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Cover pictures:
1. Electricity generation from landfill gas in Rio Azúl landfill near San José
2. Map of Costa Rica
3. Coffee processing plant Coope Libertad
4. Bioreactor generating methane from cow manure in Farm Robago

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For

Reijo Keurulainen

In Memoriam

Preface

This publication is one of the outcomes of a project SUBBE (Sustainable Biomass and Bio-Energy in Central America: CDM Project Preparation Assistance Facility) of University of Jyväskylä and CATIE (Tropical Agricultural Research and Higher Education Center), Turrialba, Costa Rica. It is a part of a Johannesburg World Summit for Sustainable Development (WSSD) type II partnership programme between government of Finland and governments of the 7 Central American countries. It was launched at Johannesburg WSSD in 2002 by the Finnish government, Central American regional intergovernmental organization SG-SICA and Central American regional intergovernmental environmental organization CCAD.

The partnership framework programme is financed by government of Finland via Ministry for Foreign Affairs. The purpose of the partnership is to increase renewable energy utilization in Central America by financing or seed funding projects of Finnish and Central American companies, universities, research institutions, NGOs and government agencies, that have signed themselves as partners in this framework. SUBBE is one of such projects, running in 2004-2005, with a purpose to build capacity in local actors to utilize bioenergy technologies and the Kyoto protocol Clean Development Mechanism (CDM) in project financing.

This background study, one of the many outcomes of SUBBE, on technological availability and potentials was written by PhD student Suvi Huttunen and associate professor Ari Lampinen from Department of Biological and Environmental Science and Renewable Energy Education and Research Programme. The authors thank Oscar Coto, Lucio Pedroni and Zenia Salinas from the CATIE Global Change Group for excellent co-operation and acting as information resources during the whole SUBBE project and especially for the hospitality given to Suvi during her visit in Turrialba in summer 2004. Our special thanks belong to Oscar for reviewing this publication and Markku Nurmi from Ministry of the Environment, chairman of the partnership programme board, for a shining example of proactive leadership of an international multicultural task force.

We thank Marja-Liisa Mustonen from Uniservices Ltd. for financial coordination of the project and Arjo Heinsola from Renewable Energy Education and Research Programme and Veli-Pekka Heiskanen from VTT Processes for taking part in the SUBBE team work in Jyväskylä.

We dedicate this work to Reijo Keurulainen who as the managing director of Uniservices Ltd. pulled all strings together and made this partnership possible, but who could not see its results due to unexpectedly passing away in May 2004.

Jyväskylä, April 2005

Ari Lampinen and Suvi Huttunen

Contents

1 Introduction

Costa Rica is one of the world leaders in utilizing renewable energy. However, there are still large unexploited potentials available, including sustainable bioenergy. The Clean Development Mechanism of the Kyoto protocol offers a new financial incentive for sustainable bioenergy use. The first part of this publication, chapters 2-3, reviews current energy use and policy as well as bioenergy potentials and potential producers/users. The second part, chapters 4-6, reviews suitable technologies for bioenergy utilization for different user categories. Both commercial and emerging technologies are described with global perspective making this survey useful for other countries as well.

2 Socioeconomic issues in bioenergy utilization

In this chapter, the current energy production and utilisation in Costa Rica is presented, with a focus on bioenergy. Biomass resources, their users and relevant policies are shortly evaluated within the frames of available literature. Drivers and barriers of bioenergy use are shortly analysed.

2.1 Bioenergy in Costa Rica

General information on Costa Rica

Costa Rica is a small republic situated in Central America. Population is about 4 million inhabitants and the land area is about 51,000 square kilometres.

Costa Rica is the most prosperous country of Central America. The purchasing power parity corrected gross domestic production per capita is about 9000 US dollars: 9% of the GDP comes from agricultural production, 30% from industry and 61% from services. The service sector has been growing significantly from the 1980's due to increasing flows of tourists to the country. Unemployment rate is about 6.7%, but there is considered to be significant underemployment. The main industries in Costa Rica are food processing, production of microprocessors, textiles and clothing, construction materials, fertilizers and plastic products. The most important export products from the agricultural sector are coffee, banana, pineapple, melon, citrus fruits, juices and sugar.

Costa Rica is famous of its natural resources. It has been estimated that about 6% of world's biodiversity can be found in Costa Rica. Climate is tropical and subtropical. The dry season lasts from December to April and rainy season is from May to November. The climate is cooler in highlands, where most of the people live.

Figure 2.1 Flag of Costa Rica.

Table 2.1. Key data for Costa Rica. Sources: Inter American Development Bank information on Costa Rica (www.iadb.org/exr/country/eng/costa_rica/), UNDP Human Development Report 2004 and Estado de la Nacion, Informe 10, 2004 (www.nacion.com).

Official name	República de Costa Rica
Government	Democratic Republic. Current President: Dr Abel Pacheco
Population (2002)	3.9 million
Annual Population Growth (2002)	1.6%
Life Expectancy	77.6 years
GDP (2002)	16.9 US$ billions
GDP Annual Growth (2002)	2.8%
GDP per capita average annual growth	1.0
Population below poverty line (2002)	22%
Human Development Index (HDI)	0.832 (ranks number 45 in the world)

Energy use pattern

Secondary energy supply in 2002 was 112 PJ (2.7 Mtoe) with petroleum based fuels responsible for a 74% share (Fig. 2.2). The bioenergy share consists of ethanol and charcoal. However, ethanol is not used for energy purposes.

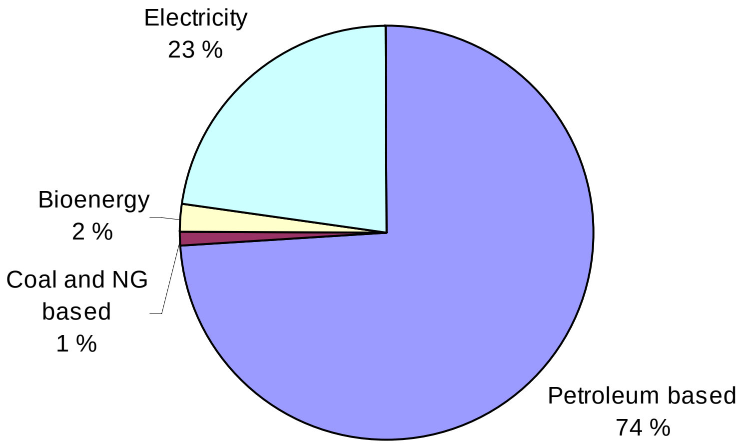

Figure 2.2. Secondary energy supply in Costa Rica in 2002 (DSE 2004).

The Costa Rican electricity system is the largest in Central America. Over 97% of the inhabitants have access to electricity. The electricity system has one of the largest renewable energy utilization percentages in the world: 98% consisting mainly of hydro, geothermal and wind (Fig. 2.3). In addition, bio and solar power are produced in small amounts. Total electricity production in Costa Rica was 7.6 TWh in 2002 and the installed electricity production capacity was about 1800 MW.

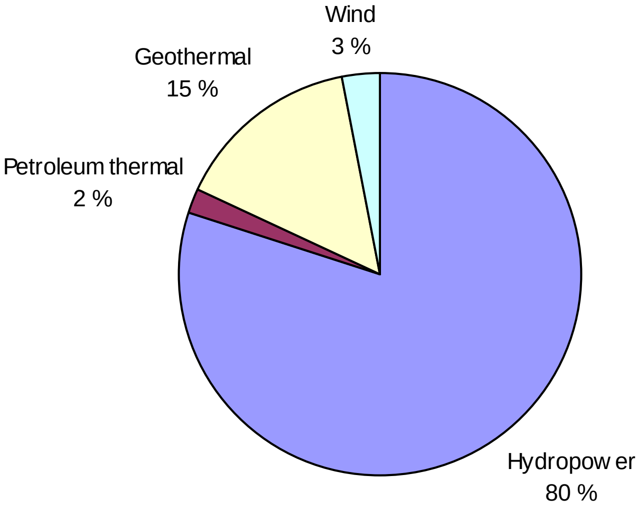

Figure 2.3. Electricity production by source in Costa Rica, year 2002.

The share of hydropower is about 80% of electricity produced in Costa Rica. The estimated commercial potential of hydropower in Costa Rica is about 9600 MW, but much of its potential new development is located in protected areas. Several new hydropower plants are under planning and development. Most important is Boruca with 841 MW of capacity, and expected to be on line by the year 2013 (according to the current expansion plan of the local utility).

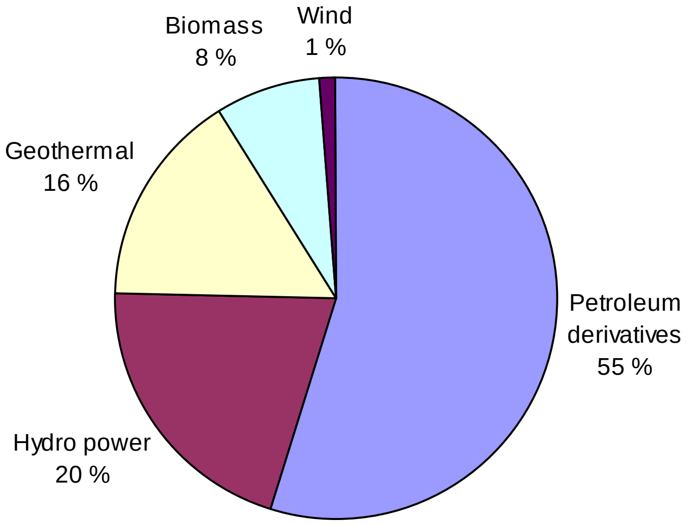

Figure 2.4. Total energy consumption by source, year 2000 (DSE 2004).

Costa Rica has the world's 10th largest geothermal electricity capacity of 145 MW_e and more could be produced but the resources are mainly on conservation areas. Estimated geothermal capacity is 865 MW_e. Costa Rica is the leading Latin American country in wind power production, with a capacity of 71 MW_e in 2004, 1/3 of Latin American wind power capacity (Windpower Monthly 4/2005). Estimated potential is about 600 MW (EVD 2003).

At the final consumption level, fossil fuels make up the largest share, about 55% of the total energy consumption by source, according to information available for the year 2000 (Fig 2.4).

End-use energy consumption by sector of the economy for the year 2000 shows that the transportation sector is an important energy consumer in Costa Rica with about 46% share of total energy consumption (Fig. 2.5) and it is 100% fossil. Another major sector in energy consumption is the industrial sector with about 23% of the consumed energy. Residential and service sector both consume little more than 10%.

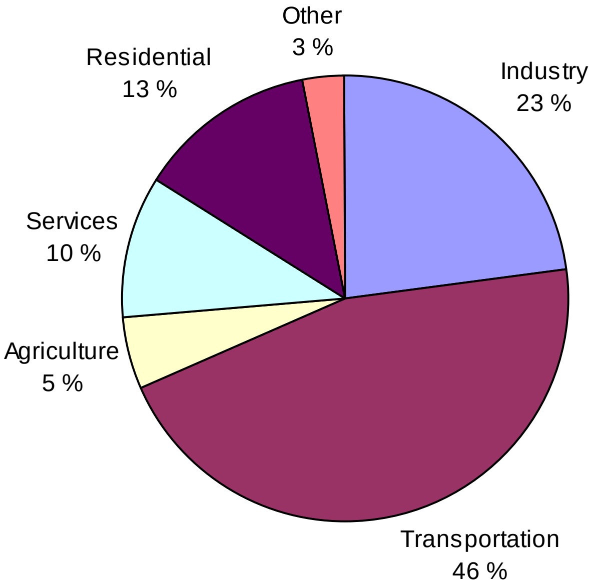

Figure 2.5. Energy consumption by sector, year 2000 (DSE 2004).

Table 2.2. Potentials for renewable energy sources in Costa Rica as estimated by MINAE (Ministry of Environment and Energy) and DSE (Energy administration) (Pachedo and Alpízar 2002).

Resource	**Annual production potential**	**Current utilization compared to the potential**
Hydropower	47 TWh	13 %
Geothermal electricity	3.5 TWh	8 %
Wind power	500 MW	4 %
Solar energy	10,000 MW	1 %
Bagasse	5.7 PJ	100 %
Other agricultural residues	2 PJ	42 %
Firewood	450 PJ	14 %
Biogas	8 PJ	minimal
Ethanol	25 PJ	minimal

Table 2.2 presents one resource estimation by MINAE and DSE (please note that not all figures are consistent within the table and with statistics presented earlier).

Current utilization of bioenergy

Currently bioenergy is utilized mainly for heat generation, either for cooking or for process heat and steam in industry. In industry, electricity is sometimes co-generated with heat (CHP). The bioenergy use in 2002 was about 11 PJ consisting of 5.8 PJ of agricultural residues and 5.4 PJ of firewood. According to recent studies conducted by UN/CEPAL, Costa Rica has a high degree of sustainability built up in the energy sector, and only about a 0.3% of firewood is of a non-sustainable nature.

Bioelectricity production capacity in 2003 was about 13 MW_e consisting of co-generation in sugarcane facilities El Viejo (4 MW_e) and Taboga (9 MW_e). In 2004 the amount increased by at least by 3.5 MW_e when a landfill gas plant in Río Azul (Appendix D1) was taken in use. Several other agricultural processing facilities, including African palm oil producers, generate both heat and power (not grid connected). Most of the coffee and rice processing facilities dry their harvest using standard combustion equipment with unit sizes in the range 45-400 kW_{th}.

Examples of bioenergy use in Costa Rica

There are various small-scale examples of bioenergy utilization in Costa Rica. They have mainly been initiated by private companies, environmental organizations or research institutes. There have been little foreign investment in bioenergy in Costa Rica, through support provided by bilateral programs as well as through normal technology transfer initiatives and in some cases foreign aid agencies have supported local projects (EVD 2003).

Here is a representative list of modern bioenergy utilization examples in Costa Rica (some more are found in Table 2.3):

- Landfill gas capturing and electricity generation (CDM project) (see Appendix D1 for more detailed information)
- Coffee processing waste water treatment for biogas with energy production (see Appendix D2 for more detailed information)
- Biogas based farm scale electricity generation from cow manure (see Appendix D3 for more detailed information)
- Gasification of wood fuels for coffee drying
- Coffee husks (cascarilla) in heat production for coffee drying
- Rice husks for heating and drying in rice factories (used traditionally)
- Bagasse in sugar mills for co-generation or process heat production
- Small scale biogas projects for pig excrement enable farms to use biogas for cooking, lightning and for keeping piglets warm
- Pilot projects on fuel ethanol
- Modern waste incinerator at a cement plant
- Forest residue energy plant in the southern part of the country

The Bioenergy sector is not well developed in Central America; markets are not yet wide and also suppliers of equipment are scarce. USA is the main supplier of the equipment needed in larger installations. Smaller installations are often installed in stages and constructed at a local level.

Table 2.3. Available bioenergy technologies in Costa Rica (BUN-CA, Coto 2005).

Technology	**Costa Rica**
Biomass gasification	One example of test runs conducted in the coffee sector.
Biogas digesters (< 50 m^3)	Technology development currently taking place. Used in small pig farms, average capacity 3-50 m^3.
Lagoons or open air treatment plants	Mainly applied in coffee industry, average capacity 160-15000 m^3.
Grate/suspension bed dryers/ovens	Used in rice industry and coffee processing , 45-400 kW_{th}
Co-generation with bagasse (1-20 MW)	Sugar industry is very interested, 2 sugar mills are currently exporting electricity to the grid.
Landfill gas plants with CHP (<5 MW_e)	Pilot project Río Azul with 3.5 MW power capacity under operation, several other sites interest.

Energy sector structure and policy

The energy sector in Costa Rica is largely in public ownership. The state's national energy company is called ICE (Instituto Costarricense de Electricidad) and it has 82% (1430 MW_e) of the installed electricity production capacity in the country. ICE also owns more than half of the distribution network (the rest is owned by national energy grid system SEN), and sells directly almost 40% of the electricity sold in Costa Rica. CNFL is the other major electricity distributing company, distributing 43% the electricity sold in Costa Rica, mainly in San José area. 95% of CNFL is owned by ICE (EVD 2003). In addition, there are other smaller regional distribution entities most of which are either of rural cooperative type or municipal enterprises. The energy sector administration is headed by the Ministry of Environment and Energy (MINAE) making environmental impacts integral part of energy policy.

The current Costa Rican National Energy Plan for years 2002-2016 identifies the following as the principal problems of the energy sector (MINAE 2003):

1) High consumption of hydrocarbons in the transportation sector
2) Limitations in the capacity development of the energy sector
3) Low utilization of alternative energy sources
4) Inefficient energy use
5) Problems in energy legislation

As a consequence, the plan aims at increasing the utilization of alternative energy sources, including the use of various biomass resources. The plan also sets as basic principle the fact that state should maintain its role in the energy sector. It also aims at preventing excessive dependency on external resources.

Environmental legislation is another area of extreme importance, when considering the biomass energy utilization. There have been major changes in the legislation in the 90's, which has resulted in a pressure to establish treatment systems for the waste flows. The treatment requires investments, and this makes it interesting for the industries to find suitable processing alternatives to take an advantage of their wastes. (EVD 2003)

Costa Rica is one of the very few countries in the region that has not undertaken energy/electricity sector reforms, aimed at the creation of deregulated markets. Generation, transmission and distribution assets of the utility have been debundled under a corporate structure, but apart from legislation that permits the private sector to connect up to 30% of the installed capacity of the country or to sell to the utility through BOOT schemes, it is hard to interconnect private sector plants. Biomass cogenerating (CHP) plants face a tough limitation due to the seasonality of generation and due to the fact that no thermal based generation to the grid can be in private sector hands. (Coto 2005)

Costa Rica face renewed discussions on the path for institutional development of the electricity sector as well as on the choice of models that can support the diversification of renewable energy based generation as well as a sound environmental management of the sector at a time of restrained public investment in the sector. (Coto 2005)

Environmental policy is currently becoming stricter considering the handling of waste and waste water flows. This means that the industries and municipalities need to invest on treatment facilities or find suitable uses for their wastes. This might open up new possibilities for energy generation from the different kinds of organic wastes.

New possibilities for renewable energy resources are opened by international emissions trading and the Kyoto mechanisms, most importantly the CDM. This makes it profitable for industrial countries to invest in efficient renewable energy technologies in the developing countries, and at the same time being able to use the achieved emissions reductions as a part of their commitments to reduce GHG gases.

Barriers and drivers in bioenergy utilization

The large public energy sector makes it difficult for private energy investments. There is a law that prevents the private generation from constituting more than 30% of the country’s total energy generation. The public energy monopolies do not support deregulation and privatization of energy sector in Costa Rica, and thus it is quite difficult to renew the system. Some actions to liberalize the energy sector have been made. Many companies have waste flows that could be used to produce the energy they need and this kind of energy production for self-sufficiency is allowed. Also small scale (2-20 MW) private electricity plants are allowed, but the electricity has to be sold to ICE, whereas ICE has no obligation to buy it. Currently the ICE is forecasting the private electricity generation to decrease (EVD 2003). For example some sugar refineries have postponed further investments in co-generation facilities due to problems in getting contracts with ICE for selling of the electricity.

Large scale electricity generation from biomass for selling purposes is not currently possible. However, there is pressure to increase the generation capacity and ICE has not sufficient funds to do all the investments. It is probable that the laws will change or ICE will become more interested in private sector contracts. Pressures are also forming for the state energy monopoly to start new types of energy production or to open up for private investments. Environmentalist groups and consumer organizations have been promoting the utilization of new renewable resources. These organizations can also be direct actors in implementing pilot projects. Also, private producers have been promoting new energy sources and introducing international knowledge and technology, e.g. bioethanol (Vargas 2002).

The current Costa Rican National Energy Plan for years 2002-2016 aims at increasing the utilization of alternative energy sources, including the use of various biomass resources. The plan also sets as a basic principle the fact that the state should maintain its role in the energy sector. It also aims at preventing excessive dependency on external resources. (MINAE 2003)

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Table 2.4. Bioenergy utilization barriers and drivers in Costa Rica.

