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MASTER'S THESIS

ECONOMY OF CONVERTING WOOD TO BIOCOAL

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ABSTRACT

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Economy of converting wood to biocoal

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The pre-treatment step has a significant influence on the performance of bioenergy chains, especially on logistics. In nowadays conditions it is important to have technologies allowing to convert biomass at modest scales into dense energy carriers that ease transportation and handling. There are such technologies as charring and torrefaction. It is a thermal treatment of organic waste (only woody biomass is considered as a raw material in this work), which aims to produce a fuel with increased energy density. Wood processing is attractive under meaning of green house gas emissions.

Charring and torrefaction are promising technologies due to its high process efficiency. It may be also attractive in the future as a renewable fuel with improved storage properties, increased energy density (compared to raw wood) for co-combustion and/or gasification.

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LIST OF ABBRIVEATIONS

a	Year
ACB	Accelerated Carbonization Biomass
Al	Aluminum
As	Arsenic
B	Boron
BAP	Biomass Action Plan
Ca	Calcium
CH ₄	Methane
CHP	Combined heat and power production
CO	Carbon monoxide
CO ₂	Carbon dioxide
cm ³	Cubic centimeter
daf	Dry ash free
EBES AG	European Bioenergy Services
ECN	Energy Research Center of Netherlands
EU	European Union
EUR	The official currency of Eurozone
FAO	Food and Agriculture Organization
Fe	Iron
g	Gram
GHG	Greenhouse gas
GJ	Gigajoule (10 ⁹ Joule)
GWh	Gigawatt hour
H ₂	Hydrogen
h	hour
ha	Hectare
HDB	High density briquette
IEA	International Energy Agency
IUFRO	The Global Network for Forest Science Cooperation
kg	Kilogram
kJ	Kilojoules (10 ³ Joule)

LHV	Lower heating value
m ³	Cubic meter
m ²	Square meter
MEUR	Million euros
Mg	Manganese
MJ	Megajoul (10 ⁶ Joule)
min	Minute
Mn	Magnesium
mm	Millimeter
MPa	Megapascal
MSW	Municipal solid waste
MW	Megawatt
MWh	Megawatt hour
NO _x	Nitrogen oxides
RES	Renewable energy source
S	Sulfur
Si	Silicon
RWEDP	Regional Wood Energy Development Program in Asia
St.P SFA	Saint Petersburg State Forest Technical Academy
TGA	Thermo gravimetric analyzer
Ti	Titanium
TOP	Torrefied wood and pellet production
UK	United Kingdom
USA	United States of America
USD	United States Dollar
VTT	Technical Research Center of Finland
%	Percent
°C	Celsius degree
K ₂ O	Potassium oxide
CaO	Calcium oxide
Na ₂ O	Sodium oxide

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FOREWORD

Today there are many definitions related to the processes of producing coal from wood: torrefaction, roasting, wood cooking, mild pyrolysis, pre pyrolysis, mild thermal treatment and others. Try to specify it. Definitions “wood cooking” and “mild thermal treatment” does not represent the exact meaning of the process; “mild pyrolysis” and “pre pyrolysis” are not correct definitions because anyway pyrolysis occurs. Wood fractions show different thermal behavior. Three zones may therefore be distinguished in weight loss curves of wood: hemicelluloses, the most reactive compounds, decompose at temperature in the range of 225–325°C, cellulose at 305– 375°C and lignin gradually over the temperature range of 250 – 500°C. [Mark J. Prins, Krzysztof J., 2006]. By process definition, in this case, torrefaction is the most suitable because under its meaning the process of the hemicelluloses decomposition in the range 225-325°C is supposed. But the processes of producing charcoal may occur in higher temperature ranges. For most areas of consumption, coal is considered qualitative, when the process is completed at 450 - 550°C. The product of the woody biomass treatment in high temperature rates is charcoal (charring) but currently there is common word for all types of wood conversion – biocoal. It is used not to mix mineral coal with coal made from different types of biomass.

1 INTRODUCTION

Bioenergy provides about 10 percent of the world's total primary energy supply (47.2 EJ of bioenergy out of a total of 479 EJ in 2005, i.e. 9.85 percent). Most of this is for use in the residential sector (for heating and cooking). In 2005 bioenergy represented 78 percent of all renewable energy produced. A full 97 percent of biofuels are made of solid biomass, 71 percent of which is used in the residential sector [IEA 2006].

The European Union (EU) aims to achieve an ambitious 10% share of biofuels by 2020 [European Commission. Green Paper, 2006]. Driven by this target the demand in biofuels in Europe is strongly increasing. With this short-term development comes the need for an integrated long-term vision for biofuels. The role of technological learning (and associated cost reductions) is also a crucial factor affecting the possible market diffusion of various 1st and 2nd generation biofuels. However, the EU import dependency in foreign energy is rising. Unless domestic energy becomes more competitive in the next 20–30 years, around 70% of the EU's energy needs are expected to be met by imported products - some from regions threatened by insecurity [European Commission. Green Paper, 2006].

At the national, regional and global levels there are as a rule three main drivers for the development of bioenergy and biofuels. These are climate change, energy security and rural development. The political motivation to support biofuels arises from each individual driver or combinations. Policies designed to target one driver can be detrimental to another. Modern biomass is becoming increasingly important to countries as a low-carbon, distributed, renewable component of national energy matrices.

Traditional biomass including fuelwood, charcoal and animal dung, continue to be important sources of bioenergy in many parts of the world. To date, wood fuels represent by far the most common sources of bioenergy and not only for less developed regions. Wood fuels provide energy security service for large segments of society and wood fuels technology is developing and expanding rapidly.

Modern bioenergy depends on efficient conversion technologies for applications at household, small business and industrial scales.

The forestry segment can be utilized to generate electricity, heat, combined heat and power, and other forms of bioenergy. Generally, the majority of biomass-derived electricity is produced using a steam cycle process, in which biomass is burned in a boiler to generate high-pressure steam, that flows over a series of aerodynamic blades causing a turbine to rotate, which in response turns a connected electric generator to produce electricity. Compacted forms of biomass such as wood pellets and briquettes can also be used for combustion. This system is known as the direct-fired system and is similar to the electricity generation process of most fossil-fuel fired power plants.

Over recent years, especially co-firing of biomass materials in coal fired boilers has increased, and some gasification technologies are nearing commercialization. Co-firing biomass with coal is currently the most cost-efficient way of incorporating renewable technology into conventional power production to use existing power plant infrastructure without major modifications. Co-combustion coal and biomass in large-scale coal plants is claimed to have significantly higher combustion efficiency (up to 45 percent) than dedicated-biomass plants (30 to 35 percent using dry biomass and 22 percent for MSW). Co-combustion technology options have been tested in Northern Europe, the United States, and Australia in approximately 150 installations using woody and agricultural residues.

This work focuses on conventional technologies of charcoal production and future aspects of torrefied wood production, their techno-economic analysis, respective impacts, in terms of costs and energy uses in various chains for biomass production and use.

2 GENERAL OVERVIEW

2.1 Cost effective climate change

In December 2005, the EC adopted a Biomass Action Plan (BAP), including measures to increase the use of biomass for heat, electricity and transport [EC, 2005]. The included impact assessment proposes and examines a scenario in which slightly more than three-fourths of the total bioenergy increase occurs in stationary applications and about one-fourth comes from the transport sector. The BAP also announced the development of future legislation on renewable energy in heating to stimulate the use of biomass for heat.

The EU can increase bioenergy use by using more domestic resources or by increasing the import of biofuels from the rest of the world. The opportunities for producing biomass differ considerably between member states, and an increased intra-European bioenergy trade in biomass and biofuels has been proposed as a way to realize the bioenergy potential in EU25 [Ericsson and Nilsson, 2006]. Central and Eastern European countries, especially, appear to have a substantial bioenergy potential compared to prospective domestic demand, and the estimated production costs are lower than in Western European countries [Faaij A., 2005]. The present world trade in wood fuels is described in Hillring (2006) and the EC-funded project EUBIONET II.

The regional and global potentials for biomass are uncertain [Berndes et al., 2003]. But, it is clear that the potential of the long-term global supply is low compared to the future required amount of climate-neutral energy in a world aiming at ambitious CO₂ stabilization targets [Azar C., 2005]. Therefore, it is important to discuss both in which sector to use scarce biomass resources and whether different policy objectives relevant to bioenergy agree on the order of priority for the different options for using biomass for energy.

RES technologies are in general more labor intensive than conventional energy technologies and bioenergy has the highest employment-creation potential [ECOTEC, 1999]. Rural regions in particular can benefit from the establishment of bioenergy industries and the related production of biomass. Since the expansion

of RES also involves establishing biomass conversion facilities in rural areas, an even larger share of the estimated job opportunities would occur in rural regions.

The trade in biomass and biofuels both within and from other world regions to EU requires further investigation. However, there are some lessons and recommendations that are valid for policy at the EU level.

First of all, it can be concluded that if climate change mitigation and import dependency reduction are the top priorities, bioenergy options based on lignocellulosic resources should be promoted. Cost-effective ways to initiate markets for lignocellulosic biomass in the EU, which can stimulate the establishment and development of a supply infrastructure leading to cost reductions along the biomass supply chain, need to be found.

In some countries, the implementation of biomass co-firing can serve as an important initial market for lignocellulosic biomass. In other countries, biomass use in district heating systems may be the best early option. The strategies have in common that they will target heat and electricity generation since the technologies for the production of second-generation biofuels for transport from lignocellulosic feedstocks have not yet been fully demonstrated on a commercial scale.

In addition to support for basic research as well as demo and pilot biofuel plants, new initiatives are desirable to stimulate the development of the lignocellulosic supply systems.

Increased energy efficiency is one important element, which will likely need to be complemented with additional measures in order to ensure that efficiency gains do not induce increased energy service consumption negating the benefits. The notion about global biomass scarcity relative to the future required levels of climate neutral energy in a world aiming at ambitious CO₂ stabilization targets [Azar, 2005] makes the energy conservation argument strong also when considering the option of large-scale bioenergy import from third countries to mitigate domestic biomass scarcity in EU. Thus, energy efficiency and other energy conservation measures should be promoted regardless of whether the fuels are of fossil or biospheric origin.

Biomass is an important energy source to create a more sustainable society. However, nature has created a large diversity of biomass, not to forget the modifications men makes to biomass to use it in industrial or domestic applications. Hence the composition and properties of biomass is subjected to many natural and human factors. Some of these need to be improved seriously to enable their application as sustainable fuel in highly efficient biomass-to-energy chains. This can be achieved through charring/torrefaction. Moreover, besides the thermal conversion of biomass also logistic properties can be improved through charring when it is combined with densification (pelletisation/briquetting). By this combination very energy dense fuel pellets and briquettes are produced [Patrick C.A. Bergman, 2005]. It can help to reduce significantly transportation costs (Table 1).

Table 1: Transportation parameters of the untreated/charred biomass

Untreated Biomass	Charred Biomass
Bulky	Dense, If Pelletized, Etc.
Moist	Dry (3-10%),
Fibrous	Easily Crushed
Perishable	Does not rot
Waste	Valuable fuel
Expensive to transport	Energy dense

2.2 Estimation of the woody biomass potential

It is estimated that there are 30% of the earth's land area of forest worldwide (Table 2), of which about 95% are natural forests and 5% are plantations [FAO, 2001]. Tropical and subtropical forests comprise 56% of the world's forests, while temperate and boreal forests account for 44% [FAO, 2001]. The average area of forest and wooded land per inhabitant varies regionally (Table 2). The area varies between 6.6 ha in Oceania, 0.2 ha in Asia, and 1.4 ha in Europe (3.4 ha in the Nordic countries) [FAO, 2001]. This fact indicates that the potential contribution

of wood to the energy supply also varies from country to country. There are also large regional differences in accessibility to forests [FAO, 2001].

Table 2: Forest resources, area (ha), year (2000), [FAO 2001, FAO 2002]

Region	Land area	Forest area	%	Plantations	Forest area per capita
	10 ⁶ ha	10 ⁶ ha		10 ⁶ ha	ha
Africa	2978	649	21.8	8	0.8
Asia	3084	547	17.8	115	0.2
Europe	2259	1039	46.0	32	1.4
North and Central America	2136	549	25.7	2	1.1
Oceania	849	197	23.3	3	6.6
South Africa	1754	885	50.5	10	2.6
World	13063	3869	29.6	171	0.6

The total above-ground wood volume (m³) and woody biomass (tonnes) in forest has been estimated in 166 countries, representing 99% of the world's forest area [FAO, 2001]. The world's total aboveground biomass in forests is 420 (109) tonnes (Table 3), of which more than 40% is located in South America and about 27% is in Brazil alone. The worldwide average above-ground woody biomass is 109 tonnes/ha [FAO, 2001]. Biomass currently represents approximately 14% of world's final energy consumption. About 25% of the usage is in industrialized countries, where a significant level of investment in environmental protection has been made to meet emissions standards, especially air emissions. The other 75% of primary energy use of biomass is in heat production for developing country household energy needs and in process heat production for biomass-based industries through the use of their generated residues [Overend RP. 2002].

Table 3: Forest resources, above-ground biomass volume and biomass (m³ and tonne). [FAO 2001, FAO 2002]

Region	Forest area	Volume	Volume	Woody biomass	Woody biomass
	10 ⁹ ha	m ³ /ha	10 ⁹ m ³	tonne/ha	10 ⁹ tonne
Africa	649	72	46	109	70
Asia	547	63	34	82	44
Europe	1039	112	116	59	61
North and Central America	549	123	67	95	52
Oceania	197	55	10	64	12
South Africa	885	125	110	203	179
World	3869	100	386	109	421

Biomass has a large energy potential. A comparison between the available potential with the current use shows that, on a worldwide level, about two-fifths of the existing biomass energy potential is used. In most areas of the world the current biomass use is clearly below the available potential. Only for Asia does the current use exceed the available potential, i.e. non-sustainable biomass use. Therefore, increased biomass use, e.g. for upgrading is possible in most countries. A possible alternative is to cover the future demand for renewable energy, by increased utilization of forest residues and residues from the wood processing industry.

2.3 World trade of the wood-based fuels

2.3.1 Review of the market situation

World timber trade has been established for centuries and can be regarded as a traditional part of international trade. Fossil fuels dominate world energy use but traditional use of biomass as fuel is still significant, some 10–15% of the world energy use [Arnold M., Kohlin G., 2003]. By tradition, local production of wood fuel and local use dominate. Markets have been established within countries or regions mainly for non-industrial use. Other existing users of wood fuel are the

forest products industry, especially pulp and paper industries. The forest products industry produces large quantities of wood as by-products which may be used as fuel. Forest resources are spread all over the globe. Some areas have very large forest resources, e.g. tropical and boreal areas. Countries with large forest resources are Brazil, Indonesia, Russia and Canada. Demand for timber products is connected to dense and fast growing populations.

In recent years all over the world have recognized the concept based on new understanding of global and commodity issues. This refers to renewable sources of energy and raw materials including fuelwood, charcoal and animal dung, that continue to be important sources of bioenergy in many parts of the world. Currently, wood fuels represent by far the most common sources of bioenergy and not only for less developed regions. Wood fuels provide energy security service for large segments of society and wood fuels technology is developing and expanding rapidly. The main industrial use is for heat production, electricity production both in stand-alone plants and in combined heat and power plants (CHP plants).

The European Union countries have jointly signed the Kyoto Agreement and have rather ambitious plans for reduction of greenhouse gases. This development increases the demand for all renewable energy including wood fuel. Asian countries have a very fast growing economy and are studying the possibilities to increase the use of renewables. The timber trade is well established in this region. Wood-fuel consumption for Asian RWEDP countries 3 is estimated at 10,000 PJ per year [Regional study on wood energy today and tomorrow in Asia, [Bangkok, 1997]. Increase in wood fuel use by 1.6% per year is reported and the value today is 30 billion USD per annum. Most of this utilization is available at local markets. Typical prices are 40 USD per tonne.

2.3.2 Production of the wood-based fuels

As shown in Table 4, most of the on average 41 million tonnes of charcoal produced annually comes from Africa (51%) and in South America (35%). Finally, on the aggregate level, statistics on production of wood fuel indicate an annual world production in the neighborhood of 1800 million cubic meters during

the 2000–2002 period. Asia, at approximately 44%, and Africa, 30%, again are the major producing regions (Table 5).

Table 4: World production of wood charcoal by region, absolute (in million metric tons) and relative numbers, [FAO, 2003]

Region	2000		2001		2002	
	10 ⁶ m ³	share %	10 ⁶ m ³	share %	10 ⁶ m ³	share %
Africa	19.8	50.3	20.9	51.3	21.7	51.2
Asia	4.2	10.6	4.3	10.6	4.4	10.3
Europe	0.3	0.7	0.0	0.1	0.0	0.1
North and Central America	1.2	3.1	1.2	3.0	1.2	2.9
Oceania	0.0	0.0	0.0	0.0	0.0	0.0
South America	13.8	35.1	14.0	34.3	14.8	34.9
World	39.2	100.0	40.8	100.0	42.4	100.0

Table 5: World production of wood by region, absolute (million cubic meters) and relative numbers, [FAO, 2003]

Region	2000		2001		2002	
	10 ⁶ m ³	share %	10 ⁶ m ³	share %	10 ⁶ m ³	share %
Africa	527.5	29.5	534.5	29.9	552.4	30.7
Asia	797.5	44.5	795.5	44.5	782.2	43.4
Europe	109.2	6.1	101.4	5.7	105.7	5.9
North and Central America	155.6	8.7	156.3	8.7	158.6	8.8
Oceania	12.2	0.7	12.6	0.7	13.0	0.7
South America	188.5	10.5	189.2	10.6	189.4	10.5
World	1790.7	100.0	1789.2	100.0	1801.3	100.0

Table 6: Exports of forest products by region, billion USD, [FAO, 2003]

Region	2000		2001		2002	
	Bill. \$	share %	Bill. \$	share %	Bill. \$	share %
Africa	2.9	2.0	2.8	2.2	2.8	2.1
Asia	17.7	12.2	17.0	12.9	17.0	12.8
Europe	71.2	49.1	65.3	49.6	69.2	51.9
North and Central America	45.1	31.1	39.1	29.7	36.9	27.7
Oceania	2.6	1.8	2.4	1.8	2.4	1.8
South America	5.6	3.8	5.0	3.8	5.0	3.7
World	145.0	100.0	131.6	100.0	133.3	100.0

The major trade flows of forest products, exports and imports between the world's regions are presented in Table 6.

Table 7: Imports of forest products by region, billion USD, [FAO, 2003]

Region	2000		2001		2002	
	Value	share %	Value	share %	Value	share %
Africa	2.6	1.7	2.6	1.8	2.6	1.8
Asia	43.0	28.1	39.4	37.7	39.7	28.0
Europe	68.5	44.7	64.1	45.1	63.8	45.1
North and Central America	34.1	22.2	31.6	22.2	30.9	21.9
Oceania	2.1	1.4	1.6	1.2	1.6	1.2
South America	3.1	2.0	2.9	2.0	2.9	2.0
World	153.4	100.0	142.2	100.0	141.4	100.0

Table 8: Countries with year 200 forest product exports greater than 1 billion USD, [FAO, 2003]

Country	Value, 1000 USD	Percent	Cum. percent
Canada	29,715,800	20.45	20.45
USA	16,711,400	11.50	31.94
Finland	10,948,100	7.53	39.48
Sweden	9,956,570	6.85	46.33
Germany	9,949,750	6.85	53.17
France	5,907,560	4.06	57.24
Indonesia	5,578,100	3.84	61.08
Austria	4,280,470	2.95	64.02
China	3,911,350	2.69	66.71
Russian Federation	3,756,810	2.58	69.30
Belgium	3,573,740	2.46	71.75
Brazil	3,218,430	2.21	73.97
Italy	2,741,710	1.89	73.86
Malaysia	2,722,230	1.87	77.73
Netherlands	2,652,810	1.83	76.55
United Kingdom	2,195,140	1.51	81.06
Japan	1,934,200	1.33	82.40
Chile	1,890,330	1.30	83.70
Spain	1,842,830	1.27	84.96
Norway	1,831,850	1.26	86.22
Korea	1,624,250	1.12	87.34
Switzerland	1,515,780	1.04	88.38
New Zealand	1,468,530	1.01	89.39
Portugal	1,284,770	0.88	90.28
Poland	1,018,000	0.70	90.98

2.3.3 Trade flows of the wood-based fuels

Data on trade flows in wood fuels are obtained from the European Forest Institute (EFI) [European Forest Institute, 2003]. This database is constructed from United Nations COMTRADE data and is elaborated and maintained by B. Michie and P. Wardle at the European Forest Institute. Trade flows between different countries of a wide range of forestry-related products and over several years can be extracted from the database. When it comes to trade in wood fuels, the database contains a handful of products that are relevant. Data are focused on [FAO, 2003]:

- charcoal;
- wood chips and wood particles;
- fuel wood;
- wood residues.

This database does not contain explicit data on trade in wood pellets (or briquettes). Data on trade are presented in the different wood-based fuels by means of export/import matrices. In Tables 9-11 the major features of trade in charcoal, wood chips and particles, fuel wood and wood residues are analyzed. Among these, charcoal and fuel wood are likely to be used for energy purposes, while chips/particles and residues are potentially used for energy, but may also have other uses for example in the forest products industry (pulp mills and particle board industries). It is not clear from the statistics for which purpose these two latter product categories are traded. The data are extracted from the EFI database one country at a time. Deriving complete global trade statistics on several commodities in this way is rather cumbersome; therefore, the following procedure was followed. Based on an expansion of the list of forest exports in Table 8, the 25 largest countries in terms of forest product exports were identified. It is assumed that these countries are also large exporters of wood-based fuels. For each of these countries, total export volumes of the above-mentioned fuel categories, distributed by importing countries, have been obtained from the database. These country data were then sorted by export and import volumes, respectively, to obtain the export/import matrices. The matrices (Tables 9-12) should be read in the following way. The data columns represent values for a given exporting country (indicated by the 'x'-prefix to the abbreviated country

name). Also, the exporting countries (columns) are ordered according to the size of the total export volume. In Table 9, we find that Indonesia (x-indo) is the largest exporter of charcoal (358,364 tonnes) followed by Malaysia (240,843 tonnes). Due to space constraints these tables do not contain the full matrices, only the 15 largest exporters are presented individually. The remaining 19 countries (of a total of 34 also including all other importing countries) are aggregated in the 'x-other'-column. The same procedure is for Tables 9-12. Each line in the table represents the single importing countries. These are also sorted by size, and Table 9 demonstrates that Japan is the largest importer of charcoal (325,655 tonnes) followed by the Republic of Korea and Germany. The individual cells in the table's show which amounts are imported by the country in the table line from the country in the table column. The tables thus show the trade flows between the different countries, and it is expected that the largest volumes of trade appear in the upper left corner of the table. As seen in Table 9, more than half of the world trade in charcoal originates in the Asian countries of Indonesia, Malaysia and China, with Japan and Korea being the major importers. Germany is by far the largest European importer, followed by Norway and UK. Poland is the largest exporter of charcoal in Europe, followed by Spain and France. Trade in wood chips and particles are summarized in Table 10. Again Japan is the largest importer, now by far, accounting for well over 60% of world trade. Four countries dominate exports: USA, Australia, Chile and China. The fuel wood trade shows a different structure (Table 11). This trade takes place mainly within countries in Europe and North America. In North America, the trade is in both directions between Canada and USA. In Europe, France, UK, The Czech Republic, Russia and Latvia are the largest exporters while Belgium and Ireland are the largest importers. A similar pattern is evident in the trade of wood residues (Table 12). Germany, France and Austria, together with Canada are the largest exporting countries. The bulk of Canadian exports go to USA, while exports from the European countries go to large importers such as Italy, Germany, Belgium, the Netherlands and France.

