



CHAPTER II

THEORITICAL BACKGROUND AND LITERATURE

REVIEW REFERENCES

2.1 Biofuels

2.1.1 Definition

Biofuels are fuels derived from living plants, animals or their byproducts. Biofuels contain stored solar energy and are a renewable source of energy. As demand and prices of crude oil increase, more countries are encouraging the use of biofuels by offering tax incentives.

Biofuels are referred to liquid, gas and solid fuels predominantly produced from biomass. A variety of fuels can be produced from biomass such as ethanol, methanol, biodiesel, Fischer-Tropsch diesel, hydrogen and methane (Nigam and Singh, 2010).

2.1.2 History

In the past nine years the popularity of biofuels has grown rapidly on a global scale. Biodiesel has been researched in over 28 countries, and there is currently large-scale production in 21 of these. There are 74 biodiesel production plants in Europe, and in Germany alone there are over 1,500 outlets to buy it. In Brazil and Argentina, where the majority of the population lives in metropolitan areas along the coast, biofuels were introduced as early as the 1980s.

Long journeys powered only by alternative fuels have been undertaken in an effort to raise media awareness and bring biofuels back to the public eye. In 1996 the “Sunrider” boat surveyed the globe using 100% biodiesel. In 1997 Joshua Tickell became the first individual to drive his “veggie van” 10,000 miles around the US using nothing but waste vegetable oil from fast food restaurants. David Modersbach and his family were the first group to partially complete the pan-American journey from Oakland to Argentina in 2003 using biofuels. Since then, the Sustainable Solutions Caravan has become an annual travel to Costa Rica and back promot-

ing renewable energies, organic farming and sustainable lifestyles in their veggie oil busses (www.nrpw.com).

2.1.3 Benefits of Using Biofuels

2.1.3.1 *Finite Reserves and Crude Oil Price*

One of the major drivers towards the development of biofuels is the simple fact that oil reserves are finite. At the end of 2009, the total proven world oil reserve was 1333.1 thousand million barrels. Distribution of proved reserves in 2009 is shown in Figure 2.1.

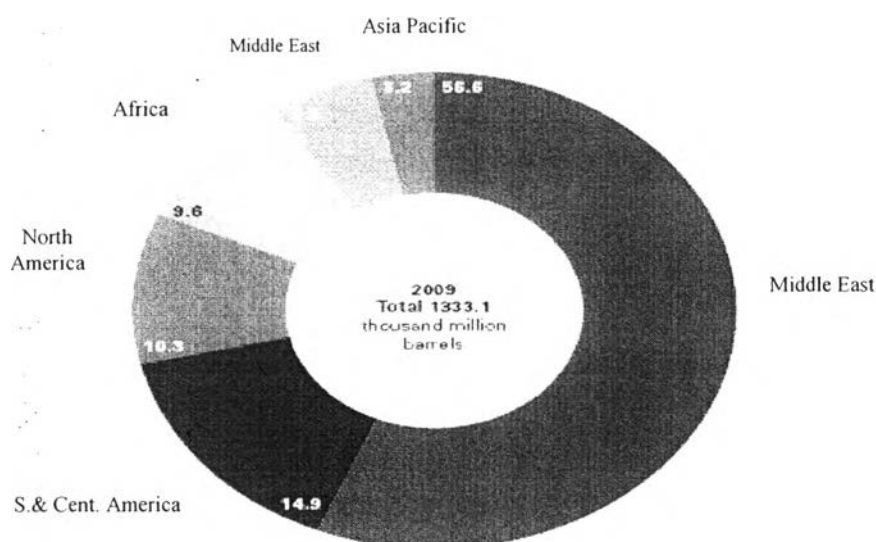


Figure 2.1 Distribution of proved reserves in 2009 (Source: www.bp.com).

Global proved oil reserves in 2009 rose by 0.7 billion barrels to 1,333.1 billion barrels, with an R/P (reserve to production) ratio of 45.7 years. Increases in Brazil, Denmark, Saudi Arabia, Egypt, and Indonesia outpaced declines in Mexico, Russia, Norway, and Vietnam.

The prices of diesel and petroleum derivatives tend to rise more and more. Every year, oil consumption grows and oil reserves get lower. Besides there's the political problem, every war threat or international crisis makes the barrel of oil prices high-rise.

Figure 2.2 shows the fluctuation of crude oil from 1970 to 2004. After 2004, trend of the price of crude petroleum oil constantly increases.

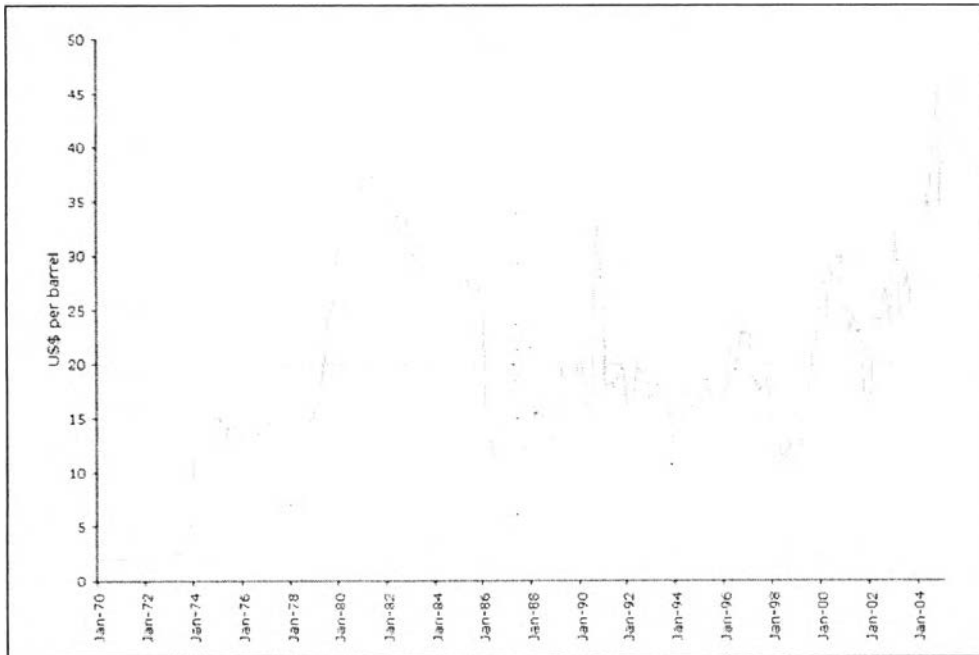


Figure 2.2 Oil prices per barrel in US dollars, 1970-2005 (Source: www.bized.co.uk).

2.1.3.2 Environmental Problems

In recent years there has been widespread and increasing concern with reducing global emissions of greenhouse gases, carbon dioxide, sulphur dioxide and nitrous oxide. Historically, heavy industry and power stations were the principle emitters of these gases. However within the last decade amounts of money have been spent by industry to reduce emissions of sulphur dioxide and nitrous oxides.

Global air pollution comes in the form of greenhouse gases. The principal greenhouse gases are chlorofluorocarbons (CFC's), carbon dioxide, methane, nitrous oxides, ozone and sulphur dioxide. These gases keep infrared radiation (heat) emitted from the earth, preventing it from escaping into space. The result of this is an increase in the atmospheric temperature. This heat trapped in the earth's atmosphere has allegedly led to the gradual melting of polar icecaps and subsequent

rise in sea levels around the World as well as exaggerating the El Niño effect. With regard to carbon dioxide biofuels are certainly beneficial. Due to their carbon neutrality these fuels produce no net output of carbon dioxide as when they grow they absorb the same amount of carbon dioxide as when they are burned. This is not entirely accurate as processes like fertilizer production and transesterification require energy and this invariably results in an output of greenhouse gases. Despite this there are still GHG savings to be made and so biofuels could help the UK meet its Kyoto Commitments.

The Rio de Janeiro (1991) and Kyoto (1997) Earth Summits have led to international agreements for industrialized countries to limit and wherever possible to reduce their emissions of six principle greenhouse gases. The six greenhouse gases are carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons and sulphur hexafluoride. The United Kingdom has agreed to reduce these greenhouse gas emissions by 12.5% on 1990 levels between 2008 and 2012. In addition to this agreement, the UK has also agreed to reduce emissions of carbon dioxide by 20% on 1990 levels by 2010 (www.esru.strath.ac.uk).

2.1.4 Classification of Biofuels

Biofuels are broadly classified as primary and secondary biofuels. The primary biofuels are used in an unprocessed form, primarily for heating, cooking or electricity production such as fuelwood, wood chips and pellets, etc. The secondary biofuels are produced by processing of biomass e.g. ethanol, biodiesel, DME, etc. that can be used in vehicles and various industrial processes. The secondary biofuels are further divided in to first, second and third generation biofuels on the basis of raw material and technology used for their production.

Biofuels are also classified according to their source and type. They may be derived from forest, agricultural or fishery products or municipal wastes, also including by-products and wastes originated from agro-industry, food industry and food services. Biofuels can be solid, such as fuel wood, charcoal, and wood pellets; or liquid, such as ethanol, biodiesel and pyrolysis oils; or gaseous, such as biogas (methane). Liquid biofuels are being researched mainly to replace conventional liquid fuels (diesel and petrol).

Figure 2.3 shows classification of biofuels. A recently popularized classification for liquid biofuels includes “First-Generation” and “Second-Generation” biofuels. The primary distinction between them is in the feedstock used. Research work is in progress for the production of “Third-generation of biofuels”.