Category	**Driver**	**Barrier**
Technical	- Large amount of different options available for all user groups in all size classes - Various pilot projects on modern bioenergy technology	- Lack of knowledge considering different technical options and their suitability - Possible lack of skilled personnel and education
Markets	- The CDM option is bringing international investments - Resources enable energy independence and export	- State monopoly in energy sector - Possible restricted access to technology
Institutional	- ICE is starting new bioenergy projects - NGOs promoting bioenergy	- Lack of supporting institutions and information dissemination mechanisms
Political	- High aims to increase the utilization of renewable energy sources in energy policy, especially in transportation sector - Demands for waste treatment and reutilization in environmental policy	- Plans to implement the policies are unclear
Energy resources	- Large biomass resources - Industries especially in the food sector have suitable biowastes for energy production	- Large hydropower resources - Cheap foreign fossil fuels
Social, Cultural and Behavioural	- Expected growth in energy utilization in all sectors	- Technologies already in use may have an advantage in meeting the growing energy needs

The bioenergy utilization context gives the basis for the analysis of different barriers and drivers for bioenergy in Costa Rica. In addition, this technology survey shows a large diversity of existing suitable technology options and biomass resources. The barrier analysis is partly based on a renewable energy implementation framework, presented by

Painuly (2001). Economical barriers were left out from this analysis. Some barriers would require deeper analysis and are marked here as possible barriers. The identified drivers and barriers for bioenergy utilization in Costa Rica are listed in Table 2.4.

2.2 Potential bioenergy users in Costa Rica

As seen in the previous section, energy consumption in Costa Rica is divided mainly between transportation sector, industrial use and domestic use. Here these sectors and their potential for increasing bioenergy utilization are discussed.

Industrial energy use

In industries, energy is mainly used for steam and heat production, production of hot water, refrigeration, air conditioning, lightning, transportation and for mechanical power. The total industrial energy use was 37.5 PJ in 2001 (Table 2.5).

Table 2.5. Energy end-uses and their share of energy consumption in industries in 2001 (DSE 2004).

Energy use	**TJ**	**%**
Heat	13 580	36.2
Steam	13 260	35.3
Mechanical power	5 810	15.5
Transportation	1 350	3.6
Lightning	1 080	2.9
Refrigeration	1 050	2.8
Hot water	980	2.6
Air conditioning	440	1.2
Total	**37 540**	**100**

The main energy source used in the industries was bunker fuel, i.e. fossil fuel oil (Table 2.6). It is used for the production of steam and heat. Another large source for heat, steam and electricity production is bagasse. Other biofuels are used mainly for the production of steam and heat. Electricity is used for mechanical power generation, lightning, refrigeration and air conditioning. Oil derivatives are mainly used for transportation.

Table 2.6. Energy sources used in industries year 2001 (DSE 2004).

Energy source	**TJ**	**%**
Bunker	11970	31.9
Electricity	8660	23
Bagasse	7880	21
LPG	2030	5.4
Diesel	1310	3.5
Firewood	1210	3.2
Coffee husks	1030	2.8
Coke	1110	3.0
Coal	1010	2.7
Rice husks	590	1.6
Kerosene	440	1.2
Gasoline	310	0.8
Nafta	2.5	0.01
Total	**37540**	**100**

The division of energy consumption between various industries can be seen in Fig. 2.6. Food (alimentation) sector is the largest energy consumer, with more than half of the total industrial energy consumption. This is mostly due to the size of this industrial sector in Costa Rica. The food industry produces a lot of biowaste suitable for energy production. Another important area when considering the possibilities to use bioenergy is the forest industries. However, in Costa Rica the forest industries only consume about 3% of the industrial energy use. (DSE 2004)

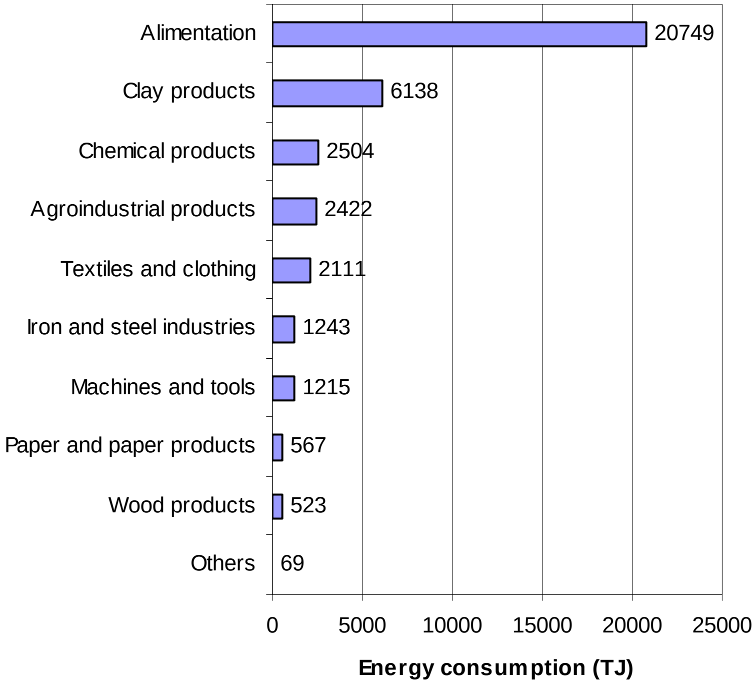

Figure 2.6. Total energy consumption by industry sector in 2001 (DSE 2004).

In the industrial sector, there are many possibilities to increase bioenergy use both in electricity generation and in heat and process steam generation. Currently, the most important biomass resource for energy production is bagasse. It is used in sugarcane processing mills in order to generate process heat and also electricity. According to BUN-CA (2002) the co-generation plants in sugar mills are rather inefficient and there is a large room to improve the utilized technology in order to generate more electricity. Also, it is more common to use bagasse for heating only, without power production.

Sugar mill “El Viejo S.A.” in the province on Guanacaste provides an example of improvement of the co-generation system. Before the improvement the sugar mill processed about 365,000 tons of sugarcane per year with a bagasse production of 109,500 tons. 30% of the bagasse was used for process steam, heat and electricity generation. The electricity generation capacity was 1.5 MW_e. Currently all of the bagasse is used and the electricity generation capacity is 6.5 MW_e of which 2.5 MW_e is used in the mill and the rest 4 MW_e is sold to ICE giving an extra income source to the sugar mill. (BUN-CA 2002)

Coffee industry is another important sector regarding bioenergy potential. Similarly to sugar industry it provides residues that could be used for the generation of heat and electricity needed in the processes, and there is also the possibility to sell the extra electricity for additional income. Energy production is also a way to handle the waste problem efficiently. Also the fruit and palm oil production offer significant possibilities.

In forest industries the wood processing provides significant amounts of utilizable waste like sawdust and wood chips. Currently these wastes are not necessarily used for energy production, or anything else, and they may be dumped to rivers providing an environmental problem. Wood residues could be used for heat production, for wood drying and for electricity generation. (BUN-CA 2002)

Domestic/residential energy use

The total energy use in domestic sector in 2001 is about 20 PJ, of which 56% is consumed in rural areas and 44% in urban areas (Fig. 2.7, Table 2.7). Domestic sector is the main user of firewood: 40% of energy in the domestic sector is provided by firewood. However, the utilization of firewood is considerably smaller than in other Latin American countries due to the high degree of electrification (BUN-CA 2002). 97% of Costa Ricans have access to electricity in their house and electricity accounts for almost 50 % of the energy use in households. Total electricity consumption in the residential sector in 2001 was about 2750 GWh (Table 2.8). (DSE 2004)

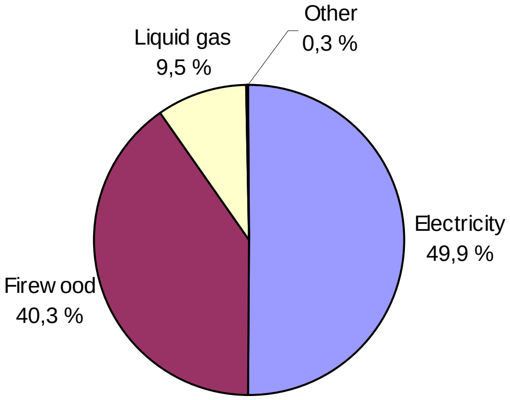

Figure 2.7. Consumption of different types of energy in domestic sector, not including energy used for transportation (DSE 2004).

Table 2.7. Mean annual use of energy sources in domestic sector in 2001 (DSE 2004).

	Urban [GJ]	Rural [GJ]	Total [GJ]
Electricity	11.964	8.069	**10.364**
Commercial firewood	0.448	3.826	**1.836**
Collected firewood	1.024	14.416	**6.525**
LPG (liquid gas)	1.579	2.545	**1.976**
Charcoal	0.035	0.013	**0.026**
Other	0.000	0.121	**0.121**
Total per household	***15***	***29***	***20.7***
Total per person	***4.2***	***7.7***	***5.64***

Table 2.8. Electricity consumption in residential sector (DSE 2004).

Residence area	Electricity consumption [GWh]	Average annual electricity consumption per person [kWh]
Urban	1920 (70%)	3320
Rural	830 (30%)	2240
Total	2750 (100%)	2880

Electricity is mainly utilized for cooking and cooling, both taking about 30% of the electricity utilisation in the household sector (Table 2.9). Heat production takes about 20% of the electricity, the rest is divided between lightning and mechanical power production for various household equipment. Table 2.10 shows diffusion of some electrical devices in Costa Rican households.

Table 2.9. Utilization of electricity in the residential sector [%] (DSE 2004).

Electricity use	Urban	Rural	Total
Cooking	34.3	32.9	33.8
Cooling	25.7	34.1	28.4
Lightning	11.2	11.9	11.4
Heat production	21.9	11.5	18.6
Mechanical power	6.9	9.6	7.8
Total	**100**	**100**	**100**

Table 2.10. Diffusion of electrical appliances in Costa Rican households (DSE 2004).

Electrical device	Households [%]
Refrigerator	91.3
Colour television	88.4
Washing machine	87.1
Telephone	65.7
Shower water heater	42.1
Microwave oven	38.8
Electrical oven	10.2
Dish washing machine	0.3

About 50% of Costa Rican households have electrical stove for cooking (Table 2.11). Others use different combustibles for cooking.

Table 2.11. Stove heating source (DSE 2004)

Stove heating source	%
Electricity	49.6
Gas (LPG)	18.6
Wood	8.8
Electricity and wood	5.1
Wood and gas	3.3
Electricity and gas	1.6
Charcoal	0.2
No stove	12.8

Gas (LPG), firewood, biomass residues and charcoal are mainly used for cooking (Table 2.12). Of these, firewood is the most common and biomass residues and charcoal are used only in few households (charcoal < 4%, biomass residues < 1%). It is estimated that households use annually about 97.4 million kg of bought firewood, 346.2 million kg of collected firewood and 91.7 million litres of LPG. In the following table some information regarding the amounts of firewood and gas utilisation is given.

Table 2.12. Shares of combustible utilisation in different residential areas [%] (DSE 2004).

	Urban	**Rural**	**Total**
Gas (LPG)	47.1	52.9	100
Collected firewood	9.2	90.8	100
Commercial firewood	471	52.9	100

Utilisation of firewood is mostly concentrated in rural areas and in low or middle income households. Utilisation of LPG is equally common in rural and urban areas. About 17% of households use firewood for cooking at least sometimes. Of the households who buy their firewood, 44 % buy all times of the year and 56 % buys in certain times of the year, usually summertime.

The potential for additional utilization of modern bioenergy in the household sector includes secondary solid, liquid and gaseous biofuels that are applicable in most situations, both for heating and cooling. In urban areas, it might be possible to build district cooling and heating networks. This could be done e.g. by utilizing heat from industrial or municipal CHP plants. The domestic sector can use biomass based electricity produced by municipal and industrial wastes, including landfill gas plants. In rural areas, farms especially could produce electricity from biogas.

Transportation sector

The transportation sector is the most important energy consumer in Costa Rica, with about 47 PJ consumed in 2000. Private transportation takes 55% of this (about 34% of households have at least one vehicle) and public sector about 10%. Most common fuels are diesel and gasoline (nothing else is used in road traffic) and the transportation occurs mostly by roads (DSE 2004). There are no railways in Costa Rica (it was demonstrated but it failed and was closed down in the beginning of the 20th century). The demand for transportation has been steadily increasing, both for the transportation of goods and also for private car utilization.

In Costa Rica, all fuels for transportation are currently imported fossil fuels. Utilization of biodiesels and bioalcohols has raised some interest in the MINAE and the aim is to introduce a share of ethanol into the gasoline. Costa Rica is large producer of ethanol but is not using it for energy production. Since the transportation sector is the largest fossil fuel consumer in Costa Rica it would be important to find ways to introduce alternative fuels in this sector. Besides bioalcohol and biodiesel, also biogas and several other alternatives could have large potentials.

3 Biomass resources

3.1 Biomass

Biomass is a renewable energy resource when used sustainably. Bioenergy is one form of indirect solar energy, since it is derived from sunlight via photosynthesis. Definition of biomass in renewable energy perspective (here “animals” include humans and “recent” means short cycle carbon to distinguish bioenergy from fossil fuels and peat where carbon has been removed from the short cycle):

”Recent organic matter originally derived from plants as a result of the photosynthetic conversion process, or from animals, and which is destined to be utilized as a store of chemical energy to provide heat, electricity, or transport fuels.” (Sims 2002, 1)

There are three main categories of biomass: woody, non-woody and animal/human waste. These include forests, woodlands and forestry plantations, agro-industrial plantations, trees outside forests/woodlands, water plants, agricultural crops, crop residues, processing residues, and animal wastes. Municipal biowastes, including landfill gas are regarded as biomass resources. (Wereko-Bobby and Hagen 1996)

The main source of woody biomass is forest residues. Forest residues include leftovers from timber production and processing by the forest industry. These are for example thinnings, forest arisings, prunings and wood process residues. Besides forest residues, woody biomass can be grown directly as energy wood. Short-rotation energy forest plantations can be harvested every 2-10 years, depending on the species and soil properties. Typical species include willow, poplar and eucalyptus.

Non-woody biomass resources include agricultural crop residues and energy crops. Common agricultural crop residues are e.g. rice husks, bagasse, maize cobs, coconut husks, coffee husks and straw. Many traditional food crops can also be grown specifically as energy crops. These are e.g. sugar cane, corn, wheat, sorghum and vegetable oil-bearing crops like sunflower, rapeseed and soya beans. Most often these are converted into liquid fuels like ethanol or biodiesel. (Sims 2002)

Forest residues as well as other woody and vegetation based biomasses can be further refined (compressed) to pellets and briquettes. The advantage is more stable fuel quality and higher energy density.

Animal and municipal wastes are another source of bioenergy. Most commonly used animal wastes are manures from pigs, chickens and cattle. The manure is converted into biogas via anaerobic digestion. Municipal and domestic sewage sludge is also an energy source and can be converted into biogas, just like manures. Municipal wastes, namely biological waste (municipal green waste), can be combusted, or treated biologically to produce energy. Also industrial wastes especially from food processing industry and fibre industry can sometimes be used as bioenergy sources.

The properties of biomass fuel vary considerably, even within wood biomass arising from the same plantation. The properties of the biomass source determine both the choice of conversion process and subsequent processing difficulties. The main properties of interest are: moisture content, calorific value, proportions of fixed carbon and volatiles, ash/residue content, alkali metal content and cellulose/lignin ratio. (McKendry 2002a)

3.2 Biomass resources in Costa Rica

The agricultural and agro-industrial activities generate significant amounts of organic wastes suitable for bioenergy applications. A summary can be found in Table 3.1.

Farm animals

Pigs

There are about 490,000 pigs in Costa Rica; they are divided to about 5600 farms with an average of 50 animals (BGT 2004). It is estimated that there are only 120 farms with 100 pigs or more (EVD 2003). There is a trend towards larger farm size. Environmental legislation controls pig farms and their waste treatment more efficiently than other types of animal farms. Pig manure has been used to produce biogas and to provide energy needed in the farm and this practice is increasing (EVD 2003).

Cattle

There is a large amount of mostly small farms with 20 animals on average; the total amount of cattle is about 1720,000 animals (BGT 2004). There are few projects that utilize cow manure for biogas based energy production. The current problem seems to be the relatively small size of the farms and lack of resources (EVD 2003).

Poultry

There are medium and large scale poultry farms with about 17 million animals in total (BTG 2004).

Fruit sector

Costa Rica is ideal for the production of various fruits like mango, melon, citrus fruits, pineapple and banana. Banana is the most cultivated fruit with more than 44,000 hectares and 1.7 million tons of bananas per year (BGT 2004). Currently plant residues are often used as fertilizer or fed to cows, or they are just let to rot. Fruit plant residues are often too moist for direct combustion applications, but they could have potential for e.g. biogas production (EVD 2003).

Agroindustry

Coffee

Coffee is the classic Costa Rican product. Currently the sector suffers from low coffee prices, which reduces the willingness to invest on waste treatment or energy production systems (BTG 2004). On the other hand the low prices also make the producers willing to lower the production costs, and by own energy production this could be possible. Coffee pulp, husk and film contain high calorific values and could be utilized in energy production. Pulps and film can be used in biogas production and husks can also be directly combusted (EVD 2003).

African palm oil

Large palm oil plantations can be found in the southern Costa Rica. They were mostly planted in the 70s and 80s. In 2003 the production area was estimated to be almost 40,000 hectares. Most of the producers are small and medium size. They are organized by associations and cooperatives. There is also one big producer: Paima Tica S.A (BGT 2004). Dried coconut shells are combusted to heat boilers for distillation. Palm oil is also used for co-generation, but some of the power producers have switched to selling the palm oil due to volatility in market prices. Currently tests are being done to investigate the possibilities to make biodiesel out of palm oil (EVD 2003).

Sugarcane processing

Sugarcane processing produces a residue called bagasse (it is the leftover after the juice has been extracted from the plant). Bagasse is an attractive fuel for the sugar industry and has been used for years to heat boilers. Nowadays bagasse is also used for combined heat and power generation. In Costa Rica there are 16 sugarcane processing factories and three of these have invested in co-generation facilities and also others are interested in the activity. In these facilities, electricity is produced in abundance and revenues could be obtained by selling the electricity to the grid. But ICE, the grid monopoly, may be reluctant to buy it. LAICA, the trade organization of sugarcane industry is very interested in heat and electricity production from bagasse. (EVD 2003)

Especially related to sugarcane industries, an interest has evolved in ethanol production. Texaco is interested in the ethanol production potential in Central America (EVD 2004). Another pressure for the production of ethanol is coming from the Costa Rican National Plan for Development (2002-2006), which includes substitution of MTBE in gasoline for ethanol or similar products. MINAE is developing pilot projects in ethanol production. (EVD 2003)

Rice

Rice is cultivated in an area of about 52,700 ha. There are 25 rice processing factories with a production of about 211,600 tons: 13 of these are large scale with a daily input of 100-600 tons (BTG 2004). Rice husks have a high energetic potential. Traditionally it has been burned to heat the factory’s boilers and for drying (EVD 2003). It is possible to use rice husks for combined heat and power production and thus cover more of the processing factory’s energy need.

Water plants

Water iris is a non-indigenous water plant in Costa Rica. Currently it causes environmental problems in the region of Tortuguero by clogging rivers and canals and causing oxygen depletion in the waters. Water iris grows faster than it can be removed, and piles of removed plants are let to rot in river and canal sides. There have been investigations on possible ways to utilize water iris biomass. These include energy production: it could be used for the generation of alcohol, or it could be combusted (EVD

2003). However, for wet biomass the most natural utilization would be anaerobic digestion.

Landfills

Landfill waste in Costa Rica is mostly organic, about 60 %. The approximated waste production is about 4.3 million tons per year (BGT 2004). In anaerobic landfill conditions the organic material is digested to landfill gas, composing mostly of methane. The potential for capturing the landfill gas and using it in energy production is large. However, the investments are costly if greenhouse gas emission reductions are not valued by CDM or other means.

Composting is not practiced in Costa Rica, except in some small-scale cases.

A good example of energy production from landfill gas is the Rio Azul case, presented in Appendix D1. It also provides an inside look to the difficulties of such projects.

Waste water

The current situation in waste water treatment in Costa Rica is various. Heavy industry and agro-industrial companies are obliged to treat their waste waters, but e.g. most municipalities don't have waste water treatment systems and the waste goes directly to rivers or sea. Some companies treat their waste waters by anaerobic processes, but they don't utilize the biogas as energy. There is potential for the biogas to be utilized, since it could reduce the need for external energy in the treatment plant. (EVD 2003)

The environmental laws in Costa Rica are becoming stricter and it is probable that a large number of new treatment facilities will be installed in the country in the near future (EVD 2003). When installing new facilities it would be important to include biogas energy utilization.

