komforts" boiler plant.

Table 7.1.1: Capital cost of the ablative pyrolysis bio-oil application equipment.

Cycle step	Pre-Cycle Processes	The Ablative Cycle	Product
Equipment	Simple handling system, conveyor and etc.	The Ablative Equipment	Tank, pump, oil line and etc.
Cost	100 000 €	7 000 000 €	170 000 €

As was written before, the ablative pyrolysis technology is underdevelopment and this is a reason of it small plant capacity. Today the biggest ablative reactor is equal to utilization of 50 t/d raw material. The target of the final thesis project brings the necessity of two ablative pyrolysis applications downloading. The final cost of the ablative plant with raw material consumption of 100 t/d will be multiply the cost of one plant by coefficient of 1.7.

The capital cost of every project, especially plant building project, includes secondary expenses. Secondary expenses are: road, telephone, water line connection costs and etc. There are building, electrification, HVAC, automatic control system, piping and other lines secondary expenses. Besides, this segment of expenses includes expenses, which were not included into account or just forgotten. The secondary expenses are around 30% of the project total capital cost. The total capital cost is a multiplication of total equipment project cost by coefficient of 0.7. The capital equipment cost of 100 t/d ablative pyrolysis application is 12 359 000 € and a cost of the 20 MW boiler plant is 14 500 000 €. It follows the total capital cost of 38 370 000 € and the secondary expenses amount is 11 511 000 € [Based on: Jerkko

Stark; Nopeaan pyrolyysiin perustuvan biooljyn tuotantolaitoksen liiketoiminnallinen malli ja kannattavuuslaskenta Savonlinnan seudulla; 2011].

Well, the combination of the 20 MW boiler plant and the ablative pyrolysis bio-oil plant cost 38 370 000 €. The Finnish government started a national bio-energy program and supports the energy projects by donations, taxes and etc. It provides a 20% discount of the project total capital cost and brings 7 674 000 € of savings for this plant combination. The final capital cost of the project is 30 696 000 €.

Table 7.1.2: Project total capital costs.

	Total equipment cost	Total capital project cost	Final total cost (Total project cost - 20%)	Savings
The ablative pyrolysis plant	1.7 x 7 270 000 €			
The boiler plant	14 500 000 €			
Cost	26 859 000 €	38 370 000 €	30 696 000 €	7 674 000 €

7.1.2 BASIC PROJECT DATA & BIOMASS EXPENSES

This table shows the evaluation process of the raw material in the ablative cycle and the quantity of needed or expended electricity. Using the biomass cost it is coming clear by several operations. By the way this table shows the basic process data for further economic calculations. Period between scheduled maintenance is 330 days per year. The conversion coefficient shows the quantity of needed electricity to operate with one ton of raw material and production efficiency is the coefficient of process efficiency. These are equal to 5 MWh/t and 70% accordingly [Based on: Jerkko Stark; Nopeaan pyrolyysiin perustuvan biooljyn tuotantolaitoksen liiketoiminnallinen malli ja kannattavuuslaskenta Savonlinnan seudulla; 2011].

Table 7.1.3: Basic process data for raw material.

Feed-biomass cost	€/MWh	13
Capacity efficiency	%	100
Feed-biomass cost	€/t	92.86
	€/MWh	18.57
Feed-biomass	t/d	100
	MWh/d	500
Feed-biomass need	t/a	33 000
	MWh/a	165 000

The raw material price €/t was obtained by the evaluation, which can be preferred as next short determination. The biomass cost was divided by coefficient of the process efficiency, multiplied by conversion coefficient and 100% [Based on: Jerkko Stark; Nopeaan pyrolyysiin perustuvan biooljyn tuotantolaitoksen liiketoiminnallinen malli ja kannattavuuslaskenta Savonlinnan seudulla; 2011].

Table 7.1.4: Basic data for pyrolysis oil.

Pyrolysis oil	t/d	70
	MWh/d	350
	t/a	23 100
	MWh/a	115 500
Total biomass cost	€/a	2 144 835

7.1.3 OTHER EXPENSES

Other operating cost expenses are not interconnected with the technologic processes. These payments are more economic origin and can be very important for the project sustainability and profitability [Based on: Jerkko Stark; Nopeaan pyrolyysiin perustuvan biooljyn tuotantolaitoksen liiketoiminnallinen malli ja kannattavuuslaskenta Savonlinnan seudulla; 2011].