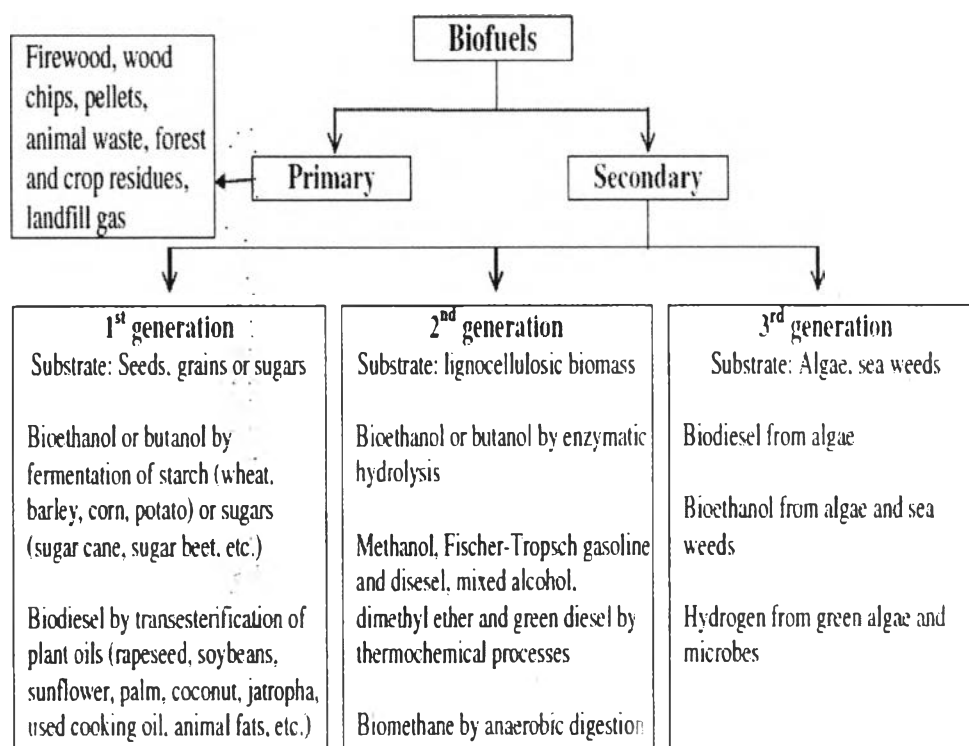


Figure 2.3 Classification of biofuels (Source: Nigam and Singh, 2010).

2.1.4.1 First Generation Biofuels

In general, first generation biofuels are produced from cereal crops (e.g. wheat, maize), oil crops (e.g. rape, palm oil) and sugar crops (e.g. sugar beet, sugar cane) using established technology. Production of first generation biofuels such as iodiesel (RME), Bioethanol, ETBE, Biogas/Landfill and Gas Straight Vegetable Oils (SVO).

First generation biofuels can offer some CO₂ benefits and can help to improve domestic energy security. But concerns exist about the sourcing of feedstocks, including the impact it may have on biodiversity and land use and com-

petition with food crops. The sustainable and economic production of first generation biofuels has however come under close scrutiny. There has the limitation that block their potential to meet liquid transport fuel targets being set by governments to help achieve the goals of oil-product substitution, economic growth, and climate change mitigation. For example, competition for land and water used for food and fibre production, high production and processing costs that often require government subsidies in order for them to compete with petroleum products and widely varying assessments of the net greenhouse gas (GHG) reductions once land-use change is taken into account (Sims *et al.*, 2010).

Many advantages and disadvantages of the first generation biofuels and obvious advantages of second generation biofuels are shown in Figure 2.4.

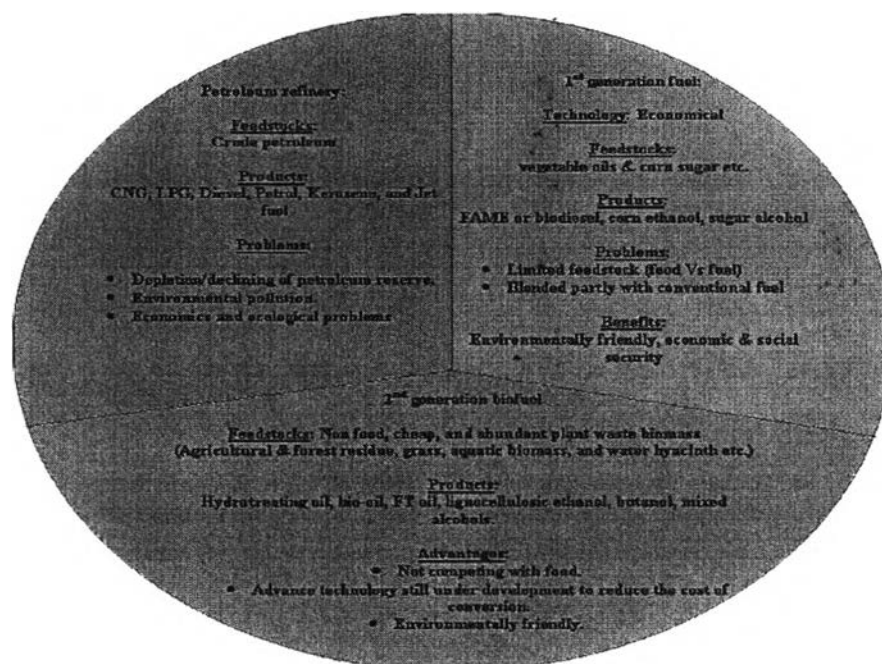


Figure 2.4 Comparison of first, second generation biofuels and petroleum fuel (Source: Naik *et al.*, 2010).

Therefore due to the previous paragraph, the recently identified limitations of first generation biofuels produced from food crops have caused greater thing to be placed on second generation biofuels.

2.1.4.2 Second Generation Biofuels

Second-generation biofuels are not yet produced commercially, but a considerable number of pilot and demonstration plants have been announced or set up in recent years, with research activities taking place mainly in North America, Europe and a few emerging countries (e.g. Brazil, China, India and Thailand). Current IEA projections see a rapid increase in biofuel demand, in particular for second-generation biofuels, in an energy sector that aims on stabilizing atmospheric CO₂ concentration at 450 parts per million (ppm).

To produce second-generation, considerable amounts of biomass have to be provided, which will require an analysis of existing and potential biomass sources well before the start-up of large-scale production. In recent studies, bioenergy potentials differ considerably among different regions; the main factor for large biomass potentials is the availability of surplus agricultural land, which could be made available through more intensive agriculture (www.iea.org).

Second generation biofuels produced from non-food biomass. Such ligno-cellulosic feedstock materials include by-products (cereal straw, sugar cane bagasse, forest residues), wastes (organic components of municipal solid wastes), and dedicated feed stocks (purpose-grown vegetative grasses, short rotation forests and other energy crops). Low-cost crop and forest residues, wood process wastes, and the organic fraction of municipal solid wastes can all be used as ligno-cellulosic feedstocks. Where these biomass materials are available, it should be possible to produce biofuels from them with virtually no additional land requirements or impacts on food and fiber crop production (Sims *et al.*, 2010).

2.1.4.3 Third Generation Biofuels

The latest generation of biofuels researchers is now directing their attention past agricultural substrates and waste vegetable oils to microscopic organisms. Therefore, on the basis of current scientific knowledge and technology projections, third generation biofuels specifically derived from microbes and microalgae are considered to be a viable alternative energy resource that is devoid of the major drawbacks associated with first and second-generation biofuels (Nigam and Singh, 2010).

The production of third generation biofuels from algae is low cost and high yield, almost 30 times more energy production per acre as compared to the land required by other conventional feedstock to produce biofuels. These algae can be grown in any location, but ideally in areas of warmth, sun and brackish water. In fact, they can be used to purify water and produce oil at the same time (www.environment2energy.blogspot.com). For microbes, genetically altered, that digest woodchips or wheat straw and the digestive by product is hydrocarbon rich. These microbes have been genetically 'tailored' to produce certain types of hydrocarbons that are almost direct substitutes for petroleum. They are claimed to be lower in carbon and sulfur content than regular fossil fuels and the overall energy and carbon emission process is claimed to be almost carbon neutral (www.greenmuze.com).

Of the available biomass conversion technologies for production of more usable energy forms, fast bio-oil pyrolysis is the second generation bio-fuel which is the least developed, but offers the benefits of a liquid fuel with concomitant advantages of easy storage and transport as well as higher power generation efficiencies than fossil fuelled systems at the smaller scales of operation that are likely to be realized from bioenergy systems. All the other thermal and biological biomass conversion processes are commercially available, usually with performance guarantees, and are steadily being implemented around the world.

2.2 Bio-Oil

2.2.1 Definition of Bio-oil

A number of researchers and companies are developing innovative processes (pyrolysis and thermochemical conversion) to turn a wide range of biomass (forestry residues, crop residues, waste paper and organic waste) into stable, concentrated bio-oil and bio-oil that is compatible with existing refinery technology and can be converted into biofuels.

Bi-oil is a replacement for geologically sourced crude oil, made from biomass. Since the carbon in biomass comes from the environment, bio-oil has low or zero carbon footprints. Bio-oil is a next-generation non-fossil form of energy

which can be transported and refined using existing petroleum facilities. Bio-oil is different from biodiesel (<http://bio-oil.org>).

The extractable bio-oil that contains a complex mixture of triglycerides, waxes, terpenes, phytosterols and other modified isoprenoid compounds can be a good source of hydrocarbons. Bio-oils can be catalytically cracked to either liquid fuels or feed stocks for chemicals (Padmaja *et al.*, 2009).

Bio-oil, essentially, is a mixture of oxygenated chemicals resulting from the degradation of complex structures. The three major components are: water, depolymerised lignin and carbonyls. Other chemical groups include carboxylic acids, carbohydrates, lignin-derived phenolics and alcohols. In order to use the bio-crude for any application it is necessary to characterize it thoroughly for its pH, viscosity, water content, ash content, alkali content, elemental composition, heating value, surface tension, stability behavior and its distillation characteristic (<http://sciencestage.com>).

2.2.2 Properties of Bio-oil

Table 2.1 summarizes select properties of pyrolysis oil. Sadaka and Boateng mentioned to the bio-oil. It is typically a liquid, almost black through dark brown (or amber). The specific gravity of the liquid is about 1.10-1.25, which means it is slightly heavier than water, heavier than fuel oil and significantly heavier than the bulk density of the original biomass. The viscosity of the oil varies from as low as 25 cP up to 1,000 cP, depending on the water content and the original feedstock. The degradation products from the biomass constituents include organic acids (like formic and acetic acid), giving the oil its low pH, typically between 2 and 4. Water is also an integral part of the single-phase chemical solution (water soluble fraction). Water contents are typically 15-35 percent. Bio-oil has the tendency to phase-separate when the water content reaches the 30-45 percent range. The heating value (i.e., the higher heating value, HHV) is below 26 MJ/kg compared to 42-44 MJ/kg for conventional fuel oils.