Forestry

The forest resources in Costa Rica are large: the total forest area is about 19,000 km^2, i.e. 39 % of the total land area. Plantations cover about 1800 km^2 and the rest is natural forest. The current trend is towards increasing amount of plantations area and diminishing amount of natural forests: almost 5% of the natural forests were lost during 1990-2000. (Earth Trends 2003)

Costa Rica produces roundwood, which is mostly used as fuel. The use of firewood was discussed in chapter 2. Firewood comes mainly from small pieces of forest, bushes, pastureland, coffee plantations, wood plantations, waste from pruning in municipalities and waste from sawing and wood treatment. Many of the technologies used are inefficient and lose an important part of the energy content in the wood. (EVD 2003)

Industrial roundwood is mainly used for sawn timber, but there are also small wood-based panel and paper industries (www.fao.org/forestry). The forest industries do not currently have co-generation facilities, although there a few sawmills operating captive power artisan units.

Table 3.1. Estimated potential for different biomass sources in Costa Rica (modified from BTG 2004).

Sector	**Production**	**Type of waste**	**Waste production [tons/year]**
Farm animals	**Amount**		
Pig	491500	Waste water with high organic content, mostly from manure	810845
		Slaughterhouse waste water	34522
Cattle/dairy	1720000	Waste water with high organic content, mostly from manure	17200000
		Waste water from slaughters/tannery processes, with solids	731000
		Waste water from dairy	390000
Poultry	17000000	Poultry manure	170000
		Waste water from slaughters processes with solids	8500
Fruit sector	**Production (tons/yr)**		
Mango	32000	Water from the process and thermal stage	224000
Melon	190900	Water from the process and thermal stage (low concentration)	1336300
Citrus	459200	Husk/pulp waste	229600
		Water from the process	3214400
Pineapple	950400	Husk waste and biomass, water from the process	47520
Banana	1739000	Water from the process in the packaging stage	12173000
		Empty fruit bunches waste	260850
Agro-industry	**Production (tons/yr)**		
Coffee	846000	Waste water	1692000
		Pulp waste	346800
African palm oil	666000	Waste water	2044600
		Nuts, pulp and empty fruit brunches	166500
Sugarcane processing	3472000	Waste water	20832000
		Bagasse	1041600
Rice	211600	Husk	25400
Forestry[1]	**Production (m^3/yr)**		
Industrial round wood	1687000		
Wood fuel	3463000		
Sawn wood	812000	Sawdust and barks	284200
Wood based panels	65 000		
Wood and fibre pulp	11 Mt/yr		
Paper and paper board	20 Mt/yr		
Landfills	4320000	Organic waste 58%, paper 19%, others 5%	4320000
Domestic waste water	246000m^3/yr	Domestic waste water into sewage	246000m^3/yr

[1] Source: FAO statistics 2004 (www.fao.org/forestry)

The MINAE estimates that the commercial potential for electricity production from wood fuels is about 2530 MW_e (EVD 2003).

4 From bioenergy to heat, power and mechanical energy

This chapter presents technologies that can be used for producing heat, electricity and mechanical power (e.g. for traffic use) from primary biomass or biomass based secondary solid, liquid or gaseous fuels.

4.1 Biomass conversion: an overview

Primary bioenergy resources are those recently living plant, animal and human based resources that can be found in nature, including plants and plant, animal and human based wastes, but not those resources that have been stored by nature into soil, i.e. peat and fossil fuels (Fig. 4.1). Secondary bioenergy resources are storable solid, liquid and gaseous fuels made of primary or other secondary fuels by mechanical, thermochemical, biological, chemical or other type of conversion (Fig. 4.1). List of primary and secondary biofuels is found in Table A1 of Appendix A.

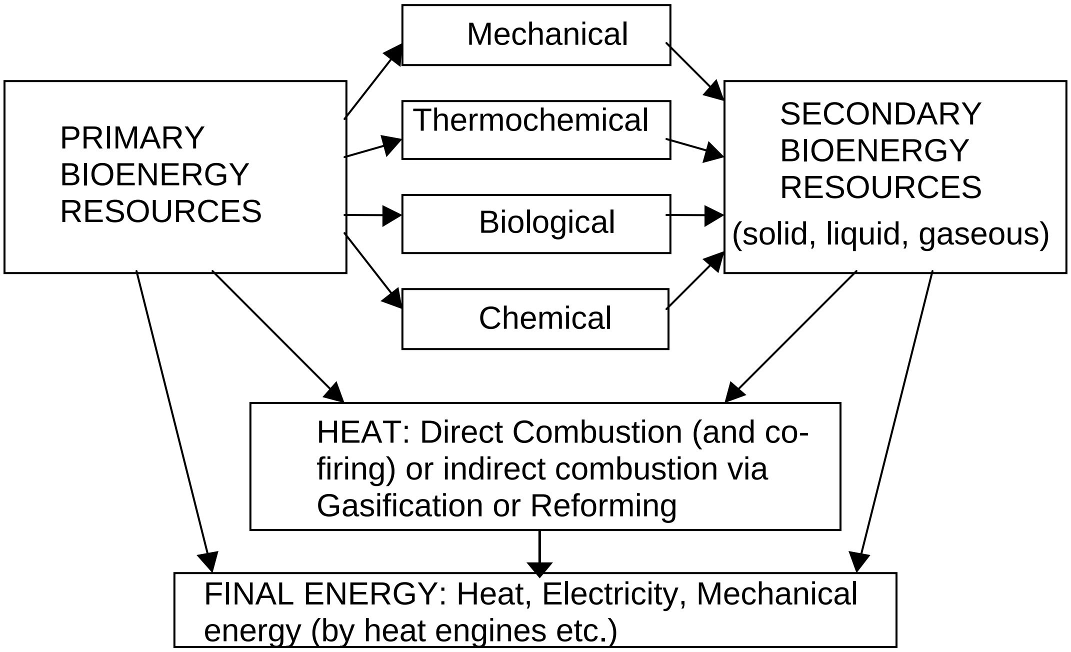

Figure 4.1. Bioenergy conversion technologies and end-uses (modified from Kautto 2005). Transportation of energy forms is not shown.

Primary and secondary bioenergy conversion into final energy that humans can use, i.e. mechanical power, electricity and heat, is usually undertaken by first converting the fuels into heat by combustion and then utilizing the heat directly or by further converting it into mechanical power and electricity by heat engines or by other technologies (Fig. 4.1). Also direct conversion from primary and secondary fuels into final energy is possible. Technologies for fuel conversion into heat are listed in Table A2. Technologies for heat or fuel conversion into mechanical power and electricity are listed in Table A3.

Thermochemical biomass conversion

Thermo-chemical conversion can be done e.g. by combustion, gasification, pyrolysis or liquefaction (Fig. 4.2). They are applicable to all forms of biomass, including wood. Combustion technologies are most widely used and mature technologies. Gasification and pyrolysis are becoming more and more important. Liquefaction is currently rarely used but it also has a long commercial history.

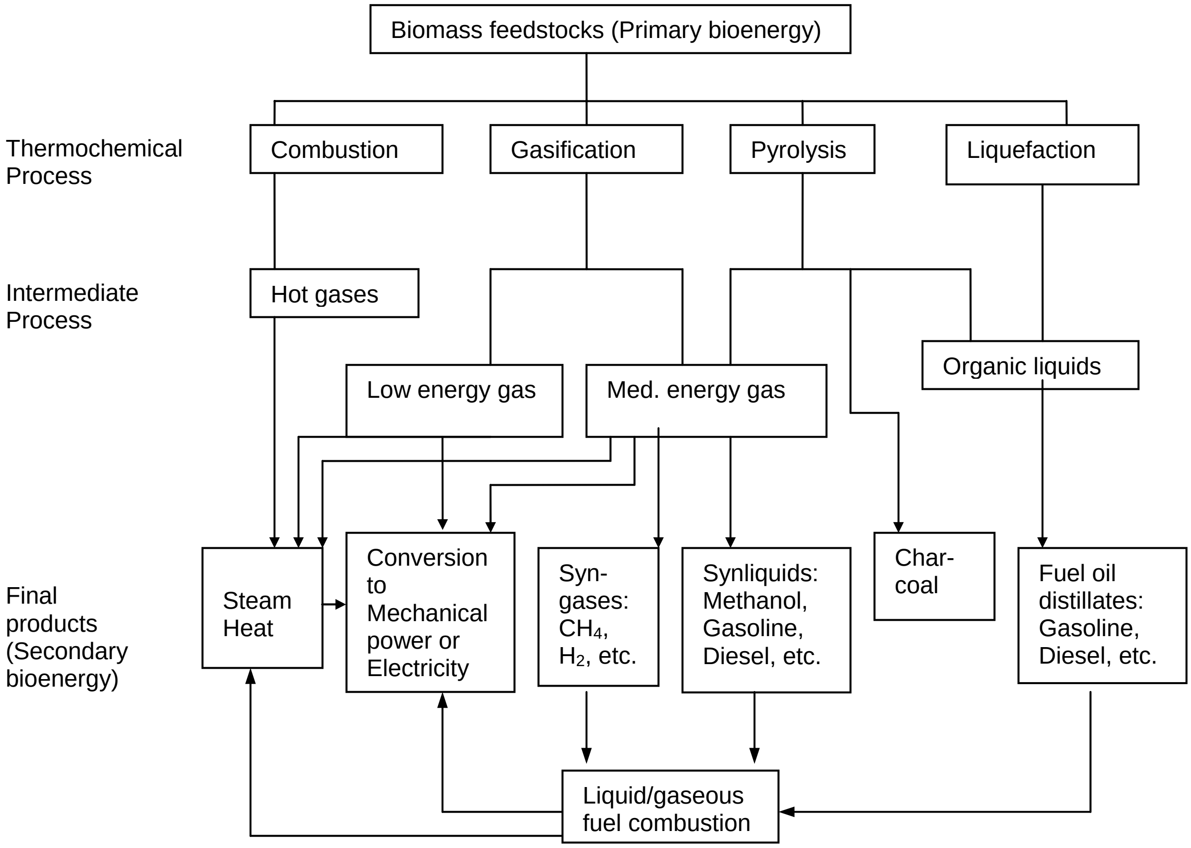

Figure 4.2. Main processes, intermediate energy carriers and final energy products from thermo-chemical conversion of biomass. Links from syngases, synliquids, charcoal and fuel oil distillates to gasification and from charcoal to combustion are not shown (modified from McKendry 2002b).

Basically all thermochemical conversion routes are based on the same oxidation process converting carbon in the fuel into carbon dioxide, hydrogen into water, sulfur into sulfur oxides and nitrogen into nitrogen oxides. Combustion is a direct oxidation process while the other three are indirect processes including intermediate energy products. Some of them can be stored, transported and used elsewhere as secondary biofuels.

Combustion of solid biomass like wood can be used for direct heating purposes in all size classes, from single family homes to large centralized heating systems. For heating-only use it is the simplest and cheapest technology. For power production it can be used in principle in all size classes, but commercial technology starts from about 50 kWe. Gasification can be used both for heating and for power production starting from as small as 1 kWe, i.e. even in single-family homes, and it is also used in the highest efficiency solid fuel power plants of hundreds of MWe size classes. Pyrolysis can be utilized in all size classes, but pyrolysis oil refining requires centralized technology. Liquefaction as well as synthetic fuel production via gasification are inherently centralized technologies, analogous to crude oil refining.

Combustion technology originates from Stone-age about 500,000 BC and it is still the simplest, most common and most versatile conversion process that is useful from small camping fires up to large centralized power plants. The reason why the other conversion routes are used is usually either demand for higher electric conversion efficiency (gasification), the ability to use on-site internal combustion engines that can not utilize solid biomass (gasification) or the ability to make liquid or gaseous secondary fuels (gasification, pyrolysis, liquefaction) for storage, transportation and use on-site or elsewhere, in all heat engines and all other fuel-to-mechanical power or fuel-to-electricity conversion processes. Also, solid secondary fuel, charcoal, can be made (pyrolysis/carbonization). Gasification, pyrolysis and liquefaction also enable fabrication of non-energy organic products such as plastics or any other products that are currently made from crude oil.

Combustion proceeds via drying phase followed by pyrolysis/gasification and the products are used completely to produce hot gases (800-1000°C), that are then used for e.g. direct heating purposes, as a source of process steam or for water heating in boiler for electricity generation.

Pyrolysis originates from Bronze-age, at least 2000 BC. It has been used for making charcoal (carbonization) at least since 1500 BC because it was required for fabricating iron, and possibly earlier for fabricating other metals. Pyrolysis oil has been made since about 2000 BC, with non-energy embalming oil (methanol etc.) in Egypt as the first known application.

Pyrolysis is thermal degradation in the absence of an external oxidation agent. Pyrolysis products are mainly tar and charcoal, but also some low molecular weight gases are produced. The process can be optimized either for char or tar (pyrolysis oil, bio-oil, bio-crude) production. The products can be combusted directly or upgraded into storable secondary fuels. Pyrolysis oil can be refined similarly with crude oil into various products. Up to 70% of solid biomass energy content can be converted into pyrolysis oil, the rest going into charcoal and gases.

Gasification has been used since 1680's for making town gas. Gasification is thermal degradation in the presence of an external oxidizing agent. The biomass is converted into a combustible gas mixture, which contains CO, CO_2, H_2O, H_2, CH_4 and other hydrocarbons. The gas can be burnt directly, used as a fuel for gas engines and gas turbines, or it can be used as synthesis gas ($CO + H_2$) input for the Fischer-Tropsch (FT) process, a catalytic polymerization process used since 1920's for producing liquid fuels like methanol and syndiesel. Also, H_2 can be separated from the synthesis gas and used in fuel cells.

Liquefaction, first used in the Bergius process, has been used since 1920's for converting biomass under high pressure into partly oxygenated liquid hydrocarbons. In the Bergius process biomass is converted into a stable liquid hydrocarbon using high hydrogen pressure. It corresponds to hydrogen cracking process in crude oil refining. Also steam and water cracking can be used in liquefaction. Compared to pyrolysis, liquefaction has a higher liquid yield and the liquid has higher calorific value and lower oxygen content (van Loo and Koppejan 2002), giving higher stability for the products.

For heating-only use combustion is usually the technology of choice. For power production and combined heat and power production gasification usually offers the highest efficiency and power-to-heat ratio, especially in medium and large units. In the smallest unit sizes combustion with Stirling engines has a potential for higher efficiency and simpler units than gasification, but this technology has not yet been commercialized fro solid biomass. For liquid and gaseous fuel production gasification with FT process is the most used technology (currently usually with fossil fuels), both historically and currently, but gasification with H_2 removal, pyrolysis and direct liquefaction have been used for a long time and do offer great promises in the future.

Microbiological biomass conversion

Microbiological conversion means a process where micro-organisms produce useful biofuels out of long-chain primary biomass. Two such processes are widely used, and have been used for millennia: anaerobic digestion (acid fermentation) and alcohol fermentation. Their conversion routes for energy products are shown in Fig. 4.3. Both processes are possible from single-family houses up to large centralized production units.

Both of these methods are selective on the biomass feedstock. Anaerobic digestion can not utilize wood or other substances with high lignin content. It suits best with putrescible biowaste, like municipal, industrial and agricultural waste, kitchen waste and food industry waste. It is utilizable also with most field crops and agricultural residues. Anaerobic digestion produces biogas, which consists mostly of methane, a useful fuel product, and carbon dioxide, a side product. The process is based on the activity of anaerobic bacteria. Alternatively, digestion can by used to produce hydrogen instead of methane, but this is not yet commercial technology.

Alcohol fermentation utilizes usually high sugar containing crops like sugar cane and sugar beet, or starch crops like barley and maize but also many other plants, including wood. Alcohol fermentation is an anaerobic biological conversion with ethanol as the final product. Fermenting organisms are usually yeast but can also be bacteria. In case of wood, acid or enzymatic hydrolysis must precede fermentation.

There are also several other microbiological biomass conversion processes, that are not yet commercially available. Anaerobic digestion (dark fermentation) for direct H_2 production was already mentioned. Photolysis means conversion of sugars into H_2 and CO_2 using solar rays and bacteria (light fermentation). Microbial fuel cells (MFC) are devices that convert wastewater directly into electricity. All of these methods are being studied in laboratory scale.

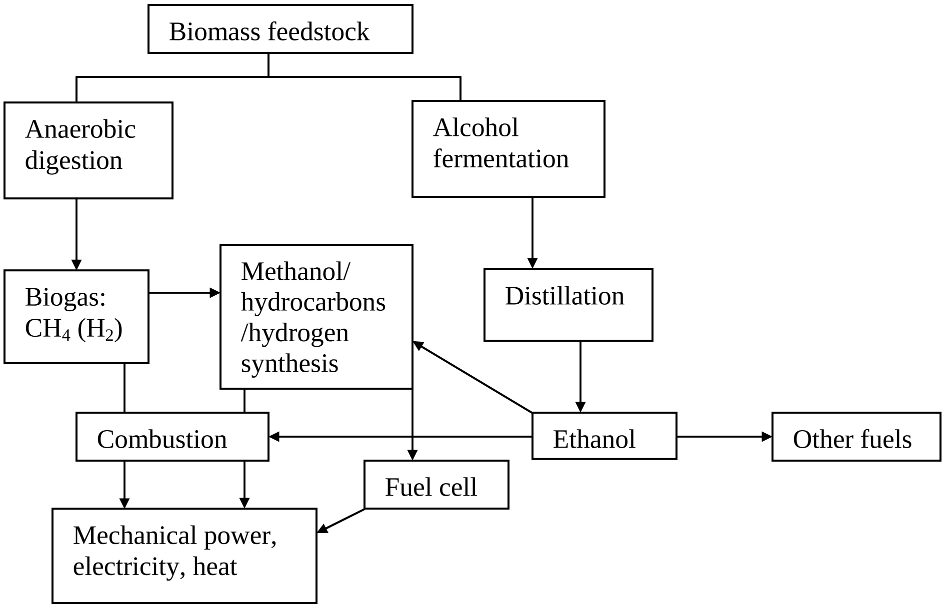

Figure 4.3. Microbiological conversion routes for anaerobic digestion and alcohol fermentation.

Mechanical biomass conversion

Both solid and liquid biofuels can be made by mechanical conversion. The most common methods are chipping and compression for higher energy density and/or better fuel to air mixing, i.e. better efficiency, in combustion.

Mechanical extraction is used to produce oil from oil plants. The extracted oil can be used as such, as pure plant oil, or it can be further upgraded by chemical conversion esterification into biodiesel. In addition to oil crops also tall oil from pulp industry and used cooking oil from restaurants and homes can be used as feedstock for biodiesel.

4.2 Biomass combustion

Solid biomass combustion

Combustion means burning the fuel in excess air to produce heat. The process includes heating and drying of the biomass, distillation of volatile gases, combustion of the gases and combustion of the residual material in the form of a carbon char. The simplest form of biomass combustion open fire is still widely used. Biomass combustion is well established technology and widely used in scale varying from 1 kW_{th} stoves to 600 MW_{th} power stations. Biomass combustion is still mostly used to produce directly usable heat in small scale, but various industrial scale heat, power or combined heat and power production units are important in many countries. In the following the combustion systems of nominal thermal power capacity exceeding 100 kW are presented. Smaller scale technology is presented in the chapter describing heat generation by combustion.

Biomass combustion plants can be fixed bed, fluidized bed or pulverized. Fluidized bed combustion plants are of special interest for medium and large-scale applications (normally exceeding 30 MW_{th}). For smaller plants, fixed bed systems are usually more cost-effective (van Loo and Koppejan 2002). For pulverizable fuels (coal, peat, charcoal, some agricultural residues) pulverized combustion offers the most cost-effective and highest efficiency power production technology.

Fixed bed combustion

There are various alternatives for fixed bed combustion, e.g. travelling grate, fixed grate, moving grate, vibrating grate, underfeed rotating grate and underfeed stoker. Grate combustion is most suitable for smaller scale, below 20 MW_{th}. In fixed bed combustion primary air passes through a fixed bed, where drying, gasification, and charcoal combustion take place. The combustible gases are burned in a separate combustion zone using secondary air.

Grate furnaces are appropriate for burning biomass fuels with high moisture and ash content, in different particle sizes. Wood fuels are easiest, while straw, cereals, and grasses are more difficult due to their low ash melting point. Thus, wood fuel boilers can be a little simpler and their efficiencies a little higher.

The design and control of the grate are aimed at guaranteeing smooth transportation and even distribution of the fuel and a homogeneous primary air supply over the whole grate surface. Irregular air supply may cause slagging, and higher amounts of fly ash, and may increase the oxygen needed for complete combustion.