Table 7.1.5: Personnel expenses and project insurance.

People at work	kpl	3
Yearly cost per person	€	70 000
Summary	€/a	210 000
Insurance	€	200 000

7.1.4 MAINTENANCE AND ELECTRICITY EXPENSES

Maintenance cost per year theoretically based on amount of the total investments not included the government discount. Usually, this expense is determinate as 3% of the total investments. The electricity price of 64,6 €/MWh is an average price in Finland and it seems acceptable for the project development. The electricity expenses calculation is for the working plant period. The expended electricity during the maintenance period is included to the maintenance expenses [Based on: Jerkko Stark; Nopeaan pyrolyysiin perustuvan biooljyn tuotantolaitoksen liiketoiminnallinen malli ja kannattavuuslaskenta Savonlinnan seudulla; 2011].

Table 7.1.6: Maintenance and electricity project data.

Electricity need	MW	4
Operating hours	h/a	7920
Electricity need	MWh/a	31 680
Electricity cost	€/MWh	64.6
Total cost	€/a	2 046 528
Maintenance	€/a	1 151 100

7.1.5 OPERATING COST SUMMARY

Total operating cost is a summary of all operating expenses. It includes biomass expenses, other expenses, maintenance and electricity expenses. Well, the total operating cost is 5 752 463 €. Further calculations of product cost and profitability need in several modifications. To simplify and to make the calculation more accurate it is necessary to make a € to €/MWh conversion. The first thing to implement this operation is determination of each part operating expenses percentage share, obtained as a share of the total operating cost [Based on: Jerkko Stark; Nopeaan pyrolyysiin perustuvan biooljyn tuotantolaitoksen liiketoiminnallinen malli ja kannattavuuslaskenta Savonlinnan seudulla; 2011].

Table 7.1.7: Shares of operating costs.

Biomass	37%	18.6 €/MWh
Personnel	3.6%	1.8 €/MWh
Insurance	3.4%	1.73 €/MWh
Electricity	35.6%	18 €/MWh
Maintenance	20%	10 €/MWh
Total	99.6%	50.13 €/MWh

7.1.6 PRODUCTION COST

Many different values influences on the production cost. But the most important value taken into calculation is the investment cost. It is converted to the €/MWh dimension and shows the product investment input and corrected the profitability of the process. To find out the value it is accurate to multiply total investment cost (included government discount) and annuity value, the done number divided by 100%, production amount and conversion coefficient. The annuity value is 7.1%. For the combination of the ablative pyrolysis application and the boiler plant this coefficient is high and equal to 46.2 €/MWh. Then it is possible to calculate the product price after the process [Based on: Jerkko Stark; Nopeaan pyrolyysiin perustuvan biooljyn tuotantolaitoksen liiketoiminnallinen malli ja kannattavuuslaskenta Savonlinnan seudulla; 2011].

Table 7.1.8: Production cost after the process.

Investment cost	€/MWh	46.2
Raw material cost	€/MWh	18.6
Summary of other operating costs	€/MWh	31.53
Total	€/MWh	96.33

This table results provides an opportunity to calculate the product total cost per year and to get approximately view of the project profitability. The conversion of the total product cost after the process from €/MWh to € shows the real product cost per year. It is 11 108 170 €. The subtraction of the yearly product cost and the yearly process expenses is the project profit. The calculation is equal to 5 355 707 €/a. Well, the payback period is less than six years, further it started a profit period (theoretically) [Based on: Jerkko Stark; Nopeaan pyrolyysiin perustuvan biooljyn tuotantolaitoksen liiketoiminnallinen malli ja kannattavuuslaskenta Savonlinnan seudulla; 2011].

7.2 RTP BIO-OIL TECHNOLOGY & CHP PLANT

This chapter is about economic calculation of combination №2 and would be done by principle of the first application. Well, this part will include less of the basic assumptions and other information, because of it identity with the first case. The calculation needed data will be preferred as description material between calculated tables.