Table 2.1 Properties of Pyrolysis Oil (Source: Sadaka and Boateng, 2009)

Physical Property	Typical Value
Moisture content	15%-30%
pH	2.8-4.0
Specific gravity	1.1-1.2
Elemental analysis	
C	55%-64%
H	5%-8%
O	27%-40%
N	0.05%-1.0%
Ash	0.03%-0.30%
High heat value	6,878-11,175 Btu/lb (16-26 MJ/kg)
Viscosity (104° F and 25% water)	25-100 cP

2.2.3 Bio-oil Applications

Bio-oil can be used as a substitute for fossil fuels to generate heat, power and / or chemicals. Short-term applications are boilers and furnaces (including power stations), whereas turbines and diesel engines may become available on the somewhat longer term. Upgrading of the bio-oil to a transportation fuel is technically feasible, but needs further development. Transportation fuels such as methanol and Fischer-Tropsch fuels can be derived from the bio-oil through synthesis gas processes. Furthermore, there is a wide range of chemicals that can be extracted or derived from the bio-oil. A general overview is depicted in Figure 2.5.

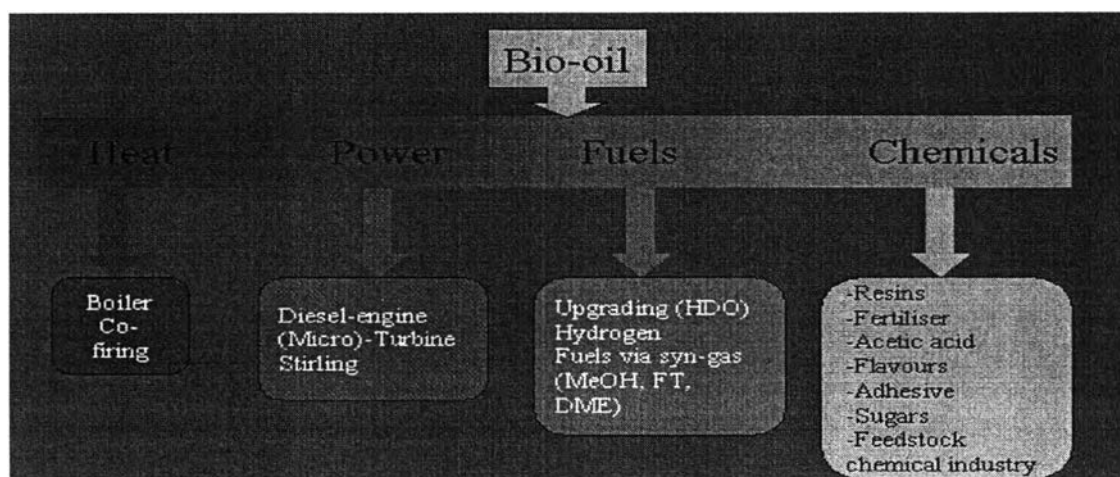


Figure 2.5 General Overview of Pyrolysis oil applications (Source: www.btgworld.com).

2.3 Feedstocks for Bio-Oil Production

This part describes an acceptable approach of utilizing agricultural by-products wastes and residues as a potential source of alternative and sustainable energy in Thailand. This study focuses on biomass (*Leucaena Leucocephala*) and agricultural residues (Rice straw and empty fruit brunch) as feedstock for producing bio-oil.

2.3.1 Rice Straw

Rice straw is one of the most abundant agricultural by-products in Thailand. The normal harvesting practice of paddy in Thailand leaves huge quantities of rice straw. Rice straw is left as a residue after rice harvesting in Thailand which is often get rid off by open burning in the field results in emissions to air that have a deleterious effect on air quality and human health. Open burning of these residues could be avoided if incentives are provided to the farmers via residue utilization which could yield monetary benefits. Straw as agricultural waste biomass could be a source of alternative energy to substitute fossil energy for reducing greenhouse gas emissions as well as avoid the local pollution problems from open burning (Suramaythangkoor and Gheewala, 2010).

2.3.1.1 *Rice Production*

Rice production in Thailand represents a significant portion of the Thai economy and labor force. Thailand has a strong tradition of rice production. It has the fifth-largest amount of land under rice cultivation in the world and is the world's largest exporter of rice. Thailand has plans to further increase its land available for rice production, with a goal of adding

500,000 hectares to it's already 9.2 million hectares of rice-growing areas. The Thai Ministry of Agriculture expects rice production to yield around 30 million tons of rice for 2008 (The Nation (Thailand)).

“The rice-planting season in Thailand usually starts in May. Around this time, showers signal the approaching end of the dry season and farmers once more prepare for rice planting as one annual cycle ends and another begins. The rice field mud walls are designed to keep the water in the paddies. By breaking holes

in these mud walls, water may be moved down from higher fields to irrigate lower ones. Once the seedlings are planted, they are later transplanted at a greater distance one from the next, almost always through a uniquely backbreaking operation that is often accompanied by generous shots of rice whisky (*lao khao*) or its local, sweeter moonshine variety, *lao sathaw*. The rice then enjoys the rainfall during the green season through to around September. The rice turns from emerald, to a darker green and finally to dry gold under the strong sun. By late November, it is ready to be harvested. Each morning, farmers go into the fields with sickles to harvest their crop. The cut rice is spread on the fields to dry for several days before being bundled into sheaves and taken to the family compound where it is threshed, and may then be milled” (www.geckovilla.com).

Utilization of rice straw in for energy has attracted considerable interest in many rice producing countries and also in Thailand. Straw remains the primary source of energy for many people in most countries and accounts for 14% of the total energy consumption in the world (Matsumura *et al.*, 2005). The rice straw production data for the year 2006 is presented in Figure 2.6. The production of rice straw is represented in kilo ton (kt) per year. It could be seen that the harvesting of rice crop is round the year in the central provinces of Thailand. It could be seen from Figure 2.6 that production of rice straw is comparatively high in the central and north eastern part of Thailand during wet season. It is understood that rice straw would be available towards the end of harvest season i.e. November/December. In contrast rice straw is available only in the central part during dry season (May/June).

Table 2.2 indicates the top ten rice straw produced provinces in Thailand and these are average values of past five years (2002-06).

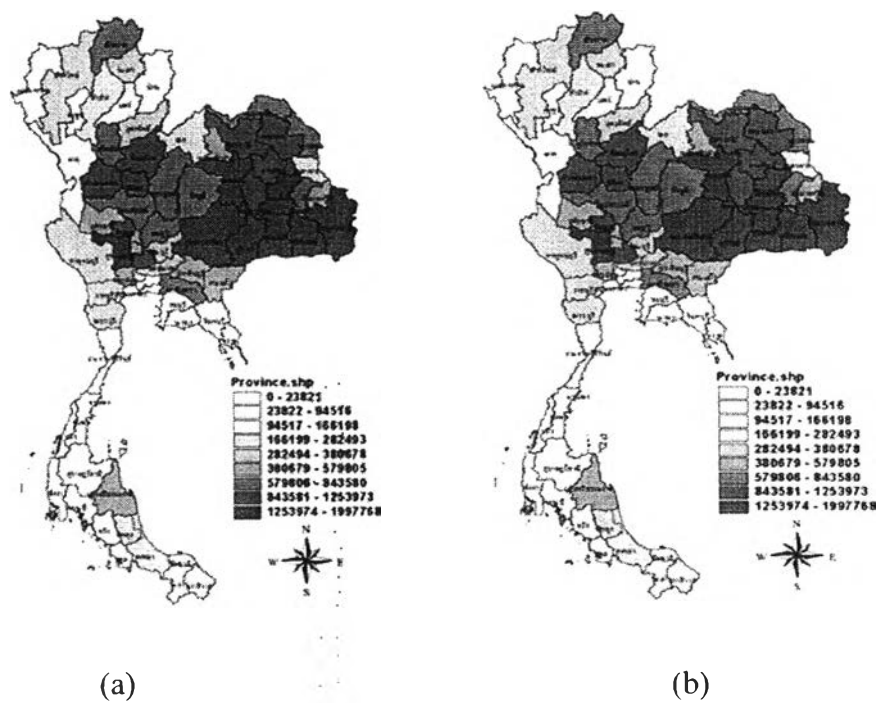


Figure 2.6 Seasonal variation and distribution of rice straw produced in Thailand in 2006 (a) Wet season (b) Dry season (Source: <http://ricestraw.rdi.ku.ac.th/>).

Table 2.2 Top ten provinces of rice straw production in Thailand (Gadde *et al.*, 2007)

No.	Province	Average rice straw production (kt)
1	Nakhon Swan	1,208
2	Suphan Buri	1,142
3	Phichit	867
4	Chai Nat	804
5	Pitsanulok	766
6	Nakhon Rachasima	717
7	Surin	706
8	Ubon Rachatani	693
9	Buri Rum	645
10	Roi Et	638

2.3.1.2 Current Use of Rice Straw in Thailand

The total amount of residue that is generated in Thailand is 21.86 Mt annually. By considering the percentage data from DEDE (DEDE, 2003), the rice straw is being used as shown in Figure 2.7. In Thailand 48% of the rice straw that is generated is being burnt in the field. About 30% is unused, 15% is being used as animal feed, 5% is used as organic fertilizer, and 1.5% is being traded (sold), 0.18% as fuel and 0.27% for other activities.