Underfeed stokers represent a cheap and safe technology for small-scale systems up to about 6 MW_{th}. The fuel is fed into the combustion chamber by screw conveyors from below and is transported upwards on a grate. Underfeed stokers are suitable for biomass fuels with low ash content (wood chips, sawdust, pellets) and small particle sizes (up to 50 mm). Underfeed stokers have a good partial load behaviour and simple load control. Load changes can be achieved more easily and quickly than in grate furnaces because there is better control of the fuel supply.

Fluidized bed combustion

Fluidized bed combustion has widened the range of biomasses and wastes to be used in power and heat generation. In a fluidized bed boiler, fuel is burned in a self-mixing suspension of gas and solid bed material (usually silica sand and dolomite). The amount of bed material is much larger than the amount of fuel in order to stabilize the combustion process even when very heterogeneous fuels are used. The air for combustion enters from below. There exist two main types of fluidized bed combustion: bubbling fluidized bed and circulating fluidized bed (Alakangas and Flyktman 2001).

In bubbling fluidized bed (BFB, ABFB, PBFB) the fluidizing air is blown at a lower velocity and the bed particles bubble, but stay in the bed. In circulating fluidized bed (CFB, ACFB, PCFB), the air velocity is high and large part of the bed material leaves the bed and is circulated via cyclone separators back to the bed. The difference in utilization lies in the choice of fuel. BFB is cheaper and simpler technology and it is suitable for low-grade fuels containing highly volatile substances. CFB can be competitive also in smaller scale and it is used with less reactive fuels, or fuels containing sulphur. For reactive fuels like wood, peat, or wood waste, both types can be used (Alakangas and Flyktman 2001). Both combustion process types can be pressurized or performed in atmospheric pressure.

In fluidised bed combustion, intense heat transfer and mixing provide good side conditions for complete and efficient combustion with low excess air demand. Ash sintering in the bed can be prevented by maintaining low combustion temperature with the help of internal heat exchanger surfaces, flue gas re-circulation, or water injection. Low NO_x emissions can be achieved by good air-staging, good mixing, and a low requirement for excess air. Also, sulphur removal works well due to the good mixing behaviour. The advantages of the fluidised bed combustion are according to Alakangas and Flyktman (2001):

1) Stable combustion in spite of wide variations in the particle size, moisture content, ash content and heating value of the fuel
2) Possibility of using low volatile fuels with high ash content
3) Possibility of firing different fuels simultaneously with one combustion equipment
4) Rapidity of load changes
5) Possibility of efficient control of SO_2 and NO_x emissions without expensive equipment

Main disadvantage is lower conversion efficiency than achievable with pulverized fuel combustion and gasification. Another disadvantage is the high dust loads taken in with the flue gas, which make efficient dust precipitators and boiler cleaning systems necessary. Bed material is also lost with the ash, making it necessary to periodically add new bed material.

Pulverized fuel combustion

Pulverized fuel (dust) combustion is suitable for fuels like coal, peat and charcoal, and to a lesser extend to sawdust and some agricultural residues. The fuel should be available as small and dry particles. The fuel is injected into the combustion chamber together with primary combustion air, which is used as primary air in the combustion. Combustion takes place while the fuel is in suspension. Secondary air addition leads to gas burnout. An auxiliary burner is used to start the furnace. It is shut down, when the temperature is high enough to start the biomass injection and combustion. Fuel gasification and charcoal combustion take place at the same time because of the small particle size. Therefore, quick load changes and efficient load control can be achieved. Since the fuel and air are well-mixed, only a small amount of excess air is required. This results in high combustion efficiencies. (van Loo and Koppejan 2002)

Table 4.1. Overview of advantages, disadvantages and fields of application of various solid biomass combustion technologies (modified from van Loo and Koppejan 2002).

Advantages	Disadvantages
Underfeed stokers • Low investment costs for plants <6 MW_{th} • Simple and good load control due to continuous fuel feeding • Low emissions at partial load operation due to good fuel dosing	• Suitable only for biofuels with low ash content and high ash-melting point (wood fuels) • Low flexibility in regard to particle size
Grate furnaces • Low investment costs for plants < 20 MW_{th} • Low operating costs • Low dust load in the flue gas • Less sensitive to slagging than fluidized bed furnaces • Suitable for energy crops and agricultural residues	• No mixing of wood fuels and herbaceous fuels possible • Efficient NOx reduction requires special technologies • High excess oxygen (5-8 Vol. %) decreases efficiency • Combustion conditions not as homogenous as in fluidized bed furnaces • Low emissions level at partial load operation is difficult to achieve
Pulverized fuel combustion • Low excess oxygen (4-6 Vol. %) increases efficiency • High NOx reduction by efficient air staging and mixing possible if cyclone or vortex burners are used • Very good load control and fast alternation of load possible	• Particle size of biofuels is limited (<10-20 mm) high wear out of the insulation brickwork if cyclone or vortex burners are used • As extra start-up burner is necessary
BFB furnaces • No moving parts in the hot combustion chamber • NOx reduction by air staging works well • High flexibility concerning moisture content and kind of biomass fuels used • Low excess oxygen (3-4 Vol. %) raises efficiency and decreases flue gas flow	• High investment costs, interesting only for plants > 20 MWth • High operating costs • Low flexibility with regard to particle size (< 80 mm) • High dust load in the flue gas • Operation at partial load requires special technology • Medium sensitivity concerning ash slagging • Loss of bed material with the ash • Medium erosion of heat exchanger tubes in the fluidized bed
CFB furnaces • No moving parts in the hot combustion chamber • NOx reduction by air staging works well • High flexibility concerning moisture content and kind of biomass used • Homogenous combustion conditions in the furnace if several fuel injectors are used • High specific heat transfer capacity due to high turbulence • Use of additives easy • Very low oxygen (1-2 Vol. %) raises efficiency and decreases flue gas flow	• High investment costs, interesting only for plants > 30 MW_{th} • High operating costs • Low flexibility with regard to particle size (< 40 mm) • High dust load in the flue gas • Partial load operation requires a second bed • Loss of bed material with the ash • High sensitivity concerning ash slagging • Medium erosion of heat exchanger tubes in the furnace

Advantages and disadvantages of various solid biomass combustion technologies are listed in Table 4.1. Gasification is treated in chapter 4.3.

Liquid and gaseous bioenergy combustion

Liquid and gaseous fuels are usually combusted directly in internal combustion engines or gas turbines, but in any other kind of heat engines are suitable as well. For direct heating use simple low cost burners are used. These technologies are available from a 100 W lamp to 1000 MW_e power plants.

Direct usable heat generation by combustion

Industrial scale heat and steam generation

The main applications of industrial scale heat generation are district heating systems, central heating of large buildings and process steam generation. In addition to space and water heating the produced heat can be used for cooling, drying, humidity control and water purification. For cooling also district cooling systems are in use. Combustion technology is usually fixed bed combustion, although fluidised bed and gasification technologies are occasionally used.

*Small scale (domestic) heat generation by combusti*on

Traditional domestic wood burning is common in developing countries, but also in some industrial countries. Wood burning can be performed via modern technologies with 90% efficiency, or it can simply be a fireplace, where the thermal efficiency is very low, under 10%. Heat can be distributed by central heating systems. Heat can be used for space and domestic hot water heating, cooking, cooling and drying.

Three stone open fire is maybe the simplest form of biomass combustion to produce heat for cooking. Cooking takes place over an open fire with the cooking vessel supported by three stones. Commonly used fuels are firewood and crop residues but also sun dried dung. (Dutt and Ravidranath 1993)

Traditional stoves have various types. Typically they are made of mud and burn fuelwood, crop residues or dung. Efficiency is only slightly better than in the three stone open fire and they also lack chimneys releasing the smoke into the kitchen. (Dutt and Ravidranath 1993)

Improved fuelwood stoves, used also in industrial countries, can be classified into four different groups: up-draught, downdraught, cross-draught and S-draught. The classification is based on the airflow path through the combustion chamber. Stoves radiate or convect the heat to surroundings. Sometimes wood-stoves are equipped with catalytic combustor. Catalytic combustor reduces incomplete combustion since it reduces the combustion ignition temperature. (Loo and Koppejan 2002)

Fireplace inserts mainly transfer heat by convection. Inserts are more efficient than open fireplaces. Heat storing stoves are constructed from a material that can store the heat and slowly release it to the surroundings. E.g. soapstone is typical material for heat storing stove. Heat storing stoves can also be of heat accumulating type.

Wood log boilers can be simple over fire boilers, where the fuel combustion takes place in the whole fuel batch at the same time. The boiler uses natural draught. The boiler can be connected to a water storage tank and an electrical heater can be placed in the storage tank to give more flexibility in choosing the heating method. Hot water is produced by a heat exchanger in the storage tank. The wood boiler can also be of under-fire or downdraught design. Besides wood logs, the boiler can use wood chips, briquettes, sod peat and peat briquettes as fuel.

Wood pellet burners can replace an oil burner in an existing boiler. The fuel is automatically fed into the burner. There are underfed, horizontally fed and overfed burners. Pellets are of defined quality and size, which eases the use and design of the boiler. There are also special kinds of pellet stoves (pellets cannot be burned in wood log stoves).

Wood chip appliances can also be used in domestic heating. Wood chips enable automatic operation and lower emissions than more conventional wood log burning. However, making and storing and sometimes drying the chips require more machinery investments and storage space. Typical appliances include pre-ovens, under-fire boilers and stoker burners.

Power generation by combustion

Power generation by combustion can be realized either by closed thermal cycles or by open processes. In closed cycles, the combustion and the power generation processes are separated using a heat exchanger. In an open cycle internal combustion engines or gas turbines are used. Open cycles are not currently commercially used for biomass combustion due to problems in the separation of particles and metals from flue gases. (van Loo and Koppejan 2002)

Typical closed processes and engine types (external combustion engines (ECE)/external combustion turbines) for solid bioenergy combustion are steam turbines, steam engines, Stirling engines and closed gas turbines (Table 4.2. and Table A3). For power production through solid biomass combustion, steam turbines and steam piston engines are available as proven technology. Several other technologies than heat engines are under development or in pilot and demonstration stage.

Power generation options for liquid and gaseous fuel combustion include all technologies in Table 4.2 and also several other technologies as presented in Table 4.3 and Table A3.

Steam turbines are suitable for applications in a wide size range from 0.5 MW_e to 1500 MW_e. Currently the largest biomass application is 240 MW_e/560 MW_{th} (Fig. 4.4). The technology is suitable for thermal power generation as well as for CHP plants. The basic steam cycle is based on the closed Rankine cycle. The heat generated in combustion process is used to produce high pressure (100 – 300 bar) steam in a boiler and a superheater. The steam is superheated in order to increase efficiency and to achieve dry steam. Then the steam is expanded through an expansion engine, i.e. turbine, and it delivers mechanical power to drive a generator. In conventional steam cycles, water is used as the working medium.

For large steam turbine plants, water tube boilers and superheaters can be used to enable high steam parameters and the use of multi-stage turbines. Process measures like feed water preheating and intermediate tapping can be implemented for efficiency improvement. This results in electricity efficiencies of around 25% in plants of 5 to 10 MW$_e$. In plants around 50 MW$_e$ and larger, up to more than 30% is possible in cogeneration mode and up to more than 40% if operated as condensing plant. In partial load the efficiency decreases.

For small-scale steam turbines only single expansion stage or few expansion stages can be used. The operation occurs at quite low steam parameters as a result of the application of firetube boilers. Plants smaller than 1 MW$_e$ are usually operated as backpressure CHP plants and electricity net efficiencies are typically 10% to 12%. The backpressure heat can be used as process heat. Partial load decreased the efficiency considerably.

Table 4.2. Power production by solid biomass combustion without gasification or liquefaction.

Technology	**Engine type**	**Size**	**Status**
Heat engine; working medium water/liquid and steam/vapour (with phase change)	• Steam turbine	100 kW$_e$ – 1500 MW$_e$	Proven technology
	• Steam piston engine	10 kW$_e$ – 1 MW$_e$	Proven technology
	• Steam screw engine	10 kW$_e$ – 1 MW$_e$	Development
	• ORC and other vapour turbines (VT)	50 kW$_e$ – 10 MW$_e$	Some commercial plants with biomass
Heat engine; working medium gas (without phase change)	• Hot air turbine (closed gas turbine)	100 kW$_e$ – 10 MW$_e$	Development, some commercial plants with biomass
	• Stirling engine	50 W$_e$ – 500 kW$_e$	Development and pilot
Magnetohydrodynamic energy conversion (MHD)		50 MW$_e$ – 1000 MW$_e$	Development
Thermoelectric effect		50 W$_e$ – 1 MW$_e$	Development and pilot
Electron thermotunneling effect		100 W$_e$ – 1 MW$_e$	Development
Thermal photovoltaic effect (TPV)		50 W$_e$ – 1000 MW$_e$	Development
Direct chemical conversion/muscle power	• Human muscle • Animal muscle	10 W$_m$ – 10 kW$_m$	Proven technology
Combined cycle (heat engines)	• μT + ST/VT • GT + ST/VT • Diesel + ST/VT	500 kW$_e$ – 1500 MW$_e$	Proven technology
Combined cycle (heat engines and fuel cells)	• FC + ST/VT • Other	500 kW$_e$ – 100 MW$_e$	Development

In the range 50 kW_e to 2 MW_e, Organic Rankine Cycle (ORC) turbines are also available and their main market is geothermal power plants. The main difference is that a thermal oil boiler is used instead of a steam boiler. Thus the working medium is not water but organic oil. This enables operation at lower temperatures and pressures (down to a few bars), due to lower boiling temperature. Efficiencies can be better than at the same size steam cycles (up to 20% when optimized). A few plants are in operation with biomass combustion, e.g. in Switzerland and Austria.

Table 4.3. Power production by liquid and gaseous bioenergy combustion and solid bioenergy combustion with integrated gasification or liquefaction.

Technology	**Engine type**	**Size**	**Status**
Heat engine, closed cycle (external combustion), working medium water/liquid and steam/vapour (with phase change)	• Steam turbine (ST)	100 kW_e – 1500 MW_e	Proven technology
	• Steam piston engine	50 kW_e – 1 MW_e	Proven technology
	• Steam screw engine	10 kW_e – 1 MW_e	Development
	• ORC and other vapour turbines	50 kW_e – 2 MW_e	Development
Heat engine, closed cycle (external combustion), working medium gas (without phase change)	• Hot air turbine (closed gas turbine)	100 kW_e – 500 MW_e	Development
	• Stirling engine	50 W_e – 500 kW_e	Commercial
Heat engine, open cycle, internal combustion engines	• Otto engine	100 W_e – 10 MW_e	Proven technology
	• Diesel engine	1 kW_e – 50 MW_e	Proven technology
	• Wankel engine	1 kW_e – 500 kW_e	Proven technology
Heat engine, open cycle, internal combustion turbines	• Gas turbine (GT)	500 kW_e – 500 MW_e	Proven technology
	• Microturbine (μT)	10 kW_e – 500 kW_e	Proven technology
Magnetohydrodynamic energy conversion (MHD)		50 MW_e – 1000 MW_e	Development
Thermoelectric effect	• Several types	50 W_e – 1 MW_e	Development and pilot
Electron thermotunneling effect		100 W_e – 1 MW_e	Development
Thermal photovoltaic effect (TPV)		50 W_e – 1000 MW_e	Development
Direct chemical conversion/muscle power	• Human muscle • Animal muscle	10 W_m – 10 kW_m	Proven technology
Direct chemical conversion/fuel cells (FC)	• Several types	10 W_e – 10 MW_e	Some are proven, some in development
Combined cycle (heat engines)	• μT + ST/VT • GT + ST/VT • Diesel + ST/VT	500 kW_e – 1500 MW_e	Proven technology
Combined cycle (heat engines and fuel cells)	• FC + ST/VT • Other	500 kW_e – 100 MW_e	Development

ORC is one type of a vapour turbine where, in addition to organic working medium, inorganic mediums, like ammonium, can also be used.

Steam piston engines are available in the power range 50 kW_e to 1 MW_e. They can be used in small plants where steam turbines are not available or in medium scale as an alternative to steam turbines. The advantage of steam engine in comparison to steam turbine is that they are less sensitive to water droplets in the outlet, or contaminants in the steam, and that they can be operated with low-pressure, saturated steam (but this reduces efficiency). Steam piston engines enable efficiencies of 6% to 10% in single-stage and 12% to 20% in multi-stage mode. The efficiency is almost independent of the partial load. A disadvantage is the need for oil injection into the steam for lubrication before it enters the engine and there is a possibility for oil traces in the expanded steam (oil free engines are under development). Steam piston engines are also often noisy and they produce heavy vibrations.

Steam screw engines are a promising new technology for small-scale power generation, but they are not yet commercially available.

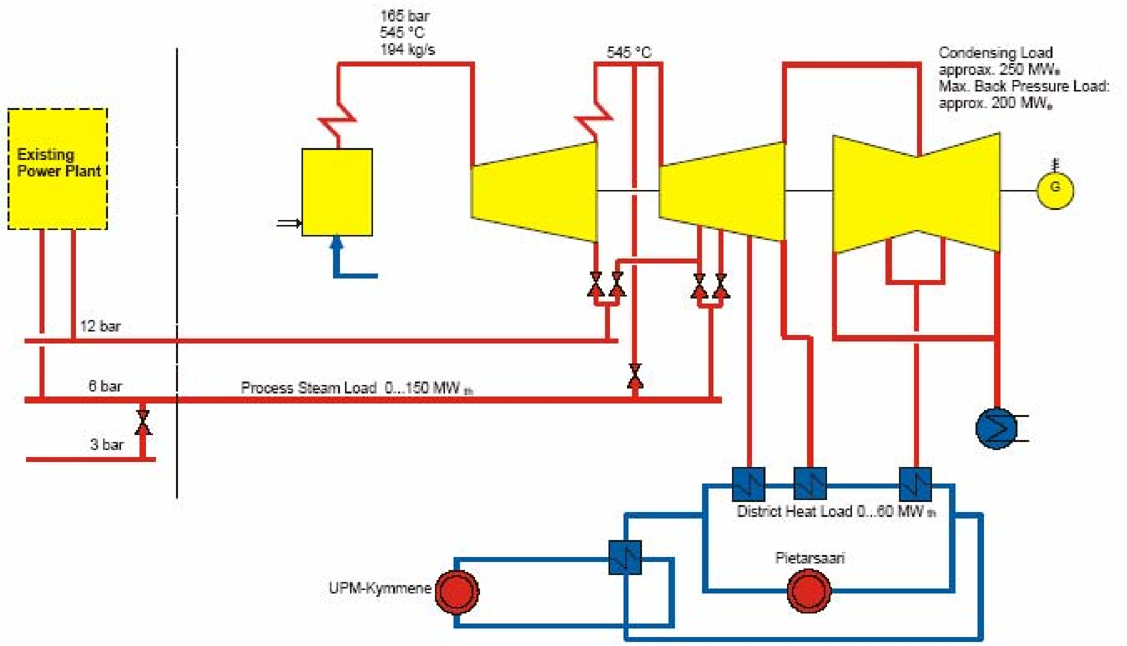

Figure 4.4. Flow sheet of currently the largest bioenergy CHP plant in the world, Alholmens Kraft in Pietarsaari, Finland with 240 MW_e capacity.

Stirling engine is an external combustion piston engine. It was used in many industries during 19th and early 20th centuries and recently the interest to develop this technology has increased again for environmental reasons. It is very promising technology for efficient micro-scale power production and CHP production. The Stirling cycle is a thermodynamically ideal process for transforming heat to mechanical energy and it can offer higher efficiencies than more conventional internal combustion engines in small sizes (30-45% compared to 20-30%, Walter et al. 2000). They are used commercially in submarine (48% efficiency in 250 kW_m size) and boat engines powered by oil, and gas powered units are used in micro-power applications.