And it is necessary to say about CHP equipment prices which were taken into account. CHP plant is a great energetic complex full of central and auxiliary equipment. This is a reason of approximate capital cost for CHP application. It is not possible to choose and calculate all of the equipment, various instruments and tools inside of this final thesis work. Only general equipment prices would be presented. The RTP technology equipment costs are based on Jerkko Stark “Nopeaan pyrolyysiin perustuvan bioöljyn tuotantolaitoksen liiketoiminnallinen malli ja kannattavuuslaskenta Savonlinnan seudulla” project.

7.2.1 CAPITAL COST

This application capital cost would be presented as a summary of both CHP and RTP plants. The first examination would be done with the pyrolysis bio-oil production plant. The capital cost of the RTP equipment is 31 364 000 €. The capital cost of every project, especially plant building project, includes secondary expenses. Secondary expenses are: road, telephone, water line connection costs and etc. There are building, electrification, HVAC, automatic control system, piping and other lines secondary expenses [Based on: Jerkko Stark; Nopeaan pyrolyysiin perustuvan biooljyn tuotantolaitoksen liiketoiminnallinen malli ja kannattavuuslaskenta Savonlinnan seudulla; 2011].

Besides, this segment of expenses includes expenses, which were not included into account or just forgotten. The secondary expenses are around 30% of the project total capital cost. The total capital cost is a multiplication of total equipment project cost by coefficient 0.7. The cost of 100 MW CHP all equipment is around 45 000 000 €. It included the approximate cost for the BFB boiler and steam turbine. These item prices are around 8 000 000 € and 3 500 000 €, accordingly. Well, the summary of applications equipment is 76 364 000 €. Finally, the calculation brings 109 091 429 €

of combination total capital cost and the secondary expense is 32 727 429 € [Based on: Jerkko Stark; Nopeaan pyrolyysiin perustuvan biooljyn tuotantolaitoksen liiketoiminnallinen malli ja kannattavuuslaskenta Savonlinnan seudulla; 2011].

The Finnish government started a national bio-energy program and supports the energy projects by donations, taxes and etc. It provides a 20% discount of the project total capital cost and brings 21 818 286 € of savings for this plant combination. The final capital cost of the project is 87 273 143 €.

Table 7.2.1: Project total capital costs.

	Total equipment cost	Total capital project cost	Final total cost (Total project cost -20%)	Savings
The RTP application	31 364 000 €			
CHP plant	45 000 000 €			
Cost	76 364 000 €	109 091 429 €	87 273 143 €	21 818 286 €

7.2.2 BASIC PROJECT DATA & BIOMASS EXPENSES

This table shows the evaluation process of the raw material in the ablative cycle and the quantity of needed or expended electricity. Using the biomass cost it is coming clear by several operations. By the way this table shows the basic process data for further economic calculations. Period between scheduled maintenance is 330 days per year. The conversion coefficient shows the quantity of needed electricity to operate with one ton of raw material and production efficiency is the coefficient of process efficiency. These are equal to 5 MWh/t and 70% accordingly. The raw material price €/t was obtained by the evaluation, which can be preferred as next short determination. The biomass cost was divided by coefficient of the process efficiency, multiplied by conversion coefficient and 100% [Based on: Jerkko Stark; Nopeaan pyrolyysiin perustuvan biooljyn tuotantolaitoksen liiketoiminnallinen malli ja kannattavuuslaskenta Savonlinnan seudulla; 2011].

Table 7.2.2: Basic process data for raw material.

Feed-biomass cost	€/MWh	13
Capacity efficiency	%	100
Feed-biomass cost	€/t	92.86
	€/MWh	18.57
Feed-biomass	t/d	400
	MWh/d	2000
Feed-biomass need	t/a	132 000
	MWh/a	660 000

Table 7.2.3: Basic data for pyrolysis oil.

Pyrolysis oil	t/d	280
	MWh/d	1400
	t/a	92 400
	MWh/a	462 000
Total biomass cost	€/a	8 579 340

7.2.3 OTHER EXPENSES

Other operating cost expenses are not interconnected with the technologic processes. These payments are more economic origin and can be very important for the project sustainability and profitability [Based on: Jerkko Stark; Nopeaan pyrolyysiin perustuvan biooljyn tuotantolaitoksen liiketoiminnallinen malli ja kannattavuuslaskenta Savonlinnan seudulla; 2011].