Table 9: Trade in charcoal, metric tonnes (2000 and 2001 average), [FAO, 2003]

	X_mdo	X_mal	X_dln	X_pol	X_sng	X_spa	X_ira	X_om	X_usa	X_ind	X_bel	X_bra	X_ita	X_ger	X_esp	X_all other	Sum imp.
Japan	51,266	120,196	132,814	0	15,401	0	0	0	1303	0	0	97	0	295	0	4284	325,655
Korea, Rep.	82,047	94,014	60,389	0	1359	0	95	0	387	0	0	0	0	35	0	1800	240,125
Germany	3405	0	37	67,411	0	3754	16,417	22,699	536	2429	5494	1473	304	0	5297	5772	135,026
Norway	59,531	0	577	5603	0	826	11	0	51	108	0	3248	2125	29	528	796	73,432
Taiwan	44,587	3532	13,795	0	5949	0	0	0	56	0	0	0	0	0	0	3240	71,159
UK	26,727	1439	31	206	267	17,623	688	29	2991	165	59	8958	0	484	0	1394	61,058
Belgium	2680	16,744	4	1909	17,527	319	8419	18	2	402	0	431	385	230	1110	268	50,444
France	1038	0	92	1540	0	12,477	0	0	74	2411	6960	393	5198	1598	1671	629	34,078
Singapore	31,755	1726	0	0	0	0	0	0	103	10	0	0	0	0	0	158	33,751
Denmark	191	0	14	4086	0	10,296	9915	0	0	14	75	0	2222	1266	29	3989	32,094
Sweden	224	0	110	19,934	154	267	0	37	130	2	0	0	7612	1561	29	1734	31,791
Malaysia	29,201	0	0	0	156	0	0	0	34	0	0	0	0	143	0	1288	30,821
Hong Kong	2425	0	10,619	0	11,214	0	0	0	17	0	0	0	0	25	0	733	25,032
United States	2332	71	1049	91	0	0	34	0	0	2995	0	938	0	1124	0	9687	18,320
Netherlands	194	32	26	2701	0	3787	334	22	194	0	7528	0	150	1860	29	344	17,198
Italy	1821	83	39	18	0	1114	287	6888	54	14	27	3915	0	854	79	195	15,383
Canada	69	0	50	38	0	0	23	0	11,331	1925	0	0	0	8	0	1795	15,236
Switzerland	290	0	0	6649	0	571	1843	1388	16	251	3	0	0	213	3308	621	15,151
Kuwait	1608	24	0	0	3554	0	0	53	345	3695	0	0	0	969	0	2122	12,369
UAE	5378	1042	5	0	487	0	0	0	2637	911	0	0	0	0	0	527	10,985
Portugal	0	0	0	0	0	6868	112	0	0	138	0	1502	0	19	0	3	8640
China	3898	181	0	0	96	0	0	0	37	0	25	0	0	0	0	3059	7295
Saudi Arabia	1813	268	195	0	1308	0	505	0	908	254	0	0	0	29	43	1615	6936
Poland	221	0	0	0	0	0	0	0	344	145	0	0	48	352	131	5084	6324
Mexico	19	0	6	16	0	24	3	0	4483	0	0	0	0	69	0	1619	6237
Hungary	4	0	74	0	0	8	9	5357	0	4	46	0	0	0	40	0	5540
Lebanon	99	0	0	0	0	83	0	21	34	4655	0	38	0	2	0	283	5213
Bahrain	685	375	100	0	2973	0	0	0	5	416	0	0	0	0	0	0	4554
Qatar	246	26	50	0	2952	0	0	0	52	1	0	0	0	9	0	834	4169
Ireland	27	0	64	0	0	20	0	0	2896	18	73	0	0	0	0	650	3746
Austria	0	0	7	63	0	373	0	2203	0	378	23	0	0	268	0	290	3602
Spain	68	0	6	0	0	0	2222	29	50	83	48	278	0	42	0	600	3423
Luxembourg	0	0	0	0	0	51	1173	0	0	42	1406	0	32	417	0	57	3178
Finland	150	0	37	148	0	74	99	0	0	18	0	0	861	14	0	1560	2958
All other importers	4369	1093	3861	453	1724	707	291	1559	6099	1796	210	431	710	865	88	10,118	34,371
Sum exports	358,364	240,843	224,045	110,861	65,117	59,238	42,475	40,299	35,162	23,273	21,975	21,700	19,645	12,776	12,380	67,139	1,355,288

Table 10: Trade in wood chips and particles, cubic meters (2000 and 2001 average), [FAO, 2003]

	XUSA	XAus	XChi	XChn	XGer	XBra	XCan	XHai	XIta	XJas	XJra	XAut	XNzl	XMal	Xswe	Xall other	Sum imp.
Japan	4,331,294	4,164,341	4,038,143	1,416,872	63	964,562	719,089	810,966	0	186,682	28	16	373,468	318,908	0	71,160	17,395,590
Canada	1,739,644	105	0	172	239	0	0	10	0	0	351	0	0	255	0	1173	1,741,948
Taiwan	39,690	76,414	0	732,538	168	0	0	74,778	0	0	0	0	0	25,310	0	91,094	1,039,990
Sweden	35	0	49	38,227	128,298	233	0	589,723	2903	0	0	0	0	254	0	257,261	1,016,982
Korea, Rep.	246,082	163,011	7837	408,066	241	0	12	4995	0	0	52	0	11,993	0	0	3836	846,123
Italy	237,712	166	0	0	32,745	0	0	0	0	143,157	326,528	0	0	51	0	37,216	777,573
Austria	0	0	0	0	606,016	0	13	0	0	0	7	0	0	0	0	29,896	635,932
Finland	2928	0	0	0	9905	0	0	12	105,227	483,711	0	7	0	0	12,780	526	615,093
USA	0	10	70,035	4170	23	0	321,940	325	0	40	3839	31	0	225	0	212	400,846
Norway	0	0	0	0	18,456	0	0	29,083	14,972	0	0	0	0	0	280,768	14,350	357,628
Belgium	234	0	0	0	146,285	0	0	2749	0	129,744	3378	0	0	0	68	17,376	299,832
France	6586	0	0	12	132,511	0	297	0	251	0	0	510	0	0	7230	108,610	256,006
Germany	1520	190	0	12	0	6	0	69	6	41,289	6694	0	0	48	2550	132,547	184,929
Netherlands	212	0	0	262	164,237	0	0	2289	0	2496	0	0	0	0	296	1707	171,497
Indonesia	839	133,285	0	22,632	13	0	0	46	0	0	0	0	157	608	0	0	157,578
Spain	8 055	0	0	120	464	50,491	955	0	0	62,736	0	0	0	0	218	6054	129,092
Switzerland	254	0	0	0	50,085	0	0	0	0	68,914	7993	0	0	0	0	227	127,472
Luxembourg	0	0	0	0	40 252	0	0	0	0	20,225	5	0	0	0	0	31,663	92,144
Slovenia	0	0	0	0	90	0	0	0	0	0	69,312	0	0	0	0	49	69,451
Portugal	68	0	0	0	33,008	0	0	0	0	23,905	0	0	0	0	0	296	57,276
China	15,592	17	25,338	0	321	1298	4057	16	0	432	0	0	0	49	0	3207	50,325
Denmark	0	0	0	0	3349	0	0	0	60	0	786	0	0	0	18,831	20,313	43,338
Colombia	102	0	26,536	0	3	0	0	0	0	0	0	0	0	0	0	15	26,655
UK	5490	0	0	8	1475	0	271	559	8418	0	70	0	0	0	358	9049	25,696
Ireland	221	0	0	0	46	0	0	0	0	480	1713	0	0	0	145	21,354	23,958
Mexico	22,022	0	0	0	0	0	0	0	0	0	17	0	0	0	0	82	22,121
Hong Kong	1040	110	0	6276	73	0	0	12,894	0	0	0	0	0	0	0	1156	21,548
Czech Rep.	140	0	0	0	17,435	0	0	0	0	0	3360	0	0	0	0	2	20,936
Lebanon	149	0	16,238	0	313	0	0	0	0	82	0	0	0	0	0	49	16,830
Slovakia	0	0	0	0	73	0	0	5210	0	0	0	0	0	0	0	10,524	15,806
Singapore	241	251	0	63	25	0	9	9	0	0	0	0	0	54	0	10,222	10,871
Australia	7430	0	0	0	227	0	17	0	0	1257	0	0	13	0	0	852	9796
Saudi Arabia	312	0	0	0	131	0	978	185	0	161	0	235	0	310	4092	2206	8609
Chile	7299	2	0	0	0	0	0	0	0	331	0	0	0	0	0	0	7632
All other imp.	19,095	1776	467	8753	5064	434	2700	37	56	2351	5159	891	83	5222	329	13,141	65,554
Sum exp.	6,694,281	4,539,675	4,184,642	2,599,952	1,301,555	1,145,088	1,050,568	904,830	743,133	690,825	505,333	420,686	385,713	351,292	327,662	897,419	26,742,650

Table 11: Trade in fuelwood, cubic meters (2000 and 2001 average), [FAO, 2003]

	X_fra	X_USA	X_UK	X_ger	X_ita	X_rus	X_can	X_lat	X_spa	X_ger	X_indo	X_swe	X_swl	X_pol	X_bel	X_ned	X_all other	Sum imp.
Belgium	197,779	185	0	0	0	0	0	0	0	7435	68	0	0	58	0	2915	218	208,657
USA	76	0	7999	0	0	163,975	0	0	0	74	9750	143	0	0	0	0	1645	183,661
Ireland	33	111	173,581	0	0	519	0	0	27	1849	0	928	0	0	171	0	402	177,618
Austria	0	0	0	142,383	0	0	0	28	0	5061	0	0	520	331	0	0	824	149,145
Finland	0	0	0	0	143,262	0	0	0	0	71	31	0	0	0	0	116	332	143,811
Italy	42,080	1503	141	24,993	0	358	0	1442	1442	3384	15	249	41,136	111	112	1940	23,413	140,874
Sweden	0	1384	662	0	30,555	2084	90,607	0	0	39	0	0	1049	0	0	858	7559	134,795
France	0	830	21,815	142	0	0	80,923	0	80,923	305	833	5956	785	715	9615	1679	3541	127,135
Denmark	0	219	0	167	53	0	43,478	0	0	26,048	0	4718	0	17,423	0	203	627	92,934
Canada	1163	89,876	0	0	0	0	0	0	0	0	54	68	0	0	0	184	131	91,476
Germany	2570	1322	0	37,991	67	13	75	0	0	131	131	4261	535	7577	732	11,669	1895	68,834
Bahamas	0	62,746	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	62,746
Norway	97	0	0	0	584	301	8934	0	0	11	0	24,933	0	901	0	1741	3220	40,719
Japan	0	4291	0	0	10,620	93	0	0	0	224	8711	0	0	0	0	0	12,897	36,610
Luxembourg	13,573	0	0	0	0	0	0	0	0	0	0	0	0	0	14,990	0	0	28,786
Switzerland	23,859	0	0	46	0	0	0	0	0	449	0	18	0	0	62	0	261	24,695
Taiwan	968	7313	0	0	0	0	0	0	0	201	2140	0	272	0	0	0	12,858	23,751
Korea, Rep.	0	7722	0	0	642	0	0	0	0	0	3386	0	0	0	0	0	7202	18,951
China	0	1389	0	0	3357	713	0	0	0	77	9345	0	0	0	0	0	3112	17,993
UK	11	6304	0	15	125	1203	852	0	0	0	1605	1421	0	1350	26	962	649	14,520
Indonesia	0	368	0	0	0	0	0	0	0	0	0	0	0	0	0	0	13,351	13,719
Greece	0	0	0	0	0	244	0	0	3453	3055	0	0	0	0	0	1472	5265	13,489
Spain	840	681	0	31	13	0	0	0	0	0	19	0	0	0	0	11	11,398	12,992
Netherlands	497	1360	13	0	0	44	0	0	0	677	474	0	0	2885	6498	0	315	12,762
Turkey	1018	1131	0	0	3411	0	0	0	0	0	0	0	0	0	0	0	6699	12,258
Costa Rica	0	10,524	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10,524
Mexico	0	5487	0	0	0	0	0	0	0	0	698	0	0	0	0	0	0	6184
Singapore	0	98	0	0	0	0	0	0	0	0	2240	0	0	0	0	0	0	5138
Saudi Arabia	1655	290	40	128	0	0	0	0	280	23	1929	0	0	0	0	58	173	4574
Portugal	1009	0	0	0	0	0	0	0	2143	0	0	0	13	0	0	1109	13	4286
Hong Kong	0	58	63	0	0	0	0	0	0	35	3829	0	0	0	0	0	269	4253
Malaysia	0	1134	0	0	0	0	0	0	0	0	141	0	0	0	0	0	2825	4099
Andorra	166	0	0	0	0	0	0	0	2507	0	0	0	0	0	0	0	0	2673
India	31	249	0	0	0	0	0	0	0	217	1454	0	0	0	0	0	336	2286
All other importers	2140	10,961	1834	151	4092	501	255	242	242	413	344	852	0	13	0	260	7951	30,007
Sum exports	289,562	217,528	206,145	206,044	196,778	170,046	144,227	91,016	91,016	49,643	47,192	43,543	43,260	32,410	32,205	25,176	132,174	1,926,946

Table 12: Trade in wood residues, cubic meters (2000 and 2001 average), [FAO, 2003]

	Xger	Xfra	Xaut	Xcan	Xbel	Xswi	Xcze	Xlat	Xusa	Xned	Xindo	Xswe	Xpol	Xspa	Xfin	Xother	Sum imp.
Italy	139,348	220,666	368,869	239	4560	351,163	148	150	5622	458	13	0	823	3100	0	9366	1,104,522
Germany	0	149,058	232,194	434	158,247	33,993	231,307	389	3022	50,655	64	4708	49,459	690	631	2859	917,705
Belgium	332,213	453,395	48	1680	0	33	0	6278	1770	44,300	939	26	86	1306	0	1466	843,537
Netherl.	308,747	39,437	6377	5119	167,441	461	34	856	319	0	7	1047	14,438	985	5132	1365	551,763
USA	3387	4210	0	479,157	2046	0	0	2078	0	2062	282	0	0	1680	40	8194	503,134
France	227,835	0	490	167	126,028	12,254	2311	0	347	11,028	245	12	33	16,546	0	8932	406,225
Sweden	18,247	349	0	76,973	283	0	169	174,577	85	934	0	0	1972	0	35,145	25,908	334,641
Denmark	21,009	1783	0	0	105	0	9135	69,317	0	3339	0	49,779	27,840	629	23,838	8977	215,824
Austria	88,483	1821	0	0	86	19,353	51,027	0	11	53	0	71	2159	9	540	3443	167,053
Switzerland	71,839	55,057	10,890	239	28	0	222	0	312	1162	9	0	161	0	0	927	140,843
Luxemb.	7848	22,737	204	0	95,382	0	0	0	33	1036	0	0	0	0	0	0	127,239
Korea, Rep.	30	40	0	100	0	0	0	0	9403	0	89,975	154	0	31	0	16,955	116,686
Japan	7755	289	45	13,584	0	0	0	0	5257	24,632	15,056	0	0	0	0	44,512	111,128
Spain	695	37,101	2297	690	91	0	17	0	5459	461	37	258	0	0	0	45,654	92,757
UK	11,680	20,164	0	79	2347	0	15	2790	1158	8456	78	3991	316	33,443	326	952	85,791
Norway	3555	1200	784	0	72	0	0	7441	240	8876	0	54,957	1991	0	1116	2338	82,568
Finland	5100	64	0	0	5	0	0	0	0	8	0	731	467	0	0	63,596	69,970
Canada	987	594	0	0	16	0	0	0	47,121	512	50	7	0	159	0	3099	52,543
Argentina	0	11,220	0	118	0	0	0	0	20,877	0	0	0	0	0	0	337	32,551
Australia	118	437	12	10	0	0	0	0	26,891	111	1533	22	0	0	0	2169	31,302
Taiwan	194	706	0	1026	0	0	0	0	2861	89	16,443	0	0	0	91	8554	29,964
Chile	0	2471	0	45	0	0	0	0	22,195	0	0	0	0	0	0	64	24,775
Portugal	11,566	2404	0	333	392	0	0	0	0	310	0	12	0	9075	0	47	24,137
Mexico	0	177	0	170	0	0	0	0	19,379	0	0	0	0	0	0	558	20,283
Singapore	250	0	0	1542	0	0	0	0	109	2735	10,782	391	0	0	0	2973	18,781
HongKong	399	1422	0	2139	90	21	0	0	8721	1697	436	0	0	0	0	2484	17,408
Bahamas	0	0	0	0	0	0	0	0	14,685	0	0	0	0	0	0	0	14,685
UAE	2368	10	0	0	0	0	0	0	0	8387	65	467	0	0	0	691	11,987
Slovenia	270	80	7830	0	0	0	120	0	696	227	0	0	0	172	0	167	9560
Saudi Arab.	3644	1826	53	0	0	0	0	0	230	10	487	0	0	17	0	1744	8009
Nigeria	8008	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8008
Czech Rep.	964	0	6483	0	0	0	0	0	0	86	0	0	178	0	0	277	7987
Brazil	70	366	0	31	0	0	0	0	6415	153	8	0	0	0	0	173	7214
Greece	288	91	0	773	790	0	0	0	1639	135	0	0	535	207	0	1937	6392
Oth. imp.	12,733	8536	2411	5483	755	1100	2308	166	8341	4532	3666	3872	722	2763	370	27,910	85,665
Sum exp.	1,289,621	1,037,705	638,984	590,202	558,759	418,377	296,812	264,040	213,191	176,438	140,169	120,502	101,177	70,807	67,226	298,623	6,282,628

2.3.4 Trade patterns

The international trade patterns show different pictures. Export of round wood dominates from Asia while more upgraded assortments like sawn wood show a pattern with Europe as the dominant region.

Africa and Asia dominate charcoal production. Quantities are significant and are here estimated to be 1800 million cubic meters. Export in forest products origins mainly from Europe, America and Asia and importing regions are often in the same geographic area.

Trade in wood fuel is rather new and not as established as for round wood or sawn wood. Fuelwood is imported mainly to European countries like Belgium, Ireland and Austria but also the United States of America. Exporters are France and the United States of America, Japan, Korea, Germany and Norway, which reflect large demand and strong or rather strong economies. Large exporters are Indonesia, Malaysia and China. These patterns reflect the demand for resources but also the market situation where domestic wood fuel may be more expensive than imported wood fuel. This is a situation similar to most other traded products and nothing unique for bioenergy.

Dominant importers of wood chips and particles are by far Japan but surprisingly also countries rich in forest resources per capita like Canada and Sweden. Large exporting countries are the United States of America, Austria and China.

When the demand for renewable energy increases these trade patterns may be changed. Countries with large forest resources will increase their export and countries dependent on fossil fuels in today's energy system will increase their import. There is a risk that less-developed countries will export their renewable energy in favor of fossil fuels while high industrialized and developed countries will benefit. As long as forest resources are larger than the demand this could be a good solution in the short run but in the longer run other patterns with more local use may occur.

2.3.5 Discussion

Forest resources are identified as one of the major supplies of renewable energy as wood fiber in different forms. Today, round wood is used for domestic heating all over the world using traditional techniques. Sometimes it is purchased on the open market but it is more common for local forest land owners to cut their energy supply for the cold season and may be for cooking from their own small wood lots. Controlled firewood cutting also occurs on public lands by local users. This small-scale use of wood for energy has a high value for the user and constitutes a significant level of cuttings and energy but could be a problem when cutting is illegal. Commercially, logging residues like tops and branches are already established for energy extraction in some Nordic countries and in North America.

Wood-based energy production could be expected to increase for heat and steam production. However for electricity production in CHP new technologies must be developed to reach profitability and to prevent price increases on electricity. It leads to the conclusion of a short-term increase for heat production and a longer perspective for CHP to be economically advantageous. The trend is for an increased use of wood in different markets - first of low cost and lower qualities, and later of more expensive, processed products. This is true for both forest products industry and for the energy industry. New quality regulations or certification could also influence this trend. The competition starts with low-value fiber, possibly without any other commercial use and when demands rises, other wood or better timber qualities will be affected. The energy industries, where some are very powerful and financially strong, look for new fuels from the forest sector, from the waste sector, from the agriculture sector and elsewhere. For them biofuels is one renewable energy source competing with another, i.e. solar panels, wind energy, small-scale hydro or other techniques.

2.3.6 Conclusion

In the past years environmental concern has also become a strong driver behind the increased interest for wood energy. Bioenergy/wood-fuel promotion policy in certain countries and within the European Union indicate an increased

competition between traditional users of wood fiber, round wood and manufacturing by-products and users of wood fuel.

A new actor has appeared on the scene for wood raw material - the modern biofuel energy production industry. What this will lead to in the future is an open question, the development of the future energy and forestry policies as well as market prices and the availability of woody biomass for energy purposes will impact on the answer. International trade in wood fuel is strong in Europe, Southeast Asia and North America. However, trade in these regions is limited to certain countries. The short-term trend is that countries and regions with a stronger position in economy and development will increase their use and import of wood fuel while less developed countries will continue their development based on fossil fuels. This might be changed in the long term.

2.4 Competition for wood between material and energy use

Bioenergy — energy from biomass — can play an important role in combating climate change as well as e.g. improving the security of energy supply in Europe. However, plant biomass is used for a large number of purposes, as apart from energy it also provides food, feed, clothing, paper, bioplastics and building materials. There can therefore be direct competition between different uses of the same type of biomass, or competition for land on which to grow biomass, also with other uses of land, e.g. for nature protection.

The political outlook has played a decisive role in the development of the production potential of woody biomass on agriculture land for energy purposes and for paper production. But the importance of the attitude of politicians has become less as oil prices have increased. The state of the oil economy has forced politicians of all types to become increasingly interested in all alternative energy sources. To bridge the remaining gaps in energy availability, both politicians and scientists have to contribute. [Commission of Oil Independency, Sweden, 2006].

Some countries such as Sweden, which has no fossil energy resources, forestry and agriculture are of considerable significance for energy supply.

Already, about 20% of energy currently used comes from forestry [Energy in Sweden, 2004]. In a world conference of IUFRO in Brisbane, Australia, it was stated in the session on Short Rotation Forestry that access to energy rules the world. Particular reference was made to the very rapidly increasing oil imports by China and the interest of the USA in supporting the dictatorship of Saudi Arabia. Even if this statement is somewhat exaggerated, it shows the political importance of access to energy and thus the importance of forestry and agriculture, an importance not always realized and fully understood by politicians and by the public [Christersson L., 2006, p. 79-81].

The concepts most discussed in today's biological world are sustainability and biodiversity, but there is no clear and universally accepted definition of either. No one asks: sustainability for whom or for what? In the general debate, these two concepts replace previous concerns about the effect of acid rain, needle drop, overproduction, leakage of chemicals and others. Together with the imminent shortage of oil [Christersson L., 2003, p. 5–20] and alarm about an increasing greenhouse effect, they are the cause of severe pressure on the development of agroforestry and silviculture. In Sweden, where district heating systems have already been developed and constructed in almost all villages and towns, and where there is a trend for private home owners to replace electricity and oil heating with utilization of chips from forestry, competition for wood for industrial purposes and for the energy market will arise [Christersson L., 2003, p. 5–20].

Once again, Swedish forest industries are expected to face the threat of shortage of wood [Enander G., 2003; Dockered B., 2003]. The last time this was predicted was in the 1960s, when a lack of wood in the 1990s was forecast [SOU, 1968, p. 9]. However, such a deficit never occurred. In the 1960s, development of nuclear power plants was in full swing in Sweden and very few people were discussing shortage of oil and oil prices. On the other hand, it was estimated at the end of the 1980s and at the beginning of 1990s that never before had there been so much wood in Swedish forests [Lindevall B., 1992]. The annual growth of Swedish forests today is about 105 million m³, of which only 80–85 million m³ is harvested [VMR, 2005; Skogsdata., 2005]. But now again a new deficit is being predicted, exacerbated by the damage caused by the storms in January 2005

[Björheden R., 2005]. Today people fear a competition for wood between the paper industry and the energy industry. This has not yet arisen but with increasing oil prices it may be imminent. However, there are many differences of opinion about the situation [Thuresson T., 2002].

The forest products industry; i.e. sawmills, the panel industry and the pulp and paper industry are the main industrial users of timber and wood fiber. The industry produces wood and paper products but also produces by-products during the process. By-products trade and use are complex with rather complicated trade patterns. For example, in the production of sawn wood the mill produces significant amounts of sawdust and chips, which are used in the pulp- and board industry. Bark is mainly used for internal energy use at the mill, and sometimes by local municipalities. At worst it is deposited in landfills. What is 'new' in this market balance is the increased demand for wood for energy outside the forest products industry. This creates competition between traditional users and the energy industry, mainly regarding small diameter wood and by-products. The waste sector has grown strong in recent years, in Europe mainly due to EU waste legislation. The result is that large amounts of fiber are being recycled for use in the paperboard industry and for energy use.

It was concluded that there is a future for a sustainable biofuels industry but that feedstock production must avoid agricultural land that would otherwise be used for food production. This is because the displacement of existing agricultural production, due to biofuel demand, is accelerating land-use change and, if left unchecked, will reduce biodiversity and may even cause greenhouse gas emissions rather than savings. The introduction of biofuels should be significantly slowed until adequate controls to address displacement effects are implemented and are demonstrated to be effective. A slowdown will also reduce the impact of biofuels on food commodity prices, notably oil seeds, which have a detrimental effect upon the poorest people.

Specific incentives must stimulate advanced technology. In the past years environmental concern has become a strong driver. Advanced/new technologies have the potential to produce biofuels with higher greenhouse gas savings and

have the benefit of being able to use a wider range of feedstocks. Energy fuel production using for example charring/torrefaction technologies maybe can help to avoid the use of land that would otherwise be used for food or paper production. This is because this technology can use current feedstocks such as wood waste, agriculture waste. Also it should be considered further necessity of pellets production and using efficiency. In the case of poor prospects in this direction it would allow redirect feedstocks using in pellet production for charcoal production. Charcoal production technology exists but requires technical and economical analysis to get the answer whether this trend of new energy fuel production is appropriate. It is the question of this work.

3 WOOD TO BIOCOAL

3.1 Charcoal production

Historically, charring was faulty process: charring heap, and various primitive "barrels" (Figure 1). Note, that since the late 19th century, thanks to medical advances have seen a dramatic increase in population, especially its increased density in the European part of the country and the Western Trans-Urals. In the last century rapidly growing demand for commodities, which are required for the manufacture of charcoal. As a result, the pressure on nature, produced by environmentally dirty industry, has become a threat to the survival of nature itself.



Figure 1: Charring heap

To date, many Asian countries and especial Brazil are still using the simplest methods of producing charcoal. In 2005 there were produced about 45.5 millions tonnes per year of charcoal in the world. More than 13 millions tons of this amounts has made Brazil [FAO, 2005]. This is explained by the fact that huge energy consumer in Brazil is the steel industry, which consumes this charcoal and it is more profitable to use domestic sources.

The methods of charcoal production are still, basically, traditional processes that have very low recovery rate with a very negative environmental and social impact (Figures 2 and 3). Powerful green house gases like methane are released during charcoal production. Used carbonization technologies have very low efficiency measured in terms of charcoal yield. These simple facilities have also ineffective cost of heat due to lack of isolation. Their service requires heavy manual labor. Weaknesses are also: impossibility of the process managing and as a result - poor quality coal.