In Stirling engine, the cylinder is closed and the combustion takes place outside of the cylinder. The cylinder is heated by external combustion. This expands the working fluid, which moves the piston in the cylinder consequently. For biomass use air, nitrogen or helium are used as the working fluid. Various fuels are suitable due to the external combustion, but with solid biomass combustion the electrical efficiencies can be as low as 15%, although pellet fuelled prototypes have been built with 23% efficiency in 1 kW_e size. It is also possible to integrate Stirling engine with biomass gasifier or use it in the last stage of combined cycle plant. It can also be powered by waste heat or direct solar energy. Units from 3 to 150 kW_e have been developed for biomass use. (Walter et al. 2000)

4.3 Biomass gasification

Gasification technologies

The process of gasification to produce combustibles from coal and biomass fuels was already used in the 17th century. Gasification is a form of pyrolysis, but it is carried out with more air and higher temperatures, to optimize the gas production. The gas is called producer gas and it contains carbon monoxide, hydrogen and methane. The gas can be burnt to produce process heat or steam, or used in internal combustion engines or gas turbines to produce electricity. The gas can also be used in synthesis operations to produce e.g. methanol or syndiesel. (Sims 2002, Walter et al. 2000)

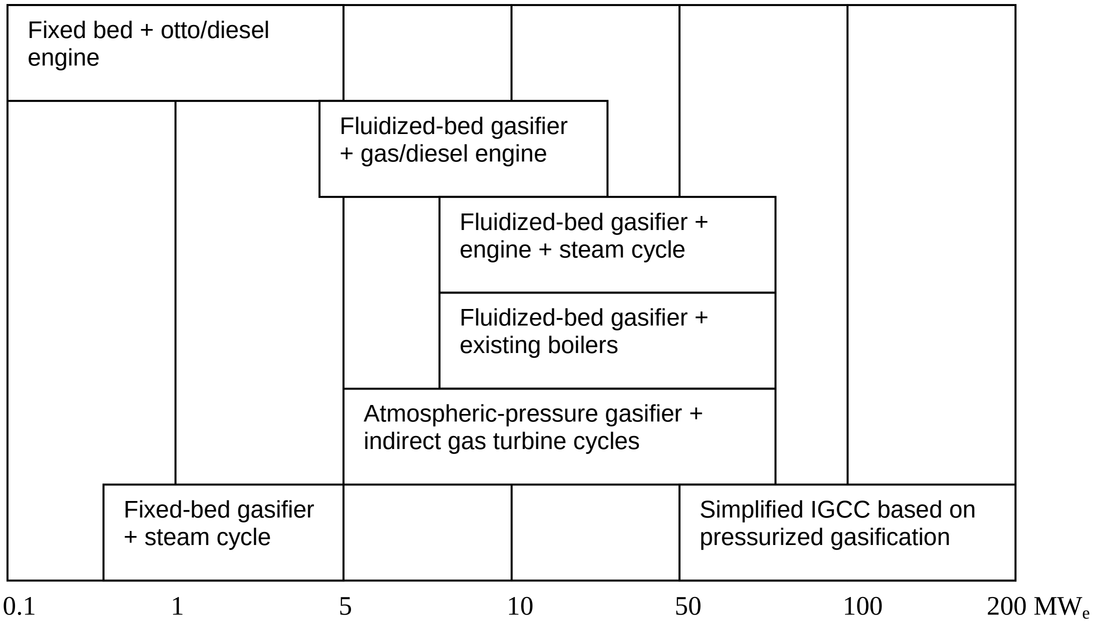

Figure 4.5. Some gasification technologies for solid biomass suitable for use in power plants from 100 kW_e to 200 MW_e (Alakangas and Flyktman 2001).

There is a wide range of commercially available technologies from 1 kW_e to 500 MW_e sizes, of which 1 kW_e – 100 kW_e are currently the most common for bioenergy use. Large-scale bioenergy applications are currently quite rare but they are under intense research and demonstration activity. The largest gasification plants at the moment are coal powered IGCC plants. Some gasification technologies from 100 kW_e to 200 MW_e are shown in Fig. 4.5. For smaller sizes from 1 kW_e to 100 kW_e fixed bed gasifiers are used combined with Otto, Diesel or Stirling engines or micro-turbines. For plants larger than 200 MW_e ST-GT combined cycle is used. Various fuels are suitable for gasification. These include wood, charcoal, coconut shells, rice husks and bagasse.

Two main variables, gasifier medium and pressure, affect the power system performance. Air-blown gasifiers (directly heated gasifiers) use exothermic reaction between oxygen and organics to produce the necessary heat to devolatilise biomass and to convert residual chars. The resulting product gas is diluted with nitrogen, and it typically has a low calorific value around 5-6 MJ/Nm^3. The calorific value can be improved by utilizing oxygen instead of air. Calorific values in oxygen are typically around 15 MJ/Nm^3. However, the production of oxygen is expensive and oxygen is used in gasification typically only when the gas is used for synthesis operations. On the other had, oxygen use minimizes NO_x emissions. The gasification can also be indirectly heated. Air is not introduced into the gasifier and biomass is heated and gasified through heat transfer from a hot solid or through a heat transfer surface. Calorific values are typically 18-20 MJ/Nm^3. (Walter et al. 2000)

Pressure is important especially for the performance of gasification-based power systems with gas turbines. Pressurized gasifiers produce the gas in suitable pressure for the turbine, and the overall efficiency of the process is improved (Walter et al. 2000). Pressurized oxygen gasifiers offer the highest efficiency but also pose great demands for materials. They are not yet commercially available.

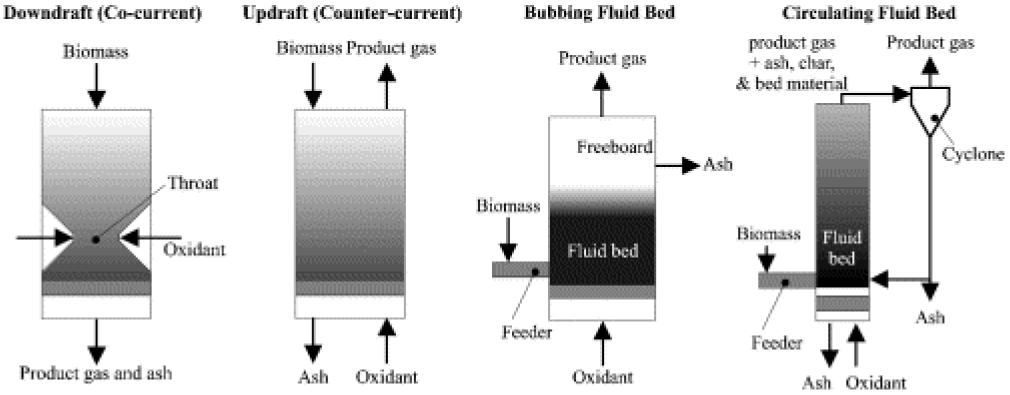

Figure 4.6. Most common gasifier configurations (Bridgwater et al. 2002).

Gasifiers can be either fixed bed, fluidized bed or entrained flow reactors. In Fig. 4.6 main configurations of fixed bed and fluidized bed gasifiers are shown. There are two basic types of fixed bed gasifiers: updraft gasifier and downdraft gasifier. Both are based on fuel descending caused by gravity. Fluidized bed gasifiers can be either of bubbling or circulating design.

In an updraft gasifier the air flows counter-currently against the fuel. The fuel is fed to the top of the gasifier, and it flows down through drying, pyrolysis, gasification and combustion zones. The product gas contains an abundance of oils and tars and the gas temperature is low, typically 80-100 °C. Bottom ash does not usually contain significant amounts of unburnt carbon. Dust content of the product gas is usually low. (OPET 2002)

Fixed bed updraft gasification is a commercially available combustion method in small district heating plants. The typical thermal output ranges from 20 kW to 1 MW (Sims 2002).

Downdraft gasifiers were used in cars and busses in Europe during the 2nd World War. The advantage of downdraft gasifiers compared to updraft gasifiers is the fact that the pyrolysis products have to flow co-currently through the hot combustion and gasification zones. Most of the tars are oxidized and the product gas can be used in an internal combustion engine. Gas temperature is typically around 700°C. This technology is not yet commercially available in larger scale applications. (OPET 2002)

Both the updraft and downdraft gasifiers require a fairly uniform particle size distribution in the feed. The feed needs to have a low ash content and high fusion temperature to prevent slagging and the moisture content should not exceed 20% in order to maintain the high temperatures needed for tar cracking. (Walter et al. 2000)

Bubbling fluidized-bed gasification is based on a constantly moving bed of sand particles that are kept in motion by air, steam or oxygen flow. A rather small feed particle size is required. There are few commercial applications. The technology is most suitable for medium size applications: 2-50 MW (Sims 2002).

Fluidized bed gasifiers have good mixing and high heat transfer. Gasification is efficient; 95-99 % carbon conversion is typical.

There are a few circulating fluidized bed gasifiers in operation in Finland and Sweden. The gas flow is increased compared to bubbling fluidized bed, thus the gas bubbles become larger and form large voids in the bed entraining solids. The turbulent bed solids are collected, separated from the gas and returned to the bed forming a circulation loop (Walter et al. 2000). This technology is suitable for larger scale: 10-120 MW (Sims 2002).

In the 1980’s a limekiln gasifier was developed and taken into use at a few paper mills. The gasifier produces limekiln fuel from bark and waste wood. The system consists of a refractory-lined reactor, where the gasification takes place, of a uniflow cyclone to separate the circulating material from the gas and of a return leg for returning the circulating material into the bottom part of the gasifier. Biomass must be dried in a special dryer before use. Another concept for circulating fluidized bed gasifier without drying is REF and biofuel utilizing facility (Kymijärvi power plant in Lahti, Fig. 4.7). Corrosion and fouling problems in boiler restrict the use of chlorine, alkali metals or aluminium containing fuels. (OPET 2002)

Entrained-flow gasification reactors do not yet exist for biomass use although tests have been made. The feed needs to have very small particle size and low moisture content and it is expensive to prepare biomass for that. The advantage of these reactors is the high temperature (1300-1400 °C), which destroys the oils and tars almost completely. (Walter et al. 2000)

Characteristics of gasifier product gas and the level of contaminants vary depending on feedstock, reactor type and operating parameters. Typical values are shown in Table 4.4. The contaminants are formed due to incomplete gasification of char and the pyrolysis tars, and typically the product gas contains some amounts of particulates, tars, alkali metals, fuel-bound nitrogen compounds and an ash residue containing some char.

Table 4.4. Gasifier product gas characteristics (Bridgwater et al. 2002).

Gasifier type	**Gas composition, %v/v dry**					**HHV, MJ/Nm^3**	**Gas quality**	
	H_2	**CO**	**CO_2**	**CH_4**	**N_2**		**Tars**	**Dust**
Fluid bed air-blown	9	14	20	7	50	5.4	Fair	Poor
Updraft, air-blown	11	24	9	3	53	5.5	Poor	Good
Downdraft, air-blown	17	21	13	1	48	5.7	Good	Fair
Downdraft, oxygen blown	32	48	15	2	3	10.4	Good	Good

Gas turbines and engines

Biomass gasification allows power production with the use of gas turbines or engines.

Standard industrial gas turbines operate on Brayton cycle and they come in sizes from 500 kW_e to 500 MW_e. Aero-derivative gas turbines originate from the aviation industry: they are lightweight, have higher thermal efficiency and higher capital and maintenance costs than industrial gas turbines.

Microturbines are similar to gas turbines. The main difference is that in micro-turbines there is a recuperator to recover part of the exhaust heat for preheating the incoming air. This enhances the efficiency. A range of liquid and gaseous fuels like syngas, biogas and alcohols can be used. Heat from the exhaust gas can be recovered for heating or cooling in absorption chillers, which makes microturbines attractive for small-scale CHP production. Electrical efficiencies are low (25-30%), especially on partial load (20-25%). Micro-turbines are compact and lightweight and have low noise and vibration levels. (Sims 2002, Alanne and Saari 2003)

Several types of internal combustion engines are commercially available. The most typical are spark ignition (Otto cycle) and compression ignition (Diesel cycle) engines, but also Wankel cycle engines are in use. They are available over a wide size range; they have fast start-up, good partial load efficiency, reliability and long life. They are suitable for various gaseous and liquid fuels: syngas, biogas, bioethanol, pyrolysis oil, biodiesel etc. (Sims 2002)

Internal combustion engines integrated to a biomass gasifier is commercial technology for very small capacity plants.

Integrated biomass gasifier/gas turbine (BIG-GT) and combined cycle (BIGCC) systems

Biomass gasification can be integrated to gas turbine cycles. This is generally called BIG-GT technology. When energy from the exhaust gases is recovered and used in power production trough a bottoming steam cycle, the system is called BIG-CC (biomass integrated gasification combined cycle). This enhances significantly the efficiency of the system. It is mainly suitable for CHP production in a medium-size range (30-100 MW_e), but also mere electricity production is possible. This technology is based on fluidized bed gasification (either bubbling or circulating), followed by gas purification, and the combined gas and steam turbine cycle. The most critical technical question is the formation of contaminants like particulates, alkalis, tars and nitrogen containing compounds in the syngas, and their removal in an acceptable way. The BIGCC technology has been demonstrated in Värnämö, Sweden (Stål and Neergaard 1998).

Gasification technology offers an interesting possibility to enhance electrical efficiency in CHP production in pulp and paper industries (black liquor gasification) or in sugar-cane mills.

Examples

Biomass gasification offers significant possibilities in small-scale applications in circumstances where electricity is not easily available. It can be used to substitute petrol fuels in standard gasoline or diesel engines that are used for power production and water pumping or in local industries. The gas can also be used in standard heat appliances. (Stassen 1995)

Small scale downdraft reactors for gasification of rice husks have been in use in China and India since the 1960s (Sims 2002). The gas is used to run Diesel or Otto engines driving generators of around 1-200 kW_e. Biomass gasification is used in China for drying and heating, domestic cooking and power generation (Leung 2004).

4.4 Cofiring

One possibility to increase the share of renewable fuels is to co-combust them with fossil fuels like coal, oil and natural gas in fossil fuel power plants. Co-firing biomass with coal in coal-fired boilers utilizes efficiently the existing infrastructure, while at the same time reduces the use of fossil coal. In many countries co-firing is the most efficient way to reduce CO_2 emissions and the easiest way to enhance biomass use in power generation. Co-firing can be used in power plants as well as industrial steam boilers.

Co-firing with coal is easiest to achieve in fluidized bed and fixed bed combustion plants as well as in gasification plants. However, coal is most often burned in pulverized fuel combustion boilers, so basically only charcoal and dry sawdust can be added as such. Otherwise, biomass needs to be pre-treated, before it can be used in co-combustion. Also some changes in the boiler might be necessary, depending on the aimed fuel mix. Co-firing can cause some problems: changes in boiler behaviour, slagging of biomass ashes and high temperature corrosion due to high chlorine content.

Following biomass utilization options are possible for pulverized coal fired power plant:

1) direct co-firing (pre-processed biomass is directly fed to the boiler)
2) indirect co-firing (after gasification of the biomass, the product fuel gas is fed to the boiler furnace); an example of indirect co-firing is shown in Fig. 4.7
3) parallel combustion (the combustion of the biomass in a separate boiler and the utilization of the steam produced within the power plant)

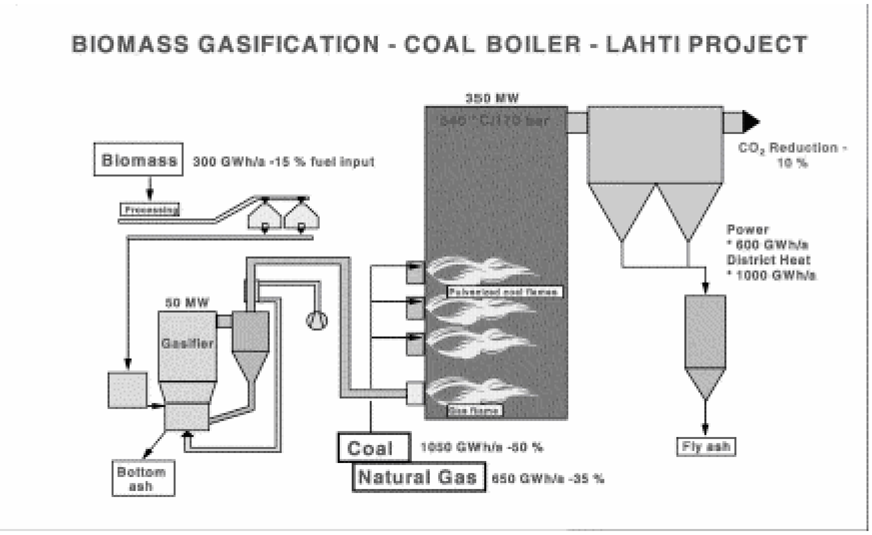

Figure 4.7. Waste biomass gasification followed by gas co-combustion with coal and natural gas in a 350 MW_{th} Lahti Kymijärvi power plant in Finland (Raskin et al. 2001).

4.5 Combined heat and power (CHP): co-generation, tri-generation and poly-generation

Co-generation, or combined heat and power production, means simultaneous production of heat and electricity. In thermal power production heat is always a side product. When the heat can be utilized, the overall efficiency of the process is greatly improved. Bioenergy CHP plants are commonly used e.g. in Finland, Sweden and the U.S. CHP is suitable for small scale and large scale production, although the small scale production systems are still mainly under development. (Sims 2002)

Maybe the most common way of utilizing CHP are large municipal and industrial plants producing electricity and district heat. An example is shown in Fig. 4.4. Heat can also be used in industrial processes, which is common e.g. in pulp industries and sugar production.

Co-generated heat can be used for cooling as well as heating. In cooling the heat is used to drive refrigeration cycles in an absorption or adsorption refrigeration process. The chill can be produced either at the site of cooling demand or at the CHP plant (then called tri-generation or MSP, multi supply plant), from where the chill is then distributed similarly to district heating systems. District cooling technology is utilized in several countries USA, France and Japan being the largest users, but it is used in many cities in Sweden as well. Another example of tri-generation are municipal and industrial plants producing electricity, district heat and industrial steam.

The co-generation process can use either topping or bottoming cycle. In topping cycle a boiler is used to produce steam, which is passed trough a turbine to produce electricity. Heat is derived from the residual lower-pressure steam. In bottoming cycle the residual heat is recovered first and then used to generate steam trough a boiler and finally the steam is used to generate electricity. Bottoming cycle is suitable when the initially produced heat is of high quality (temperature and pressure). Gas turbines can be used just as well as steam turbines if co-generation is practiced with gasification processes, or from biogas. (Sims 2002)

Poly-generation means that the same plant produces more than 3 usable energy or other products. An example is a plant producing electricity, industrial steam, district heat and district cooling, and possibly also liquid and gaseous traffic fuels. In addition, the same plant could clean water and produce CO_2 for fertilizing greenhouses as well as plastics and other organic materials originating from gasification connected with Fischer-Tropsch synthesis process. If waste is used as a feedstock then also recycled metals like aluminium can be produced. In case of biogas plants fertilizers are automatically produced as the solid digestion residue. An example of a polygeneration plant is shown in Fig. 5.2.

4.6 Emerging technologies for electricity production

Fuel cells

In fuel cells, electricity is generated trough a catalytic chemical reaction. Hydrogen is the energy carrier usually used. Hydrogen is combined with oxygen to produce water, thus no emissions are formed. Efficiencies of fuel cells can be very high (45-70%), since the Carnot efficiency does not limit the process. Fuel cells can use various sources for hydrogen generation e.g. biogas or syngas. With syngas utilization it is also possible to integrate biomass gasification with fuel cells. In addition to hydrogen, also other types of fuels, like methane, methanol and DME, can be used directly, but currently only hydrogen fuel cells are commercially available.

A fuel cell system consists of a fuel reformer, a power section and a power conditioner and inverter. The fuel reformer is used to generate hydrogen-rich gas from fuels like methanol, methane, gasoline and diesel oil. Fuel reformer is not needed when supplying hydrogen directly.

Fuel cells are modularly designed, which allows a wide variation of power ranges to be produced by combining several modules. In the future, fuel cells can be used e.g. in vehicles and in small and large power plants. There are several types of fuel cells, e.g. phosphoric acid fuel cell, proton-exchange membrane fuel cell, alkaline fuel cells, direct methanol fuels cells or solid oxide fuel cells. The type of the fuel cell determines the suitable fuel, operating temperature, the heat liberated during the process, and the cell's suitability for cogeneration applications. Characteristics of several FC types are shown in Table 4.5.

Table 4.5. Technical characteristics of several fuel cell types (Stanbouli and Traversa 2002).

Types	**Electrolyte**	**Operating T [°C]**	**Fuel**
Alkaline (AFC)	Potassium hydroxide	50-200	Pure hydrogen or hydrazine
Direct methanol (DMFC)	Polymer	60-200	Liquid methanol
Phosphoric acid (PAFC)	Phosphoric acid	160-210	Hydrogen from hydrocarbons and alcohol
Sulphuric acid (SAFC)	Sulphuric acid	80-90	Alcohol or impure hydrogen
Proton-exchange membrane (PEMFC)	Polymer, proton exchange membrane	50-80	Less pure hydrogen from hydrocarbons or methanol
Molten carbonate (MCFC)	Molten salt such as nitrate, sulphate, carbonates etc.	630-650	Hydrogen, carbon monoxide, natural gas, propane, marine diesel
Solid oxide (SOFC)	Stabilized zirconia and doped perovskite	600-1000	Natural gas or propane
Solid polymer (SPFC)	Solid sulphonate polystyrene	90	Hydrogen

Other

There are several other physical principles at our disposal to produce electricity out of fuels either directly or by first converting fuels into heat. Several of them are listed in Tables 4.2, 4.2 and A3. One of them is thermophotovoltaic effect reviewed by Coutts (1999). None of them are currently proven bioenergy technologies, but some, e.g. Peltier thermoelectric effect devices, are commercially used in other applications and are also available as pilot equipment for power production. Most of these technologies, just like fuel cells, are suitable for micro-scale power production, e.g. individual houses.