Table 7.2.4: Personnel expenses and project insurance.

People at work	kpl	18
Yearly cost per person	€	70 000
Summary	€/a	1 260 000
Insurance	€	300 000

7.2.4 MAINTENANCE AND ELECTRICITY EXPENSES

Maintenance cost per year theoretically based on amount of the total investments not included the government discount. Usually, this expense is determinate as 3% of the total investments. The electricity price of 64,6 €/MWh is an average price in Finland

and it seems acceptable for the project development. The electricity expenses calculation is for the working plant period. The expended electricity during the maintenance period is included to the maintenance expenses [Based on: Jerkko Stark; Nopeaan pyrolyysiin perustuvan biooljyn tuotantolaitoksen liiketoiminnallinen malli ja kannattavuuslaskenta Savonlinnan seudulla; 2011].

Table 7.2.5: Maintenance and electricity project data.

Electricity need	MW	20
Operating hours	h/a	7920
Electricity need	MWh/a	158 400
Electricity cost	€/MWh	64.6
Total cost	€/a	10 232 640
Maintenance	€/a	3 272 743

The quantity of needed electricity is obtained by comparison with the first case and approximate data of working equipment. As a result the needed quantity of electricity for the RTP bio-oil production and CHP plant combination working processes is reached around 20 MW. Now it is possible to make one more assumption about the electricity bills. The fact of pyrolysis plant combination with the CHP plant brings the opportunity of free electricity use. The only costs which can be taken into account are the costs of combusted fuel and equipment wear & tear. The project economic calculation neglects these quantities.

7.2.5 OPERATING COST SUMMARY

Total operating cost is a summary of all operating expenses. It includes biomass expenses, other expenses, maintenance and electricity expenses. Well, the total operating cost is 23 644 723 €. Further calculations of product cost and profitability need in several modifications. To simplify and to make the calculation more accurate it is necessary to make a € to €/MWh conversion. The first thing to implement this operation is determination of each part operating expenses percentage share, obtained as a share of the total operating cost [Based on: Jerkko Stark; Nopeaan pyrolyysiin perustuvan biooljyn tuotantolaitoksen liiketoiminnallinen malli ja kannattavuuslaskenta Savonlinnan seudulla; 2011].

Table 7.2.6: Shares of operating costs.

Biomass	36%	18.6 €/MWh
Personnel	5%	2.73 €/MWh
Insurance	1.3%	0.65 €/MWh
Electricity	43%	22.15 €/MWh
Maintenance	14%	7.1 €/MWh
Total	99.3%	51.23 €/MWh

7.2.6 PRODUCTION COST

Many different values influences on the production cost. But the most important value taken into calculation is the investment cost. It is converted to the €/MWh dimension and shows the product investment input and corrected the profitability of the process. For the combination of the RTP technology and the CHP plant this coefficient is equal to 13.4 €/MWh. Then it is possible to calculate the product price after the process [Based on: Jerkko Stark; Nopeaan pyrolyysiin perustuvan biooljyn tuotantolaitoksen liiketoiminnallinen malli ja kannattavuuslaskenta Savonlinnan seudulla; 2011].

Table 7.2.7: Production cost after the process.

Investment cost	€/MWh	13.4
Raw material cost	€/MWh	18.6
Summary of other operating costs	€/MWh	32.63
Total	€/MWh	64.63

This table results provides an opportunity to calculate the product total cost per year and to get approximately view of the project profitability. The conversion of the total product cost after the process from €/MWh to € shows the real product cost per year. It is 29 810 900 €. The subtraction of the yearly product cost and the yearly process expenses is the project profit. The calculation is equal to 6 166 177 €/a. Very long payback period is a fact of the high yearly expenses in the combination processes and cheap product outcome price. There are several significant improvements or corrections which can bring clarity into the second calculation. The CHP plant brings a grate benefits to the second combination. As was written before it means almost free electricity use. To calculate the profit of the process without the part of electricity expenses it is possible to obtain all the shares of operating cost and calculate a new product price (42.48 €/MWh) or to subtract the electricity expenses from the operating cost. With the analysis it is fact that calculation of these two possible solutions gives approximately the same answer with the same profitability around 6 000 000 €/a. But the next idea is the outcome price could not be very low because of the competitiveness in this sector. So, the best decision is to save the outcome price, which include electricity expenses and to subtract it (electricity expenses) from the operating total cost. As a result it brings 10 232 640 € of savings per year and the total operating cost would be 13 412 083 €. In this case the profit would be equal to 16 398 817 €. Well, it means that the payback period would be done in five years [Based on: Jerkko Stark; Nopeaan pyrolyysiin perustuvan biooljyn tuotantolaitoksen liiketoiminnallinen malli ja kannattavuuslaskenta Savonlinnan seudulla; 2011].