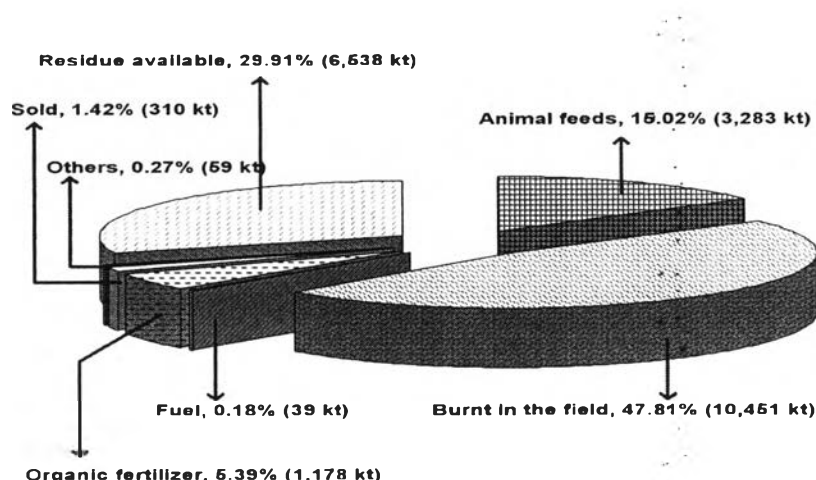


Figure 2.7 Current uses of rice straw in Thailand (Source: Modified from Gadde *et al.*, 2007).

2.3.1.3 Properties & Characterization of Rice Straw

Proximate analysis of rice straw is reported in Table 2.3. Moisture content is of important interest since it corresponds to one of the main criteria for the selection of energy conversion process technology. The ash content of biomass influences the expenses related to handling and processing to be included in the overall conversion cost. Taking into account both ash and volatile matter contents of rice straw seem to be the one problem for pyrolysis it should be used with well adjusted operational conditions considering their high ash contents (Garivait *et al.*, 2006). The LHV is an important parameter that is required in the analysis of energy potential from available rice straw. The data indicated a LHV of 10.30 MJ/kg of rice straw.

Table 2.3 Proximate analysis of rice straw (Source: Garivait *et al.*, 2006)

Proximate analysis	
Properties	Value
Moisture (%)	6.71
Ash (%)	23.55
Volatile matter (%)	58.64
Fixed carbon (%)	11.09
Higher heating value (MJ/kg)	11.54
Lower heating value (MJ/kg)	10.30

Organic elemental contents, i.e. carbon (C), nitrogen (N), hydrogen (H), sulfur (S) and oxygen (O) contents are listed in Table 2.4. Obtained results show that rice straw in Thailand, contain higher proportion of hydrogen and oxygen, which leads to calorific value reduction.

Table 2.4 Ultimate analysis of rice straw (Source: Garivait *et al.*, 2006)

Ultimate analysis (dry basis)	
Element	Value
N (%)	0.6
C (%)	44.4
H (%)	5
S (%)	0.1
O (%)	30.8

Ash-forming elements such as Silicon (Si), Calcium (Ca), Iron (Fe), Potassium (K), Magnesium (Mg), Sodium (Na), and Phosphorus (P) in biomass are important to be documented for any thermochemical conversion process. Actually, high contents of alkali are well-known to conduct to critical technical problems when biomass is used as feedstock for thermal power production, since they contribute to slagging, fouling, and sintering formation. Elemental analyses of rice straw are shown in Table 2.5.

Table 2.5 Elemental analyses of rice straw (Source: Garivait *et al.*, 2006)

Element	Unit(mg/kg)
Na	3,641
Mg	1.35
Si	4.30
P	54.96
K	2,799
Ca	1,221
Sc	0.24
Cr	559.42
Mn	852.27
Fe	2,594
Cu	6.70
Zn	29.46
As	1.04
Cd	0.06
Pd	1.55

2.3.2 *Leucaena leucocephala*

Leucaena leucocephala is a fast growing tree popularly grown as a low cost and low maintenance plant which is easy to harvest or combusted for its energy content to generate electricity or heat (Figure 2.8). Energy crops are generally categorized as woody or herbaceous. Ministry of energy reported that Thailand's Renewable Energy Development Plan (REDP) provides funding to support the fast growing trees such *leucaena leucocephala*. The goal is to increase the proportion of using renewable energy to be 20% of total energy consumption in 2565.

2.3.2.1 *Leucaena leucocephala* Cultivation and Managment

In Thailand, *leucaena leucocephala* can be cultivated at all regions but it does not popular in the southern part. It forms thickets in dry limestone and dry coastal regions

(pH > 5.5) (Royal Forest Department).



Figure 2.8 *Leucaena leucocephala*

Freshly harvested *leucaena* often has a high degree of hard seed due to an impermeable waxy coat which must be broken before the seed will imbibe water and germinate. Scarification to break this dormancy usually involves treatment with hot water; mechanical scarification is, however a very practical alternative and is recommended for farm use in Queensland by Larsen, (1998). Seed must be inoculated before planting with a suitable Rhizobium strain. TAL1145 is recommended. Lime pelleting will protect the Rhizobium in very acid soils. *Leucaena* is partially dependent on endomycorrhizal fungi of the genera Glomus and Microspora (Domergues *et al.*, 1999). *Leucaena* can be sown by seed or planted as 'bare root' seedlings. Large areas are best sown in rows into a fully prepared seed bed, or into cultivated strips in existing grasslands. Seeding rates of 1-2 kg/ha at depths of 2-3 cm is usually recommended in rows 3-10 m apart. Sowings is best done early in the growing season, but when rainfall is reliable using good weed control measures (cultivation and herbicides) to minimize competition; leucaena seedlings are very susceptible to competition in the root zone. Trifluralin (0.5 kg active ingredient (a.i.)/ha) for grass species and Dacthal (8-10 kg a.i./ha) or 2,4-D amine (6 kg a.i./ha) for broadleaf species are recommended for pre-emergence control of weeds (Brewbaker *et al.* 1985). Fusilade (2 kg a.i./ha) and Basagran (2 kg a.i./ha) are recommended for post-emergence grass and broadleaf weed control respectively. Hand weeding or mechanical cultivation are also effective.

Fertilization at planting will be necessary on most soils to achieve vigorous seedling growth as many tropical soils are infertile following years of intensive cropping, leaching and erosion from high intensity rains. *Leucaena* is particularly susceptible to phosphorus deficiency and is dependent on vesicular arbuscular mycorrhizae to extend the capacity of its root system to access immobile nutrients such as phosphorus. In soils low in phosphorus, or low in natural mycorrhizal activity, quite high rates of phosphorus (100 kg P/ha) should be applied. *Leucaena* is also sensitive to calcium deficiency as this will reduce nodulation. Other nutrients may be necessary if soil tests indicate a deficiency, to ensure vigorous early growth of seedlings. In very acid soils (pH < 5.0), liming is necessary.

Leucaena may be planted as single plants, single hedgerows or multiple hedgerows depending on its use. In the latter case, hedgerows may be

closely spaced (75-100 cm) to achieve maximum yield per hectare for cut-and-carry feeding or more widely spaced (3-10 m) for alley cropping or grazing. Intra-row plant spacing of 25-50 cm is adequate. In widely spaced rows for grazing, grasses may be planted between *leucaena* rows to increase total fodder supply to animals (Suttie, 2000).

2.3.2.2 Feedstock Potential of *Leucaena leucocephala*

In 2007, Haruthaithanasan and co-worker mentioned that when wood age increase more and more, the mass ratio of biomass will be increased. At 24 month, Biomass ratios of *L. leucocephala* stem is 81.3% (91.5% for *Eucalyptus*, 73.66% for *Acacia mangium* and 69.55% for *Acacia hybrid*). Biomass ratios of stem leaves and twig of *L. leucocephala* at different ages (12, 18 and 24 month) are shown in Figure 2.9.

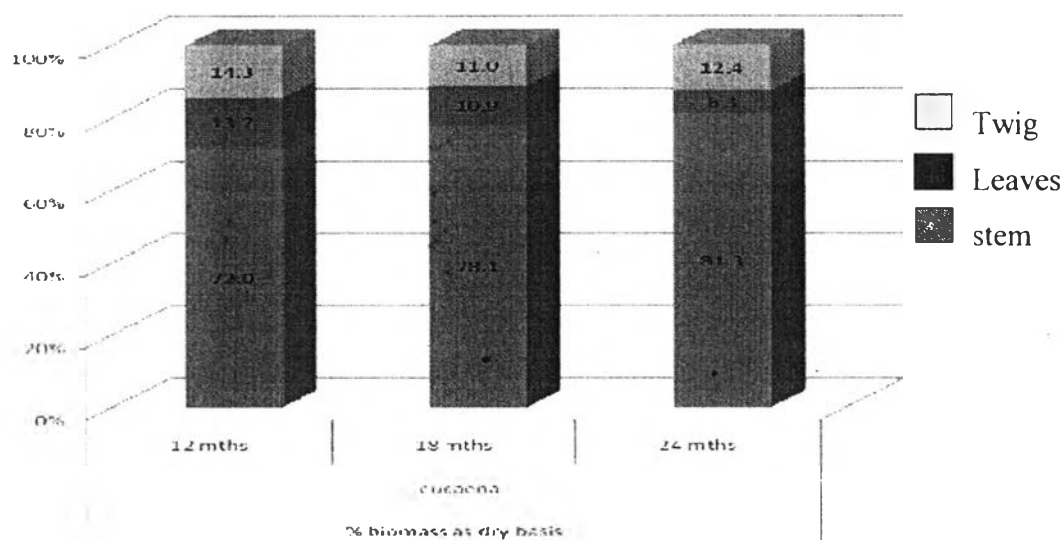


Figure 2.9 Biomass ratios of stem leaves and twig of *L. leucocephala* at different ages (Source: Haruthaithanasan *et al.*, 2008)

There are several kinds of *leucaena leucocephala* which are used to produce biofuels. Table 2.6 shows the production of various *leucaena leucocephala*'s species that cultivated at Korat's Pak Chong district area.

Table 2.6 Production of various *leucaena leucocephala*'s species that cultivated at Korat's Pak Chong district area (Source: Tudsri, 2009)

Species	1 st year		2 nd year	
	stem	total (leaf + branch)	stem	total (leaf + branch)
Tarumba	6.2	8.1	7.5	10.1
Cunningham	3.1	4.8	5.1	7.6
Peru	2.4	3.6	3.1	4.7
KU 3	5.5	7.6	12.5	16.3
KU 19	4.4	6.8	13.4	18.5
KU 38	5.0	7.0	13.4	18.6
KU 45	5.9	8.7	13.7	18.0

Among of four fast growing tree species, *Leucaena*, *Eucalyptus*, *Acacia mangium* and *Acacia hybrid*, which are cultivated in Thailand. *Leucaena leucocephala* is the secondary rank of survival rate at one year. Survival rate of *L. leucocephala*, *E. camaldulensis*, *Acacia mangium* and *Acacia hybrid* at 1 year old is shown in Table 2.7.