5 Secondary biofuels

Biomass can be upgraded to higher quality solid, liquid or gaseous fuels with specific properties. Many of these fuels and their production are presented in this chapter. Biofuel emissions in their use and also during their life cycle are much lower than fossil fuel emissions, if good practises are utilized in the conversion processes – otherwise conversions may lead to resource wasting and subsequently to higher emissions. Conversion efficiencies may vary from under 10% to over 90%. At the end of this chapter life cycle traffic fuel greenhouse gas emissions of several different fossil and biofuel cycles are compared showing vast potential benefits of biofuel use, and on the other hand great differences between biofuels. Of all the different biofuels waste based biogas has the potential for lowest greenhouse gas emissions. Thus, more space is reserved for it below than for other biofuels, although it does not belong to conventional biofuels.

5.1 Solid secondary biofuels

Mechanical conversion of biomass

Mechanical conversion of biomass has been practised since about 2,500,000 BC when our ancestors in Africa learned to use tools and biomass was used for heating and illumination since about 500,000 BC in Africa and China.

Woody biomasses can be pre-treated in order to obtain more homogenous fuels. Particle size reduction can take place by chunking (50-250 mm pieces), chipping (5-50 mm pieces), grinding (0-80 mm pieces) and baling. The energy needed for chipping is about 1-3% of the energy content of the wood fuel. There are various types of chippers in various sizes, e.g. disc chippers and drum chippers. Chippers can be stationary and located at end-user sites (e.g. sawmills) or they can be mobile and operated in forests. (van Loo and Koppejan 2002)

Pellets (6-8 mm) and briquettes (30-100 mm) are dense solid fuels made out of wood or agricultural wastes. They are high quality fuels suitable for systems where stabile fuel quality is essential. They usually enable low emissions. Transportation and storage costs can also be reduced, due to the density of the fuel.

Usually pellets and briquettes are produced in centralized, large factories, for example bagasse briquettes can be produced near sugar industries. The produced fuel can then be distributed to users. Also charcoal dust is suitable feedstock for briquettes. Commercial production of charcoal briquettes from waste biomass (sawdust, bagasse, coffee husk) is found e.g. in Kenya (UNDP 2002).

Pelletising process includes drying and milling of the biomass, conditioning by steam addition in order to improve adhesion, compression and cooling. In Sweden, sawdust pellets are used to substitute coal in large-scale power plants.

Briquettes are used instead of firewood in manually charged domestic stoves. Pellets can be burned in special furnaces designed for pellets, in pellet stoves, or in normal furnaces modified for pellet use. The whole heating system can be automated.

Charcoal production by thermochemical conversion (carbonization)

Charcoal production, i.e. carbonization technology, has been used at least since about 2000 BC. It was a prerequisite for the Iron-Age, since it was required for iron production. Presently charcoal is extensively used as a domestic fuel in developing countries. It is produced by carbonization, one form of pyrolysis (Table 5.1): heating wood with restricted airflow. Carbonization takes place in four main stages: first the wood or other solid biomass, including agricultural wastes, is dried, and then it is pre-carbonized in 170-300 °C, producing methanol and acetic acids and CO and CO_2 as by-products. At the third stage the temperature is increased up to 350 °C and light tars (i.e. pyrolysis oil) and pyroligneous acids also are released from the wood steadily. In the fourth stage the remaining volatile components of the charcoal are driven off, increasing the carbon content of the charcoal. The charcoal properties depend significantly on the carbonizing temperature, wood type, moisture content of the wood and its chemical composition. In addition to charcoal the process also produces some useful liquid and gaseous fuels. Both of them can be used for heating the carbonization process but the liquid fuels can also be stored and sold. They are discussed in the pyrolysis chapter below.

Charcoal can be produced in various types of kilns, with large differences in production efficiencies. Traditionally earth kilns are used. Basically this means stacking the wood on the ground and covering with soil. To start the carbonization process the kiln is light from the bottom. Traditional earth kilns are improved using e.g. metal and clay. Other, more advanced kiln types are metal kilns, brick kilns and masonry kilns. (Wereko-Bobby and Hagen 1996, Hollingdale et al 1999)

Charcoal can be combusted in all types of boilers, including pulverized fuel boilers, alone or co-fired with coal. It can also be used industrially: e.g. in Brazil charcoal is used in steal industry instead of coke as a reduction agent (Rosillo-Calle 2000). This practise reduces greenhouse gas emissions of steal industry dramatically if biomass is sustainably used.

5.2 Liquid and gaseous secondary biofuels

Liquid and gaseous biofuels can be used to completely replace petroleum and natural gas based transportation fuels – gasoline, diesel, natural gas (NG), liquefied petroleum gas (LPG) and jet kerosene - or they can be blended with fossil fuels. Some biofuels – e.g. biodiesel, syndiesel, syngasoline, syn-LPG, syn-kerosene and methane - can be used alone in existing fossil fuel road, rail or aviation vehicles without any modification to engines and fuelling systems. Many other biofuels – e.g. ethanol, methanol, ETBE, MTBE, hydrogen and pure plant oils - can be used in existing fossil fuel vehicles without any modification when they are blended with fossil fuels. And these and some other biofuels – e.g. DME, synthesis gas and specialized synfuels – can be used alone or blended in modified vehicles. Besides road, rail and aviation fuels, biofuels can be used similarly to crude oil or natural gas based fuels in different applications of heating and electricity production.

Liquid and gaseous biofuels are made by

- microbiological conversion: methane and hydrogen by digestion; ethanol by alcohol fermentation; hydrogen by metabolic processing
- mechanical conversion: pure plant oils by extraction
- chemical conversion: biodiesel by esterification; ETBE, MTBE, hydrogen, methane and methanol by reforming; pure plant oils by solvent extraction
- thermochemical conversion: synthesis gas, synfuels, DME, methanol, ethanol, methane and hydrogen by several processes
- electrochemical conversion: hydrogen

Currently large quantities of biofuels, especially so called conventional biofuels ethanol and biodiesel, are already used in many countries, e.g. Brazil (Moreira & Goldemberg 1999), USA and EU, and a potential exists to greatly expand their use in the future (IEA 2004). Ethanol is globally the most widely used liquid biofuel at the present. The estimated fuel ethanol production in 2004 was 16 Mtoe, of which Brazil had 43% share, USA had 36% share and also Central America was a large producer with over 2% share (www.distill.com). Costa Rica produced 2.5 PJ in 2002 but it is not used for energy purposes (DSE 2004), i.e. it is not fuel ethanol. If it were used as traffic fuel it would be enough to meet 5% of Costa Rican ground transport fuel needs.

In the EU biodiesel is currently the leading biofuel. The estimated global biodiesel production in 2004 was about 2 Mtoe, of which Germany has 50% share and France 25% share (www.ebb-eu.org). And both ethanol and biodiesel world markets are growing very fast.

Anaerobic digestion for biogas and landfill gas methane production

Anaerobic digestion (AD) is a microbiological conversion technology that has been used for biogas production originally for lighting for at least a thousand years, perhaps much longer, especially in China. It is used from household size up to municipal size systems in over 10 million reactors worldwide. Waste based biogas may enable the lowest lifecycle GHG emissions of all biofuels, even lower than wind and solar based hydrogen since conversion of methane into carbon dioxide, i.e. 20-60 times weaker GHG, may be gained as a side effect. It is also the most democratic fuel because it is available wherever people live (Fig. 5.1). And it does not compete with food production unlike many forms of bioenergy.

Biogas is produced by bacteria that ferment biodegradable matter into methane and carbon dioxide, in the absence of free oxygen, i.e. anaerobic conditions. Typical biogas contains 60-70 % of methane, 30-40% of carbon dioxide and smaller amounts of other gases. Anaerobic digestion is a natural process occurring for example in the bottom sediments of lakes and ponds, in swamps, peat bogs, intestines of ruminants, and even in hot springs. Anaerobic degradation can take place over a wide temperature range from 10°C to 120°C and at a variety of moisture contents from around 60% to more than 99%.

Proper circumstances for anaerobic digestion can be artificially created by placing fermenting bacteria and organic wastes into digesters (large enclosed tanks). The process is then optimized by maintaining suitable temperature, pH, moisture content and level of nutrients. The proportions of CH_4, CO_2 and other gases (most typically H_2S) depend on the feedstock material, the design and the size of the plant and temperature. The digestion process can be inhibited by toxic chemicals, antibiotics or even high ammonia or sulphur concentrations containing feedstocks. Usually mesophilic bacteria living in about 35 °C temperature, or thermophilic bacteria living in about 55 °C are used.

Anaerobic digestion is suitable for various feedstocks. It has traditionally been used for the treatment of sewage sludge and agricultural manures. More recent plants use municipal biowastes, industrial biowastes, industrial wastewaters, agricultural residues and energy crops. Type of the feedstock determines much of the methane production. Wood and woody wastes with high lignin content cannot be converted to methane at present technology. Co–digestion is the simultaneous digestion of a homogenous mixture of two or more feedstocks.

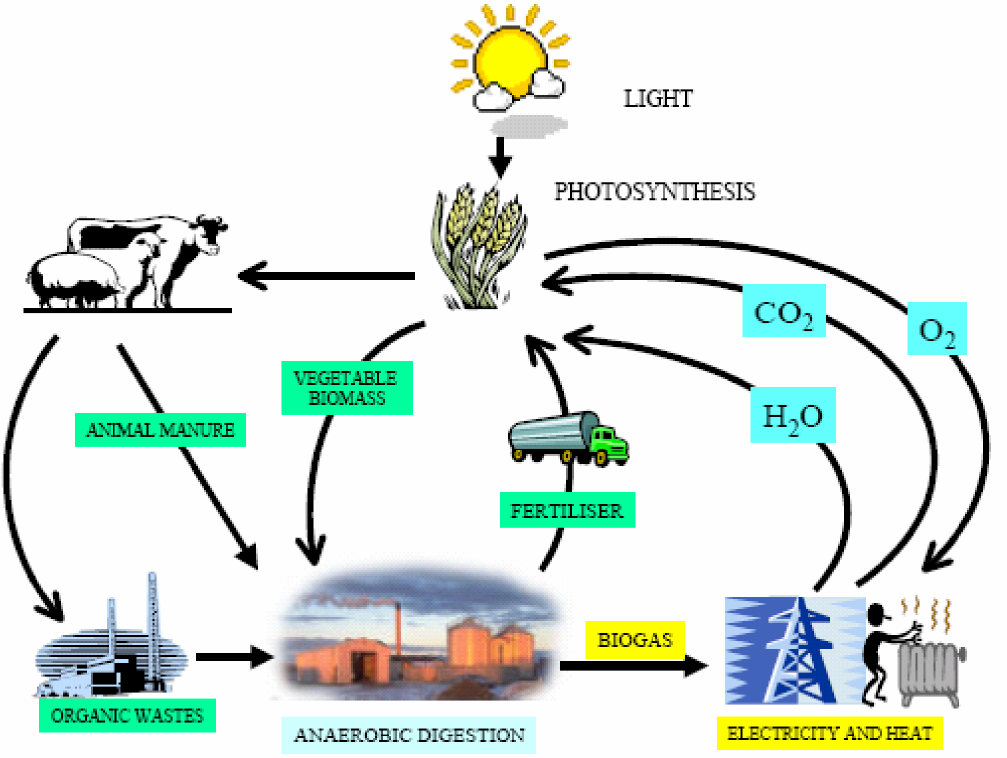

Figure 5.1. Schematic representation of the sustainable cycle of anaerobic co-digestion of animal manure and organic wastes (IEA 2001a).

There are many different digester reactor possibilities for various sizes, from single household to centralized municipal or industrial reactors. Anaerobic digesters can be made of concrete, steel, brick, or plastic. They are shaped like silos, troughs, basins or ponds, and may be placed underground or on the surface. All designs incorporate the same basic components: a pre-mixing area or tank, a digester vessel(s), a system for using the biogas, and a system for distributing or spreading the digestion residue for fertilizing. The digester types can be divided into two basic types: batch digesters and continuous digesters. Batch-type digesters are simpler to build. Their operation consists of loading the digester with organic materials and allowing it to digest. The retention time (feedstock processing time) depends on temperature and other factors. Once the digestion is complete, the effluent is removed and the process is repeated. The size of the digester depends on the amount of feedstock and retention time. Smaller units are more economic, thus the shorter the retention time is the better.

In a continuous digester, organic material is constantly or in regular intervals fed into the digester. The material moves through the digester either mechanically or by the force of the new feed pushing out digested material. The advantage of continuous digesters compared to batch digesters is that the continuous digesters produce biogas without the interruption of loading material and unloading effluent. They may be better suited for large-scale operations. There are three types of continuous digesters: vertical tank systems, horizontal tank or plug-flow systems, and multiple tank systems. Proper design, operation, and maintenance of continuous digesters produce a steady and predictable supply of usable biogas.

There are some 7 million reactors in China and 3 million in India, almost all household size reactors. The household scale digesters are simple and easy to manage. Most often they use animal wastes and provide gas for cooking and lighting (van Buren 1979). Pura village in India is an example where biogas is used also for electricity production and for purifying water (Johansson et al. 1993, UNDP 2000). In the 15 EU member states (before extension to 25) there are more than 500 landfill gas plants and more than 4000 biogas reactors producing about 28 TWh annually. It is about 1% of traffic fuel use. The potential of agricultural waste only is about 20% of EU15 traffic use (Lampinen et al. 2004).

Small-scale biomass digesters for animal waste are also common in farms in some industrialized countries like Germany and Denmark. The reactor size is somewhat larger than in developing countries and the gas is used to generate heat and electricity both for the farm and for sales. Sometimes the plants are co-operated by several farms. These larger facilities can also accept some amounts of industrial or municipal wastes. An example of a farm that produces also vehicle fuel is shown in Fig. 5.2 and described by Lampinen (2004).

Many livestock operations store the manure they produce in waste lagoons, or ponds. A growing number of these operations are placing floating covers on their lagoons to capture the biogas. They use it to run an engine/generator to produce electricity. The digester usually needs to be heated since the bacteria need a relatively stabile temperature. The heating can be realized using various heating sources, most often the produced biogas directly or waste heat from a micro-CHP unit.

Larger scale biomass digesters using mainly municipal and/or industrial wastes are in use in some European countries and in North America. The technology is appealing, since it stabilizes and hygienizes the waste and reduces the costs of disposal, besides providing energy.

Digestion of sewage sludge is well-established technology and widely in use all over the world, e.g. in UK. The main idea in sewage sludge digestion has been the reduction of the amount and improvement of the quality of sludge. Biogas has often been only an unused by-product. Nowadays in some wastewater treatment facilities biogas is utilized to drive the plant, and the extra biogas can be exported from the plant. Landfill gas is another resource that is available everywhere. It can be collected and used the same way as biogas produced by reactors.

Figure 5.2. At Kalmari farm near Jyväskylä in Finland all electricity, heat and traffic fuel demands are met by self-produced biogas from cow dung and waste – and extra energy is sold for additional income. In this photo farmer Erkki Kalmari is fuelling his Volvo V70 Bi-fuel car by on-the-farm generated biogas methane. Biogas reactor is shown behind, as well as a building housing an Otto micro-CHP unit, and a container housing water scrubbing biogas upgrading unit for vehicle use. (Lampinen 2004)

Biogas can be use like natural gas, so the options include heating, CHP-engines and power production, vehicle fuel, work engine fuel and fuel cells. Usually Otto engines are used, but also e.g. dual fuel Diesel engines and microturbines. Requirements for the different applications vary. Less demanding options are heat production and electricity production where very simple raw gas treatment and 40% or even lower methane content is enough. The most demanding applications regarding fuel quality are vehicle use and feeding biogas into natural gas grid, because about 90% or higher methane content is required and achieved by various upgrading technologies, e.g. water scrubbing (IEA 2000). Methane is a very high quality Otto engine fuel with octane number above 120.

About 4 million methane vehicles that are suitable for upgraded biogas are currently in use, over half of them in Argentina and Brazil (www.iangv.org). Most of them are dedicated methane Otto vehicles or bi-fuel Otto vehicles that can also utilize gasoline (Fig. 5.2). Sweden is the current leader in biogas vehicles, with more than 4000 in use and a network of almost 70 filling stations has already been established or will be established by 2005 (Fig. 5.3). Most of the existing methane cars are converted gasoline cars, but they are also serially manufactured, usually bi-fuel models. Heavy methane vehicles are usually serially manufactured dedicated Otto engine vehicles, but also dual-fuel Diesel engines and microturbines are sometimes used. Dual-fuel Diesel engine uses gas as the main fuel (over 90%) but liquid diesel oil is needed for ignition. This technology is available for stationary uses, trucks and buses, and also locomotives and ships.

Alcohol fermentation for ethanol production and reforming for ETBE

Ethanol has been produced for beverage by alcohol fermentation, a microbiological process, since about 2500 BC (Egypt, Mesopotamia) and it has been utilized as engine fuel since the 18th century (UK). It can be produced in all size classes, from individual households to centralized industrial plants.

Ethanol is produced by fermentation and distillation from sugars (sugar cane, molasses), starches (cassava, corn) and cellulose (wood, agricultural residues) (Wyman 1996). Sugars are most appealing, since they already contain the simpler sugar forms, glucose or fructose. The crops used for ethanol production vary by region, including sugar cane in Costa Rica and Brazil, grain and corn (maize) in North America, grain and sugar beets in France, and surplus wine grapes in Spain.

If woody and fibrous biomass is used, the cellulose has to be hydrolyzed into sugars before fermentation. This process is economically very interesting; since the price of bioethanol is largely dependent on the price of the biomass material used in ethanol production and cellulose biomass tend to be considerably cheaper. This technology is already in use in Sweden.

Ethanol can be blended with gasoline or used as pure fuel in ethanol powered Otto engines. In addition to its energy value, it is blended with gasoline because it is an octane enhancer due to its high octane number 108, and oxygenate due to its high oxygen content.

In Brazil ethanol already has 1/3 share of road traffic fuels and it is also utilized in aeroplanes. Modern Otto vehicles can use ethanol blends with little or no modification to their engines and fuelling systems when the ethanol portion does not exceed 15%. In

Brazil 22% blend (E22) is used with all gasoline in addition to using pure ethanol in dedicated ethanol vehicles. Blends of 5% (E5) and 10% (E10) are used in many countries, like USA and Sweden, without labelling the fuel products since they fit into all gasoline vehicles. Flexible fuel vehicles (FFV) have also been developed and are commercially available, for the same price as ordinary gasoline vehicles. These vehicles can be operated with a range of fuels from gasoline to blends containing as much as 85% ethanol (E85) (Fig. 5.3). Ethanol is also used in 93% blends in Diesel buses in Sweden.

Figure 5.3. A “gasoline” station in Stockholm selling biogas (97% methane), ethanol (E85) and electricity. Also biodiesel is sold in gasoline stations in Sweden and elsewhere in Europe.

ETBE (ethyl tertiary-butyl ether) is formed by reforming ethanol with isobutylene, which is currently crude oil based, but could be synthesized from biomass. The ETBE is blended with gasoline at concentrations of 5-10% to increase the oxygen content. The blended fuel burns cleaner than gasoline and reduces the emissions of carbon monoxide and unburned hydrocarbons from vehicles. ETBE is most widely used in Spain and France at present (EurObserv'ER 2005).

Biodiesel and pure plant oil fuels

Animal fat was the first liquid biofuel used by mankind, since about 40,000 BC (Europe). It was first used for illumination and this practise was still common in the 19th century. Vegetable oils and bee wax have also been used since ancient times for illumination. Vegetable oils and biodiesel can be produced in all size classes, from single household to centralized industrial plants. They can be used as traffic fuels or for power and heat production. Conversion routes and various utilization alternatives for plant oils, fat and biodiesels are shown in Figure 5.4.