Table 7.2.8: Profit comparison.

	Dimension	With electricity expenses	Without electricity expenses	The case of the product price maintenance without electricity expenses
Product price	€/MWh	64.63	42.48	64.63
Product price	€/a	29 810 900	19 594 106	29 810 900
Total operating cost	€/a	23 644 723	13 412 083	13 412 083
Profit	€/a	6 166 177	6 182 023	16 398 817

8 RESULTS

First of all it is logic to present and analyze the case of the ablative pyrolysis bio-oil production and boiler plant combination. It is necessary to say a few words about the boiler plant. At the present days boiler plants is not economic efficient except of individual or particular cases. A boiler plant has the best thermal efficiency which theoretically increase it cycle efficiency. The economic activities bring this application sector behind of different power plants. Combined use of these plants is the best way of using the applications.

The combination of the ablative pyrolysis plant and the boiler plant shows an efficient work. The boiler produced the heat for the ablative reactor and the heat for the combination is almost free. The biggest expenses of the combination are biomass purchase and electricity use. The boiler plant auxiliary is not very high, but as a result per year presents much of all operating expenses. Other side, more weaknesses of this combination are the ablative underdevelopment technologies and still low production capacity.

The used economic data from Jerkko Stark project brings next facts to this thesis calculation. The combination has low production capacity and high rate of electricity expenses. This fact brings a high product price and necessity to download two pyrolysis applications, follows the opportunity to make this combination non competitive. If the competitor product prices are lower, customers will change the supply place. Customers are trying to find the most profitable way for the purchase.

As we can see, the strongest sides of the ablative pyrolysis application and the boiler plant combination are: high efficiency of the boiler cycle, free heat transfer and supply between the plants, the ablative cycle not need a biomass preparation system and has a low heat input to reactor. By the way, economic calculation shows several positive things. This combination seems cheap and not need high investments at designed period and through the investment period (compare to other energy projects). And finally the one more advantage is the short payback period and each year brings less of expenses and inputs than previous, which is making this project very attractive for investors.

The next case is the RTP technology plant and the CHP plant. As was written before the CHP plant is the most efficient way to generate both of electricity and heat at the one cycle. But the processes of control and operating are harder intellectual and more expensive, the process of design and construction is longer and need regular investments (compare to the boiler plant application).

The combination of these plants is very efficient and presented in the economic calculation. The idea of these plants combination is high rate money savings and high production capacity. The CHP plant is generating the electricity for it auxiliary and RTP plant needs. The RTP technology needs electricity for conveyors, pumps, auxiliary equipment and biomass preparation system. Well, the combination cycle has almost free electricity and quantity of unexpended electricity and heat for sale.

The second combination has a high yield of bio-oil, low operating expenses and high product price. These facts are making the case profitable, except of the product price. Therefore, the project has a short payback period. The cycle operating expenses are very low compare to the total investment cost.

Well, to conclude the results part it is good to say that both of combinations are very effective and profitable. The economic calculation brings a lot of theory in comparisons and will help to realize and manage this kind of projects in reality, but still in practice the projects activities would be different and it necessary to use the experience of previous companies. The central idea of the final thesis is pyrolysis bio-oil production. To improve the bio-oil production application and economy it is effective to close download the applications generated energy.

These types of combinations should be improved and developed together and as a further result will bring the profitability and sustainability for the project and investors budget. The second combination is more economic efficient than the first combination and the first combination is the more effective than stand-alone application. To show the difference between combinations would be done a pair of graphics. The calculation before, results and graphics based on Jerkko Stark project “Nopeaan pyrolyysiin perustuvan biooljyn tuotantolaitoksen liiketoiminnallinen malli ja kannattavuuslaskenta Savonlinnan seudulla; 2011”.