Table 2.7 Survival rate *L. leucocephala*, *E. camaldulensis*, *Acacia mangium* and *Acacia hybrid* (Source: Haruthaithanasan et al., 2008).

Species	<i>Leucaena</i>	<i>Eucalyptus</i>	<i>Acacia mangium</i>	<i>Acacia hybrid</i>
Survival rate (%)	97.11	99.28	96.44	84.99

2.3.2.3 Current Use of *Leucaena leucocephala*

In Thailand, *leucaena leucocephala* has long been grown throughout the country. *Leucaena leucocephala* can be utilized in many applications. *Leucaena leucocephala* is grown for their variety of uses, including as green manure, a charcoal source, livestock fodder, soil conservation, alcohol, shelterbelt, paper pulp, animal feeding and for transformed wood (Green country project).

It has been considered for biomass production, as its reported yield of foliage corresponds to a dried mass of 2000-20000 kg/ha/year, and that of

wood 30-40 m³/ha/year, with up to twice those amounts in favorable climates. It is also efficient in nitrogen fixation, at more than 500 kg/ha/year. It has a very fast growth rate; young trees reach a height of more than 20 ft in 2-3 years.

2.3.3.4 Properties & Characterization of *Leucaena leucocephala*

The physical properties of a feedstock play a major role in bio-oil yield and its properties. The moisture content of *leucaena leucocephala* used for the pyrolysis was found to be as 0.63 wt% which is very low when compared to the other two feedstocks (rice straw and EFB). *Leucaena leucocephala* used in this study had a higher heating value of 15.91 MJ/ kg. The ash content of *leucaena leucocephala* sample was found as 1.78 wt%. Table 2.8 shows proximate analysis of *leucaena leucocephala*.

Table 2.8 Proximate analysis of *leucaena leucocephala* (Source: Arjharn, 2008)

Proximate analysis	
Properties	Value
Moisture (%)	0.63
Ash (%)	1.78
Volatile matter (%)	81
Fixed carbon (%)	17
Higher heating value (MJ/kg)	15.91

Organic elemental contents, i.e. carbon (C), nitrogen (N), hydrogen (H), sulfur (S) and oxygen (O) contents are listed in Table 2.9.

Table 2.9 Ultimate analysis of *leucaena leucocephala* (Source: Arjharn, 2008)

Ultimate analysis (dry basis)	
Element	Value
N (%)	0.38
C (%)	47.55
H (%)	6.55
S (%)	0.01
O (%)	54.49

Characterization of *leucaena leucocephala* is highly invasive. It grows quickly, and forms dense thickets which crowd out any native vegetation. It is a thornless long-lived shrub or tree which may grow to heights of 7-20 m. Leaves are bipinnate with 6-8 pairs of pinnae bearing 11-23 pairs of leaflets 8-16 mm long. The inflorescence is a cream coloured globular shape which produces a cluster of flat brown pods 13-18 mm long containing 15-30 seeds. Three morphological types are noted by Domergues *et al.* (1999) a small, bushy Hawaiian type under five meters; a tall Peruvian type with several stems to 15 meters; a Hawaiian giant type with a trunk and great size to 20 meters. The commonest form is the shrubby free-seeding one which tends to be weedy and low yielding. It was this form which was transported around the world from the 16th to 19th centuries and is now pan-tropical. The true giants have better forage and wood production than the shorter varieties (Suttie, 2000).

2.4 Conversion Routes and Technologies

This study focuses on biomass pyrolysis as a process as an alternative for the production of 2nd generation biofuels. In term of this assessment, pyrolysis will be given a position among existing biomass-to-energy production techniques, leading to evaluation of the entire concept of 2nd generation biofuels from energy and land use perspectives.

Renewable energy is of growing importance in satisfying environmental concerns over fossil fuel usage. Wood and other forms of biomass including energy crops and agricultural and forestry wastes are some of the main renewable resources for this process, which can provide renewable liquid, gaseous and solid fuels. In general such conversion methods are divided into biological (anaerobic digestion and fermentation) and thermal. The production of biofuels from ligno-cellulosic feedstocks can be achieved through biological and thermal conversion process. In this study focuses on thermal conversion process.

The thermal conversion process is pyrolysis/gasification technologies produce a synthesis gas ($\text{CO} + \text{H}_2$) from which a wide range of long carbon chain biofuels, such as synthetic diesel, aviation fuel, or ethanol, can be reformed, based on the Fischer–Tropsch conversion (Sims *et al.*, 2010). High temperatures are applied for biomass treatment. Initially there are three main processes distinguished under this route, respectively, combustion, gasification and pyrolysis. At present, thermochemical conversion of biomass by pyrolysis and gasification is becoming increasingly important for the efficient production of fuels in commercial and industrial applications for power generation in diesels or boilers; according to literature study (Bridgwater *et al.*, 2002) pyrolysis is mentioned to be one of the most suitable processes. In particular, liquid fuel from biomass pyrolysis, called as bio-oil, is expected to play a major role in the future energy supply (Luo *et al.*, 2004).

There are three main thermal processes available for converting biomass to a more useful energy form – combustion, gasification and pyrolysis. Their relationship to each other and the oxygen requirements are summarized in Figure 2.10.

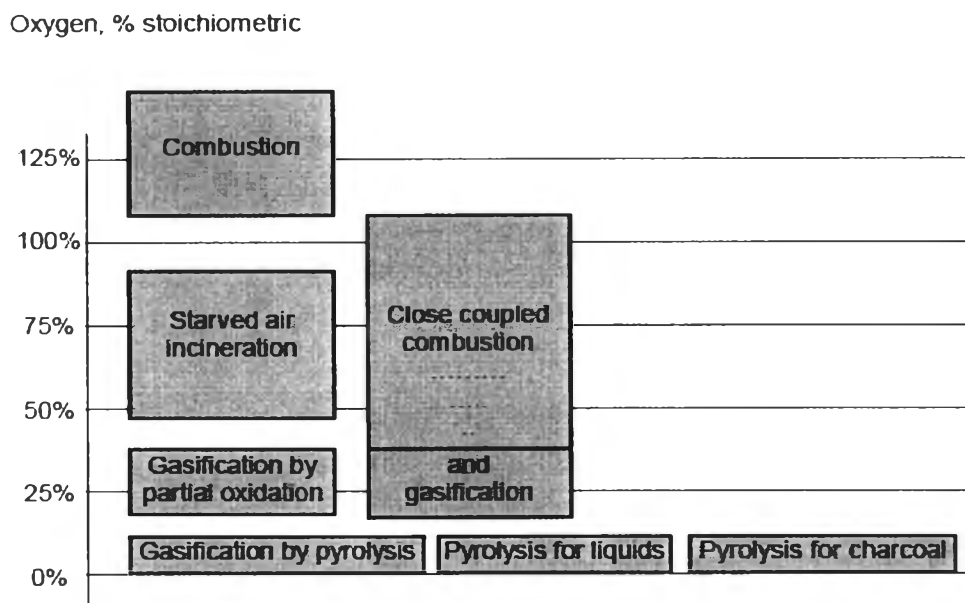


Figure 2.10 Thermal conversion process (Source: Bridgwater, 2002).

It indicates that pyrolysis is a thermal conversion process typically occurs in the absence oxygen and their products and applications are summarized in Figure 2.11.

Thermochemical biomass conversion does include a number of possible routes to produce from the initial biomass feedstock useful fuels and chemicals. The base of thermo chemical conversion is the pyrolysis process, which include all chemical changes occurring when heat is applied to a material in the absence of oxygen. The products of biomass pyrolysis include water, charcoal (or more correctly a carbonaceous solid), oils or tars, and permanent gases including methane, hydrogen, carbon monoxide, and carbon dioxide.

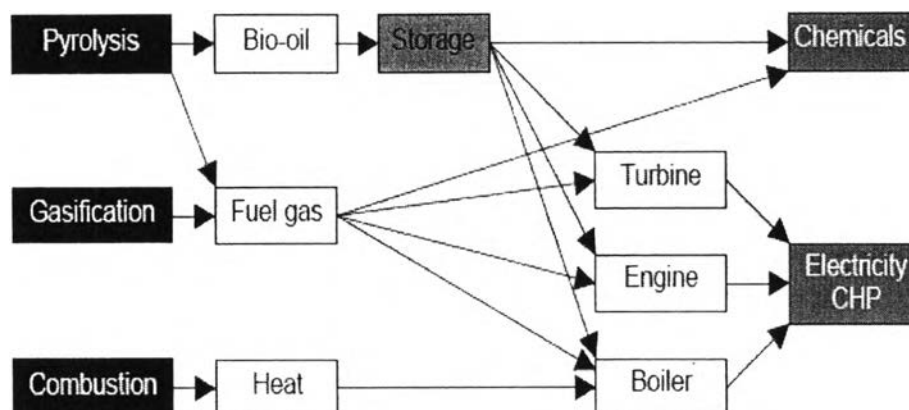


Figure 2.11 Products from thermal biomass conversion (Source: Bridgwater, 2002).

2.5 Pyrolysis

2.5.1 Pyrolysis Reaction

Pyrolysis is a thermo-chemical decomposition process in which organic material is converted into a carbon-rich solid and volatile matter by heating in the absence of oxygen. The solid, termed variously as char, biochar, charcoal or coke, is generally of high carbon content and may contain around half the total carbon of the original organic matter. The volatiles can be partly condensed to give a liquid fraction leaving a mixture of so called 'non-condensable gases. Primary products of hemicelluloses and cellulose decomposition are condensable vapors (hence liquid products) and gas. Lignin decomposes to liquid, gas and solid char products. Extractives contribute to liquid and gas products either through simple volatilization or decomposition. Minerals in general remain in the char where they are termed ash. This distribution of components into products is shown schematically in Figure 2.12.