Over 300 crops can be used in fuel oil production. The suitable plants include e.g. coconut, cotton seed, groundnut, palm, rapeseed, soy bean and sunflower. There are two alternative extraction technologies: mechanical pressing and solvent extraction. Solvent extraction is more effective, but it requires relatively large units and sophisticated technology, compared to mechanical extraction.

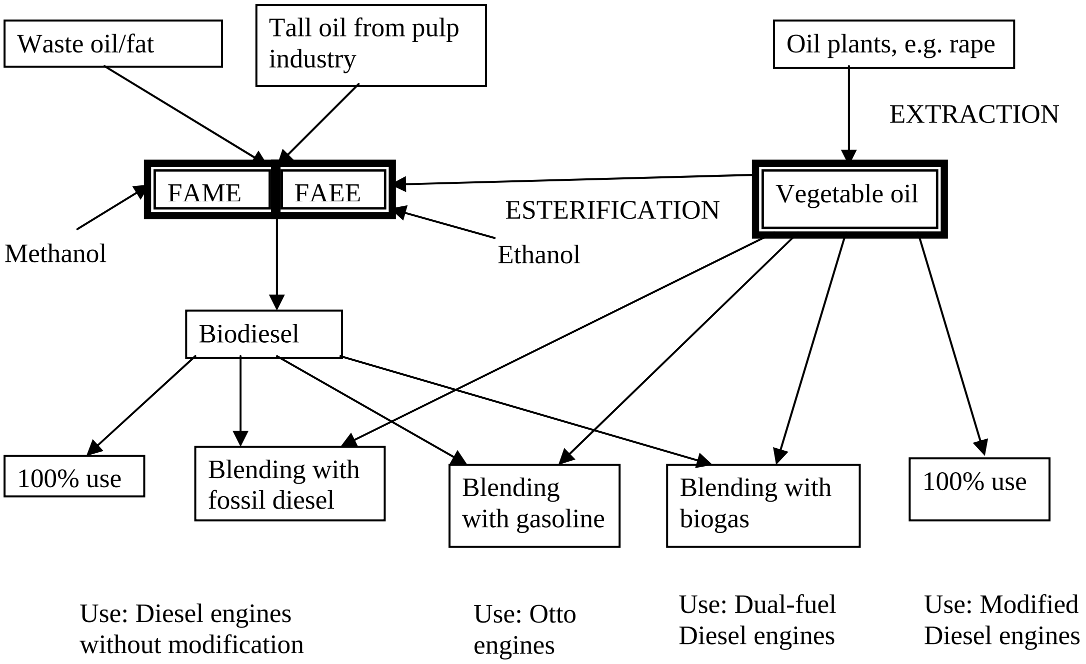

Figure 5.4. Conversion routes for pure plant oil and biodiesel production (FAME and FAEE) and use in internal combustion engines (also many other heat engines can be used).

Vegetable oils can be used in pure form (pure plant oil, PPO). This is rare due to the high viscosity of vegetable oils requiring engine modifications or at most 60% blending with crude oil based diesel or biodiesel in Diesel engines or at most a couple of per cent blending in Otto engines as an oxygenate. In principle its use in dual fuel Diesel engines with biogas or syngas with 1-30% share is also possible. PPO use is easiest in large engines, like buses and trucks, where only oil preheating needs to be installed. This was the original fuel (peanut oil) of the first Diesel engine in 1890's. It is still used in heavy vehicles in Southern Germany where the first commercial Diesel engines were made and where a large share of current global heavy vehicle Diesel engine production is located. In addition, kits are available for converting light Diesel vehicles for PPO in a single working day. Conversion workshops are found e.g. in Germany and Denmark. After such conversion the vehicle can utilize PPO, diesel and biodiesel in any mixtures. One of the converted Diesel engine types is the German Elsbett engine that has been used since the early 1980's.

The customary way of utilizing vegetable oils is in the form of biodiesel requiring chemical conversion called (trans)esterification (Tickell 2000). The oils are combined with ethanol or methanol with a catalyst leading triglycerides in the oils to be transformed into esters. Methanol or ethanol requirement is 10% of the oil mass. The products are called FAMEs (fatty acid methyl ester) when methanol is used and FAEEs (fatty acid ethyl ester) when ethanol is used for esterification. RME (rape oil methyl ester) and SME (soy methyl ester) are most common types of FAMEs. REE (rape oil ethyl ester) is the most common type of FAEE. Biodiesel can be used alone (B100) in existing diesel engines without modification or it can be blended with fossil diesel (e.g. B5 and B20). It can also be used in couple of percent blends in ordinary Otto engines as oxygenate or together with biogas in dual-fuel Diesel engines.

Various vegetable oils can be converted to biodiesels; even micro-algal oils and animal fat are suitable since they contain triglycerides. Waste fat and oils from restaurants and food industries are large potential source of biodiesel feedstock. Also pulp industry produces a large amount of wood oils, like tall oil from pines and they can be converted into biodiesels.

The transesterification process produces glycerol (glycerine) as a side product, amounting to 10% of the mass of biodiesel. It can be used as soap, sold as industrial raw material or burned as a solid fuel. After the removal of glycerol and excess alcohol esters are purified by water washing, vacuum drying and filtration.

Currently industrial biodiesel is produced with methanol derived from natural gas. The utilization of bioethanol or biomethanol would considerably reduce the lifecycle GHG emissions. However, lifecycle GHG reductions are obtained even when using fossil methanol (Sims 2002, IEA 2004).

Biodiesel is currently produced and used in many countries, especially Germany and France. Processing plants for medium scale industrial production of biodiesel have been developed in France, Italy, Austria, and the USA. In Austria, Sweden and Germany, pure biodiesel (B100) is used in unaltered vehicles. In France, commercial diesel fuel typically contains up to 5% of RME (B5).

Synfuels by thermochemical conversion

Synfuels are synthetic fuels made by thermochemical conversion from solid, liquid or gaseous feedstocks. Sometimes synfuels mean only synthesis gas based fuels, but here all thermochemical conversions are included. Sometimes a term sunfuel is used to mean synfuels made from biomass, to separate biomass based synfuels from fossil synfuels. Here such separation is not needed. Synfuels can be produced for any current engines, e.g. syn-gasoline, syn-diesel, syn-kerosene, and also new kind of fuels can me made for new engine types. In addition, these conversion processes can be utilized for making non-energy products like plastics.

The main synfuel production processes are shown in Fig. 5.5. The low molecular weight fuels – hydrogen, methane, methanol, ethanol, DME – are sometimes excluded from the group synfuels.

Gasification has been the most common route for synfuel production historically. Large quantity of synthesis gas has been produced and delivered as town gas since the late 17th century, first from coal and later from biomass as well. Synthesis gas (syngas) has been used for lighting and heating and especially during the 2nd World War over a million Otto vehicles were utilizing it directly as traffic fuel, generated from wood, peat and coal. Currently synthesis gas is produced and used on-site in stationary power plants for electricity and heat generation, but rarely as a storable secondary energy source.

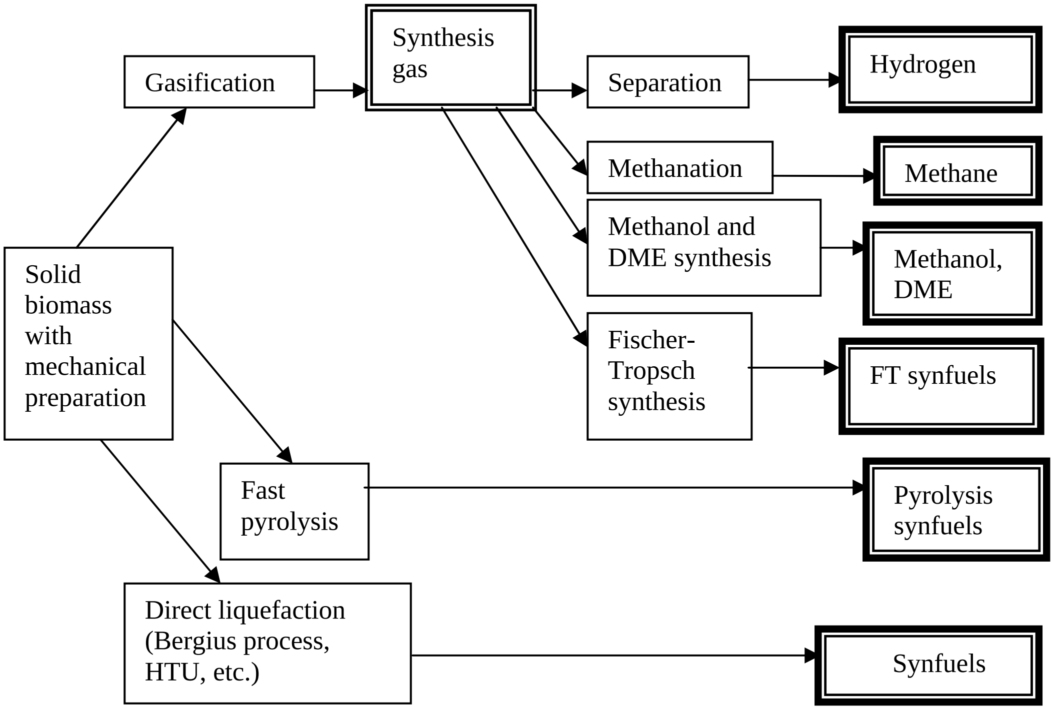

Figure 5.5. Main thermochemical routes for synfuel production.

Syngas based secondary biofuel production is currently rare, but it is utilized commercially in large scale for coal and natural gas based secondary fossil fuel production. There is, however, very large technological potential for biofuel production. All of the processes are suitable for large scale plants only.

The most direct way of producing secondary biofuels from syngas is to separate its components. Usually hydrogen and carbon monoxide are the main constituents of syngas, and hydrogen can be separated, or on other words, syngas can be purified for hydrogen (this can be called gasification hydrogen). The rest, especially carbon monoxide, is burned for gasification energy needs. The gasification process can also produce syngas with high quantity of methane, like town gas until late 19th century, instead of hydrogen and it can also be separated.

Syngas can be catalytically converted (reformed) resulting in methane, methanol and dimethyl ether (DME). These processes are called methanation, methanol synthesis (Walter et al. 2000) and DME synthesis. DME is produced in pilot plants e.g. in Japan. For example in Finland over 50% of all traffic fuels, 1.9 Mtoe, could be produced in existing pulp plants by black liquor gasification followed by methanol and DME synthesis (Ekbom et al. 2003). A pilot plant has been built in Sweden, another country with large forest industry. Costa Rica and other Central American countries could utilize these technologies with wood or agricultural residues, e.g. bagasse and coffee husk.

Methanol can be used like ethanol in existing Otto vehicles in blends up to 15% (e.g. M15), in higher blends in flexible fuel vehicles (e.g. M85) and in pure form (M100) in dedicated vehicles. Methanol can also be used in the production of biodiesel and MTBE (methyl tertiary butyl ether), an ETBE-like oxygenate. Methanol can also be produced by pyrolysis or by reforming from biogas.

DME is gaseous fuel that can be used in existing Diesel engines without modification but a specific fuel infrastructure needs to be created both in refilling stations and in vehicles.

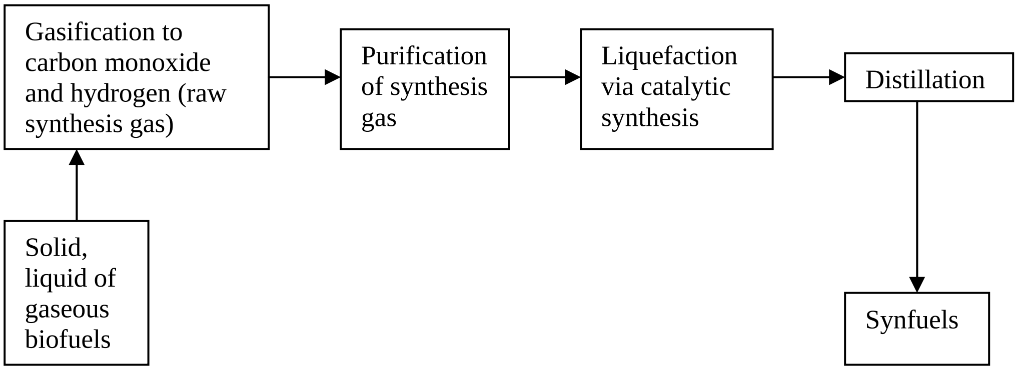

Figure 5.6. Generalized flow diagram of FT synfuel production.

Fischer-Tropsch (FT) fuel is the general name for synfuels produced catalytically from syngas (Perry and Green 1984, Fig. 5.6). The FT process converts CO and H_2 over iron or cobalt catalysts into a range of hydrocarbon and alcohol fuels, like syngasolin, syndiesel, synkerosine and synethanol. Hydrocarbons are predominantly alkanes or alkenes. It was invented in 1920’s in Germany and was used in large scale in Germany during the 2nd World War, when half all road vehicle and aviation fuels were made synthetically from coal. The FT and Bergius processes were used in over 20 large scale factories to produce over 4 Mtoe of traffic fuels annually (Yergin 1991). This technology is now in commercial use in South Africa (over 7 Mtoe annually) and USA; and commercial plants using natural gas as a feedstock are found in South Africa and Malaysia (Higman and der Burgt 2003). Solid biomass can also be converted by the same processes, and they are used in pilot plants, but not yet commercial large scale plants.

Direct liquefaction means splitting solid fuel, e.g. coal and biomass, in high pressure and temperature with a presence of catalysts directly into short chain liquids, analogously to hydrogen and steam cracking processes in crude oil refining. In contrast to pyrolysis in which thermal treatment only leads to depolymerization of the macromolecules of biomass, further reactions are introduced in direct liquefaction by addition of pressurized reducing gas and a catalyst.

Bergius process was invented in Germany in the 1910's and gave to its inventor Nobel Prize in chemistry in 1931. It was used, like the FT process, in large scale during the 2nd World War in Germany, UK and other countries to convert coal into traffic fuels, including 95% of aviation fuels in Germany (Yergin 1991). The process, also called hydrogenation or hydrocracking, splits solid fuels by hydrogen and catalysts at 200 bar and 450 °C (Perry and Green 1984). It was developed for biomass feedstocks in the 1920's in Sweden.

Another method is hydrothermal or steam cracking, also invented in Germany in the 1920's. In that process steam is used in high temperatures and low pressure with catalysts (Perry and Green 1984). It has been used commercially in Germany at 200 °C and 1-10 bar.

New versions of liquefaction processes are being developed for biofuel production. Hydrothermal upgrading (HTU) is using liquid water in high pressure (150 bar) and moderate temperature (350 °C) followed by Bergius or catalytic hydrodeoxygenation (HDO) process. As water is required, wet biomasses like sewage are suitable feedstocks and the retention time is much shorter than in anaerobic digestion. This, however, is not yet commercial technology, but in pilot plant stage.

The catalytic direct liquefaction processes are not currently commercially used for making biofuels, but pilot plants are being operated (Bridgwater and Grassi 1991).

Pyrolysis oil, mostly methanol but many other liquid components as well, has been made from biomass since about 2000 BC (Egypt) in small scale. Pure methanol, also called wood alcohol, has been produced from wood since late 17th century (UK).

When thermal decomposition process in anaerobic conditions is optimized for liquid production it is generally called pyrolysis. Pyrolysis is the first step in gasification and combustion. It occurs in low pressure in the absence of oxygen or with such a limited supply of oxygen that gasification does not occur to an appreciable extent. It is similar to carbonization, but the process temperatures are higher and gaseous and liquid products are retrieved in addition to charcoal. Lower process temperature and longer vapour residence times favour the production of charcoal. High temperature and longer residence time increase the biomass conversion to gas and moderate temperature and short vapour residence time are optimum for producing liquids. The product distributions obtained from different modes of pyrolysis process are summarized in Table 5.1.

Pyrolysis liquid is called pyrolysis oil, bio-oil or biocrude (although sometimes biocrude refers to HTU or other processes). It is a dark brown mobile liquid which has a heating value about half that of conventional fuel oil. The biocrude can be transported and refined similarly to crude oil (Bridgwater and Grassi 1991, Ojasmaa and Peacocke 2001). The pyrolysis gas is usually used within the process to provide the process heat requirements. Charcoal can also be used for process heat but it can also be stored and sold as solid secondary biofuel.

Table 5.1. Typical product yields (dry wood basis) obtained by different modes of pyrolysis of wood (www.pyne.co.uk, modified).

Mode	Conditions	Liquid	Char	Gas
Fast pyrolysis	moderate temperature (500-800 °C)	75%	12%	13%
Carbonisation (slow pyrolysis)	low temperature (260-380 °C)	30%	35%	35%
Gasification	high temperature (800-1100 °C)	5%	10%	85%

Hydrous pyrolysis or thermal depolymerization (TDP) means pyrolysis in the presence of water, e.g. wet biowaste in high pressure and moderate temperature. It is in commercial use in USA for producing synfuels from biowaste with a very short retention time.

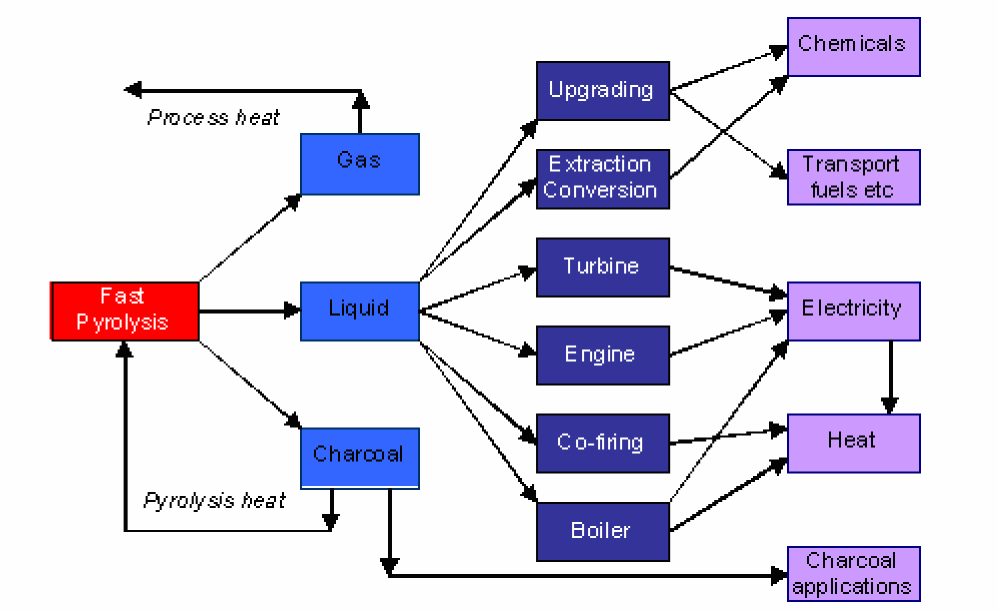

Figure 5.7. Applications for bio-oil (www.pyne.co.uk).

Like FT, Bergius and HTU processes fast pyrolysis is suitable for almost all biomasses, including wet biowaste. Wood is most studied, but nearly 100 different biomass types have been tested by many laboratories including agricultural wastes, energy crops, forestry wastes and solid wastes. Biomass fast pyrolysis technologies have been successfully demonstrated at small-scale and several large pilot plants or demonstration projects are in operation or at construction. Bio-oil can substitute for fuel oil or diesel in many applications like boilers, furnaces, engines and turbines for electricity generation (Fig. 5.7). There is also a range of chemicals that can be extracted or derived including food flavourings, specialities, resins, agri-chemicals, fertilisers, and emissions control agents. Upgrading bio-oil to transportation fuels is feasible but currently not economic.

Hydrogen

Hydrogen is a fuel that can be made in numerous different ways from biomass, see Fig. 5.8. At least some of those methods are available to all energy users. It can be produced by most of the processes discussed earlier but also by electrochemical conversion and photobiological processes.