Figure 2: Charring kilns (Brazil)

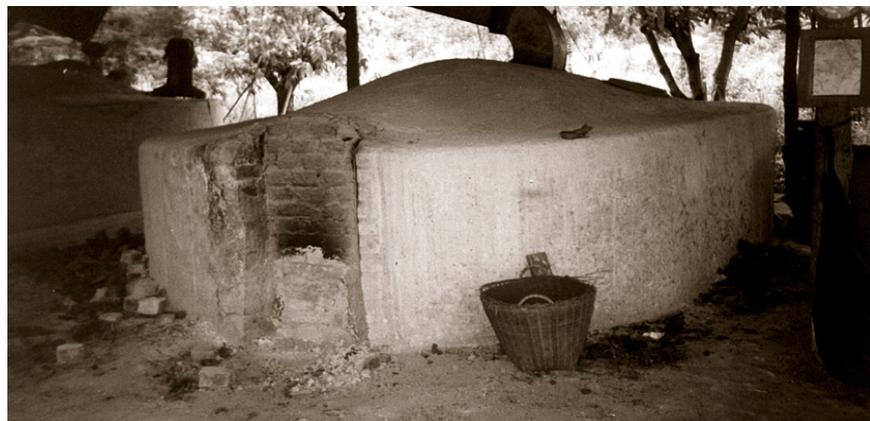


Figure 3: Charring kiln (Thailand)

Based on provisions described above it is clear that such installations (methods) have no future. For further organization of the production of charcoal are needed installations allowing to receive high-quality coal from waste wood of various natural composition. These installations must meet the following conditions:

- Performance on raw material corresponds to the volume of waste in the enterprise. Thus, long-distance transports of raw materials are excluded because of more expensive production costs;
- In a small performance impractical to process liquid products. They should be burned, covering the needs of the process in the warmth;
- The installation should be clean. Necessary to exclude the emissions into the environment and pollution;
- Installation should be simple to manufacture;
- The installation should be easy to manage, explosion and fire safety. It is necessary to provide continuity of installation.

3.1.1 Pyrolysis of the wood. Basic concept

Charring/torrefaction are pyrolysis processes. To understand the specificity of the wood treatment it is necessary to consider main provisions of the pyrolysis of the wood.

Thermal decomposition (pyrolysis) of wood - is the decomposition of wood in the absence of oxygen at elevated temperatures. In the result of this process are solid, liquid and gaseous products. Solid products remain in the form of charcoal, and liquid and gaseous products stand together in the form of vapor-gas mixture. Vapor mixture, if necessary, is divided by the cooling of gases to obtain condensate. The condensate can be recycled to the acetic acid, methanol, tar and other products, and non-condensing gases are burned.

The process of decomposition of wood during pyrolysis can be divided into four stages: 1 – drying (ends at about 150°C), 2 - the beginning of decomposition (150-280°C). During this period begins expansion less heat-resistant components of wood with the release of reaction water, carbon dioxide, carbon monoxide, acetic acid and some other products, changes the chemical and elemental composition; 3

- formation, evaporation of the main products of decomposition of wood (directly - pyrolysis reactions), occurring at 280-400°C with heat (exothermic process); 4 – carbonization of the charcoal to the final temperature, usually no higher than 450-600°C and removal of the rest of volatile compounds. All stages, except stage 3, require heat supply.

The thermal effect of the process of thermal decomposition of wood depends on the pyrolysis conditions and practically does not depend on the type and design of the installation. Magnitude lower thermal effect is 1000-1250 kJ/kg, or 5.6% of the calorific value of the original timber.

The first component of wood - xylan, even at temperatures below 150°C, starts to decompose, but mostly its decay occurs at 250-260°C with the formation of furfural, acetic acid and gases. Lignin decomposition begins at about 200°C, a process due to hetero- and homolytic dissociation of chemical bonds between structural units of lignin within them leads to the formation of low molecular weight volatile compounds and a complete restructuring of the primary structure of lignin. The process of depolymerization of cellulose occurs at temperatures above 300°C. Cellulose and lignin during the pyrolysis give the yield of coal, gas and tar. Output of coal from cellulose is 35%, and from lignin about 50%. Gases obtained by the lignin decomposition contain about 50% CO, 35-40% of CH₄ and only a little CO₂, while the cellulose yield is a low-calorie gas containing more than 60% of CO₂. Methane formation occurs mainly due to methoxyl groups of lignin.

The aromatic compounds contained in the resin (phenols, etc.), are formed by thermal decomposition of lignin, aliphatic compounds - mainly from cellulose and other polysaccharides. Also there is a formation of methanol from cellulose and small amounts from lignin [Gordon L.V., 1988].

3.1.2 The process of the charcoal production

The main idea of the charcoal/torrefied wood production is based on provisions described in previous section (Pyrolysis of the wood. Basic concept).

The result of the process taking place during the charring affect the rate of heating of biomass, residence time of raw materials at a given temperature, the final heating temperature, initial moisture content, particle size of wood, type of the installation. A variety of secondary reactions take place simultaneously with the primary decomposition of wood. Some of them lead to an additional splitting of the decomposition products, others to the polymerization of primary products. The composition of the final products depends mostly on the residence time in the hot zone of the vapor mixture formed during the initial decomposition. According to regularity of the pyrolysis process, it can be argued that the longer the process and the higher the temperature, the more thermally stable products are formed.

The table 13 shows the yield of products of thermal decomposition (wood and bark) of the main species growing in the European part of the world. These findings should be viewed as the average, as output is also dependent on growth conditions, age of trees, even from part of the trunk, which was treated [Gordon L.V., 1988].

Size of particles of raw material affects the duration of the pyrolysis and the type of used equipment. Dispersion (small) raw material has, compared with lump, high specific surface and good flow ability. Since the pyrolysis of wood - a process of joint heat and mass transfer, the specific surface of the material has a direct impact on its speed [Yuriev U.L., 2007], which can be seen, for example, from the basic equation of heat transfer:

$$Q = k \cdot A \cdot \Delta T,$$

where Q - the amount of heat passing through the interface per unit time, W; k- heat transfer coefficient, [W/m²K]; A- the heat transfer surface, [m²]; ΔT – temperature gradient, [K].

Table 13: The yield of products of thermal decomposition, [St.P SFA, 2000]

Raw material		Thermal products, % of mass of the dry wood				
		Charcoal	Tars	Acids, alcohols and others	Gases	Water of the decomposition
Spruce	wood	37.9	16.3	6.3	18.2	22.3
	bark	42.6	18.4	1.9	19.8	17.4
Pine	wood	38.0	16.7	6.2	17.7	21.4
	bark	40.6	18.9	6.7	19.7	16.9
Birch	wood	33.6	14.3	12.3	17.0	22.8
	bark	37.9	24.0	4.7	18.6	14.8
Aspen	wood	33.0	16.0	7.3	20.4	23.3

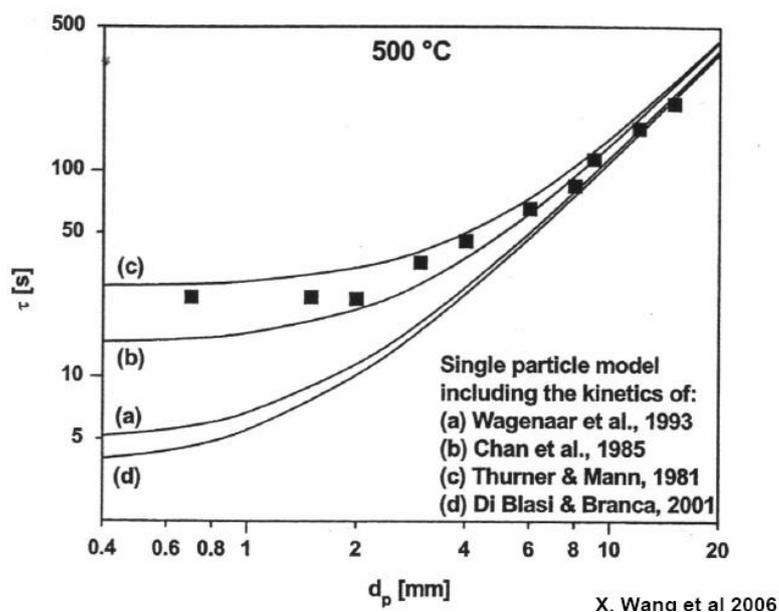


Figure 4: [X. Wana et al, 2006]

Figure 4 shows that with increasing particles size, increasing time to complete pyrolysis. It is clear because as bigger the particles as more time required to heat the mass (thermal conductivity).

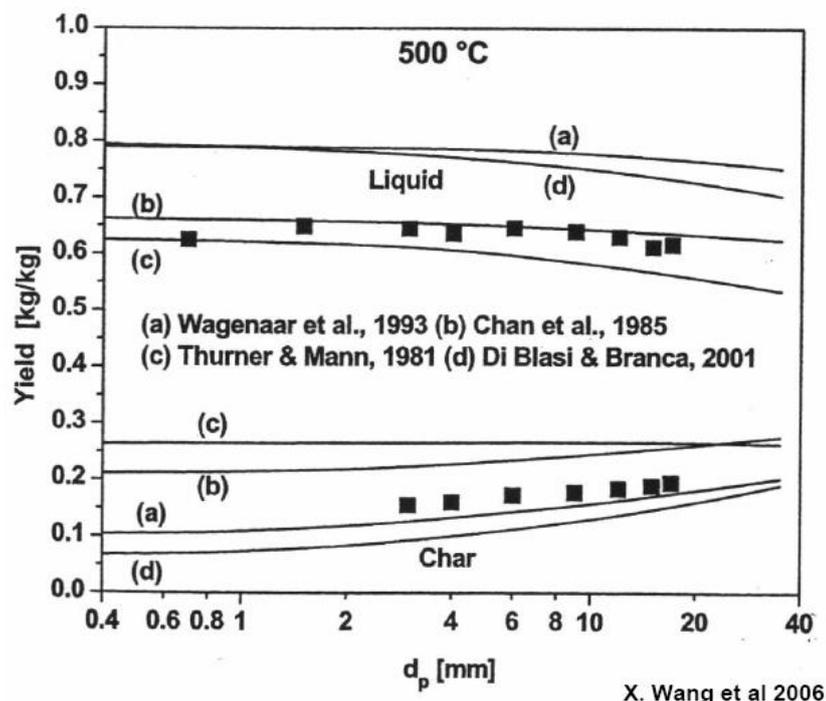


Figure 5: [X. Wanna et al, 2006]

Figure 5 shows that the yield increases with increasing of the particle size. It is also explained by the fact of thermal conductivity of biomass. It results in slow heat and mass transfer rate within particles.

But it should be noted that a high-speed pyrolysis (it means rapid increasing of heating rate) increases the yield at 30-50% less than in case when the mass is staying longer in the reactor. So, it is the question of the technical optimization of the process.

It is found already that gaseous, liquid and solid pyrolysis products consist, like the original wood, of three basic elements, carbon, hydrogen and oxygen. They contain a small amount of nitrogenous substances. The composition of gases generated during pyrolysis of wood practically does not depend on the type of wood [Gordon L.V., 1988].

The average composition of gases by charring of wood at 400°C (% of volume) is shown in Table 14.

Table 14: Gas components of charred wood obtained at 400°C, [Gordon L.V., 1988]

Wood species	Gas components, %				
	CO ₂	CO	CH ₄	C ₂ H ₄	H ₂
Birch	49.0	28.4	18.2	1.4	3.0
Pine	49.5	28.5	18.0	1.0-	3.0
Spruce	48.0	28.0	19.0	1.0	4.0

However, the composition and calorific value of pyrolysis gas varies at different temperatures of pyrolysis, as shown in Table 15. Table 15 shows that the pyrolysis gases obtained at temperatures below 280°C consist mainly of CO₂ and do not burn. The content of combustible gases (CH₄, H₂) increases with the temperature and calorific value greater than 12.5 MJ/m³ [Yuriev U.L., 2007].

Table 15: Gas components of charred wood obtained at different temperatures, [Yuriev U.L., 2007]

Temperature °C	Gas components, %				Calorific value of the gas MJ/m ³
	CO ₂	CO	CH ₄	H ₂	
150 - 200	68.0	30.0	2.0	0.0	4.89
200 - 280	66.5	30.0	3.3	0.2	4.98
280 - 380	37.5	20.5	36.5	5.5	16.13
380 - 500	31.3	12.5	48.7	7.5	19.69
500 - 700	12.4	24.5	20.4	42.7	14.95
700 - 900	0.4	9.6	8.7	81.3	12.98

75-90 m³ of non-condensable gases are formed in the pyrolysis of the 1 m³ of wood. Lower heating value of the 1 m³ of non-condensable gases can be determined with equation, [kJ/m³].

$$Q_{LHV} = 127.5 \cdot CO + 108.1 \cdot H_2 + 358.8 \cdot CH_4 + 604.4 \cdot C_2H_4,$$

where CO, H₂, CH₄, C₂H₄ – volume content of these gases in the mixture, [%]
[Gordon L.V., 1988].

It is important also to follow the changes of harmful compounds in volatiles and in charcoal.

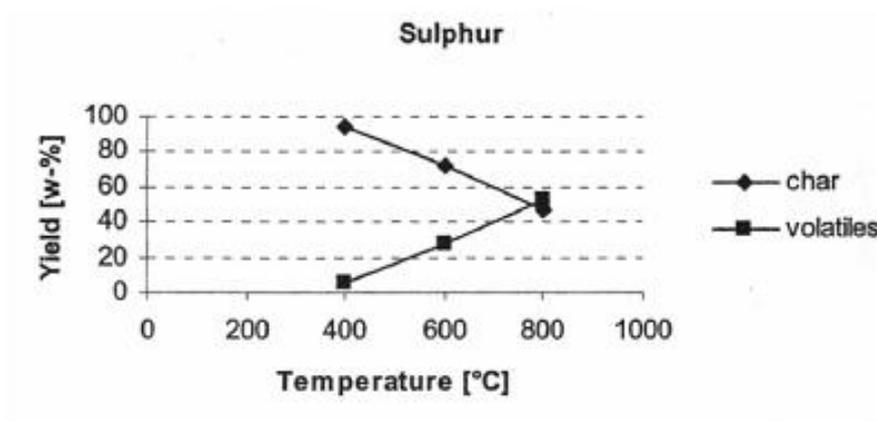
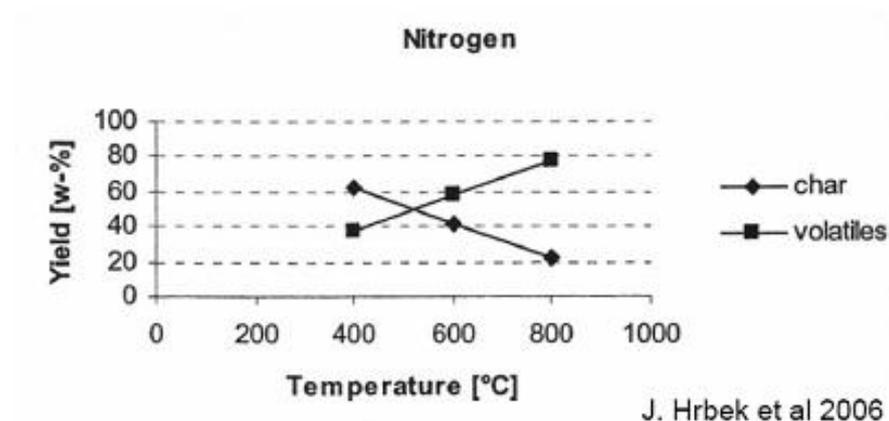


Figure 6: Sulfur migration, [J. Hrbek, 2006]



J. Hrbek et al 2006

Figure 7: Nitrogen migration, [J. Hrbek, 2006]

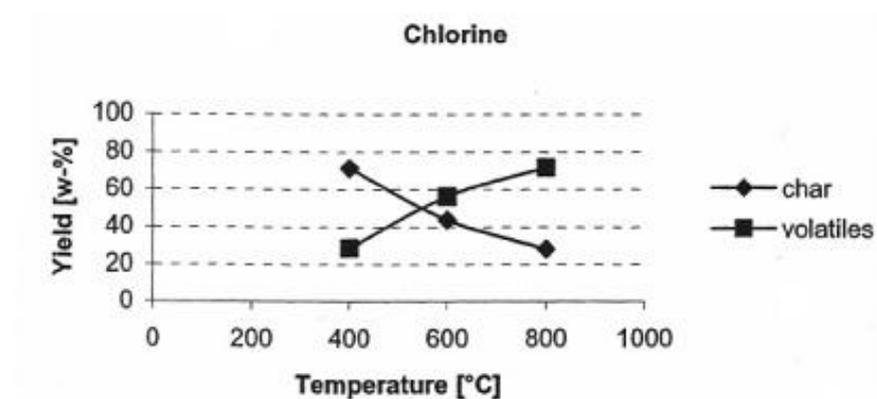


Figure 8: Chlorine migration, [J. Hrbek, 2006]

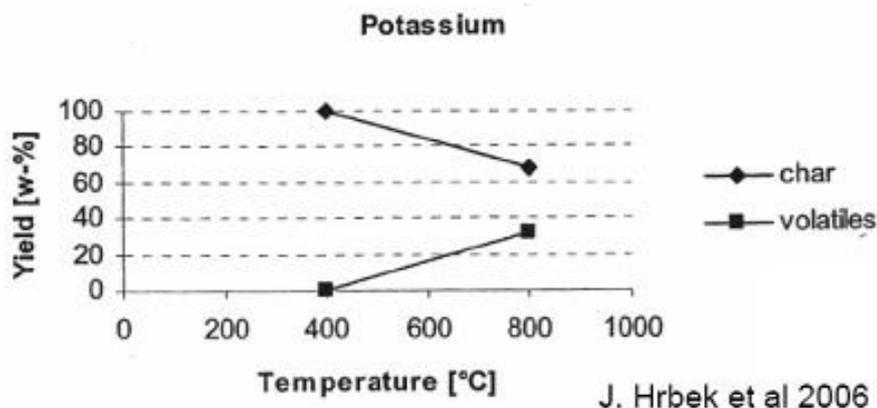


Figure 9: Potassium migration, [J. Hrbek, 2006]

The decomposition process of dry and wet wood occurs differently. Dry wood, with humidity below 10%, provides less heat form decomposition per unit time than wet wood; exothermic reaction begins quickly and goes more rapidly, the process accelerates, the output of coal decreases. The decomposition of wet wood is “self-regulated process”: the temperature decreases due to the large flow of heat through evaporation of moisture, the exothermic reaction is extended and the rate of charring is reduced, resulting in output of acid and carbon number increases. A compromise between these two requirements makes choice for drying at temperature around 220°C. While wood is not dry, its temperature (at normal pressure) remains at 100°C or slightly higher. Dried wood is heated and begins to decompose. To begin the intensive process of decomposition, wood temperature should reach 270-280°C. After this, process in dry wood goes spontaneously with evolution of heat and increase in temperature. But if next layers contain moisture, it formed water vapor, reducing the temperature in the outer layers. Thermolysis process is complicated by the fact that the products of thermal decomposition of the underlying layers pass through the outer, hotter layers, and subjected to further transformations. It should be noted that the wood has low thermal conductivity and heat spreads slowly inside. Constant heat source to maintain the process to achieve the exothermic stage is needed. Further, the heat is enough that the process will become independently (without heat source) and without heat losses.

The pyrolysis process also depends on the rate of heat supply. With rapid heating, at temperatures around 300°C, lignin is melted. Further, after fast cooling lignin changes in greater extent its structural than chemical composition. Considering

the process, it should be noted that the rate of heating in the installation with the external heating is determined by heat transfer, heat conduction and radiation, but inside the unit of natural thermal convection from the wall to the wood. The slowest processes - thermal conductivity through the wall of the installation is decisive for the rate of the overall process. At moderate temperatures, the rate of heat supply in the pyrolysis is not high, so the processes are the predominant in coal formation [Gordon L.V., 1988].

Charcoal products

Under identical conditions of charring of different wood species, charcoal has nearly the same composition. With increasing charring temperature, the yield of coal decreases, but at the same time quality of such charcoal is better (Table 16).

Coal must be produced with respect to certain conditions. Otherwise, in one case, the charcoal can be fragile, which has many cracks because of an excess of oxygen. In another case, the charcoal is not “ready” because of the low temperature or duration of the process. It contains smut, has a brown color, burning with flame.

Ash and moisture

The ash content of charcoal ranges from 1 to 4%, while the ash content of coal from a large timber land delivery usually does not exceed 1.5%. Coal, discharged from the installation does not contain moisture, but it absorbs from the air to a maximum moisture content of 10-15% [Gordon L.V., 1988]. (Detailed ash analyses see in the chapter “Co-combustion”).

Table 16: The yield, composition and heating value of charcoal produced at different temperatures, [St.P SFA, 2000]

Final temperature of charring	Yield of the dry charcoal from the dry wood	Charcoal composition, %			Heating value
		°C	%	C	
350	45.2	73.3	5.2	22.5	31.56
400	39.2	76.1	4.9	19.0	32.74
450	35.0	82.2	4.2	13.6	33.12
500	33.2	87.7	3.9	8.4	34.21
550	29.5	90.1	3.2	6.7	34.42
600	28.6	93.8	2.6	3.6	34.50
650	28.1	94.9	2.3	2.8	34.71
700	27.1	95.1	2.2	2.7	34.88

Carbon content

The content of fixed carbon is also an important characteristic for charcoal. The fixed carbon is a balance of short-term carbonization of charcoal in strictly defined conditions. The nonvolatile carbon is the carbon converted by carbonization from the charcoal and contained in gaseous products. The higher the carbonization temperature of charcoal, the higher the content of nonvolatile carbon.

Porosity of the charcoal

Charcoal has a high porosity, which explains its adsorption properties (Table 17, Figure 10). The porosity of coal can be determined by its density given the density of the coal mass equal to about 1.8 g/cm³.

Table 17: Density and porosity of charcoal, [Gordon L.V., 1988]

Charcoal properties	Wood species			
	Spruce	Pine	Birch	Aspen
Density, g/ cm ³	0.271	0.347	0.424	0.309
Porosity, %	85	81	77	83

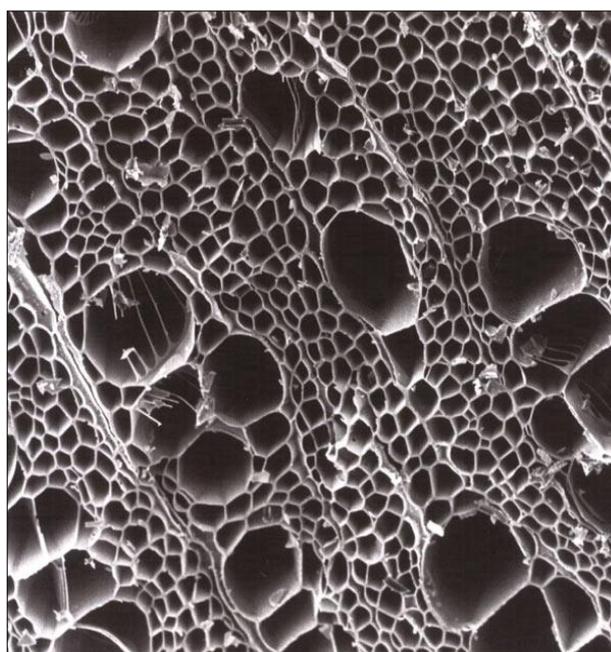


Figure 10: Charcoal, [Yuriev U.L., 2007]

Spontaneous ignition of charcoal

Hot charcoal absorbs oxygen from the air, while unloading from the installation and charcoal is still heated. As a result, spontaneous ignition of charcoal may occur. Coal charred at low temperatures and containing up to 30% volatile compounds has the greatest ability for spontaneous ignition, spontaneous ignition temperature of such coal below 150°C. Coals with a low content of volatile compounds may ignite spontaneously at temperatures above 250°C. Spontaneous ignition of charcoal - the result of its autoxidation, developing an avalanche, with a rapid increase in temperature under the influence of available coal paramagnetic centers. This is a chain branching process having certain critical parameters. If by

contact of coal with air these settings are not being exceeded, then the coal will not ignite. Therefore, it is concluded that the stabilization of the hot charcoal can be accomplished by a controlled cooling of charcoal with air. Under certain conditions coal absorbs oxygen from the air slowly, not warming up, stable and loses the ability of spontaneous ignition. Such coals have the temperature of spontaneous ignition at 340°C. It should be noted that at low ambient temperature charcoal is cooled too quickly and do not have time to stabilize.

Raw material

Raw material for charring can be divided into 3 groups. The first group includes birch and hardwood – beech, ash, hornbeam, elm, oak, maple; the second - deciduous - aspen, alder, linden, poplar, willow; third group consists of conifers - pine, spruce, cedar, fir, larch.

The yield of charcoal from softwood slightly higher than from hardwood, but the quality of charcoal from the hardwood is higher. The content of the bark in the raw material increases the ash content of coal, so the presence of the bark is not desirable, but in industrial practice removal of the bark is usually not produced.

It should be noted that birch wood and especial aspen wood in older age is often struck rot, and if not properly stored it in stock, the processes of decay is accelerating. This leads to a decrease in wood mass per unit volume and decrease in the yield of pyrolysis products, in addition, the charcoal is small and fragile.

Along with special harvested wood different kind of woody biomass can be used also, which by their chemical composition not much different from the stemwood.

Agricultural waste as bagasse (sugar cane stalks after sugar extraction), leaves of sugar cane, coffee husks and straw, are a potentially powerful source of raw materials for biocoal production. The feature of such raw materials is a high ash content and low mechanical strength [Yuriev U.L., 2007].