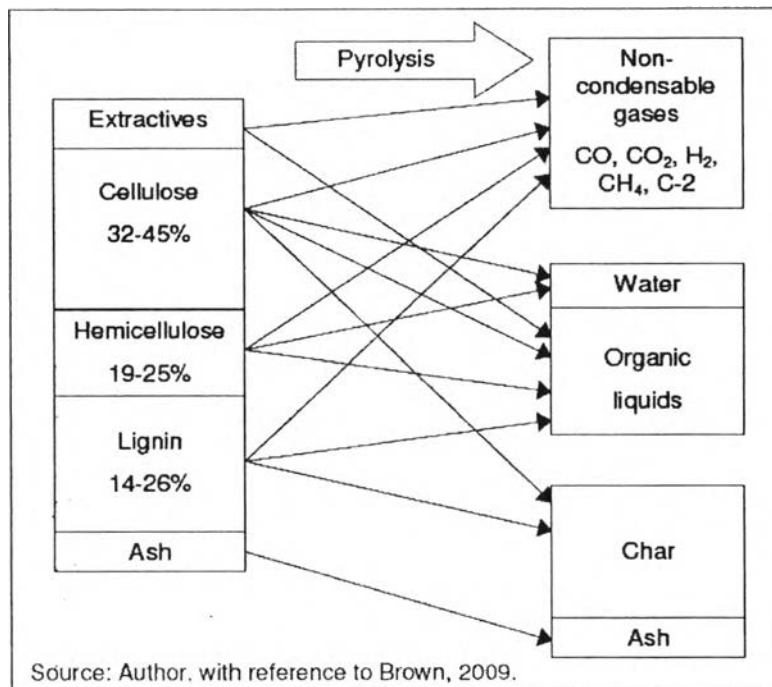


Figure 2.12 Representation of biomass pyrolysis (Source: Brownsort, 2009).

Under fast pyrolysis, there are many important factors that affect yields of gaseous and liquid products. A rapid heating rate and a rapid rate for cooling primary vapors are required to minimize the extent of secondary reactions. These reactions not only reduce the liquid yield but also tend to reduce its quality, giving a more complex mixture, an increased degree of polymerization and higher viscosity. The effect of temperature on liquid and gas yields is more complex. Liquid yields are higher with increased pyrolysis temperatures up to a maximum value, usually at 400-550°C but dependent on equipment and other conditions. Above this temperature secondary reactions causing vapor decomposition become more dominant and the condensed liquid yields are reduced. The primary and secondary pyrolysis products are mixed with oxygen and burned prior to passage over the hot charcoal (Table 2.10, Reaction 1).

Table 2.10 Reaction step in pyrolysis process (Source: Overend, 2004)

Summary Reaction steps	Results Produced
Generation of pyrolysis gases and char from biomass	
	Biomass $CH_{1.4}O_{0.6} + Heat \rightarrow Char + pyrolysis\ gases$
Primary and secondary pyrolysis products, mixed with oxygen and burned prior to passage hot charcoal	
1	Pyrolysis gases + $O_2 \rightarrow CO_2 + H_2O + CH_4 + CO/H_2 + Heat$
Solid carbon reactions	
2	$CO_2 + C \leftrightarrow 2CO$
3	$2H_2O + C \leftrightarrow CO + H_2$
4	$2H_2 + C \leftrightarrow CH_2$
5	$H_2O + CO \leftrightarrow CO_2 + H_2$

The main fuel gases are H_2 , CO , and CH_4 produced in the reaction steps 2 – 5. The solid carbon reactions after the injection of air/oxygen result in the fuel gas mixture shown in the reaction steps 2 - 5. Each of these reactions is, in fact, composed of multiple steps. They are also equilibrium reactions so that, in the water gas shift (Table 2.10, Reaction 5), an excess of steam in the presence of carbon monoxide will form hydrogen; and the reverse is also true, in that a mixture of carbon dioxide and hydrogen will form carbon monoxide and water.

2.5.2 Pyrolysis Bio-Oil System

Pyrolysis is the first step in combustion and gasification processes where it is followed by total or partial oxidation of the primary products. Lower process temperature and longer vapor residence times favor the production of charcoal. High temperature and longer residence time increase the biomass conversion to gas and moderate temperature and short vapor residence time are optimum for producing liquids.

In order to efficiently manufacture bio-oil on an industrial scale, a number of steps must be followed. The headings below outline these steps in chronological order;

➤ Drying

A fast pyrolysis process includes drying the feed to typically less than 10% water in order to minimize the water in the product liquid oil because water is the most abundant single component in bio-oils.

➤ Grinding

Feed particle size can significantly affect the balance between char and liquid yields. Larger particle sizes tend to give more char by restricting the rate of disengagement of primary vapour products from the hot char particles. Hence larger particles are beneficial in processes targeting char production and small particles are preferred to maximize liquid yields in fast pyrolysis (Brown-sort, 2009).

➤ Pyrolysis reactor

Not surprisingly, the reactor is one of the most important parts of the bio oil equation. Despite only representing 10-15% of the total capital costs involved in producing bio oil, reactors have long been the chief subject of research and development.

➤ Char separation

Charcoal and gas are present after the reaction as byproducts in ratios of 25 and 5%, respectively. The char product can be separated at this point and used to drive the pyrolysis reaction further by burning it for heat to drive the forward reaction.

➤ Cooling and collecting

Rapid cooling of the pyrolysis vapors emanating from the reactor is necessary to maximize fluid yield. Once this is achieved, the bio-oil can be collected and distributed for burning or further refinement.

General pyrolysis bio-oil system is shown in Figure 2.13.

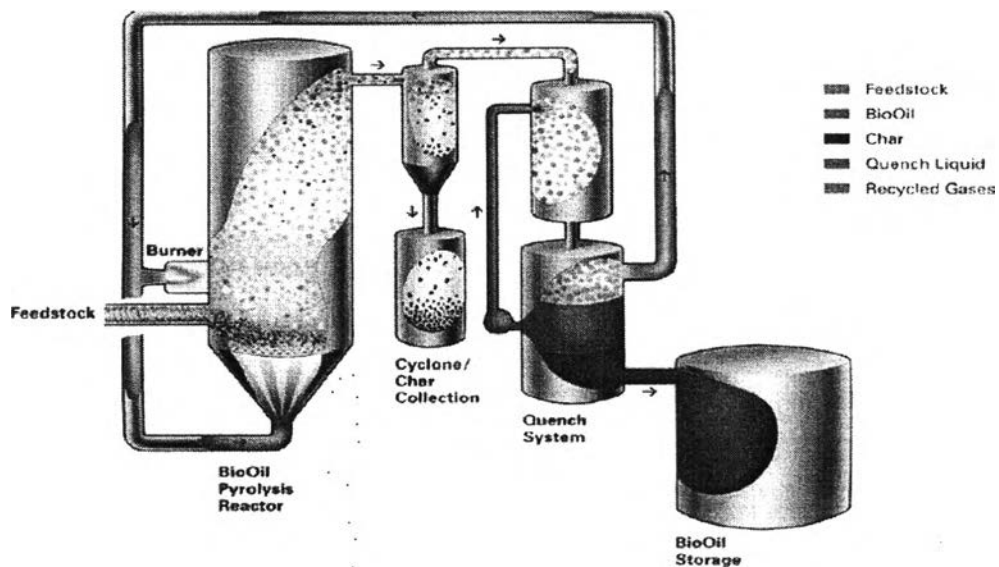


Figure 2.13 General pyrolysis bio-oil systems (Source: <http://blogs.princeton.edu>).

2.5.3 Classification of Pyrolysis

Depending on the operating conditions, the pyrolysis process can be divided into three subclasses: fast pyrolysis, Intermediate pyrolysis and slow pyrolysis. The product distribution obtained from different modes of pyrolysis process is indicated in Table 2.11. Fast pyrolysis for liquids production is of particular interest currently. The aim of pyrolysis is to obtain the highest possible yield of condensation products (liquid product) and only small amounts of char and gas (Bridgwater, 2002). Pyrolysis operating conditions are shown in Table 2.12.

Table 2.11 Typical product yields (dry basis) of pyrolysis of wood (Source: IEA)

Mode	Condition	Liquid	Char	Gas
Fast	500°C, short hot vapor residence time 1s	75%	12%	13%
Intermediate	500°C, hot vapor residence time 10-30 s	50%	25%	25%
Slow-Torrefaction	290°C, solid residence time 30 mins	-	82% solid	18%
Slow-Carbonization	400°C, long vapor residence time hrs → days	30%	35%	35%
Gasification	800°C	5%	10%	85%

Table 2.12 Operating conditions of various pyrolysis technologies (Source: Dinesh *et al.*, 2006)

Technology	Residence time	Heating rate	Temperature (°C)	Main products
Carbonization	Days	Very low	400	Charcola
Coventional pyrolysis	5-30 min	Low	600	Oil, Gas, Char
Fast pyrolysis	0.5-5 s	Very High	650	Bio-oil
Flash pyrolysis	<1 s	High	<650	Bio-oil
Flash gas	<1 s	High	<650	Chemicals. gas
Untra pyrolysis	<0.5 s	Very High	1000	Chemicals, gas
Vacuum pyrolysis	2-30 s	Medium	400	Bio-oil
Hydro pyrolysis	<10 s	High	<500	Bio-oil
Methano pyrolysis	<10 s	High	>700	Chemicals

Since the oil crisis in the mid 1970s, considerable effort has been directed toward development of processes for producing liquid fuels from lignocellulosic biomass. This led to the development of several fast pyrolysis technologies. Several reactor configurations have been shown to assure this condition and to achieve yields of liquid product as high as 70-80% based on the starting dry biomass weight (Anthony *et al.*, 2004). They include bubbling fluid beds (Scott *et al.*, 1985) circulating and transported beds (Graham *et al.*, 1988) cyclonic reactors (Diebold *et al.*, 1988 ; Czernik *et al.*, 1995) and ablative reactors (Peacocke *et al.*, 1996).

Examples of current research with pyrolysis process are listed in Table 2.13.