Table 8.1: Biomass and bio-oil comparison.

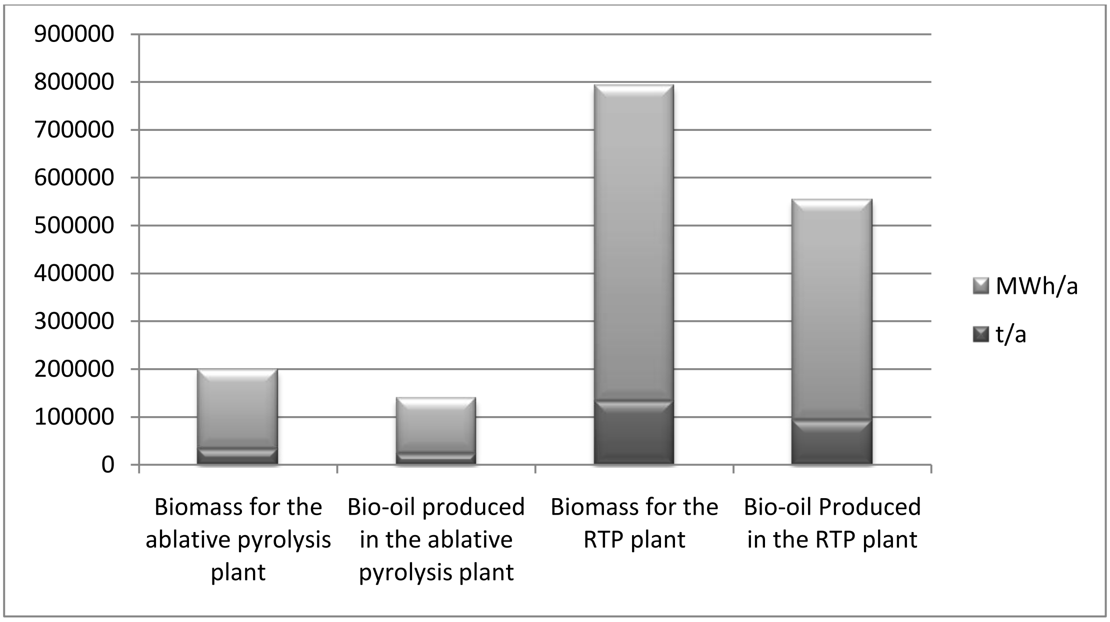


Table 8.2: Needed electricity comparison MWh/a.

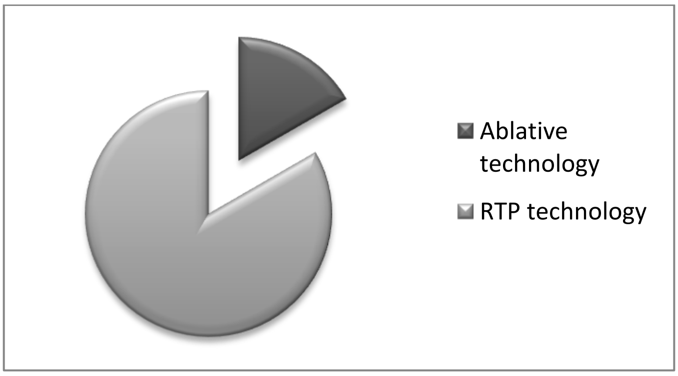
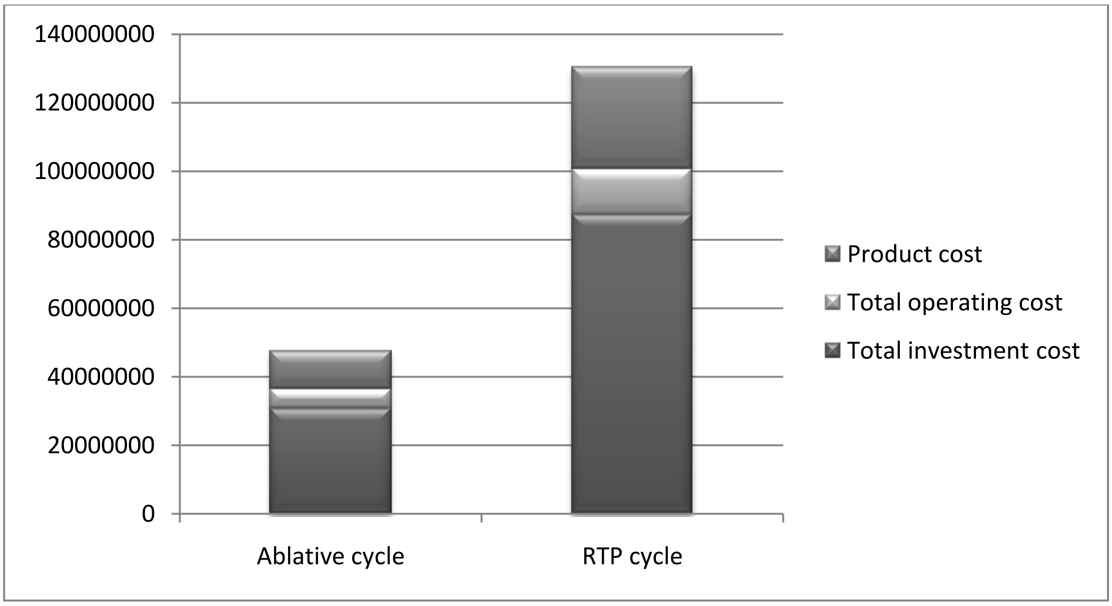