3.1.3 Current technologies

Estimation of charcoal production value

Charcoal is produced more than in 130 countries around the world, i.e. almost all countries with forest resources. Assessment of production control is carried out by FAO. These data are available in the statistical database of FAO [FAOSTAT] online. The vast majority of data is tentative, because only 10-15% of global production of charcoal, as reported by FAO, is based on statistics reported by the countries themselves.

The geographical distribution of charcoal world production (45.5 million tonnes estimated by FAO, 2005.) is shown in Figure 11.

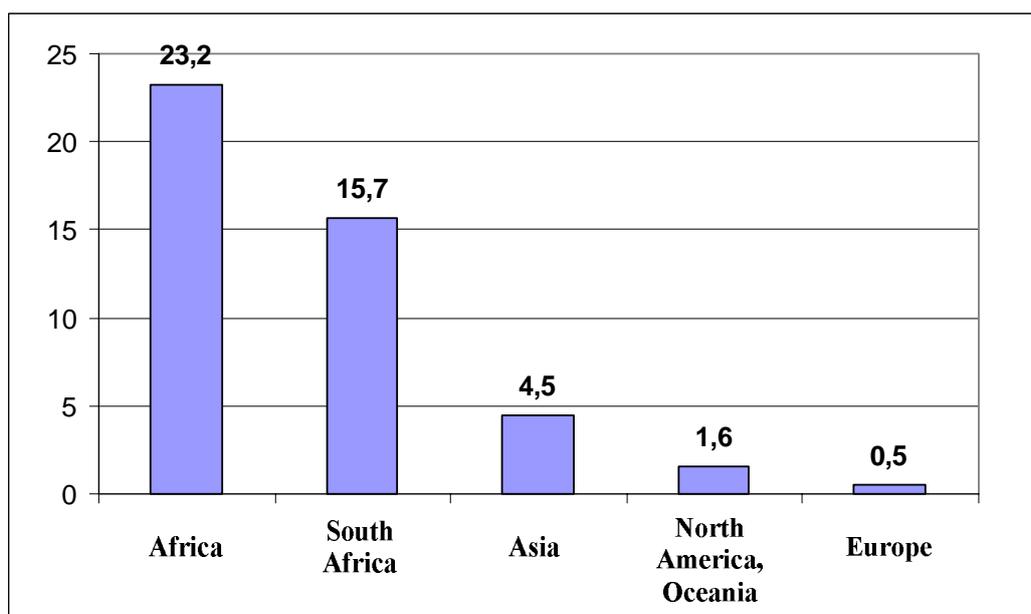


Figure 11: Distribution of charcoal world production, [FAO, 2005]

From Figure 11 it follows that more than half of charcoal world production (51%) are in Africa. Europe's share is about 1%, the Americas and Oceania account for 38%, 10% in Asia. FAO estimates that in 2005 there were 9 countries, each of which produced more than 1 million tons of charcoal per year, as shown in Figure 12.

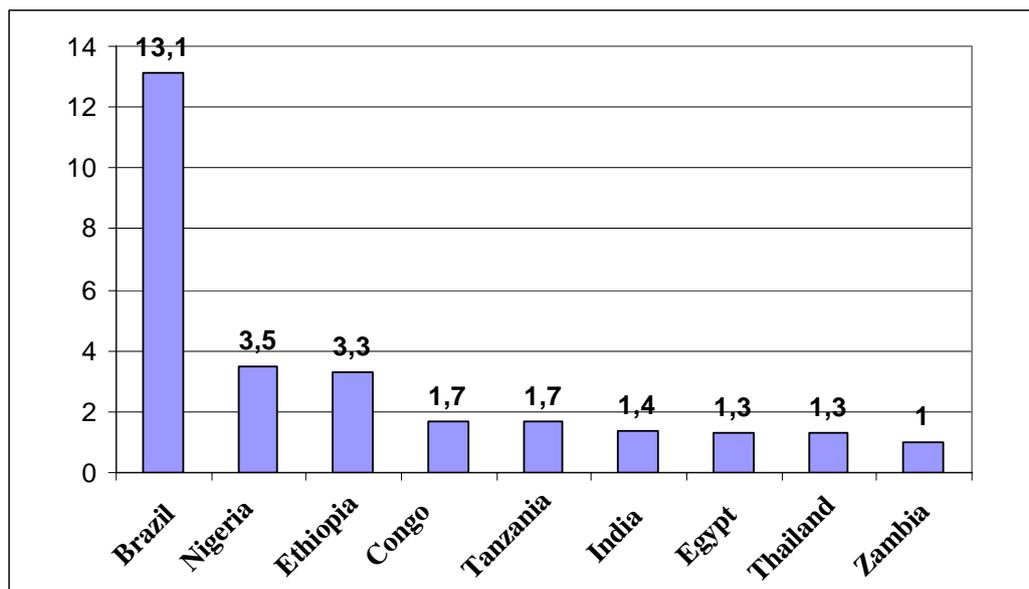


Figure 12: Countries with more than 1 million tons of charcoal production, [FAO, 2005]

From Figure 12 that leader in the production of charcoal is Brazil. Almost all charcoal in the country has industrial applications and is used as a reducing agent in metallurgy.

Production volumes in six African countries represented in the figure can be viewed as purely indicative, and the data for Egypt were not credible and they appeared to be excessive, bearing in mind the almost total lack of timber resources in the country.

Types of installations for charcoal production

The plants can be classified according to the principle of operation: periodic action and continuous operation (Table 18).

Table 18: Types of installations

Types of the installations	Yield, %
Bath process	
Earth pits and mounds	>10
Brick, concrete, and metal kilns	20-25
Retorts	30
Continuous process	
Retorts and Lambiotte retorts	30-35
Multiple hearth reactors	25-30

Brazilian method

Metal kilns – external heating (Figure 13)



Figure 13: Charcoal production in Brazil

Raw material is special harvested wood from eucalyptus plantations. Trucks deliver prepared raw material to the plant. Metal boxes with raw wood are installed into the metal kiln. Pyrolysis process is provided through circulation of hot gases obtained from combustion of the firewood and from partial combustion of volatile compounds converted from the wood during the pyrolysis process. Produced charcoal is discharged from the kiln, cooled in open air and stored in pits (Figure 14).

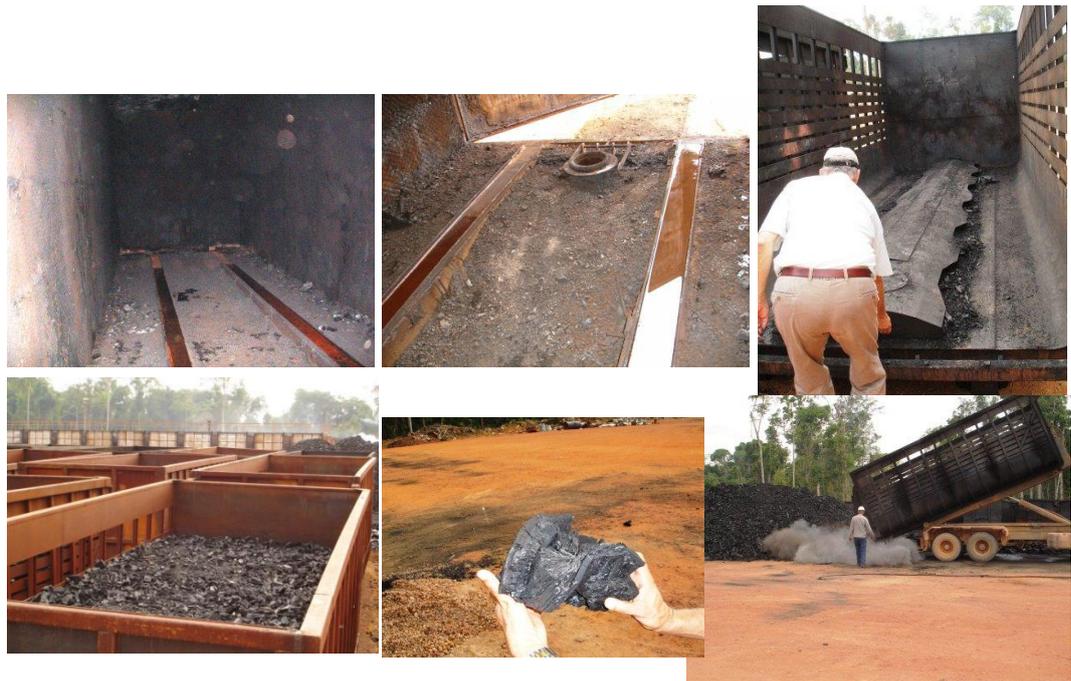


Figure 14: Brazilian metal kiln

Charcoal production in Russia (Figure 15)

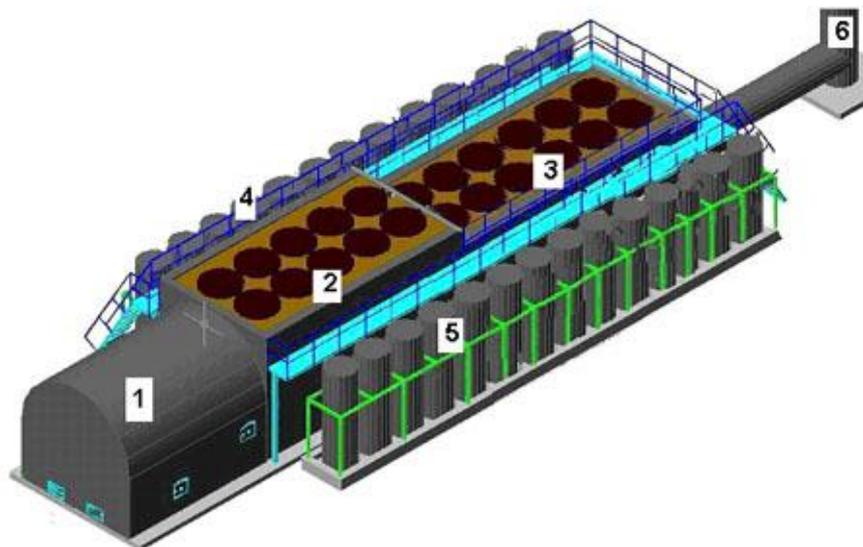


Figure 15: Russian installation. 1 - furnace; 2 - pyrolysis chamber; 3 - drying chamber; 4 - retort with woody biomass; 5 - retort with the cooling charcoal; 6 - stack

- Productivity – 1800 t/a charcoal (18000 m³/year raw material);
- Continuity of production;
- Fixed Carbon – 75-94 %; Moisture – < 6%; Ash – 2.5-4 %;
- Charcoal Yield – 30-40%;
- “Clean production”;
- Capital cost – 240,000 EUR (the installation with 1000 t/a charcoal – 110,000 EUR), [St.P FI].

The idea of the technical solution set is that the retractable retorts are installed in the holes in the top the floor furnace device. Retorts are installed in the oven with a shift in time. So, when one is drying, in the other - pyrolysis and in third-drying of coal. Drying and pyrolysis zones are divided among themselves that allows using the heat with higher efficiency. Steam-gas goes through the gridiron and special ducts in the furnace and it burns. It means that heat demand that is necessary for the technology covered by combustion of gases produced during the production. Due to this requirement is met in the heat, if the initial relative humidity of woody biomass below 50%. At higher humidity firewood is added into the furnace. The furnace operates continuously, and the retort, in which the process is completed, extracted and set to cool in a special stand. In the vacant hole is inserted into another retort, filled with green woody biomass. Thus, combustion space is not cooled, and the heat losses are reduced. Cooling of the coal occurs as efficiently as the heat transfer is only from the coal, of the single wall of the retort. There is no need to pour water coal. Installations are universal - capable to process wood and woody biomass in different temperature ranges. Only retractable retort cools (not whole installation), so the heat is gained and turnover retort is significantly reduced.

All combustible gases, converting from wood during the pyrolysis process, are burned in the furnace. It provides the work of the installation on own heat without burning additional fuel and without harmful emissions into the atmosphere. It is also possible to use waste heat for the production of thermal energy (for example: hot water or low pressure steam).

Continuous retort (Figure 16)

- 1 - wood elevator; 2- hydraulic gate;
 3 - outlet of the vapor mixture;
 4, 9- unloading hoppers;
 5 - cone of hot gas;
 6- inlet of the heat transfer agent;
 7, 13- outlet of the warm gas;
 8 - cone of the warm gas;
 10 - outlet of the cool gas;
 charcoal elevator; 12- floodgates.

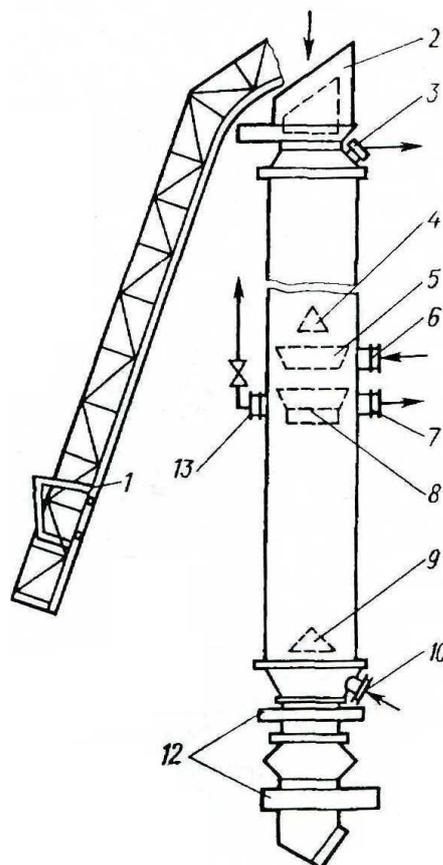


Figure 16: Continuous retort, [Koverninskiy I.N., 2002]

Retort is a steel cylinder with an internal diameter of 0.5-2.8 m. The most common are vertical retorts with an internal diameter of 2.7-2.8 m, the thickness is 14 mm in height with gates 26-29 m, effective height 15.1-18 m. Technological process of charcoal production includes drying the wood, pyrolysis of wood, coal, and cooling of charcoal and circulation of flue gases and volatile pyrolysis products .

Production capacity – 9 000-14 000 t/a of charcoal.

Fixed carbon is not less than 88%, ash content not high than 2.5% [Koverninskiy I.N., 2002].

Lambiotte retort (Figure 17)

- 1 - loading of the wood;
- 2 - outlet of the vapor mixture into the atmosphere;
- 3 - drying zone;
- 4 - combustion zone (vapor mixture); 5- pyrolysis zone;
- 6 - fan; 7,14 spreading cone; 8- cooling zone;
- 9 - inlet of cooling gas; 10- outlet of the charcoal;
- 11 - damper; 12- outlet of the hot gas;
- 13 - dividing cone; 15- inlet of the air; 16- air collector.

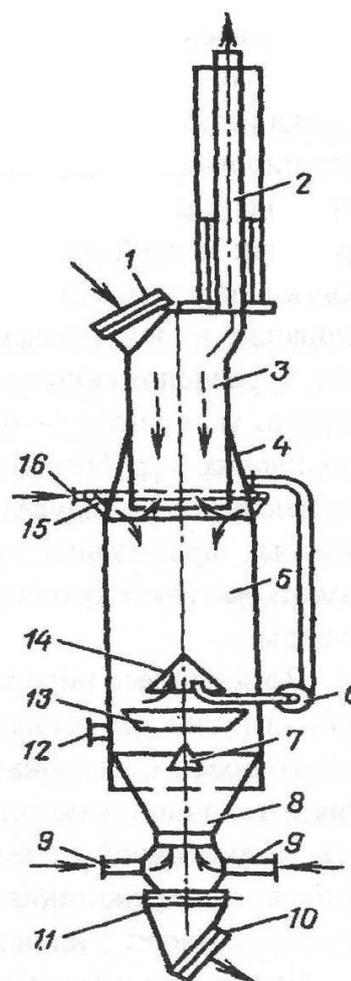


Figure 17: Lambiotte retort, [Koverninskiy I.N., 2002]

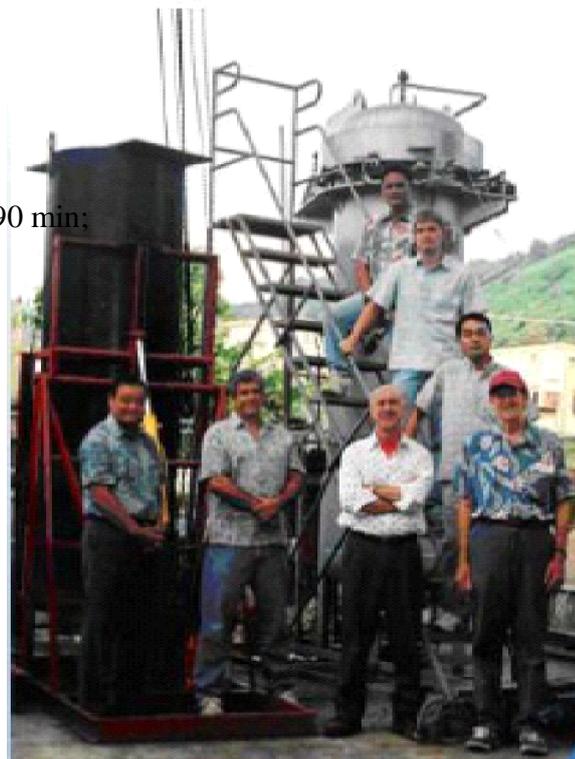
The retort was designed by Belgium Company “Lambiotte” [www.lambiotte.com]. Retort is a cylinder with the transition to the bottom of the cone. Retort has a height of 18.4 m and a diameter of 4.3 m. Raw materials in the retort descends from the top down and passes successively through three zones: drying, pyrolysis and cooling.

Production capacity – 2 000 – 6 000 t/a of charcoal.

Fixed carbon is 82-90%, water content 3-4% [Koverninskiy I.N., 2002].

Demonstration reactor in Canada “HNEI Flash Carbonization” (Figure 18)

- Batch operation – 10 t/day charcoal;
- Biomass loaded to a canister then heated up to 350°C at 0.7 MPa for 30-90 min;
- Charcoal yield 40-50 %;
- Fixed carbon – 70-80 %;
- Catalytic after burner for tars eliminates smoke from reactor effluents;
- Capital cost \$200,000.



[Fernando Preto, 2008]

Figure 18: Canadian installation

3.1.4 Main charcoal consumers

Charcoal has a domestic and industrial use. Consumption of charcoal only as a domestic fuel is characteristic of the vast number of developing countries. Mostly charcoal is used by urban population.

Industrial and semi-use of charcoal in the developing countries is very limited. A certain amount of charcoal is used in the handicraft enterprises, for drying tobacco in the forges, etc.

Industrial application of charcoal is based on the use of its unique properties - high reducing capacity, low ash content and a well-developed porous structure.

Crushed charcoal is used in the production of granulated ferrous metals, in the production of steel, cast iron, galvanized wire, glass, heat treatment of steel parts. Charcoal can be also processed into activated charcoal, which is used in the sorption technique to capture and return to the production of valuable organic solvents, for the separation of gas mixtures, as an absorbent and as a basis for catalytic and chemisorptions-active additives, in water purification, in medicine for the absorption of various harmful substances [Koverninskiy I.N., 2002].

Currently, such property of the charcoal like porosity is under careful consideration because of the possibility to use charcoal in the form of fertilizer. It can be added to agricultural land. This is a natural additive which helps catalyze the action of both organic and chemical fertilizers used on crops. A single treatment can help increase yields for several years. The use of charcoal dates back to pre-Columbian Indian civilizations, as reflected in their Terra Preta – very fertile fields surrounded by poorer soils – which has been the subject of much scientific research. The use of charcoal helps in carbon sequestration, whilst at the same time reducing the consumption of fertilizers and bringing a spectacular improvement in yields.

However, currently, metallurgy is the main industrial consumer of charcoal, where it is used in the smelting of iron and ferro-alloys, such as ferrosilicon and silicon.

3.1.5 Charcoal briquette production

The idea of the charcoal briquettes production was arisen because of large amount of the charcoal fine particles produced during pyrolysis process of waste wood, especially in installations with heavy duty and forced mixing of the material. Fine particles of the charcoal had no sales. With the time the competitiveness of charcoal briquettes became higher, since their quality can be adjusted within wide limits, and they are well preserved during transportation over long distances and cheaper to handle unlike usual charcoal. The advantages of charcoal briquettes to lump charcoal are desirable size, strength and porosity. In consequence, manufacturers whose plants are located a long distance from their markets generally briquette their charcoal, both to take advantage of these economies.

Charcoal briquettes are a high-quality fuel. Briquettes have high mechanical strength (6.9-9.8 MPa), high density (0.9-1 g/cm³), high calorific value (30-32 MJ/kg), low water absorbency [Koverninskiy I.N., 2002].

The production of charcoal briquettes consists of few stages: grinding of coal, the preparation of briquette mass, briquetting, drying. Briquettes are usually produced using binders, which can be: products of thermal processing of solid fuels and oil refining, food processing plant materials - dextrin, starch, molasses, lignosulphonate, willow pitch, etc.

The main factors affecting the quality of charcoal briquettes are pressure, the temperature of heat treatment and quality of the binder material. Organic substances are usually used as a binder, not to increase the ash content of the final product.



Figure 19: Charcoal briquettes

Optimal conditions for charcoal briquettes production are: the mass fraction of binder 15-20%, water 40% of the mass of the dry raw material, cooking time of the mixture 60-90 minutes, pressing pressure 5 MPa, the drying temperature 500-550°C [Koverninskiy I.N., 2002].

Production of charcoal briquettes does not represent a significant environmental hazard, as a binder (for example starch), non-toxic and does not emit harmful substances during drying. Drying of charcoal briquettes are usually carried out by hot air and no danger to the environment. However, dust emissions are during charcoal briquettes production, so it is needed an effective dust control. Costs of charcoal briquettes production are mainly related to the cost of raw materials and energy.

The plant in Suolahti, Finland (KS Party Oy) can be considered as an example of charcoal briquettes production. The building of factory has begun in 1944 with help of State. In that time the general production was a fuel produced from tar for tanks (biodiesel). After the end of the war the factory was sold to a private owner, and the main production was a tar till 1970, but produced charcoal was being sold for different aims. As a demand for a tar became low, so the general product is a production of charcoal for a grill. In 1977 the first line for packing of briquettes was effected, by the pressing of charcoal dust. The name of KS Party Oy has been given to the company in 1999 and till now the general product are charcoal and briquettes produced by the pressing of charcoal dust [KS Party Oy].

The line of briquettes production consists of screw conveyor, mixers, press, packaging line, weigher, drying kiln and generator with burner and fan [KS Party Oy, 2010]. Three hangars for the production and the manufacture building are located on the territory of the plant. There is also the building (old plant) where tar was produced but it is partially destroyed.

Table 19: Certificate of the charcoal briquettes quality, [KS Party Oy, 2010]

Certificate of the charcoal briquettes quality			
Analysis №1			
Properties of the charcoal briquette	Method	Unit	
Volatiles (daf)		%	7.2
Water vapor (105°C)	V20	%	0.9
Ash content (550°C)	V20	%	4.6
Analysis №2			
Volatiles (daf)		%	13
Water vapor	V20	%	1.8
Ash content	V20	%	6.3

3.2 Torrefaction of the wood

3.2.1 Torrefaction principle. Research of the Mark J Prins team

There were made two researches: first research was devoted to study the kinetics of the process and the second to analysis of products obtained by torrefaction.

As was said in the beginning, the wood fractions show different thermal behavior. Three zones may therefore be distinguished in weight loss curves of wood: hemicelluloses, the most reactive compounds, decompose at temperature in the range of 225 – 325°C, cellulose at 305 – 375°C and lignin gradually over the temperature range of 250 – 500°C. The research of the Mark J. Prins team was addressed specifically the first zone, i.e., a process also known as torrefaction - decomposition of hemicellulose in the relatively low temperature range of 225–300°C.

The weight loss kinetics of lignocellulosic fuels have been determined in many different experimental devices. Such devices include thermogravimetric analyzers (TGA), tube furnaces and fluidized bed reactors (Figure 20). The research

described used static conditions, in which the sample is kept at a constant temperature.



Figure 20: Bench-scale experimental set-up for wood torrefaction, [Mark J. Prins, 2006]

An important research parameter was the type of biomass, the composition of which determines its behavior in the torrefaction process. Deciduous wood types as well as coniferous wood types are considered. These types are often referred to as hard wood and soft wood, respectively. There is not much difference in the distribution of the three wood fractions between these types. Coniferous wood may contain slightly more lignin than deciduous wood (25–35 wt% versus 18–25 wt %), slightly less cellulose (35–50 wt% versus 40–50 wt %), and, on average, comparable amounts of the hemicelluloses (20–32 wt% versus 15–35 wt%) [R. Wagenfuhr, 1974]. However, the composition of the polysugars that form the hemicelluloses fraction is very different. In the case of deciduous wood, the

hemicelluloses contain 80–90 wt% of 4-Omethyl glucuronoxylan (referred to as xylan) whereas they contain 60–70 wt% of glucomannan and 15–30 wt% of arabinogalactan for coniferous wood %) [R. Wagenfuhr, 1974]. The thermal behavior of these components may be different. Therefore, it is an important question whether the thermal behavior of deciduous and coniferous wood types is the same, i.e. do they react with comparable rates in the torrefaction temperature range. Furthermore, weight loss kinetics of wood is compared to wood components such as xylan.

Several biomass types have been tested in the experiments: deciduous wood (beech and willow), coniferous wood (larch) and straw. The deciduous wood types were obtained from Rettenmaier, Germany, the coniferous wood from Praxis, Netherlands and wheat straw was taken from a field in North- Holland. Particle sizes were in the range of 0.7–2.0 mm in all cases, except for straw where it was <5 mm. Model compounds of wood, such as cellulose and 4-O-methyl glucuronoxylan, extracted from oak spelt, were also used. These were purchased from Sigma–Aldrich in powdered form. [Mark J. Prins, Krzysztof J., 2006].