Table 2.13 Organizations with pyrolysis processes for liquids (Source: Bridgwater, 1999)

Reactor type	Method of heating	Organizations
Ablative coil	Wall heating	BBC + Castle Capitalc now Enervi-sion
Ablative mill	Wall (disc) heating	Colorado School Mines
Ablative plate	Wall heating	U. Aston, CNRS—Nancy
Ablative vortex	Wall heating	Interchem, NREL
Auger kiln	Wall heating	U. Tubingen, WTC
Circulating fluid bed	In-bed gasification of char to sand heating	CRES Agric. U. Athens
Cyclone or vortex	Wall heating	CNRS-Nancy, See also Ablative vor-tex
Entrained flow	Combustion products Hot sand	Egemin, GTRI U. Western Ontario
Fixed bed	Combustion product Partial gasification Overfired gas	Bio-Alternative, Chemviron Alten, Italenergiel U. Cardiff
Fluid bed	Heated recycle gas Hot inert gas Partial gasification Fire tubes	Dynamotive, INETI, IWC RTI, Union Fenosa, U. Hamburg U. Waterloo, Wellman, Worthing CPERI, NREL, U. Aston, U. Leeds, U. Sassari, U. Stuttgart Alten, Italenergie MTCI
Multiple hearth	Hearth heating	U. Laval
Reactor type	Method of heating	Organizations
Rotary kiln	Wall heating	Deutsche Babcock, PKA, Stenau, Siemens + KWU, Waste Gas
Rotating cone	Wall and sand heating	U. Twente + BTG + KARA
Stirred bed	Partial gasification	Alten
Transported bed	Recirculated hot sand	Ensyn (& at ENEL), VTT , Red Ar-row
Vacuum moving bed	Direct contact with hot surface	U.Laval + Pyrovac

2.5.4 Fast Pyrolysis

For fast pyrolysis, it is possible to convert the majority of the input biomass material not into charcoal and gases, but into a reactive liquid (So, called bio-oil) by rapidly quenching the vapors from the pyrolysis process.

There are several fast pyrolysis processes under development and in the process of commercialization, with the goal of providing a liquid fuel from ligno-cellulosic biomass that can substitute for fuel oil in any static heating or electricity generation application. The liquid can also be used to produce a range of speciality and commodity chemicals. The essential features of a fast pyrolysis process are:

- Very high heating and heat transfer rates, which require a finely ground feed.

- Carefully controlled reaction temperature of around 500°C in the vapor phase
- Residence time of pyrolysis vapors in the reactor less than 1 sec
- Quenching (rapid cooling) of the pyrolysis vapors to give the bio-oil product.

In order to meet the time and temperature configuration, a wide range of reactor configurations have been tested and operated. Bubbling fluid beds are the most popular configurations due to their ease of operation and ready scale-up. There are several companies that are developing this type of operation including Union Fenosa in Spain, Dynamotive in Canada, and Wellman in the UK (Overend, 2004).

In a bubbling fluid bed (BFB), the inert fluid bed medium (silica sand, dolomite, alumina, and olivine) is retained in the body of the bed, which is expanded and in motion (literally bubbling) due to the flow of the fluidizing gas medium into the bed. The terminal velocity of a particle in the flow is still higher than the linear flow rate of the gas, and thus the particle remains in the body of the unit (Bridgwater, 2002). The essential features of a bubbling fluid bed pyrolysis are:

- Good temperature control & high reaction rates,
- Higher particulates in the product gas and moderate tar levels in product gas,
- Good scale-up potential to 10-15 dry t/h with high specific capacity and easily started and stopped,
- Easy scaling
- Greater tolerance to particle size range,
- Good temperature control,
- Tar cracking catalyst can be added to bed,
- Limited turndown capability,
- There is some carbon loss with ash.

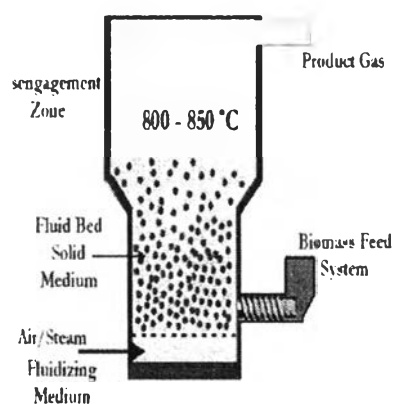


Figure 2.14 Bubbling fluid bed pyrolysis (Source: Overend, 2004).

2.5.5 Bio-oil Upgrading

Bio-oil is an alternative energy source produced from pyrolysis of biomass. However it is undesirable as a ready alternative transportation fuel due to its unfavorable nature i.e., high oxygen content, instability and lower energy content

make direct use as an advanced liquid fuel unfeasible. To overcome these physico-chemical issues, bio-oil upgrading is needed.

Hydrodeoxygenation (HDO) is one of the examples of the hydro-treatment process in which hydrogen is used to reduce the high oxygen content in bio-oil in the presence of suitable catalysts such as Cobalt Molybdenum (CoMo) or Nickel-Molybdenum (NiMo) sulphides (Senol, 2007; Mahfud, 2007; Gutierrez *et al.*, 2007). Table 2.14 shows that the oxygen and moisture content in bio-oil are decreased via HDO, resulting in significant increase of heating value. HDO also reduces the viscosity to that required for fuel applications.

Table 2.14 Properties of bio-oil and upgraded bio-oil (Source: Huber *et al.*, 2006)

Aspect of comparison	High pressure liquefaction	Flash pyrolysis	Hydro deoxygenated bio-oils
Elemental analysis			
Carbon (wt %)	72.6	43.5	85.3-89.2
Hydrogen (wt %)	8.0	7.3	10.5-14.1
Oxygen (wt %)	16.3	49.2	0.0-0.7
Sulfur (wt %)	<45	29.0	0.005
H:C atom ratio (dry)	1.21	1.23	1.40-1.97
Density (g mL ⁻¹)	1.15	24.8	0.796-0.926
Moisture (wt %)	5.1	24.8	0.001-0.008
Higher heating value (MJ kg ⁻¹)	35.7	22.6	42.3-45.3
Viscosity (cP)	15,000 (61°C)	59 (40°C)	1.0-4.6 (23°C)
Aromatic/aliphatic carbon			38/62-22/78
Research Octane Number (RON)	Not available	Not available	77
Distillation range (wt %)			
IBP-225°C	8	44	97-36
225-350°C	32	Coked	0-41

Furthermore, the formation of saturated C-C bonds and water from the reaction of oxygen and hydrogen increases the stability of the oil and reduces the acidity level of the oil. On the other hand, the octane number was taken into consideration as it measures the maximum compression ratio which can be utilized in an engine without some of the fuel/air mixture self ignited (Ahmad *et al.*, 2010).

2.6 Life Cycle Assessment (LCA)

2.6.1 Overview

Life cycle assessment (LCA) is a method for determining the environmental impact of a product (good or service) during its entire life cycle—from extraction of raw materials through manufacturing, logistics and use to scrapping and recycling. In LCA substantially broader environmental aspects can be covered, ranging from GHG emissions and fossil resource depletion to acidification and toxicity aspects, hence it is a good tool for quantifying environmental impacts of a defined product system. However, LCA as it stands has its limitations such as the difficulties in data acquisition and validation, and the misleading results due to the choice of methodology especially on allocation issues. Figure 2.15 illustrates the life cycle of biofuels involving to CO₂ emission.

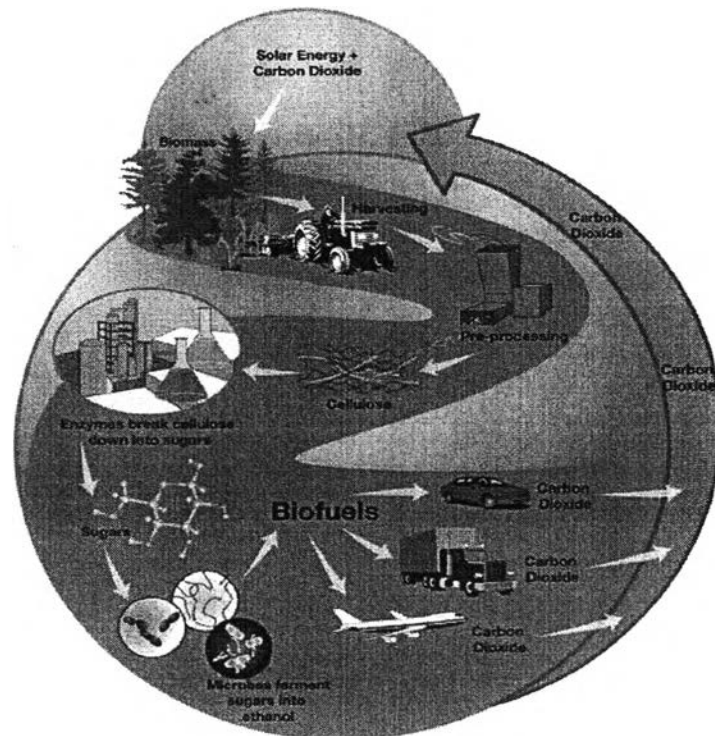


Figure 2.15 Life cycle of biofuels (Source: www.alternative-energy-news.info/images/technical/biofuel-conversion.jpg).

In the case of petroleum-derived fuels, this means LCA includes everything from the time the oil is extracted from the ground, transported to the refinery, made into fuel and distributed to your local gas station. This is also known as a Well-to-Wheels Study because it starts at the oil well and ends at the wheels - or more specifically the tailpipe of your car or truck.

2.6.2 Definition of LCA

Life Cycle Assessment is a process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and materials used and wastes released to the environment; to assess the impact of those energy and materials used and releases to the environment; and to identify and evaluate opportunities to affect environmental improvements. The assessment includes the entire life cycle of the product, process or activity, encompassing, extracting and processing raw materials; manufacturing, transportation and distribution; use, re-use, maintenance; recycling, and final disposal (SETAC, 1993).

2.6.3 Methodology

The LCA framework was standardized by the International Organization for Standardization (ISO), and it is constituted by four elements:

A) Goal and Scope is where the intention of the use of LCA is defined, and where the setting of the boundaries for the product system takes place. Through these are also defined the technological and temporal scope, as well as the assessment parameters. The system is quantified in the functional unit which is the function or service that determines the reference flow of products. For instance a packaging study might choose to define the functional unit as —packaging of 1000 liters of milk in containers of 1 litre. Taking this, the relevant significant comparison can be between 1000 carton boxes and 40 returnable polycarbonate bottles, which can be used in average 25 times. Usually what LCA does is compare different ways of obtaining the same function. Therefore in order to guarantee fairness and relevance it is crucial to be comparing between product systems that actually provide the same function, being this assured through carefully defining the functional unit. This step follows ISO 14040 series.