Table 8.3: Cost's comparison.



9 CONCLUSION

The thesis is about economics of pyrolysis bio-fuel production combined with power plant working on bio-fuel. The idea of this bio-fuel production type is to get other fuel from initial, the fuel with different properties and physical condition, getting liquid bio-oil from solid wood chips. It is in connection with thermal and economic foundations.

Pyrolysis is thermochemical process of organic material decomposition at increased temperatures and in the absence of oxygen. The customary pyrolysis process proceeded under a pressure at the temperature around 430 0C. Practically, it is almost impossible to achieve absolutely oxygen-free atmosphere. The reason is the fact of small oxygen particles presence in any pyrolysis model.

Duration of the fast pyrolysis process takes around of few seconds. Also, the pyrolysis cycle includes several very important, basic processes: kinetics of chemical reaction, phase transition, heat & mass transfer processes. The main cycle issue is to handle the reacting biomass particles at effective parameters and minimize the opportunity for the charcoal formation. There are several available methods to achieve the optimum cycle model.

The liquid product of the pyrolysis processes is bio-oil. The bio-oil could be different even of the same production process, because of the raw material nature and characteristics. Pyrolysis liquid has a heating value of nearly half that of a conventional fuel oil – typically 16–18 MJ/kg.

For the final thesis pyrolysis applications research was chosen for wood chips raw material. This decision is logical in many project aspects. Wood chips which had been gathered and produced inside the Finnish territory are very cheap. It could be easy storage and transported, preparation and utilization equipment are high developed and also easy in use. Wood chips material has good characteristics for pyrolysis bio-oil production. Wood chips as a fuel resource has a number of collection residue methods and numbers of production processes.

The given task was to make an economic comparison between two different applications. There are: boiler process below 20 MW in combination with ablative pyrolysis plant for bio-oil production and quite big co-generation cycle plant below 100 MW in combination with the RTP pyrolysis bio-oil production technology. The target of the final thesis is economic comparison, but not a technical characterization.

As was written before, the ablative pyrolysis technology is under development and this is a reason of it small plant capacity. Today the biggest ablative reactor is equal to utilization of 50 t/d raw material. The basic data of the final thesis project brings the necessity of two ablative pyrolysis applications downloading. The capital cost of every project, especially plant building project, includes secondary expenses. Secondary expenses are: road, telephone, water line connection costs and etc. Well, the second combination includes the same objects and expenses. There are building, electrification, HVAC, automatic control system, piping and other lines secondary expenses. Besides, this segment of expenses includes expenses, which were not included into account or just forgotten. The secondary expenses are around 30% of the project total capital cost.