Researches showed the following provisions:

1. The kinetics of torrefaction reactions in the temperature range of 230–300°C can be described accurately by a two-step mechanism. The first step is much faster than the second step, so that these steps can be demarcated in time. The first step is representative of hemicellulose decomposition, while the second step represents cellulose decomposition. The solid yield for the first step is higher than for the second step: 70–88% (decreasing with temperature) versus 41%. This may be explained because deciduous wood, such as willow, contains less xylan (the reactive component in its hemicellulose fraction) than cellulose.

Figure 21 compares the elemental composition of fresh beech wood and the torrefied product. It was obtained after heating beech wood from 200°C (around this temperature, wood starts to decompose) to temperatures between 220 - 280°C in 3-12 minutes respectively, where after the temperature is kept constant for 30 minutes. The triangle points closest to the original beech wood were measured at the lower temperatures (220-230°C) and those furthest away at the higher

temperatures (270-280°C). Due to removal of water and carbon dioxide, the composition of the torrefied product has a lower O/C and H/C ratio. The product composition is still very different from charcoal, which requires much higher temperatures to produce.

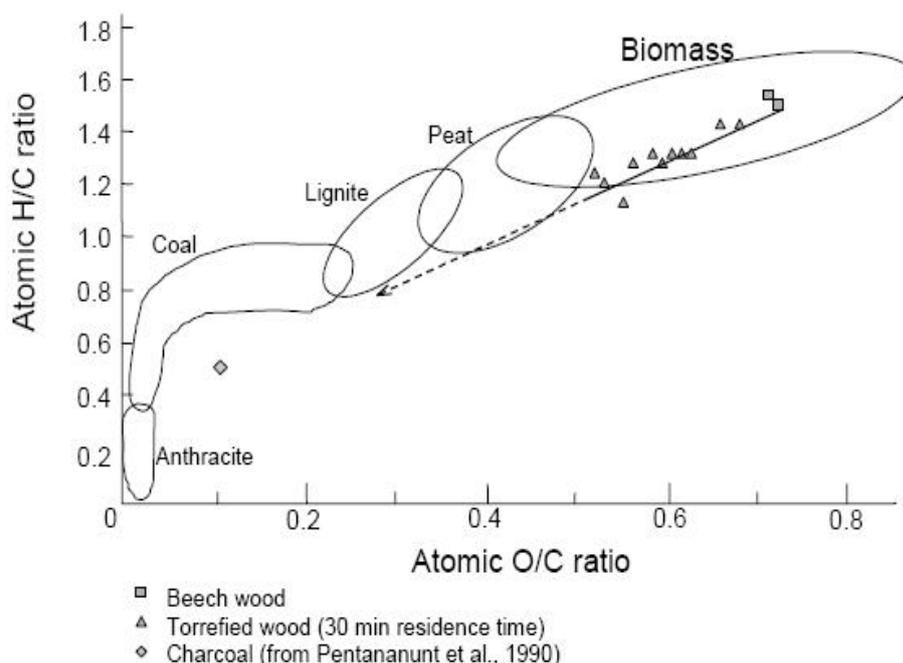


Figure 21: Composition of beech wood and torrefied beech wood (obtained at temperatures from 220-280°C) in van Krevelen diagram, [Mark Jan Prins, 2005]

2. It can be concluded that deciduous xylan-containing wood (beech and willow) and straw are more reactive in the torrefaction process than coniferous wood (larch). In the first case, the mass conserved in the torrefied wood is lower: 73-83% (depending on residence time) versus 90% at a temperature of 270°C.

3. The yield of solid product decreases with temperature and, to a lesser extent, residence time, whereas the yield of volatiles increases accordingly. The volatiles consist of a condensable fraction and a non-condensable fraction. The extent of devolatilization increases with temperature and reaction time. For both fractions (solid yield and volatile compounds), the amount formed increases with torrefaction temperature.

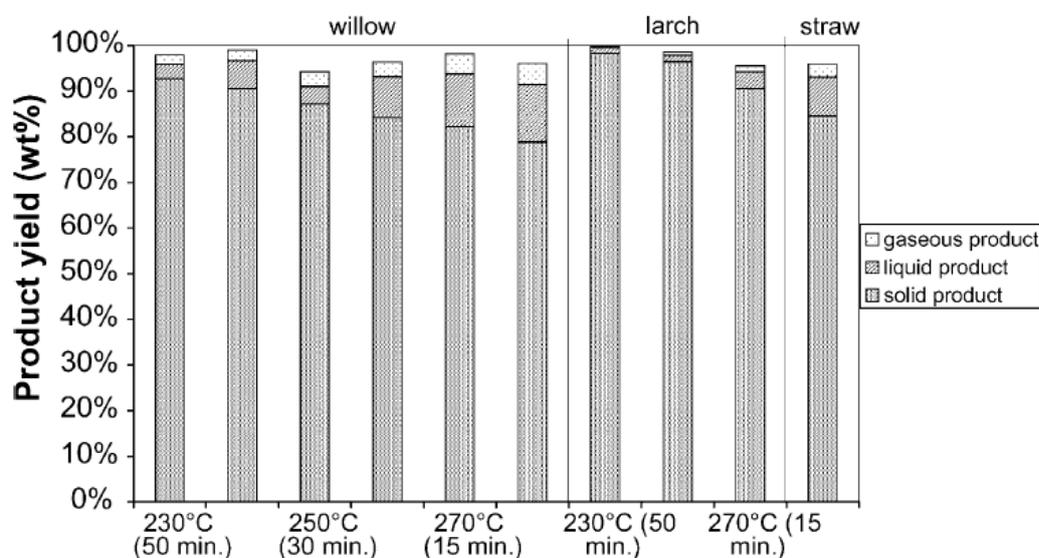


Figure 22: Overall mass balance of several torrefaction experiments, [Mark J. Prins, Krzysztof J., 2006]

In torrefaction of the deciduous wood types and straw, more energy is transferred with the volatiles in the form of combustibles such as methanol, acetic acid and carbon monoxide. The energy contained in volatiles increases with temperature and reaction time. For torrefaction of larch, energy conservation is almost complete below 250°C as volatile formation is very low.

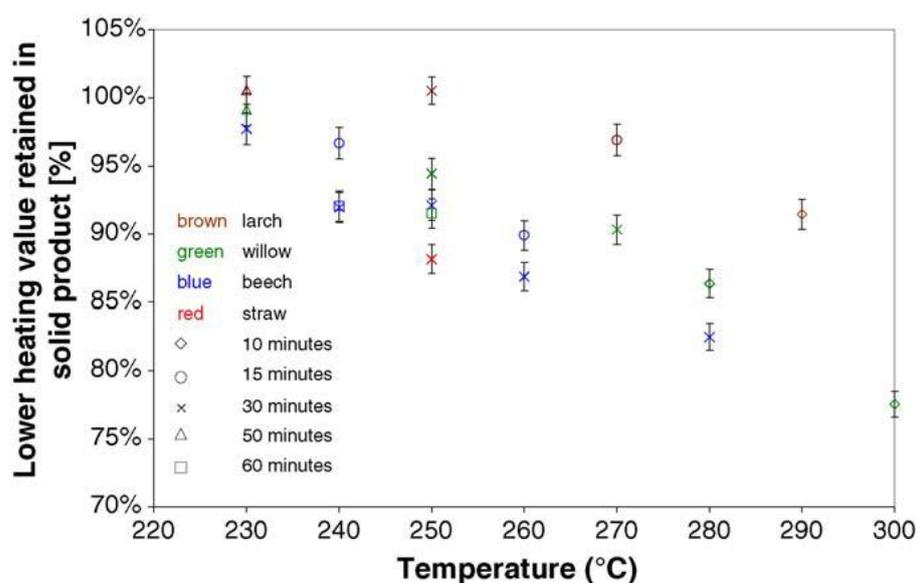


Figure 23: Lower heating value retained in torrefied wood on dry basis as a function of temperature and residence time, for different biomass types, [Mark J. Prins, Krzysztof J., 2006]

The energy retained in the solid product is shown in Figure 23. Clearly, in torrefaction of the deciduous wood types and straw, more energy is transferred with the volatiles in the form of combustibles such as methanol, acetic acid and carbon monoxide. The energy contained in volatiles increases with temperature and reaction time. For torrefaction of larch, energy conservation is almost complete below 250°C as volatile formation is very low.

4. The chemical composition of torrefied wood is comparable to that of peat. Torrefied wood has a brown color and retains 70-90% of the weight of the biomass feed. The properties of torrefied wood were found to be in between wood and coal. Compared to the original wood, torrefaction decreases the content of volatiles from ca. 80% to 60-75% and the moisture content from typically 10% to 0-3%, whereas the heating value increases by 5-25%. The properties of torrefied wood depend on the type of wood used, and the reaction temperature and residence time that is applied.

Table 20 presents the composition of wood and torrefied wood, obtained by two experiments using willow: at a reaction temperature of 250°C and reaction time of 30 minutes, and 300°C and 10 minutes respectively. Reaction times exclude a heating time from 200°C to the reaction temperature of 8.5 and 17 minutes respectively. As a result of the torrefaction process, the lower heating value of the wood increases from 17.6 MJ/kg to 19.4 MJ/kg and 21.0 MJ/kg respectively.

Table 20: Composition of wood and torrefied wood (for willow), [Mark Jan Prins, 2005]

Element	Wood	Torrefied wood (250°C, 30 min.)	Torrefied wood (300°C, 10 min.)
C, %	47.2	51.3	55.8
H, %	6.1	5.9	5.6
O, %	45.1	40.9	36.2
N, %	0.3	0.4	0.5
Ash, %	1.3	1.5	1.9
LHV (MJ/kg)	17.6	19.4	21.0

Table 21 presents mass and energy balances for the experiments of Table 20. At higher temperature, more volatiles are formed so that the mass yield for the two cases is 87% and 67% respectively.

Figure 24 shows the overall mass and energy balances for the two experiments. The energy balance shows that 95% and 79% of the respective energy input (the lower heating value of the wood plus heat supplied to the process) is retained in the solid product. These values have been determined by an ASTM method using an adiabatic bomb calorimeter, which has an inaccuracy of approximately 240 kJ/kg.

Table 21: Mass and energy balances for torrefaction of (dry) willow at a temperature of 250°C (reaction time of 30 minutes) and 300°C (reaction time of 10 minutes). Data per kg of wood input, [Mark Jan Prins, 2005]

	Torrefaction (250°C, 30 min.)			Torrefaction (300°C, 10 min.)		
	Mass	LHV	Sensible heat	Mass	LHV	Sensible heat
Torrefied wood	kg/kg	kJ/kg	kJ/kg	kg/kg	kJ/kg	kJ/kg
Org. material	0.859			0.655		
Asch	0.013			0.013		
Total	0.872	16883	202	0.668	14024	189
Volatiles	kg/kg	kJ/kg	kJ/kg	kg/kg	kJ/kg	kJ/kg
Steam	0.057	0	24	0.066	0	35
Acetic acid	0.021	300	6	0.072	1001	28
Other organics	0.018	258	6	0.142	2280	59
CO ₂	0.029	0	6	0.040	0	11
CO	0.003	30	1	0.012	121	3
H ₂	trace	1	0	trace	1	0
CH ₄	negl.	0	0	trace	2	0
Total	0.128	589	43	0.032	3405	136

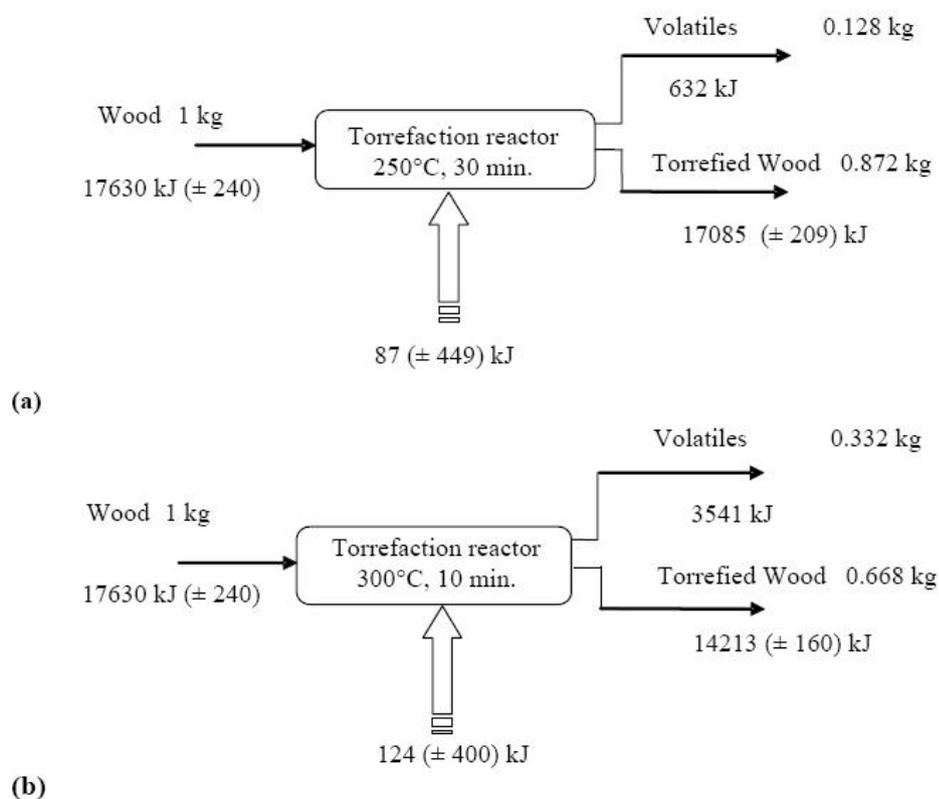


Figure 24: Overall mass and energy balances for torrefaction of (dry) willow at temperature and reaction time of (a) 250°C and 30 minutes (b) 300°C and 10 minutes, [Mark Jan Prins, 2005]

It is clear that it is necessary to consider studies and experiences of other researchers; to examine parameters of treated biomass in different temperature rates and different types of raw materials to understand the possible industrial application of the method – woody biomass to biocoal processing.

3.2.2 Current technologies

Currently, there are no plants for torrefied wood production at industrial scale. Only pilot installation can be remarked.

EBES AG – European Bio Energy Services

The ACB Pilot Reactor at 50 kg/h (Figure 25). ACB - Accelerated Carbonization Biomass.



Figure 25: The ACB Pilot Reactor, [EBES AG]

Raw material:

- Wood residues
- Agricultural (by) products
 - straw
 - miscanthus
 - FFB
 - Grass/Hay
 - Bagasse
- Other Solid Biomasses
 - Bark
 - Nutshell, Husk

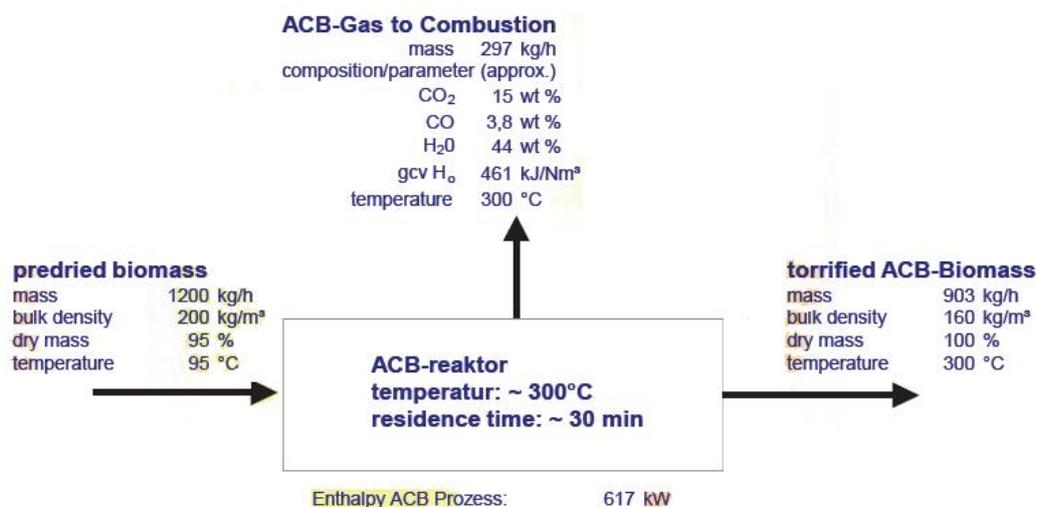


Figure 26: Mass balance of the torrefaction process, [EBES AG]

Torrefaction, properties

By the example of miscanthus:



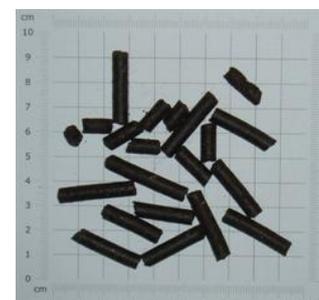
Raw material:

- gcv (db): 17.500 J/g
- BD: 150 kg/m³



Torrefied material:

- gcv (db): 23.300 J/g
- BD: 200 kg/m³



ACB-pellets:

- gcv (db): 23.300 J/g
- BD: > 700 kg/m³

Energy research Centre of the Netherlands (ECN). TOP technology

The TOP process is the process of torrefied wood and pellets production (in one chain). The TOP process (Figure 27) is based on direct heating of the biomass during torrefaction by means of hot gas that is recycled. The hot gas consists of the torrefaction gas itself and is re-pressurized and heated after each cycle. The necessary heat for torrefaction and pre-drying is produced by the combustion of the liberated torrefaction gas. Possibly a utility fuel is used when the energy

content of the torrefaction gas is insufficient to thermally balance the torrefaction process. Use is made of a dedicated torrefaction reactor that is based on moving bed principles, but with unique features for optimal heating and temperature control with minimal pressure drop.

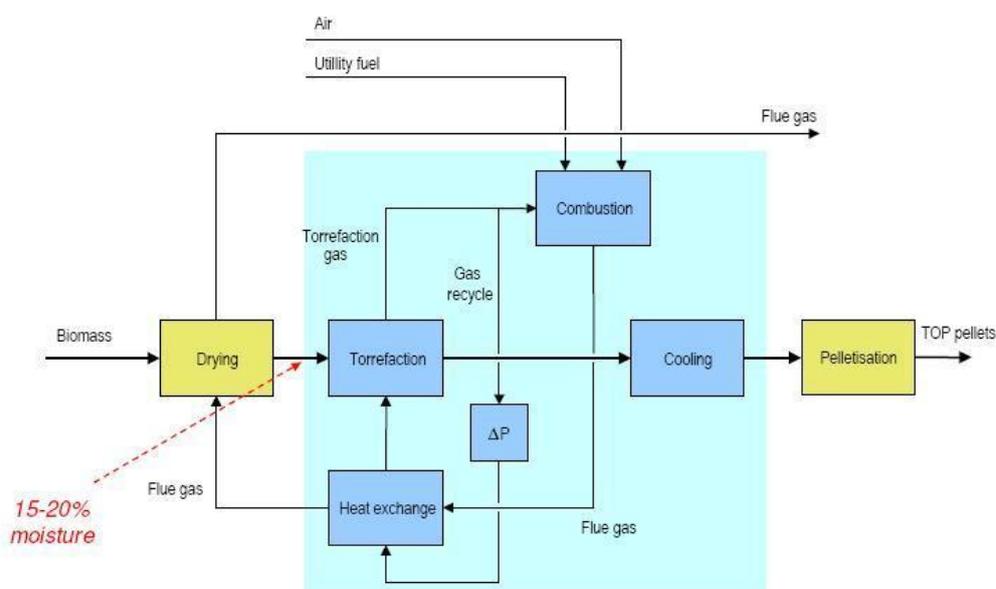


Figure 27: Plant – layout of the ECN TOP technology

Currently, this reactor is under development at ECN. The typical commercial scale of operation is expected to be 60-100 ktonne/a of product, which is on energy basis comparable to the typical production scale of pelletisation (80- 130 ktonne/a). Scale-up is in practice limited by scale-up characteristics of the drying unit.

The thermal efficiency of the TOP process is typically 96% on LHV basis (net process efficiency typically 92%) for a feedstock moisture content of 50%. Heat losses are mainly encountered in the drying of the biomass. This high efficiency can be achieved, as long as the torrefaction gas can be used as dryer fuel and does not contain more energy than needed. A decrease of efficiency will occur when the devolatilisation of the biomass during torrefaction is too severe. Therefore tuning of the energy content of the liberated torrefaction gas to the total heat demand of torrefaction and drying is crucial for obtaining high energy efficiency [Patrick C.A. Bergman, ECN, 2005].

3.2.3 Wood briquette torrefaction

Biomass residues have a great potential in most developing countries, since they are able to replace energy sources such as firewood [Suárez et al., 2000]. However, only a small proportion of biomass residues are being used as fuel because of their high moisture, high polymorphism and low energy density. These troublesome characteristics increase costs for transport, handling, and storage, making the use of biomass as a fuel impractical. Some of these drawbacks can be overcome if the biomass residues are densified into briquettes, in order to provide more energy per unit volume and uniformity in shape and size [Bhattacharya, 1990].

Some disadvantages of the biomass briquettes are their high sensitivity to moisture and low combustion efficiency. For example, briquettes are seen to crumble when exposed to water or high humidity. Also, during the initial combustion stage briquettes emit a great amount of smoke because of their high volatile matter content, causing losses as unburnt fuel gas. The technology “wood briquette torrefaction” was considered in Brazil to eliminate these disadvantages.

Briquette torrefaction consists of thermally treating the briquettes at temperatures between 230 and 280°C in a non-oxidizing environment. The idea of the process includes all main provisions of the torrefaction process in case when raw material is green woody biomass (see the chapter “Torrefaction of the wood”). Torrefied biomass get advantageous properties (such as low moisture, lower emission of smoke and increased heating values) that improve fuel quality.

Research was conducted to investigate the characteristics of torrefied briquettes and the relationship between these characteristics and the torrefaction process parameters. The tests were carried out in a torrefaction unit, which consisted of a biomass combustion chamber for heat generation and an overhead torrefaction chamber, Figure 28 [Felix F.F., 2005a].

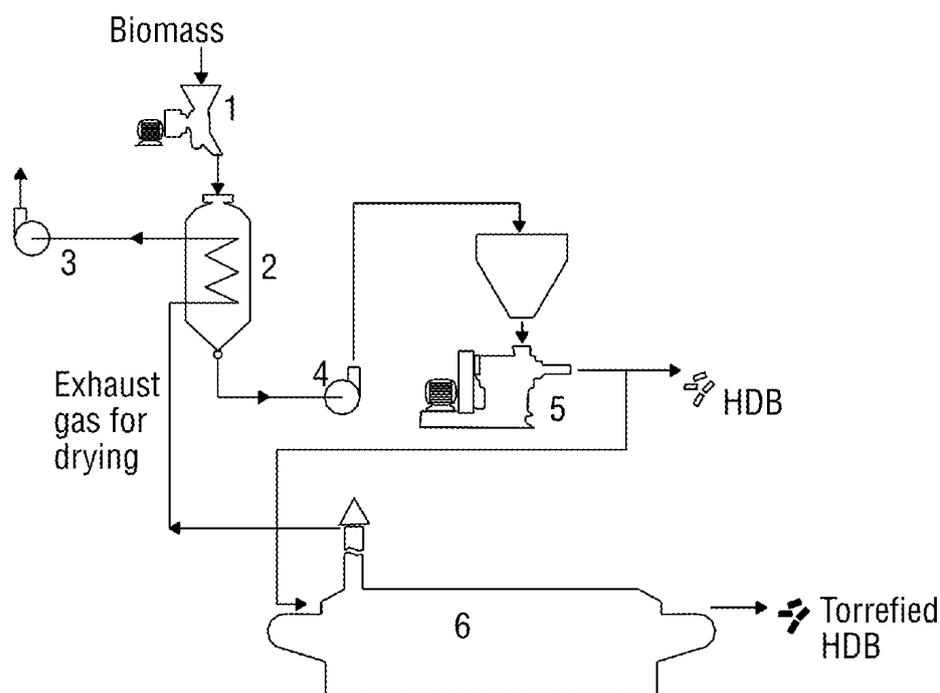


Figure 28: Flowsheet of a briquette factory with a torrefaction system installed. 1- grinder; 2 - drying silo; 3 - exhauster; 4 - pneumatic loader; 5 - extruder; 6 – torrefactor, [Felix F.F., 2005b].

Characterization of torrefied briquettes

Torrefaction tests were run on briquettes obtained from wood residues, whose characteristics are shown in Table 22. Experiments were performed under different torrefaction conditions.

Table 22: Properties of the wood briquettes, [Felix F.F., 2005a]

C	H	O	Ash	Fixed carbon	HHV
%					kJ/kg
49.37	6.59	40.24	2.80	19.20	20.00

Proximate analysis and heating value

ASTM D 1762-82 (standard method for proximate analysis of wood charcoal) and ASTM D 3286-85 (standard test for higher heating value of coal) were utilized to characterize the torrefied briquettes, Table 23.

Table 23: Proximate analysis and higher heating value of torrefied wood briquettes, [Felix F.F., 2005a]

Temperature	Time	Volatile content	Fixed carbon	Ash	HHV
°C	hour	%			kJ/kg
220	0.5	75.2	18.2	6.6	20.456
	1	74.6	19.0	6.4	20.989
	1.5	73.6	19.8	6.6	21.065
250	0.5	65.2	27.0	7.8	21.209
	1	65.0	27.2	7.8	22.061
	1.5	60.0	32.1	7.9	22.674
270	0.5	55.7	34.6	9.7	22.772
	1	52.1	38.2	9.7	22.981
	1.5	41.0	49.2	9.8	23.066

From the results of Table 23 it also can be concluded (as in case of green woody biomass torrefaction) that the temperature has more effect on the briquettes than the residence time.