B) Inventory Analysis is where all the necessary input and output data for the processes regarding the product system is gathered. These gathered data are related with the reference flow given by the functional unit. Typically the data for the different processes is combined over the life cycle and presented as the total emissions of a substance or total use of a resource. This step follows ISO 14041.

C) LCIA, which as was referred previously means life cycle impact assessment, has the purpose of translating the inventory data on input (materials and resources) and output (waste and emissions) into information regarding the impacts the product system has on the environment, human health, and resources. This step follows ISO 14042.

D) Interpretation is where the results from the previous step will be related with the goal of the study. In order to quantify the results sensitivity and uncertainty are also analyzed in this step. This step follows ISO 14043.

The relationships of these elements are illustrated in Figure 2.16.

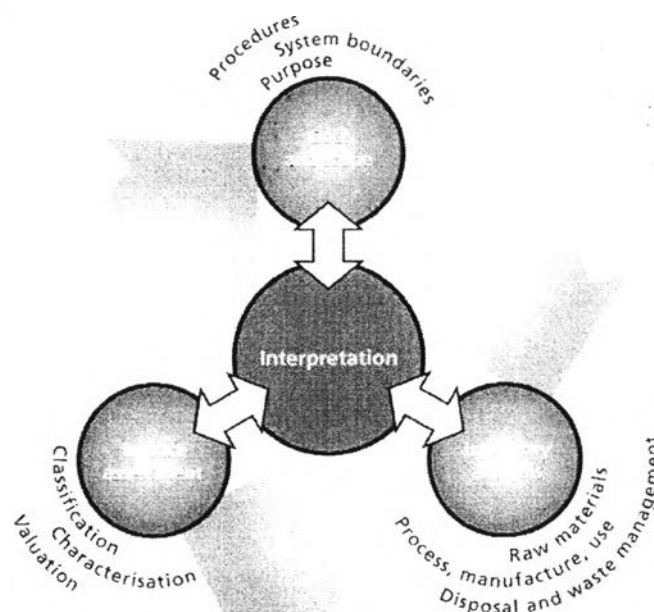


Figure 2.16 Life cycle assessment framework (Source: www.co.uk/TI/LCA_Introduction.html).

2.6.4 LCA Studies on Bio-Oil

Bio-oil is qualified as environmentally friendly alternative fuel by various governments. Use of alternative green energy is stimulated. The side effect of bio-oil production from waste materials is the reduction of various waste materials.

In 2009, Khoo studied Life cycle impact assessment of various waste conversion technologies. The results of global warming potential (GWP) of Eight different technologies are shown in Figure 2.17,

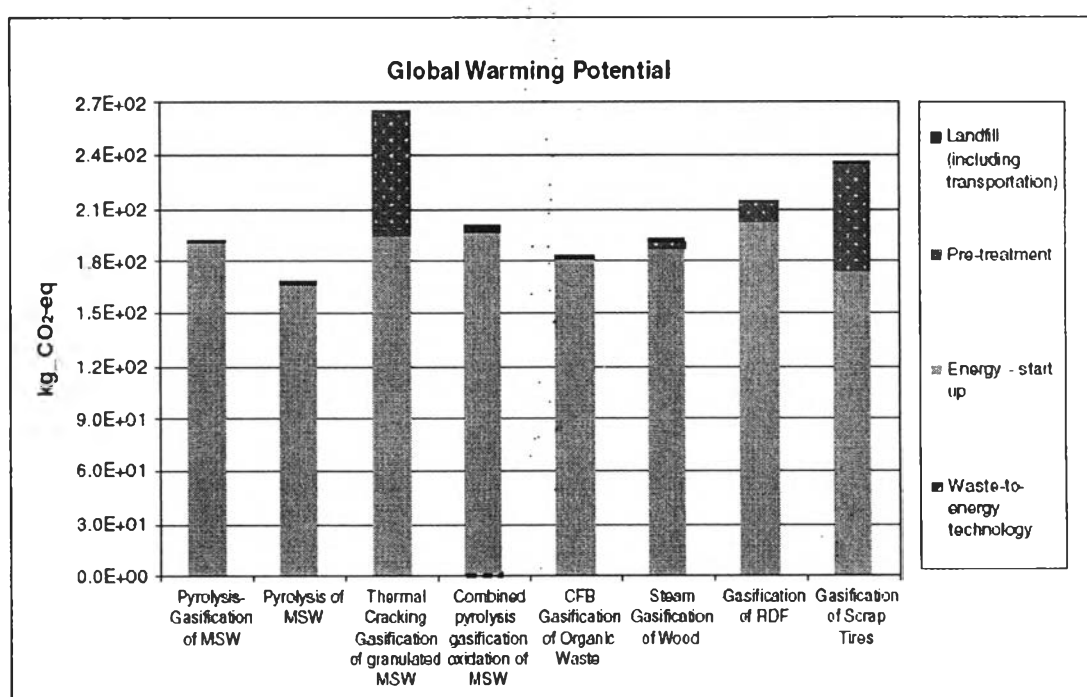


Figure 2.17 Comparison of the global warming potential (GWP) of eight waste conversion technologies.

For the GWP results shown in Figure 2.17, each of the graphs is dominated by the energy required during the start-up of the pyrolysis and/or gasification processes. The pre-treatment requirements for the thermal cracking gasification of granulated MSW and the gasification of shredded scrap tyres both add to the impacts of global warming making these two waste systems the highest contributors. The least three global warming impacts are from, first of all, the pyrolysis of MSW, next

the CFB gasification of organic waste, and the pyrolysis gasification of MSW. GWP impacts from the transportation and landfilling of ash/residues are hardly noticeable.

Zhong *et al.* (2010) worked on life cycle assessment of flash pyrolysis of wood waste. This work analyzes a process known as flash pyrolysis, which produces biofuels using biomass for power generation. The results obtained are shown in Figure 2.18.

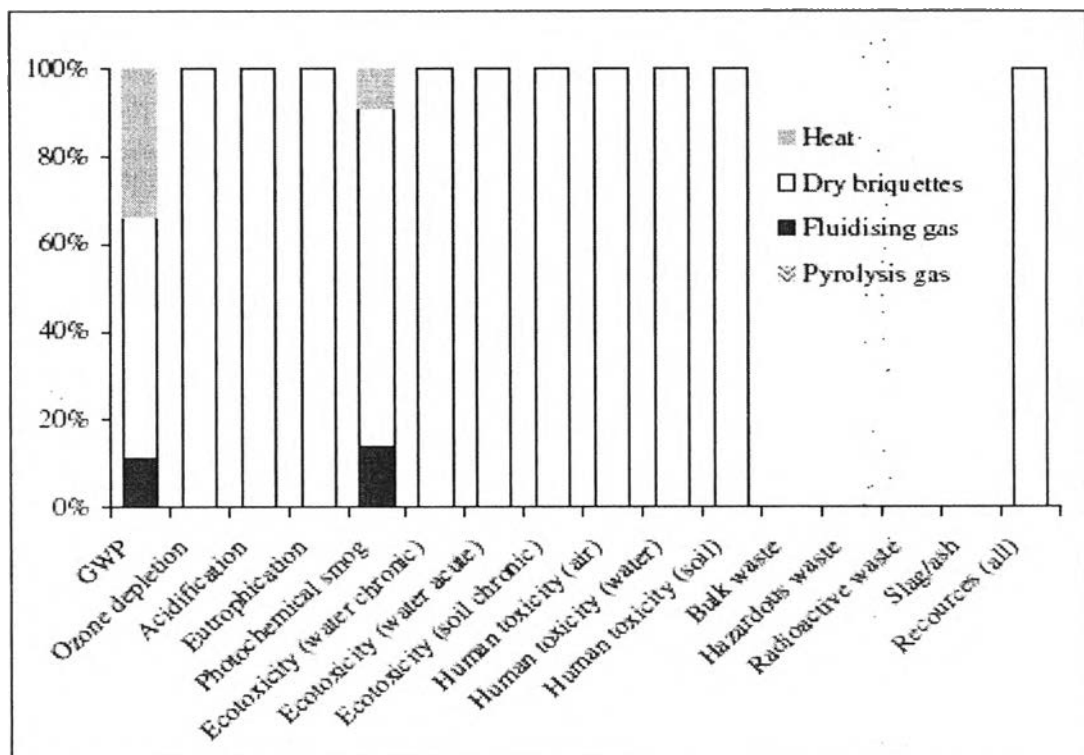


Figure 2.18 Characterization of the impacts of the flash pyrolysis process.

Figure 2.18 shows the characterization of the impacts of the flash pyrolysis process. The impacts of the three inputs and one output of the process are compared. The three inputs are fluidizing gas, dry briquettes and the heat supplied to the reactor, while the output is the pyrolysis gas. Pyrolysis gas does not have any impact on any of the impact categories. This may be due to the fact that the whole pyrolysis gas is used as an input for the next process which is the filtration process where pyrolysis gas is heavily filtered. The dry wood briquettes, when they are burnt, have im-

pacts on all the categories. The fluidizing gas, which is made up of nitrogen, water and carbon dioxide, has certain impacts on GWP and photochemical smog with impact percentages of 11% and 14%, respectively. The heat energy supplied to the flash pyrolysis reactor or from the char combustor is 33% responsible for the GWP and only 9% responsible for the effect of photochemical smog.

In view of the global warming potential effect due to the plant's processes, it is important for the plant to minimize or control this effect. For this to materialize, the root of the problem of global warming needs to be addressed. As already known, GWP is caused by green house gases such as carbon dioxide, methane and nitrous oxides. For the flash pyrolysis plant, there are no emissions of nitrous oxides, and thus more efforts have to be made concentrating on reducing the amount of carbon dioxide and methane emissions. Methane is not a product of any processes considered and is only released as part of the generation of the electricity to supply power for certain processes considered.