The total capital cost is the most significant value in the calculation and catch the attention of all potential investors. The final thesis work is done to prove the fact of economic phenomena. The biggest capacity plant is planned to construct, the biggest profitability it has. This means even that the big plants are chipper than small. And this work presented that the total cost two small ablative plants and the boiler process is almost one third part of the CHP and RTP application, which is approximately five times bigger. The next thing, proven by this work is the fact that to get more efficiency from the project it is good possibility to built plants in combinations. Based on Jerkko Stark project “Nopeaan pyrolyysiin perustuvan biooljyn tuotantolaitoksen liiketoiminnallinen malli ja kannattavuuslaskenta Savonlinnan seudulla; 2011”, the economic calculations proves that stand-alone plants are more economic expensive. All the evidences were made by comparisons. The method of different plant combination is not only increase the efficiency of the cycle, but it increases a total cost savings.

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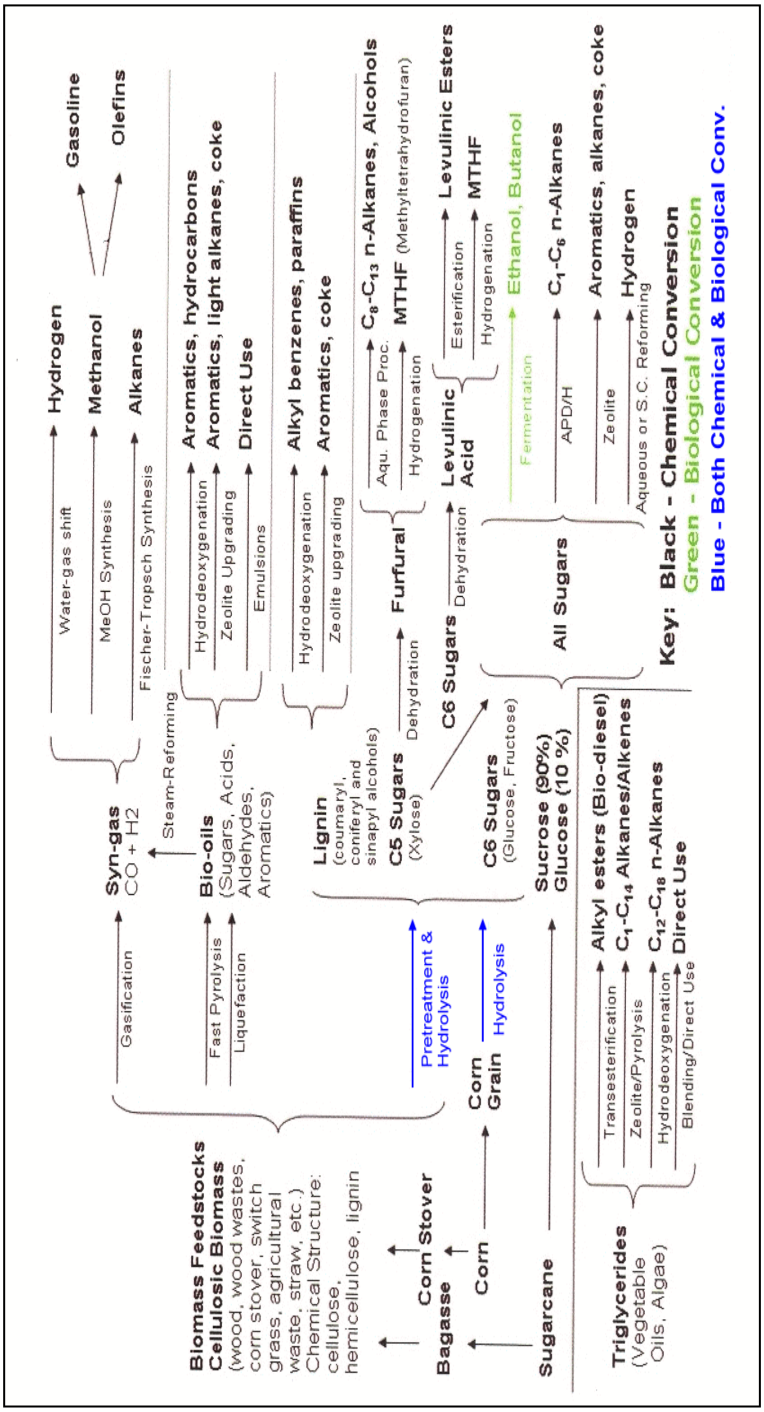
APPENDICES

Pyrolysis “tree”.



Fast pyrolysis system sketch.