Since combustion and torrefaction processes take place in separate chambers, it is relatively easy to control biomass torrefaction temperature and residence time inside the torrefaction chamber. This allows a high degree of standardization in production of torrefied briquettes for different energy applications.

Elemental analysis

Data from elemental analysis was obtained from a CH analyzer (D 3178-84: standard test method for carbon and hydrogen). Table 24 shows a summary of elemental analysis results for briquettes torrefied under different conditions. It can be observed that as torrefaction parameters increase the elemental carbon fraction rises too, suggesting a decrease in the molecular H/C and O/C ratios. Thus, the degree of aromatization and oxygenation of briquettes decreases proportionally

with the increase of the torrefaction parameters torrefaction temperature and residence time.

Table 24: Elemental analysis of the wood briquettes, [Felix F.F., 2005a]

Temperature	Time	C	H	O	Ash	H/C[1]	O/C[1]
°C	hour	%					
220	0.5	51.58	6.87	34.95	6.60	1.59	0.50
	1	52.02	6.50	35.08	6.40	1.49	0.50
	1.5	53.79	6.28	33.33	6.60	1.40	0.46
250	0.5	54.66	6.10	31.44	7.80	1.34	0.43
	1	55.81	6.60	29.79	7.80	1.40	0.40
	1.5	57.63	6.00	28.47	7.90	1.24	0.37
270	0.5	58.85	5.52	25.93	9.70	1.12	0.33
	1	59.82	5.26	25.22	9.70	1.05	0.31
	1.5	63.00	4.28	22.92	9.80	0.81	0.27

[1] Molecular basis

Analyzing the molecular ratios, torrefied briquettes could be classified as an intermediate product between raw biomass and charcoal, i.e., adjusting temperature and process time it is possible to make the product more or less similar to charcoal [Felix F.F., 2005a].

Moisture and hydrophobic characteristics

Figure 29 indicates that the briquette equilibrium moisture decreased by approximately 73 % after torrefaction. The lower moisture is the result of the tar condensation inside the pores, obstructing the passage of moist air through the solid, and then avoiding the condensation of water vapor.

Figure 29 also shows that the equilibrium moisture increases when the torrefaction parameters are raised. This happens because the emission of volatiles becomes more intensive as torrefaction temperature is raised, increasing the porosity and hygroscopic characteristics. The hydrophobic characteristics of torrefied briquettes were investigated by immersing several torrefied briquettes in

water and determining the moisture content by measuring the change in briquette weight.

Figure 30 displays the results as a function of immersion time and torrefaction temperature.

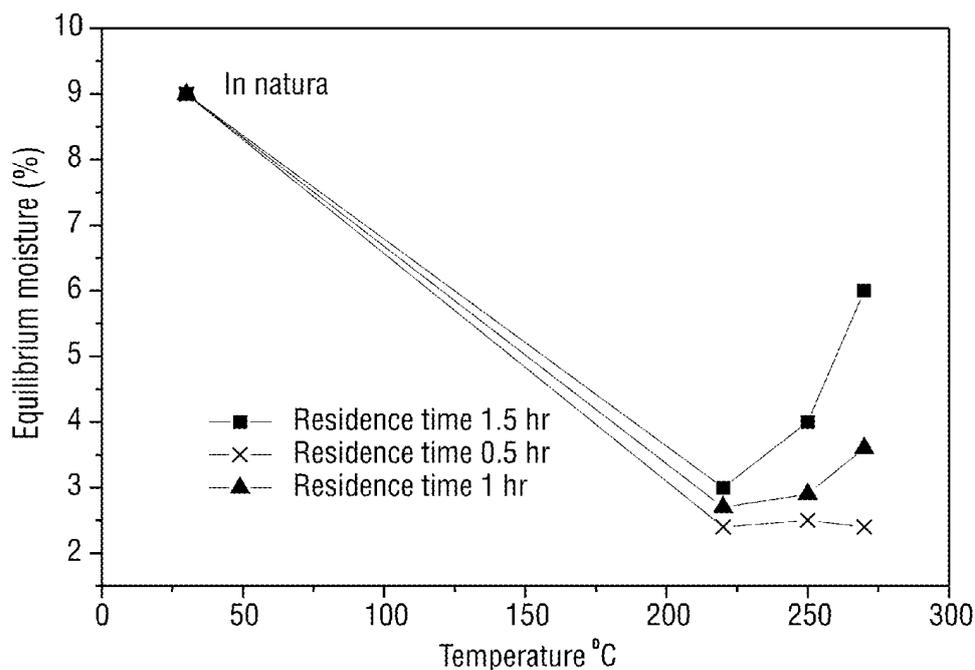


Figure 29: Equilibrium moisture of the torrefied briquettes, [Felix F.F., 2005a]

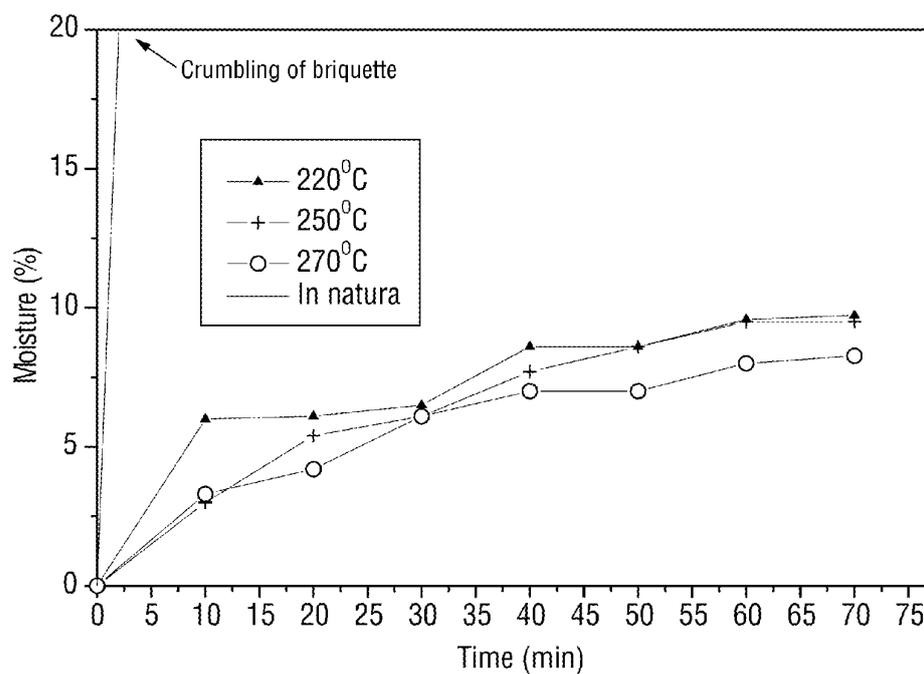


Figure 30: Hydrophobic test, [Felix F.F., 2005a]

Torrefaction yields

Weight and energy yields values are showed in Table 25. Energy and weight yields ranged from 43 to 94 % and from 50 % to 97 % respectively, depending on the torrefaction time and temperature parameters.

Table 25: Torrefaction yield, [Felix F.F., 2005a]

Temperature	Time	Weight yield	Energy yield
°C	hour	%	
220	0.5	94	97
	1	90	94
	1.5	72	77
250	0.5	74	80
	1	65	72
	1.5	60	67
270	0.5	56	65
	1	54	62
	1.5	43	50

Wood briquette torrefaction can be one of the methods to produce energy fuel with increased energy properties compared to green biomass, green wood briquettes and pellets.

3.3 Co-combustion

Quality requirements

There are requirements for lump charcoal - DIN 51749: fixed carbon - not less than 80%, ash content– not higher than 4%, moisture content – not higher than 8%, basically size of particles must be 20-80 mm, but it is allowed 5% of particles with size more than 80 mm and 10% particles with size less than 20 mm.

The quality of charcoal produced in developing countries for domestic consumption, is controlled by very weak, as a means of control is largely absent.

Since the main amount of charcoal is used as domestic fuel, then it is required to sufficiently high calorific value. Strength indicator is also essential, since produced charcoal must to withstand transportation from the place of production to local consumers (up to 200 km) without the formation of a large number of fine particles.

In the case of charcoal as an energy fuel, more stringent requirements should be presented. The charcoal should have primarily a minimum ash content, high fixed carbon content, high energy density, high calorific value and satisfactory strength, allowing to transport it with minimal losses. It should be noted that charcoal produced from a mixture of tropical species, may have ash content up to 10%, and practically unsuitable for industrial use even if its strength is satisfactory. Charcoal produced from eucalyptus wood (usually grown on plantations) and from coconut shells have a relatively high quality. It is a solid charcoal with a relatively low (4%) ash content.

The content and composition of the ash in charcoal is variable. It depends not only on the temperature and the method of pyrolysis but also on wood species, the ratio of wood and bark, growing place of wood, cutting time and transportation method to the plant. The ash content, in hardwood, especially in aspen is higher than in conifers. Moreover, different parts of the tree have different ash content, as shown in table 26, 27.

Table 26: Ash content of the charcoal produced from bark and wood, %, [Yuriev U.L., 2007]

Wood species	Ash content of charcoal produced from:		
	trunk	bark	branches with bark
Pine	0.24	1.72	0.62
Spruce	0.32	4.26	1.52
Birch	0.35	2.42	1.57
Aspen	0.75	4.44	1.29

Table 27: Ash content of the charcoal produced from different wood species and parts of tree, %, [Yuriev U.L., 2007]

Wood species	Ash content of charcoal produced from:					
	bottom of tree	middle trunk	treetops	knags	branches	bark
Pine	0.53	0.55	1.03	1.05	1.70	1.88
Aspen	0.98	1.27	2.08	5.54	10.06	10.14
Birch	0.57	0.56	1.21	1.00	2.79	4.07

The charcoal ash is a mixture of oxides of alkali, alkaline earth (CaO, K₂O, Na₂O) and other metals, as well as phosphorus, arsenic and several other items, those are not desirable by combustion charcoal in boilers. Presence of alkaline can lead to decreasing of ash melting temperature and slugging. The contents of some elements determined in charcoal ash, produced under specific conditions of different tree species are presented in Table 28.

Table 28: The content of some elements in charcoal ash, %, [Yuriev U.L., 2007]

Ash, %	Elemental content of total ash content									
	Si	Fe	Al	Ca	Mg	Mn	P	Ti	B	As
Birch										
1.94	1.62	0.36	0.28	36.0	6.22	3.23	1.69	0.35	0.036	0.0007
2.78	4.37	1.24	0.56	31.5	4.71	1.36	0.84	1.14	0.03	0.0007
3.20	4.12	0.51	3.31	17.4	3.32	1.31	1.14	0.12	0.01	0.0007
1.42	4.26	0.56	1.27	36.9	5.97	1.87	1.56	0.10	0.03	0.0012
1.30	1.08	0.41	0.68	29.1	4.33	3.63	1.43	0.07	0.049	0.0002
Beech										
2.42	2.73	0.28	0.17	30.2	5.25	1.37	1.53	0.048	0.017	0.0008
1.47	1.88	0.13	0.05	33.2	5.10	2.22	2.58	0.034	0.031	0.0018
Pine										
0.75	11.5	1.29	2.03	26.8	2.29	2.20	0.96	0.16	0.046	0.0002

The content of such elements like phosphor and sulfur is very low that gives to charcoal large emission benefits compared to coal.

Unfortunately, there were not found materials related to ash analysis of the torrefied wood, but it is known that torrefied wood is something between charcoal and raw woody biomass. It may be suggested that torrefied wood has similar ash content to raw wood and has minimal content of harmful compounds.

Strength properties of the biocoal depend on the specie and quality of wood and the conditions of pyrolysis. Final temperature has the greatest influence on the mechanical strength of the biocoal.

Hardgrove index for charcoal (115) was obtained by CanmetENERGY Canada [Fernando Preto, 2008]. Data for torrefied wood (38-48) were obtained by Topell, Netherlands [Topell on torrefaction, 2009].

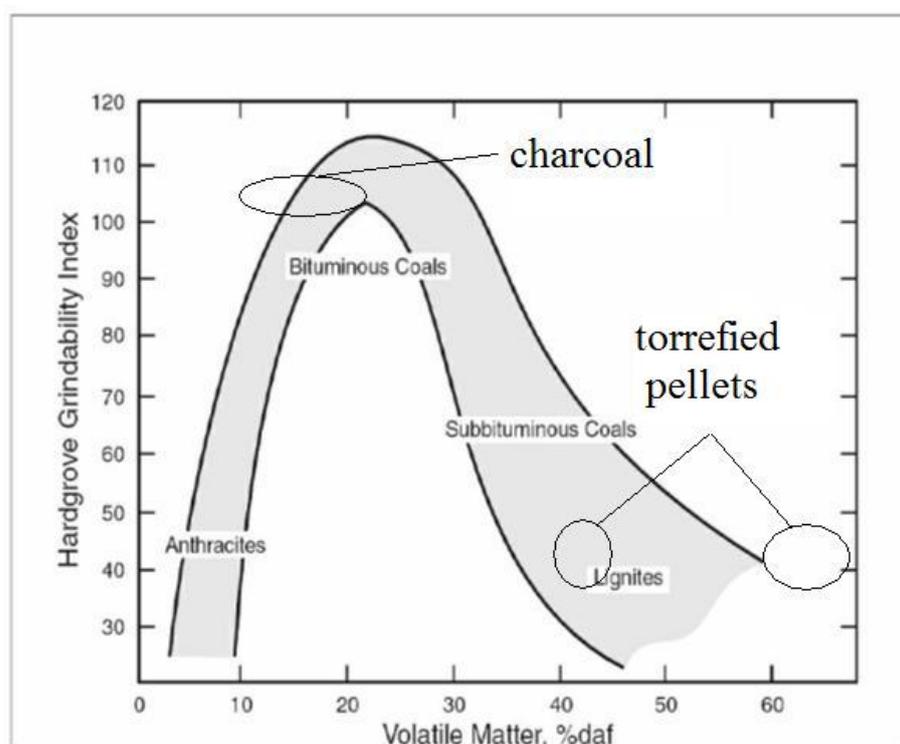


Figure 31: Hardgrove grindability index vs. volatile matter of the coal

Size reduction results of various torrefied biomass and feed biomass. Coding: Biomass (torrefaction temperature, reaction time), W - willow, C - woodcuttings, D - demolition wood (Figure 32-33).

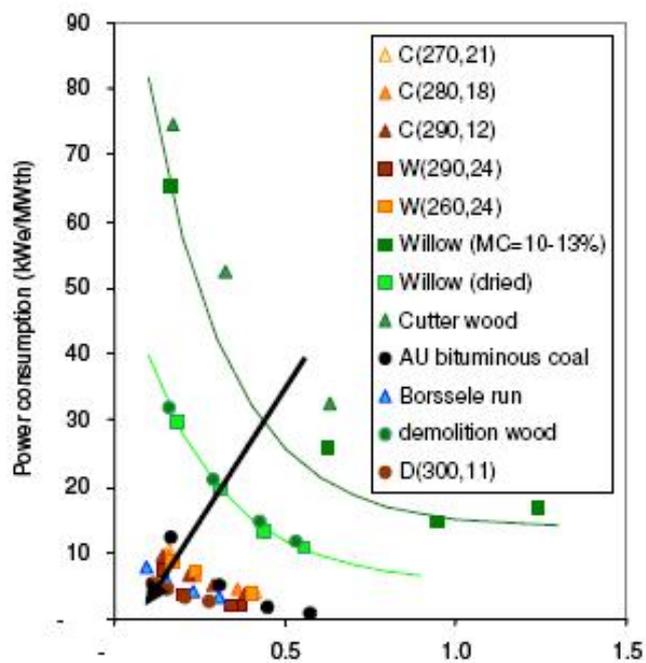


Figure 32: Average particle size (mm, volume based), [Topell on torrefaction, 2009]

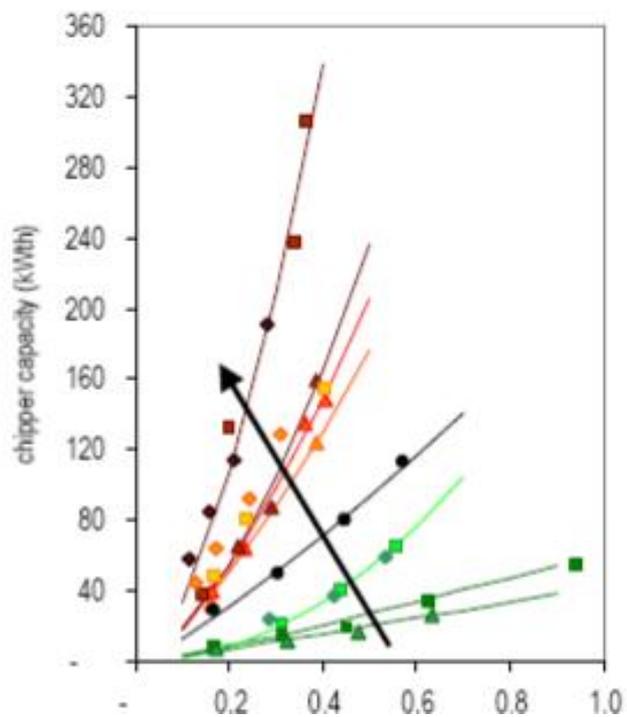


Figure 33: Average particle size (mm, volume based), [Topell on torrefaction, 2009]

Tests conducted by chipping of the torrefied wood samples (Figure 32-33) showed decreasing in chipper power consumption.

Issues in co-combustion [EBES AG]:

- Characteristics of existing biomass types cause extra costs
- Not so with ACB – Accelerated Carbonized Biomass

	Coal	Wood chips	Wood pellets	ACB
Handling + Logistics	Green	Red	Red	Green
Extra investment	Green	Red	Red	Light Green
Energy content	Green	Red	Yellow	Light Green
Moisture content	Green	Red	Yellow	Green
CO2 Emission	Red	Green	Green	Green
co-firing ratio		5-10%	8-15%	50%

Figure 34: Characteristics of biomass types cause extra costs, [EBES AG]

EBES AG says that ACB can be very attractive in co combustion issues by using existing combustion technologies in proportions up to 50%.

Theoretically, based on chemical and physical properties of the biocoal, it can be concluded that it is possible to use the biocoal as energy fuel in co-combustion with coal for power production. But it should be taken into account that currently co-combustion experience (biocoal with usual coal) does not exist at industrial scale, thereby it is difficult to talk about real impacts associated with the operation of boiler equipment. It is recommended to do performance tests at the small power plant (maybe running on pellets) and if the feasibility study is positive than it will be possible to make tests at large industrial power plant running on coal.

4 TECHNICAL AND ECONOMIC ANALYSIS OF THE BIOCOAL PRODUCTION

4.1 Charcoal production in Russia Federation

There were examined the charcoal production plant located in Russia Federation and estimated the operation cost of one tonne of charcoal (Table 29). The plant has the following operation parameters:

- Production capacity ~ 1000 tonne of charcoal per year;
- Raw material – in form of logs in length 2-6 m (hardwood species); further, cut raw material is loaded into the installation; Moisture content $W_{\max} = 55\%$, $W_{\text{averag}} = 35\%$;
- Operation of the main production – continuous, 3 shifts of 8 hour;
- The use of primary fuel (to provide heat demand) – 0.0041% of the annual plant productivity.

The constructive solutions that provide savings of heat allow to ensure work for their own heat practically without burning additional fuel and also to use heat surpluses for the production of thermal energy. By lowering the temperature of flue gases it is possible to generate heat in the form of steam or hot water by installing of waste heat recovery boiler. Parameters of the recovery boiler:

- Production capacity – 0,4 MW;
- Steam production capacity – summer – 650 kg/h, winter – 500 kg/h, pressure – 0,06MPa.

Properties of the produced charcoal:

- Calorific value – 32 MJ/kg;
- Moisture content < 6%;
- Ash content < 2,5 %;
- Fixed carbon > 90%.

Table 29: Charcoal plant operation costs indications, [Dubovy V.K., 2010]

Charcoal plant operation costs indications		
Raw material	EUR/t charcoal	140
Manpower and fixed charges	EUR/month + taxes	5,212
Maintenance cost	EUR/month	2,500
Operation cost	EUR/month	17,512
	EUR/t charcoal	250
	EUR/MWh	28
Retail price	EUR/t	350-450
	EUR/MWh	40-50

Production capacity 1000 tons charcoal per year was taken from the fact that the transportation of raw materials does not exceed a distance of 100 km. In the case of increasing the productivity of the plant there is a problem with the availability of raw materials in the area of 100 km. Production cost of charcoal is considerably increased by transporting raw materials in distances more than 100 km.

4.2 Charcoal briquette production in Finland

The example of charcoal production plant was reviewed in section 3.1.5. There is presented charcoal briquette production cost (Table 30). Parameters of the plant are following:

- Production capacity ~ 6600 t/a of charcoal briquettes;
- Raw material in form of lump charcoal and charcoal dust (fine particles) is delivered from Russia Federation from plants described above;
- Operation of the main production – continuous, 3 shifts of 8 hour.

Properties of charcoal briquette are presented in Appendix 1.

Table 30: Charcoal briquette plant operation costs indications, [KS Party Oy, 2010]

Charcoal briquette plant operation costs indications		
Raw material	EUR/t	309.6
Manpower and fixed charges	EUR/t	208.8
Maintenance cost	EUR/t	100.8
Management and office	EUR/t	52.5
Profitability	EUR/t (7%)	48.2
Total	EUR/t	772
Retail price	EUR/t + 22% tax	1220
	EUR/MWh	137

4.3 Torrefied briquette production in Brazil

It is a fact, however, that biomass briquettes are not yet widely commercialized in the Brazilian market. Expansion of this market is a technical and marketing challenge, of which the first step is to develop high-quality briquettes. In this sense, torrefaction is an option to improve their quality and, consequently, open up new commercial possibilities.

The scheme of the process is shown in the Figure 28.

Considering that the biomass briquette factory operates 8 hours a day, 300 days a year, the annual production should be 1,200 tonnes (t). The production of torrefied briquettes requires the installation of a torrefaction oven - torrefactor (see Figure 28). Maintaining a nominal production of 1,200 t and considering that 60 % of the production could be torrefied at 280°C, with a yield of 70 %, 504 t of the produced torrefied briquettes (HDB₂₈₀) could be assigned to domestic consumption and 480 t of HDB would be for consumption in commercial and industrial furnaces.

The cost of the fuel was considered to be 10 % of that of raw materials since part of the residues would be burnt to produce heat for torrefaction of the briquettes.

Table 31 represents investment costs for briquette factory with a torrefaction system installed. Table 32 shows the cost structure of the proposed system.

The price of charcoal on the retail market is about 330 EUR/t. The price of the HDB₂₈₀ could then be 150 EUR/t on the wholesale market. The sale price of HDB is 60 EUR/t and HDB₂₈₀ is 150 EUR/t. Therefore, one can conclude that the introduction of the torrefaction system enables a “leverage” without the need to increase the factory’s production level. The possibility of producing various types of briquettes is the factor that makes the factory more competitive [Felix F.F., 2005b].

Table 31: Fixed investment for briquette factory with a torrefaction system installed, [Felix F.F., 2005b]

Assets	Investment	Annual depreciation	Industrial depreciation
	EUR	%	EUR/a
Briquetting and torrefaction equipment [1]	71,500	10	7,150
Industrial installation [2]	7,150		715
Auxiliary equipment [3]	1,666		167
Total	80,316		8,301

[1] Extruder, grinder, drying silo, exhauster and torrefaction oven (see Figure 28)

[2] Installation cost, considered to be 10% of the briquetting and torrefaction equipment costs

[3] Pneumatic loader (see Figure 28)

It was concluded that the introduction of a torrefaction system in a briquette factory makes production more flexible and competitive. From a technological point of view, it improves the quality of the briquettes, opening up new possibilities for application and, consequently, other markets. It also allows easy adaptation to market demands. By producing different types of briquettes, more than one consumer market can be explored. At the same time, it gives the factory an operational leverage without the need to increase the production level. This is an interesting alternative when operating in markets that are limited or saturated by competitors. This increased efficiency occurs because the factory becomes a multi-product manufacturing facility.

Table 32: Annual costs of the briquette factory with a torrefaction system installed, [Felix F.F., 2005b]

Costs	HDB	HDB ₂₈₀	Total
	EUR/a		
Fixed costs (FC)	9,800	14,695	24,493
Industrial depreciation	3,213	4,819	8,032
Payment of service rendered	4,000	6,000	10,000
Accountable fees	384	576	960
Amortization of the pre-operational costs	67	100	167
Industrial shed rent	1,248	1,872	3,120
Maintenance	572	858	1,430
Other administrative expenses	314	470	784
Variable costs (VC)	11,488	17,232	28,720
Raw material	2,560	3,840	6,400
Fuel	256	384	640
Industrial labor	5,120	7,680	12,800
Electric energy	2,085	3,128	5,214
Packaging	800	1,200	2,000
Commercial expenses	667	1,000	1,666
Total	21,288	31,927	53,213
Variable unit cost (EUR/t)	44,3	63,4	

4.4 Ability to pay of biocoal at the Finnish market

Biocoal price was measured based on current coal, wood pellets prices including CO₂ cost and net efficiency 36%. There was made also the future prices overlook (Figures 35-36).

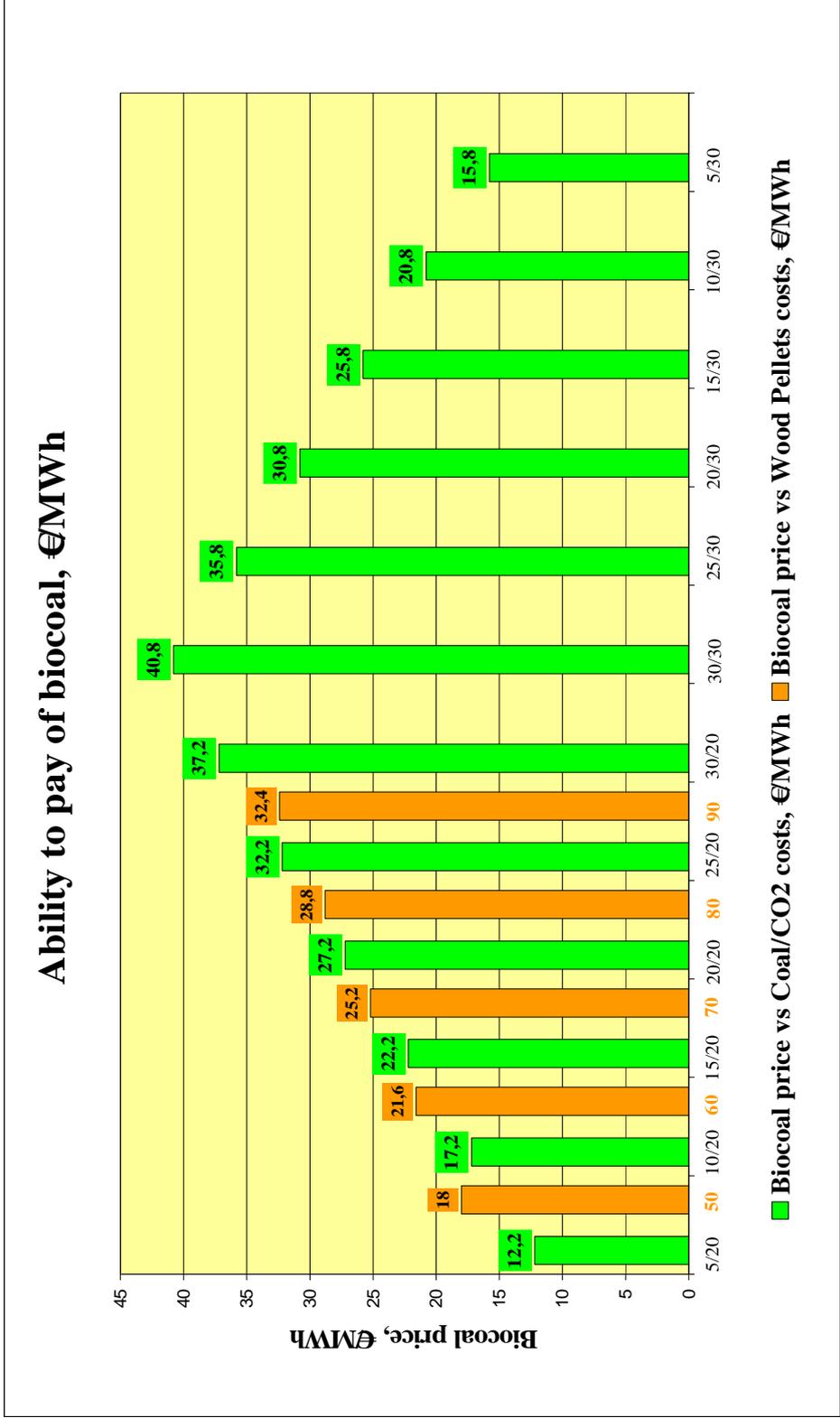


Figure 35: Ability to pay of biocoal

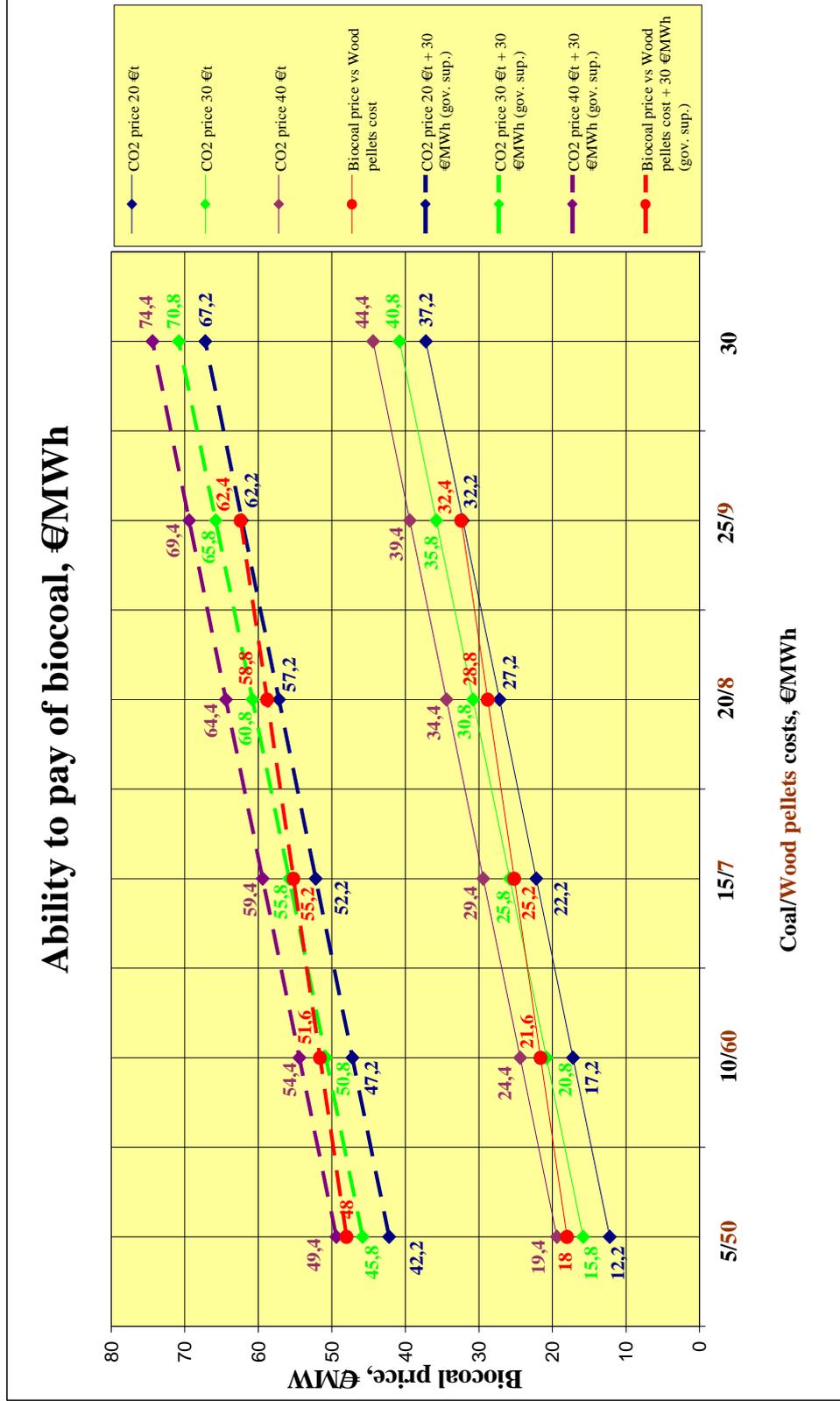


Figure 36: Ability to pay of biocoal with government support

Figure 36 presents roughly estimated biocoal prices including government support. By electricity production using biomass (replacement of coal) government supports in the amount of 30 EUR/MWh for bioelectricity [Esa Vakkilainen, 2010].

4.5 Preliminary analysis of the investment and operation costs of the biocoal (TOP pellet) production plant located in Finland

Many companies, mainly from the wood industry, which have appropriate raw material available for the production of biocoal (TOP pellets) are already active in this field or are thinking of entering this market. To start a biocoal production plant it is essential to calculate their production costs in advance in order to consider and investigate specific framework conditions of the producer for an economic operation.

Estimation of biocoal plant investment cost, investigations and calculations of the production costs of biocoal under consideration of relevant parameters and different production patterns have been performed in this section. The calculations are based on data on planned TOP pellet production plant [Topell on torrefaction, 2009], TOP technology, [Mark J. Prins, 2006] and data on existing wood pellet production plant (UPM-Kymmene).

TOP pellet plant investment costs

Two cases of investment costs were taken into account. The first case the new biocoal production plant (Figure 34). The general investment includes investments for construction, offices, main and auxiliary equipment as well as market introduction and planning. Investments amounted ~ 12 MEUR. Low general investment costs can be achieved by using existing infrastructure (Table 33).

Table 33: Biocoal (TOP pellet) plant investment cost estimates (based on investment cost of wood pellet plant UPM-Kymmene, 70 000t/a, 2007)

	Unit	New plant		Conversion of the wood pellet plant to TOP pellet production	
Stump grinding	k EUR	no			
Raw material receiving station	k EUR	50			
Grinder	k EUR	600			
Buffer silo	k EUR	110			
Dryer	k EUR	2174			
Torefaction equipment	k EUR	4000	Torrefaction reactor	4000	Replacement of pellet mill to TOP pellet production equipment
			Heat exchanger		
			Combustor		
Buffer silo	k EUR	50			
Cooler	k EUR	140			
Conveyors	k EUR	325			
Ducting	k EUR	150			
Pressurized air production unit	k EUR	20			
Automation	k EUR	200			
Electrification	k EUR	300			
Plant house	k EUR	500		250	
Concrete and steel foundations and rain cover	k EUR	1800		900	
Project handling (engineering, management)	k EUR	415		24	
Equipment erection, supervising, start up	k EUR	675		36	
Miscellaneous	k EUR	376		18	
Total	k EUR	11885	~ 12000		
Total (in case of conversion)	k EUR			5228	~6000

Biocoal (TOP pellet) production costs

Two production patterns were examined for estimation of the biocoal production costs: integrated biocoal production plant and stand alone plant (Figure 37-38).

The following main parameters were taken into account for biocoal production costs calculations:

- ✓ The efficiency of conversion wood to biocoal: 60%, 90%;
- ✓ The raw material costs as well as the water content and the bulk density of the raw material used; raw material costs (wood) – 20/30/40 EUR/m³ (0,9 MWh/m³ solid);
- ✓ The price for electricity required for electrical installations;
- ✓ The maintenance cost;
- ✓ The heat costs for drying of the raw material;
- ✓ The heat cost for torrefaction process.

Integrated biocoal production plant (Figure 37)

In case of the integrated plant there was investigated that there is free waste heat source (with temperature ~ 300°C) from some industrial processes. In addition there is also needed the heat for drying of the raw material (Figure 37).

As was marked above, one of the main parameters is the efficiency of conversion which was taken: 60% and 90%. Moreover there was accepted that combustible gases produced during torrefaction process can be burned in the furnace of boiler at industrial plant (Figure 37), thereby reduce consumption of primary fuel and in the result reduce biocoal production cost. Estimated biocoal production costs are presented in Tables 34-35.

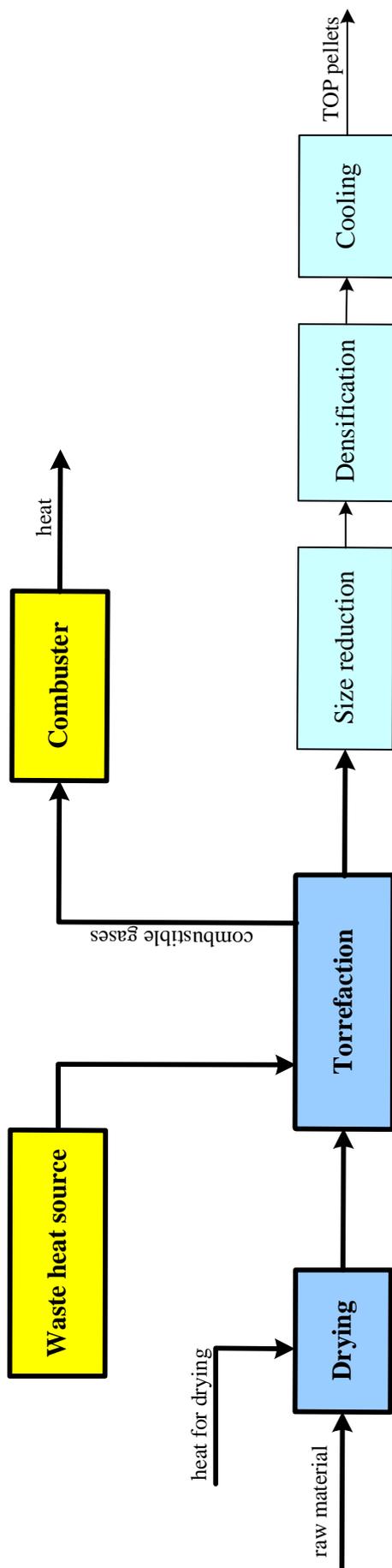


Figure 37: Integrated biochar (TOP pellet) production plant

Table 34: Biocoal production costs, EUR/MWh (integrated plant)

		Efficiency of conversion wood to biocoal - 60%											
Mannpower		1,8											
Electricity		3											
Maintenance cost		3											
Raw material	EUR/MWh	22,2				33,3				44,4			
	EUR/1,67 MWh	37,1				55,7				74,2			
Heat cost		0											
Heat for drying	EUR/MWh	0	3	6	10	0	3	6	10	0	3	6	10
	EUR/0,4 MWh	0	1,2	2,4	4	0	1,2	2,4	4	0	1,2	2,4	4
Total		44,9	46,1	47,3	48,9	63,5	64,7	65,9	67,5	82,0	83,2	84,4	86,0
Total average		46,8				65,4				83,9			

Table 35: Biocoal production costs, EUR/MWh (integrated plant)

		Efficiency of conversion wood to biocoal - 90%											
Mannpower		1,8											
Electricity		3											
Maintenance cost		3											
Raw material	EUR/MWh	22,2				33,3				44,4			
	EUR/1,11 MWh	24,7				37,0				49,3			
Heat cost		0											
Heat for drying	EUR/MWh	0	3	6	10	0	3	6	10	0	3	6	10
	EUR/0,25 MWh	0	0,75	1,5	2,5	0	0,75	1,5	2,5	0	0,75	1,5	2,5
Total		32,5	33,2	34,0	35,0	44,8	45,6	46,3	47,3	57,1	57,9	58,6	59,6
Total average		33,7				46,0				58,3			

The material mass balance with efficiency of conversion 60%:

1.67 MWh is needed for production of 1 MWh of biocoal (TOP pellet).

- 100% - raw material – 1.67 MWh;
- 90% - biocoal (TOP pellet) – 1MWh;
- 35% - combustible gases – 0.58 MWh;
- 5% - losses – 0.083 MWh.

35% (0.58 MWh) of combustible gases can be burned in the boiler of the industrial plant, thus reducing the biocoal production cost.

The material mass balance with efficiency of conversion 90%:

1.11 MWh is needed for production of 1 MWh of biocoal (TOP pellet).

- 100% - raw material – 1.11 MWh;
- 90% - biocoal (TOP pellet) – 1MWh;
- 5% - combustible gases – 0.055 MWh;
- 5% - losses – 0.055 MWh.

5% (0,055 MWh) of combustible gases can be burned in the boiler of the industrial plant, thus also reducing the biocoal production cost.

Stand alone biocoal production plant (Figure 38)

In case of stand alone biocoal production plant there is need in heat for drying of the material as well as the heat for directly torrefaction process. The scheme of biocoal production is based on “TOP technology” where combustor and heat exchanger are installed. The process is provided with heat through combustion of the primary fuel (woody biomass for example) and combustible gases produced during torrefaction process (Figure 38). Estimated biocoal costs are presented in Tables 36-37.

The material mass balances are the same like in case of integrated plant.

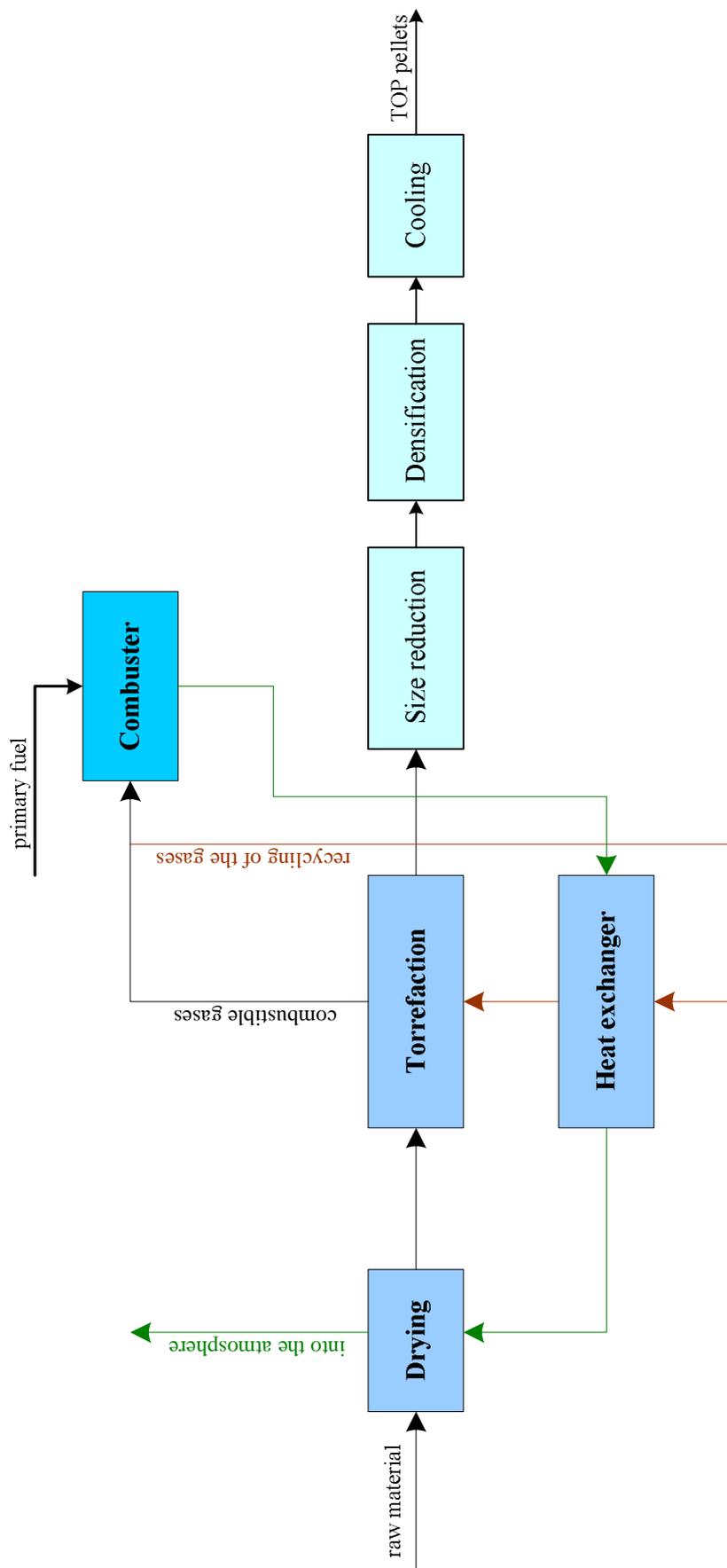


Figure 38: Stand alone biocoal (Top pellet) production plant

Obviously, that economy of biocoal production is strongly dependent on the raw material cost. The efficiency of conversion plays also an important role.

A strong influence on the technical solutions is given by heat demand for thermal treatment and drying. However, the possibilities to influence the heat demand are confined to the choice of the process scheme (Figure 37-38).

The combination of a biocoal (TOP pellet) production plant with pulp and paper mill or biomass CHP plant could be a good solution due to decreasing investment costs for heat producing equipment (combustor, heat exchanger). Therefore, the heat cost required for the process could be lower because only the operating and consumption costs of the pulp and paper mill or CHP plant are included in the heat price, at the same time heat production and heat consumption can be optimally adjusted. As stated before, the formed combustible gases from torrefaction process can be burned in the boiler of industrial plant, thus reducing consumption of primary fuel.

The direct approximate economic comparisons of different biocoal production costs indications showed that integrated plant with the efficiency of conversion 90% and stand alone plant with the same efficiency are most cost effective.

The question how large should be biocoal production plant is closely related to availability of the raw material. Taking into account that raw material for biocoal production is the same in case of wood pellet production (woody biomass) it can be concluded from wood pellet production studies that the transportation distance for raw material should not be more than 200 km (in best case ~ 100 km). The plant production capacity influences all production cost factors (except raw material costs) and can contribute substantially for decreasing of biocoal production costs.

5 FUTURE ASPECTS OF THE WOODY BIOMASS CONVERSION

The wood has a complex polymer structure. Based on this statement it would be interesting to consider existing wood conversion technologies, because the future development of a controlled, flexible, multi-products and integrated carbonization industry is a pressing need. The improvement of carbonization industry could be framed into a more ambitious strategy for the creation of a global biomass economy. A global biomass economy requires the development of units for the initial biomass conversion near to biomass resources, centers of densification and larger centralized conversion units or bio-refineries allowing the production of electricity, bio-fuels, fertilizers and chemicals at costs competitive with the ones obtained by the petroleum economy.

Condensable liquids could represent up to 42 mass% of the initial biomass. The total condensation of pyrolysis vapors leads to the formation of a liquid made up of two phases: bio-oil (pyroligneous acid) and tar. Water is the main component of pyroligneous acid. In addition to water, several other chemical compounds exist in bio-oil, for example: acetic acid, sugars, methanol, acetone, etc. Their recovery in the XIX century was made at industrial scale. The partial condensation at temperatures higher than 60°C leads to the formation of an oily material commonly known as whole pyrolysis oil. Pyroligneous acid with very low contents of tar materials is obtained with the further condensation of lighter fractions.

The studied charcoal and torrefied wood compared to the mineral coal do not contain practically sulfur, mercury and has lower ash content. All this makes the charcoal the best option in the process of iron reduction. Charcoal and torrefied wood are an appropriate feedstocks for gasification. It can be gasified in conventional single step gasifiers to produce a synthesis gas with very low tar content.

Biocarbo (<http://www.biocarbo.com>) in association with Vallourec & Mannesmann Tubes (V&M) is the only Brazilian company commercializing

products from decanted tars [BIOCARBO]. Up to 30 mass% of the tar is used by the Biocarbo to produce glues and a sealing material, the rest is used to generate energy within the V&M [BIOCARBO].

Important progresses have been made in the last 30 years in the development of new products from pyrolysis liquids. Today it is possible to visualize new concepts of biorefineries from pyrolysis liquids. Figure 39 shows some of proved alternatives to obtain products from pyrolytic oils.

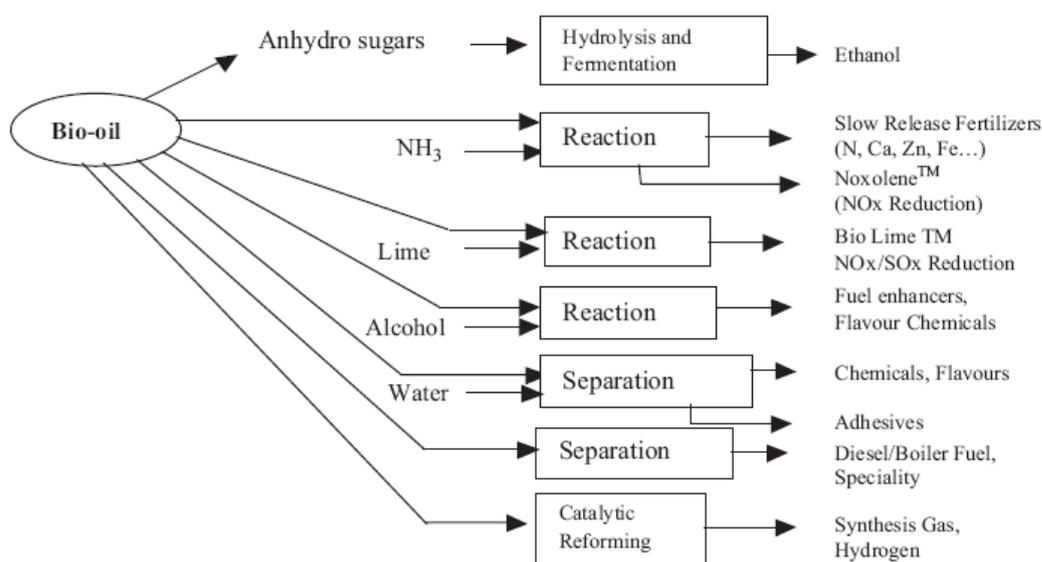


Figure 39: Bio-oil conversion products, [Radlein D., 1999]

It can be also noted that the production of the biocoal from other residual organic solids could be an interesting option for Europe. Reactors adapted to carbonize the very diverse residues must be available.

There are few important stages that could be help to implement these ideas:

- The use of biomass by-products resulting from the forest and agriculture activities. These resources are more expensive to collect and to transport than the wastes but they are still profitable. The main limitation is that this stage requires the construction of a new infrastructure;
- The development of a regional biomass market, with larger and flexible conversion units. An increase in the transport cost must be expected as a result of the increase in the distances. However, economic improvements

due to the use of the economy of scale must help to the viability of these units. Important political measures are needed to arrive to this stage;

- The development of a national market with an increase in the number of providers and buyers. Bio-refineries are a key component at this stage, more complex logistics is needed;
- The natural and fast process of growth in plantations, technologies and business associated with the biomass economy. This means increase in the number of people dedicated to the production, conversion and commercialization of biomass.

A biomass economy requires the existence of multiple technologies, at all the scales, allowing the integral and economic conversion of all biomass resources. New technologies for biomass primary conversion for densification and for bio-refineries must be developed. The main goals are to obtain energy, chemicals, fertilizers, food, fuels and other products substituting the ones presently produced from petroleum. Particular attention should be given to technical solutions described below.

5.1 Production of charcoal and combustion of paralytic vapors

This idea raises the possibility of producing charcoal as primary product in plants that operate with pyrolysis reactors coupled with boilers. The combustion of gases and pyrolysis vapors could be carried out with heat recovery to produce steam to generate electricity in steam turbines. The coupling of pyrolysis reactors with boilers is a very promising alternative because it allows the use of biomass as a fuel in boilers designed to operate with natural gas or other liquid fuels without any major modification in the combustion chamber. A similar co-combustion concept but using gasifiers has been demonstrated with the successful tests of co-combustion schemes in Lahti (Finland) and in Amer (Holland) [van Loo S., 2002]. A scheme of this alternative [Szernick S., 2004] is presented in Figure 40.

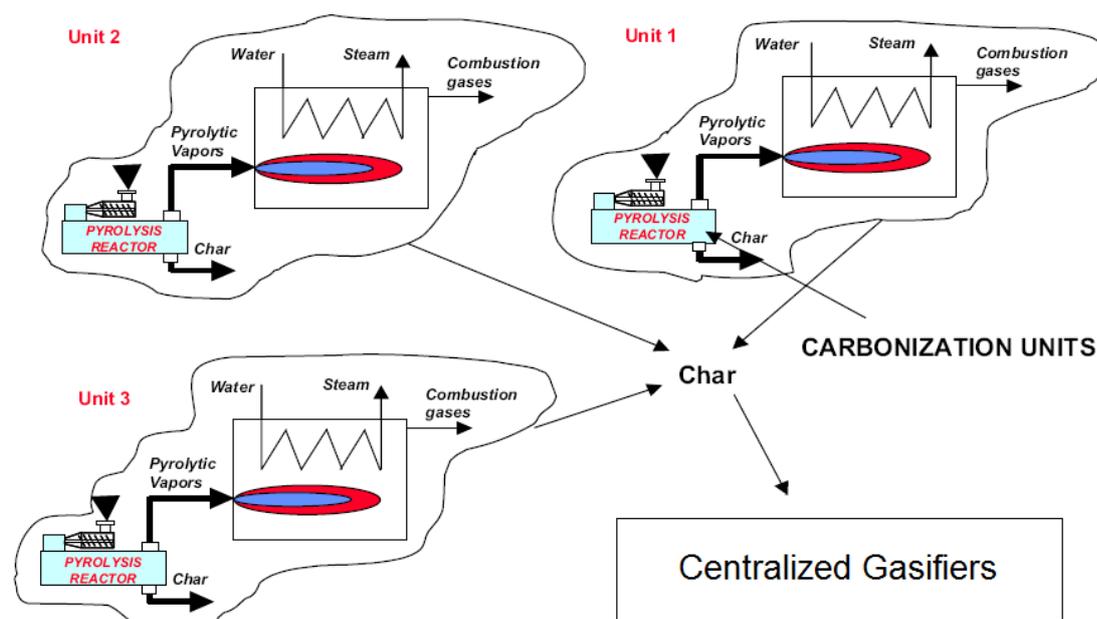


Figure 40: Integration of charcoal production units with gasification units

The charcoal produced in this concept could be transported towards consumption centers and/or to centralized gasification units to produce synthesis gas. The great advantage of gasifying biochar is that the produced gases will have very low content of tar, making it a very attractive option for using gas turbines and diesel engines designed to operate with clean gases [Bhattacharya S. C., 2001]. Synthesis gases with low content of tar can be used to produce transportation fuels throughout Fischer-Tropsch. The coupling of pyrolysis reactors with boilers is an area very poorly studied in the literature that is why there is necessity in this study.

There is idea behind combining torrefaction and gasification proposed by Mark Jan Prins research team. The biofuels such as wood are converted in gasifiers into combustible product gas and heat. This heat is normally recovered in the form of medium or high-pressure steam, which may be exported and/or used for electricity generation. Alternatively, steam can be partially used to supply the heat for the torrefaction process. Bone-dry torrefied wood with increased heating value is formed, which is subsequently gasified. In this way, advantage is taken of the high reactivity of wood (which is related to its relatively high chemical exergy), and part of the sensible heat of gasification product gas is put 'back into' the gasifier.

The design of a torrefaction reactor, which is placed in front of the gasifier, is similar to a drier. In this case, indirect heat transfer based on heat conduction is selected, which allows precise temperature control. A steam tube drier, possibly with rotation to promote contact between the solid particles and hot steam tubes, may be used [Mark Jan Prins, 2005].

It is expected also that, in the near future, gasification systems can be coupled with fuel cell systems that convert hydrogen gas to electricity or heat using an electrochemical process with very little air emissions and water vapour as the primary exhaust. When the costs of fuel cells and biomass gasifiers come down, these systems could proliferate.

5.2 Production of charcoal/torrefied fuel and/or synthetic gas by means of biomass gasification

Syngas is the name granted to gases generated in the process of gasification of mineral coal, biomass, natural gas or other organic remainders. It consists mainly of CO and hydrogen. Transportation fuels can be produced from syngas using the Fischer-Tropsch synthesis.

The range of products immediately obtainable from syngas extends from bulk chemicals like ammonia and methanol, through industrial gases to utilities such as clean fuel gas and electricity. Some of the catalytic pathways to convert syngas are presented in Figure 41. Syngas conversion technologies to obtain mixed alcohols, NH₃, aldehydes, ethanol, waxes, diesel, olefins, formaldehyde, MTBE, DME has been extensively documented in the literature [Spath P.L., 2003].

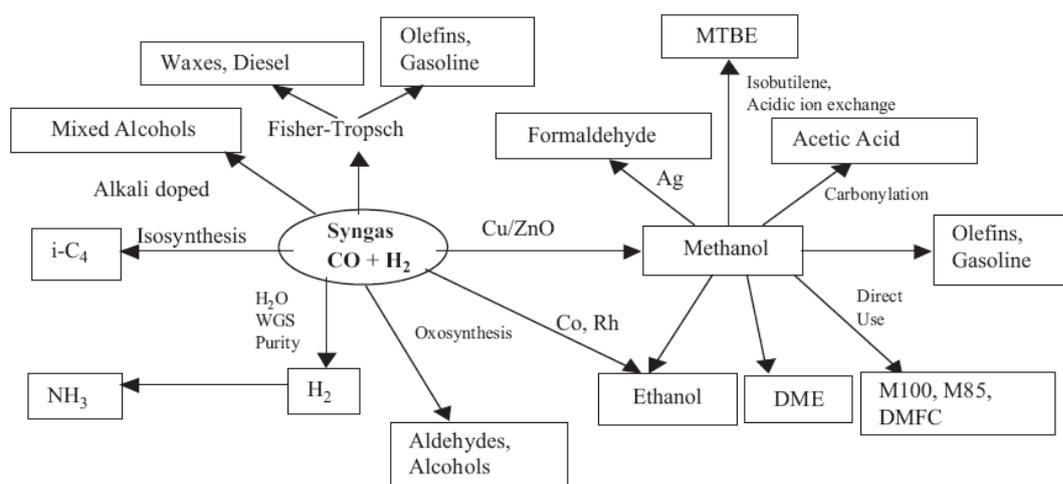


Figure 41: Syngas conversion products, [Spath P.L., 2003]

5.3 Production of charcoal and bio-oil. The use of bio-oils as fuels in advanced cycles

The pyrolytic vapors are condensed and the obtained oils used in advanced cycles like for example integrated gasification combined cycles (IGCC), in gas turbines or in diesel engines. The integration of pyrolysis units with these advanced cycles is known as integrated pyrolysis combines cycles (IPCC) [Garcia Perez M., 2005]. The bio-oil is transported from units located near to the biomass resources to larger central power plants (Figure 42).

The bio-oils can be gasified in high-pressure gasifiers. A very interesting process for the gasification of bio-oil in charcoal slurries is under study in Germany [Henrich E.]. The produced syngas can be directly used in gas turbines or to generate transport fuels throughout Fisher-Tropsch. The IPCC has efficiency larger than that one of a Rankin cycle [Garcia Perez M., 2005]. This kind of system does not require the use of gas compressors and the difficulty is reduced to join the biomass processing units with the systems of power generation. Leader companies in the production of high-pressure gasifiers are Foster-Wheeler (USA) [Foster Wheeler] and Carbona Technology (Finland) [Carbona Technology].

The direct use of bio-oil in gas turbines, as tested by Teledyne CAE (USA), Orenda Aerospace Corporation (Canada), University of Rostock (Germany) [Szernick S., 2004], etc., is another interesting alternative, but this scheme

requires of the use of a compressor for the operation, aspect that influences in the reduction of the cycle efficiency.

The only system on commercial scale producing heat from bio-oils operates in the plant of Red Arrow Products, Wisconsin [Szernick S., 2004], with capacity of 5 MWth. The emissions of CO, NO_x and formaldehydes are under the allowed levels of emissions. All these results confirm the viability of replacing heavy fuel oils per bio-oils [Sanders JPM, 2005].

The use of the bio-oil to operate diesel engines and to generate electricity has been evaluated elsewhere, with promising results. The diesel engines offer high efficiency (over 45%) in the power generation and can easily be adapted in combined cycles for generation of heat and power (combined heat and power process, CHP) [Szernick S., 2004].

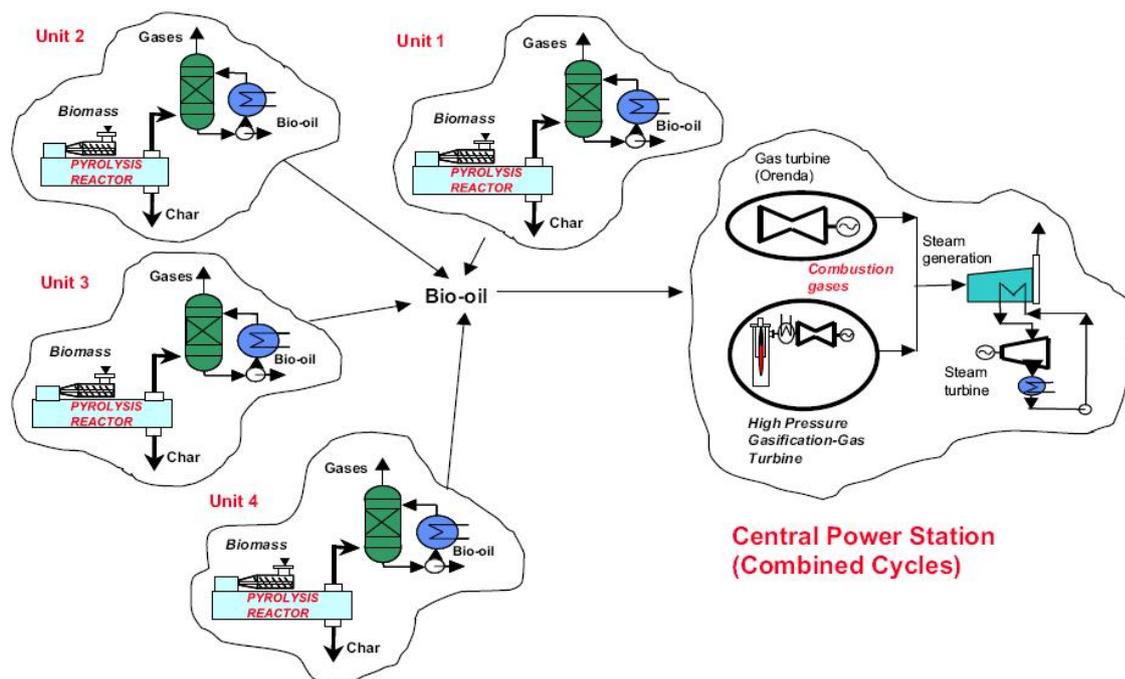


Figure 42: Integration of charcoal production with the generation of electricity energy in combined cycle

5.4 Bio-oil separation. Bio-refinery

The bio-refinery is a system integrating several processes of biomass conversion having the necessary infrastructure to produce fuels, chemical products and

energy from biomass. This concept is similar to the one of a modern petroleum refinery, but modified to accept different types of biomass.

The idea of bio-refineries is not new. Before first half of the last century, important industrial movements exposed that anything that is elaborated from hydrocarbons can also be elaborated using lignocellulosics.

All viable bio-refinery concepts require some kind of densification units located near the biomass resources from where the densified material is supplied to centralized units. Existing carbonization units with condensation of pyrolysis vapors considered can have a function in the biomass economy similar to the one petroleum wells have in the petroleum economy. In this regard, some existing carbonization units could play a function as densification units. Other alternatives could be: wood torrefaction, or the production of pellets.

Products of better quality, with better performance and reproducibility could be obtained if the bio-oils were refined and separated in fractions. The most common strategies are based on solvent extraction or in distillation to achieve the desired separation. The existing solvent separation methods are based on the differences of polarity or acidity as the driving force for the separation. An excellent review of the different schemes of separation has been presented by Fagernas [Fagernas L., 1995] and Oasmaa et al. [Oasmaa A., 1997]. Any of these strategies could lead to a new concept for bio-refinery. The scheme presented in Figures 43-44 is only one of these possible alternatives.

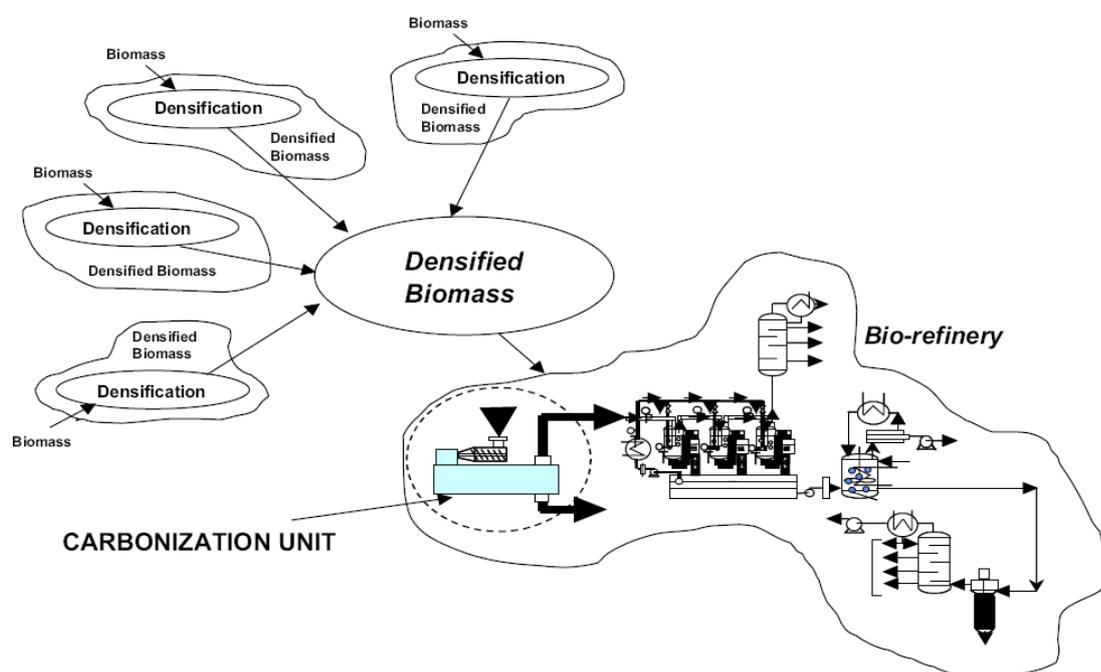


Figure 43: Integration of densification units with a centralized bio-refinery

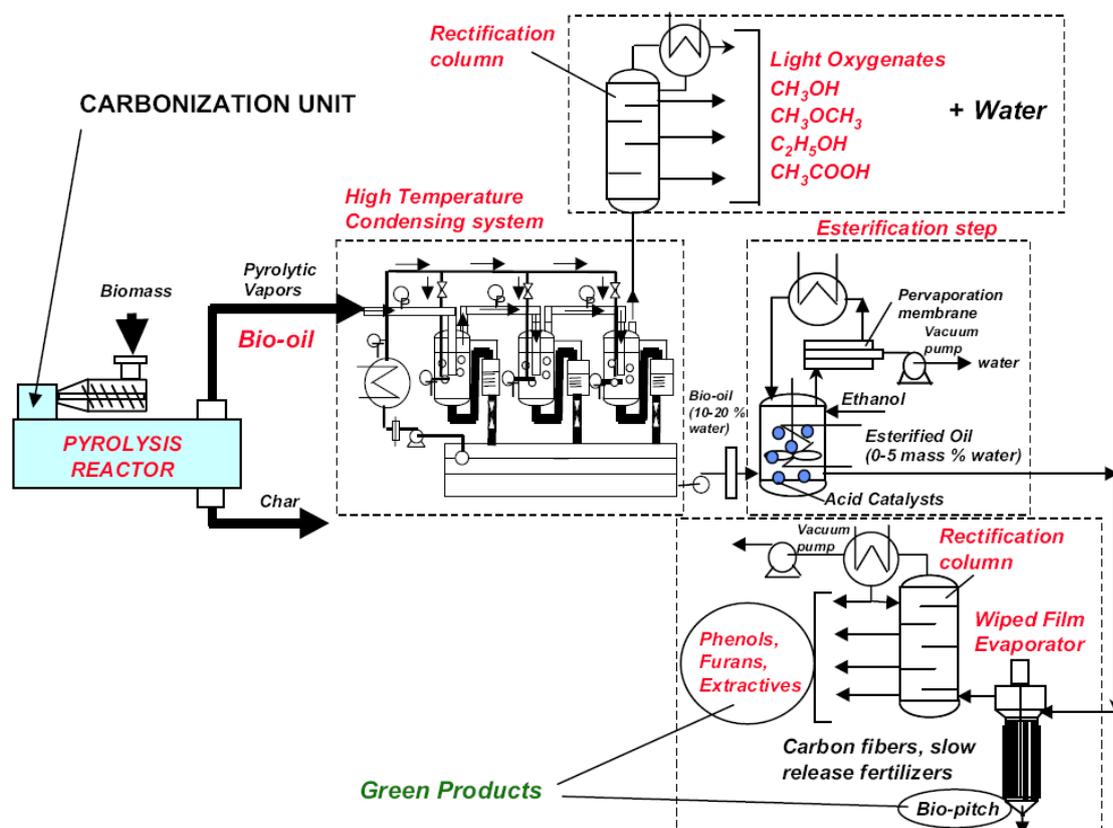


Figure 44: Tentative concept for a bio-oil base refinery

6 CONCLUSIONS

The technology of charcoal production is clear. Different installations were presented and described their operating principle. Various charcoal applications were examined.

There was also studied torrefaction technology and possible schemes of torrefied fuel production. This technology is new and not commercialized yet. Many aspects such as the energy yield and general process yield, the potential benefits are still not clear but production technologies and equipment are developing. Existing technologies in real phases could be examined further.

One of the goals of this work was to consider the possibility to use the biocoal as energy fuel. This possibility was evaluated and results, based on chemical and physical properties of the biocoal, showed that biocoal could have potential to be an energy fuel.

Power generation on the basis of biocoal can be realized in existing power stations designed for fossil fuels (coal fired power plants). There are two main common types of biocoal power generation technologies: co-combustion and gasification.

Co-combustion involves substituting biocoal for a portion of coal in an existing power plant. It is generally considered the most economic near-term option for introducing biocoal power generation. Because much of the existing power plant equipment can be used without major modifications, co-firing is less expensive than building a new biomass power plant. Compared to the coal it replaces, biocoal reduces sulfur dioxide, nitrogen oxides and other air emissions. The cost of generating electricity from biocoal is not estimated yet but it is clear that it depends on the type of technology, the size of the power plant and the cost of the biocoal supply.

The principle of biocoal gasification is the same like for coal and other types of biomass. Biocoal is processed in an oxidizing environment (with oxygen, air, steam, CO₂ or often their mixture) where the biocoal breaks down to form a combustible gas. This offers advantages over directly burning biocoal, as the

biogas can be cleaned and filtered to remove problematic chemical compounds. The biogas can be used in more efficient power generation systems that combine gas turbines and steam turbines to produce electricity. The efficiency of these systems can reach 60%. It is expected that, in the near future, gasification systems can be coupled with fuel cell systems that convert hydrogen gas to electricity or heat using an electrochemical process with very little air emissions and water vapour as the primary exhaust. When the costs of fuel cells and biomass gasifiers come down, these systems could proliferate.

Economic analysis of charcoal production showed real prices in Russian, Brazilian and Finnish markets. Because of the lack of information about torrefied fuel production it should be marked that economic analysis of the biocoal (TOP pellet) investment and production costs have approximate character.

Future aspects of the wood conversion were reviewed to understand potential of wood for such industries like power generating industry, chemical industry.

It is thus recommended to test this integrated process in practice and also to continue study related to torrefaction process economics. The profitability of integration should also be examined in more detail. Especially the investment costs of a forest biorefinery should be better defined based on the technology studied in the literature review.

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APPENDIX

COMPARISON OF MAIN PARAMETERS OF DIFFERENT FUELS

	Wood chips	Wood Pellets	Torrefied wood	TOP pellets	Charcoal	Briquettes from charcoal	Torrefied briquettes	Coal
Lower heating value, MJ/kg	17-18	16-17	19-23	19-23	30-35	30-32	dry 20-23	17-33
Moisture, %	3-30	5-10	1-5	1-5	5-10	< 10		6.5-12
Ash, %	0.7-10	0.4-1	< 3	< 3	< 6	< 6		10-40
Bulk density, kg/m ³	200-450	550-700	180-300	750-850	170-220	330-440		800-850
Energy density (bulk), GJ/m ³	3-4	7.8-10.5	3.5-6	15-18	5-8	10-14		25-40
Yield, %			70-95		25-40		43-94	

Appendix 2

LIST OF COMPANIES OFFERING OR DEVELOPING
TECHNOLOGY FOR TORREFACTION AND BIOCARBON
PRODUCTION

1. Wyssmont

1470 Bergen Blvd.

Fort Lee, NJ 07024

Phone: 201-947-4600

Fax: 201-947-0324

E-mail: sales@wyssmont.com

Website: <http://www.wyssmont.com/home.php>

<http://www.wyssmont.com/lib/images/pdf/torrefaction-newsletter.pdf>

2. Sea 2 Sky Corporation

2287 Slater Road

Ferndale, WA 98227

Phone: (877) sea-2sky

E-mail: ir@sea2skyenergy.com

Website: <http://www.sea2skyenergy.com/index.php>

3. Agri-Tech Producers, LLC

116 Wildewood Club Ct.

Columbia, S.C. 29223

Phone: (803)-462-0153

Fax: (803)-462-9676

Website: <http://www.agri-techproducers.com/>

4. Integro Earth Fuels, LLC

204 Charlotte Highway, Suite E

Asheville, NC 28803

E-mail: wchilds@integrofuels.com

Website: <http://www.integrofuels.com/>

5. Earth Care Products, Inc.

P.O. Box 787

800 N. 21st Street

Independence, KS 67301

(620) 331-0090

(620) 331-0095 FAX

E-mail: ecpi@ecpisystems.com

www.ecpisystems.com

<http://www.ecpisystems.com/wcms/index.php?Torrefaction>

6. Genesis Industries

212 Yacht Club Way A-12

Redondo Beach, CA 90277

Phone: 310-399-9775

Fax: 310-697-3032

E-mail: info@eGenIndustries.com

Website: <http://www.egenindustries.com/technology.php>

7. NewEarth Renewable Energy Inc.

Phone: (206)-310-1205

Fax: (206)- 577-3874

E-mail: info@newearth1.net

Website: <http://www.newearth1.net/about-newearth.html>

8. Terradyne Energy Inc.

3732 SW 30th Ave.

Hollywood, FL, 33312, USA

Phone: 506-863-7135

Website: <http://www.terradyneenergy.com/>

9. Biochar Systems, LLC

1125 Lancaster Avenue

Berwyn, PA 19312,

Phone: 877-326-1909

Website: <http://www.biocharsystems.com/biochar/index.html>

10. Biochar Engineering

701 Pine Ridge Rd #3

Golden, CO 80403

Phone 303-279-3776

Fax: 303-279-3734

Website: <http://www.biocharengineering.com/technology/index.html>

11. Carbon Char Group

Phone: 828-254-7418

E-Mail: sales@carbonchar.com

Website: <http://www.carbonchar.com/>

12. Mantria Industries

555 City Avenue, Suite 430

Bala Cynwyd, PA 19004

Phone: 484-483-1010

Website: <http://www.eternagreen.com/home>

13. BioChar Products

PO Box 875

Halfway, OR 97834

Website: <http://www.biocharproducts.com/>

14. International Biochar Initiative

Main inquires: Thayer Tomlinson, Communications Director

Office Phone. (914)-693-0496(United States)

Mobile Phone. (202)-247-5251(United States)

E-mail: info@biochar-international.org

Website: <http://www.biochar-international.org/>

15. Vega Biofuels, Inc.

Phone: 800-481-0186

Fax: 866-421-1216

Website: <http://vegabiofuels.com/>

16. EcoTechnologies Group, LLC

1125 Lancaster Avenue

Berwyn, PA 19312

Phone: 877-ECO-1909

Fax: 610-993-9938

E-mail: Info@EcoTechnologies.com

Website: <http://www.ecotechnologies.com/technologies.html>

17. Terra Green Energy, LLC

100 Four Falls Corporate Center, Suite 215

W. Conchohocken, PA 19428-2960

United States

Phone: (610) 940-4420

Website: <http://www.terragreenenergy.com/>

18. R & A Energy Solutions, LLC

Website: <http://randaenergysolutions.com/index.html>