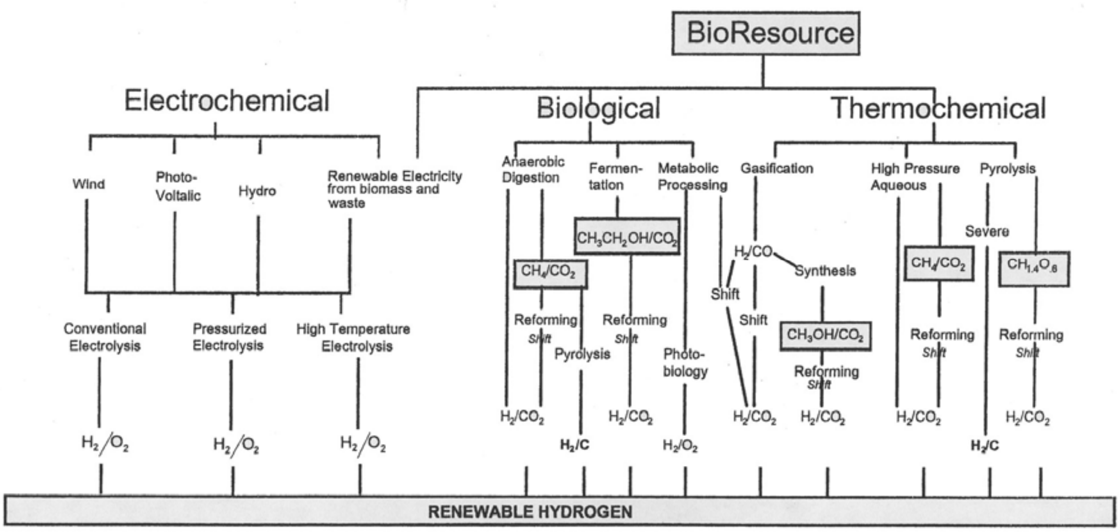

Figure 5.8. Production options for renewable hydrogen. Most of the options are bioenergy based (Milne et al. 2001).

Environmental impacts of transport biofuels

A broad lifecycle greenhouse gas emission comparison of traffic biofuels is shown in Fig. 5.9 (LBS 2002). Crude oil, natural gas, bioenergy and electricity based traffic fuels are compared in Opel Zafira minivan using either internal combustion engine (Otto or Diesel) or fuel cells with electric motors. Natural gas enables lower emissions than crude oil based fuels but only if the cycle if carefully chosen. Biofuels offer significant emission reductions compared to best natural gas cycles, but variations within biofuels are much larger than variations within fossil fuels.

The largest emission reduction is available by biowaste based biogas in Otto engine; emissions are 90% below those of the best natural gas cycle, using advanced fuel cells. It is followed by waste wood and energy wood based gasification hydrogen with fuel cells and waste wood based FT diesel with Diesel engine. Sugar beet ethanol based hydrogen in fuel cell vehicles has the highest lifecycle emissions of biofuels, but they are still somewhat lower than in the best natural gas cycle. Biodiesel was not included in this comparison, but the results from other studies show approximately similar values as those of ethanol. Thus, the biofuels that currently are rarest in use offer great emission benefits compared to the convential biofuels ethanol and biodiesel. For electricity use variations are even larger than for biofuels, depending on primary fuel mix used for power production. The large bar means EU average electricity mix where fossil based generation has a high share. And the zero-emission alternative is local wind power.

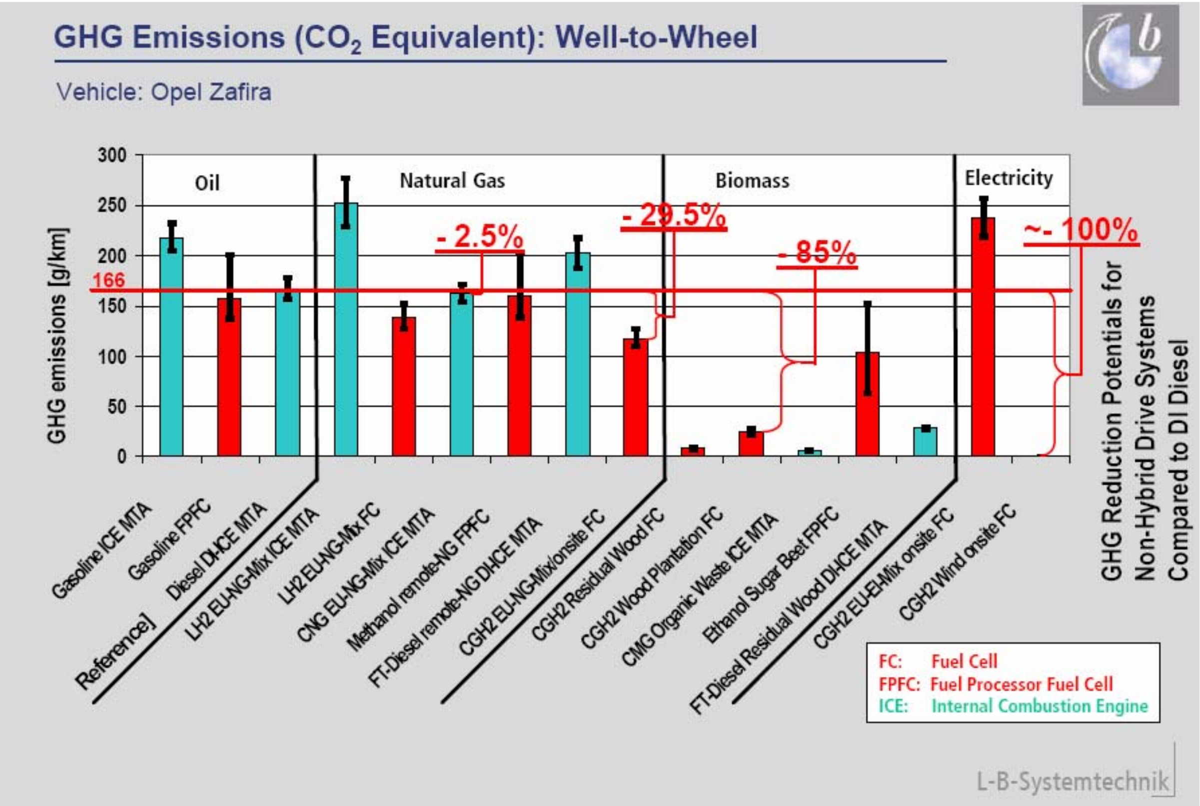

Figure 5.9. Comparison of lifecycle greenhouse gas emissions of various traffic fuels (LBS 2002). Red (dark) bars mean fuel cell cycles and green (light) bars mean internal combustion engine cycles. The lowest bar labeled ”CMG organic waste ICA MTA” means biogas produced from biowaste and used in ordinary Otto engine. The only zero-emission alternative is local wind power electrolysis hydrogen used in a fuel cell vehicle (”CGH2 Wind onsite FC”).

6 Availability of energy technologies for different user groups

Table 6.1 presents the main categories of primary bioenergy resources available to various energy user groups for energy production either for their own use or also for additional income by selling.

Table 6.1. Main biomass resources (modified from EUREC 2002).

Biomass resources	**Examples**
wood wastes	wood processing waste, sawmill waste, construction residues
forest residues	
short rotation forestry	willow, poplar, eucalyptus
sugar crops	sugar beet, sugar cane, sweet sorghum
starch crops	maize, wheat, corn, barley
oil crops	rape seed, sunflower
herbaceous lignocelluloses crops	miscanthus
agricultural by-products and residues	straw, animal manure, bagasse, coffee processing residues
organic fraction of municipal solid waste	
sewage sludge	
industrial residues	e.g. food and paper industry residues

In tables 6.2-6.5 technologies currently available for various energy user categories are presented. The categories are:

1) Micro-scale technology 1, $P < 3$ kW$_e$ (Table 6.2)
    - rural households
    - shops and other service companies
    - other individual small buildings
2) Micro-scale technology 2, $P < 100$ kW$_e$ (Table 6.3)
    - farms
    - rural villages
    - companies
    - large buildings, e.g. urban blocks of flats and office buildings
    - small factories
3) Small-scale technology, $P < 10$ MW$_e$ (Table 6.4)
    - plantations, e.g. coffee, sugarcane
    - factories with waste biomass production
    - towns and urban suburbs
4) Medium-scale technology, $P < 100$ MW$_e$ (Table 6.5)
    - cities
    - grid condensing fast reserve power: $P < 50$ MW$_e$
5) Large-scale technology, $P < 1500$ MW$_e$
    - grid condensing baseload power and slow reserve power

Table 6.2. Availability of commercial bioenergy technologies for individual houses with electricity demand max. 3 kW_e and total energy demand max. 10 kW_{th}.

Energy product	Technology	Bioenergy resource
Direct heat	All fixed bed stove types	All solid biomass
	Gaseous or liquid fuel burners	All gaseous and liquid secondary biofuels
Electricity and micro-CHP	Gasification with Otto or Diesel engines	All solid biomass
	Otto, Diesel and Stirling engines	All gaseous and liquid secondary biofuels
	Hydrogen PEM fuel cells	Hydrogen
Gaseous and liquid secondary biofuels for traffic, CHP and work engine use	Methane (biogas) by digestion (AD)	Animal and human manure and sludge, kitchen biowaste, straws, non-wood energy crops
	Ethanol by fermentation	Sugar and starch crops
	Pure plant oil by extraction	Oil crops
	Biodiesel by esterification	Oil crops, kitchen waste fat, ethanol
	Hydrogen by biopowered electrolysis	Water, bioelectricity

Solid secondary biofuel production is not included in Tables 6.2-6.5, but it is available for all user groups. Solid biomass in the tables refers to both primary and secondary biofuels.

In addition to the technologies mentioned in the tables there are many other technologies currently at development phase as shown in Tables 4.2-4.3 and Appendix A. Most of them are most suitable for electricity generation in the micro-level, i.e. user groups presented in Tables 6.2-6.3.

Table 6.3. Availability of commercial bioenergy technologies for farms, companies, factories, villages and large buildings with electricity demand 3-100 kW_e and total energy demand 10 kW_{th} - 1 MW_{th}.

Energy product	Technology	Bioenergy resource
Direct , central and district heating and cooling	All fixed bed furnaces	All solid biomass
	Gaseous or liquid fuel burners	All gaseous and liquid secondary biofuels
Electricity and micro-CHP (with central or district heating and cooling)	Steam engine	All solid biomass
	ORC turbine	All solid biomass
	Gasification with Otto or Diesel engine	All solid biomass
	Gasification with microturbine	All solid biomass
	Otto, Diesel, Wankel and Stirling engines	All gaseous and liquid secondary biofuels
	Microturbine	All gaseous and liquid secondary biofuels
	Hydrogen fuel cells	Hydrogen
Gaseous and liquid secondary biofuels for traffic, CHP and work engine use	Methane (biogas) by digestion (AD)	Animal and human manure and sludge, kitchen biowaste, straws, non-wood energy crops, food industry waste
	Ethanol by fermentation	Sugar and starch crops
	Pure plant oil by extraction	Oil crops
	Biodiesel by esterification	Oil crops, kitchen waste fat, industrial waste fat, ethanol
	Hydrogen by biopowered electrolysis	Water, bioelectricity

User group 5 (large-scale technology) is not presented in a table format. Technologies available are combustion and gasification presented in chapter 4. In many countries the fastest way of increasing bioenergy use in this size class would be to convert existing fossil power plants for co-firing with bioenergy.

Table 6.4. Availability of commercial bioenergy technologies for plantations, factories, towns and urban suburbs with electricity demand 100 kW_e -10 MW_e and total energy demand max. 1-50 MW_{th}.

Energy product	Technology	Bioenergy resource
Central and district heating and cooling	Fixed and fluidized bed combustion, gasification	All solid biomass
	Gaseous or liquid fuel burners	All gaseous and liquid secondary biofuels
Electricity and CHP (with central or district heating and cooling)	Steam engine	All solid biomass
	Steam turbine	All solid biomass
	Hot air turbine	All solid biomass
	ORC and other vapour turbines	All solid biomass
	Gasification with Otto or Diesel engine	All solid biomass
	Gasification with gas turbine or microturbine	All solid biomass
	Otto, Diesel, Wankel and Stirling engines	All gaseous and liquid secondary biofuels
	Gas turbine and microturbine	All gaseous and liquid secondary biofuels
	Hydrogen fuel cells	Hydrogen
	Combined cycle (μT/GT/Diesel + ST/VT)	All gaseous and liquid secondary biofuels
Gaseous and liquid secondary biofuels for traffic, CHP and work engine use	Methane (biogas) by digestion (AD)	Animal and human manure and sludge, animal carcasses, kitchen biowaste, straws, non-wood energy crops, food industry waste
	Methane (landfill gas) (AD)	Biowaste in landfills
	Methanol by reforming	Methane
	Ethanol by fermentation	Sugar and starch crops
	Pure plant oil by extraction	Oil crops
	Biodiesel by esterification	Oil crops, kitchen waste fat, industrial waste fat, ethanol, methanol
	Hydrogen by gasification and separation	All solid biomass
	Hydrogen by reforming	Methane, ethanol, methanol
	Hydrogen by biopowered electrolysis	Water, bioelectricity

The energy product in Tables 6.2-6.5 can be used for various final energy use categories. Both direct and CHP heat can be made by all primary and secondary biofuels in all size classes for cooking, domestic hot water, space heating, illumination, cooling, humidity control, water purification, drying, and industrial steam. Electricity for all its various applications can be made by CHP or condensing electricity. And finally, direct mechanical power can be made for stationary or transport engines, water pumping etc. These sets of information have been written into matrix forms in Appendix B.

Table 6.5. Availability of commercial and nearly commercial bioenergy technologies for cities, large factories and large plantations with electricity demand 10-100 MW_e and total energy demand 50-1000 $MW_{th.}$

Energy product	**Technology**	**Bioenergy resource**
District heating and cooling	Fixed and fluidized bed combustion	All solid biomass
	Gaseous or liquid fuel burners	All gaseous and liquid secondary biofuels
Electricity and CHP (with district heating and cooling)	Steam turbine	All solid biomass
	Gasification with Diesel engine	All solid biomass
	Gasification with gas turbine	All solid biomass
	Diesel engine	All gaseous and liquid secondary biofuels
	Gas turbine	All gaseous and liquid secondary biofuels
	Combined cycle (GT/Diesel + ST)	All gaseous and liquid secondary biofuels
Gaseous and liquid secondary biofuels for traffic, CHP and work engine use	Methane (biogas) by digestion (AD)	Municipal sludge and biowaste, agricultural waste, non-wood energy crops, industrial waste
	Methane (landfill gas) (AD)	Biowaste in landfills
	Methane by gasification and methane synthesis	All solid biomass
	Methanol by reforming	Methane
	Methanol by gasification and methanol synthesis	All solid biomass, black liquor
	Methanol by pyrolysis	All solid biomass
	DME by gasification and DME synthesis	All solid biomass, black liquor
	Ethanol by fermentation	Sugar and starch crops
	Ethanol by enzymatic hydrolysis and fermentation	Wood
	Pure plant oil by extraction	Oil crops
	Biodiesel by esterification	Oil crops, restaurant waste fat, industrial waste fat/oils (tall oil etc), ethanol, methanol
	Synfuels (LPG, gasoline, diesel, jet kerosene, etc.) by gasification and FT synthesis	All solid biomass, black liquor
	Direct liquefaction synfuels (gasoline, diesel, etc.)	All solid biomass, wet biowaste
	Pyrolysis synfuels by pyrolysis + refining of biocrude	All solid biomass, wet biowaste
	Hydrogen by gasification and separation	All solid biomass
	Hydrogen by reforming	Methane, ethanol, methanol, DME, LPG, gasoline, diesel, jet kerosene
	Hydrogen by biopowered electrolysis	Water, bioelectricity
	Ethers ETBE and MTBE by reforming	Ethanol, methanol, synfuels

7 Recommendations and priorities

As much as 46% of energy consumption of Costa Rica goes for traffic use (Fig. 2.5). It is very high share internationally compared, and it is 100% imported fossil fuel powered. These reasons make traffic sector the number one focus for bioenergy applications. Of all different energy end-uses, self-sufficiency is in the lowest level in transportation sector in Costa Rica, Central America and almost all countries of the world. In that sector bioenergy has the highest technological potential in all user categories. But unfortunately, it is also the most passive sector of all renewable energy sectors. Thus, when setting new bioenergy policy agendas transportation sector would deserve the highest priority, as is the case in the Costa Rican National Energy Plan for years 2002-2016 (MINAE 2003).

Costa Rica already has large ethanol production that would be enough to meet 5% of national ground transport energy needs but it is not yet used for energy purposes. If the MINAE and DSE estimated potential of 25 PJ (Table 2.2) is realized it corresponds to 50% of current traffic use. Blending ethanol with gasoline is an easy first step. Also biodiesel and biogas could be taken into use in the short term, the latter requiring technology transfer, however. The MINAE and DSE estimated potential of 8 PJ of annual biogas production (Table 2.2) would meet 16% of current traffic use. In the medium and long term several other conversion processes enable large expansion of traffic fuel production, including export opportunities, but many of those require both applied and adaptation research as well as technology transfer. There is little competition from other renewables in the traffic sector in the short and medium term. In the long term they may surpass bioenergy by electric vehicle technology, including fuel cell use.

Electricity sector in Costa Rica is already 98% renewable making bioelectricity production a low priority from national point of view in the short term. And there are still large unexploited potentials from other renewables. However, bioelectricity may be important for autoproducers already in the short term and nationally in the long term due to continues rapid increase of electricity consumption. In addition, exporting to other Central American countries may become economically attractive since all of them except Belize have large fossil fuel percentage in their power generation portfolio.

Heating sector offers a medium priority opportunity for primary and secondary biofuels in residential and industrial sector and much of that can be utilized in the short term since many required technologies are available in Costa Rica. Some technologies, like secondary biofuels in residential use, could increase bioheat utilization quickly in the short term and reduce both electricity and fossil fuel consumption. Some other, like district heating, could have large impact in medium term. And yet some other, like district cooling, could be important in the long term by responding to energy end-use that is guaranteed to increase a lot in the future. Of other renewables solar and geothermal energy could offer competition in meeting heating needs, already in the short term.

The barrier and driver analysis (Table 2.4) showed that Costa Rica has both significant drivers and significant barriers for bioenergy implementation. The most important issue to address in the current situation seems to be the restrictions to private investments in the energy sector. Another big issue is the formation of bioenergy utilization and knowledge networks, which could significantly aid in the formation of new projects.

The main conclusion from Tables 6.2-6.5 and Appendices A-B is that the diversity of existing technology options is very large in all studied cases compared to options usually presented in feasibility studies or technology policy documents. This also applies to academic research papers, making it necessary to review a large set of publications, as seen in the literature list, to compile options for this technology survey. In addition, many other options are emerging as seen in Tables 4.2-4.3 and Appendix A, usually for the benefit of small user categories more than large producers.

Thus, it is obvious, that in the short term spreading information of this extensive list of opportunities is one necessary activity. Furthermore, techno-socioeconomic surveys are needed for characterizing e.g. the following parameters for each technological system:

- availability: technical and commercial
- potential: resources, technology transfer, CDM
- performance: efficiency, availability factor, load factor
- use: maintenance, weather sensitivity, altitude sensitivity
- environmental impacts: emissions, deforestation etc.
- social impacts: energy self-sufficiency and income
- economic impacts: employment, price, trade, ancillary benefits

For all user groups several other renewable energy resources are available to complement bioenergy. Actually, for the fullest utilization of the intermittent energy forms, like solar and wind, energy storage must somehow be implemented, either virtually by using grids and networks, or by physical storage technology. Bioenergy, as well as hydropower, offers a natural storage medium and enables high usage level for intermittent energy forms. These energy forms have much larger domestic resource base and much lower environmental impacts than bioenergy, with the exception of some waste-to-energy technologies, but they need support from bioenergy or hydropower.

Exploitation of this valuable feature of bioenergy requires energy systems to be designed in such a way, that bioenergy acts as the supporting energy form for the other types of renewables, rather than the sole focus. This means a paradigm shift and a comprehensive re-evaluation of energy policies in countries endowed with a relevant base of biomass for energy production. Suitable policy making and barrier removal actions to promote bioenergy use must arise from this fundamental paradigm shift in order for our society to take advantage of the energy, environment and sustainability linkages existing in bioenergy use.

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APPENDIX A. Lists of bioenergy resources and technologies.

Table A1. Primary and secondary bioenergy resources.

Primary bioenergy	• wood and its processing waste • crops and their processing waste • plant, animal and human based biowaste, including black liquor
Secondary bioenergy: solid fuels	• mechanical conversion without compression: chips, sawdust etc. (wood, crops) • mechanical conversion with compression: pellets, briquettes, bales etc. (wood, crops, waste) • thermochemical conversion: charcoal (wood)
Secondary bioenergy: liquid fuels	• alcohols o biological conversion (fermentation): ethanol (sugar crops, starch crops) o biological conversion (enzymatic hydrolysis, fermentation): ethanol (wood) o thermochemical conversion (FT): ethanol (all solid biomass) o thermochemical conversion (several processes): methanol (wood, crops, waste) o chemical conversion: methanol (biomethane) • ethers o chemical conversion: ETBE (ethanol) o chemical conversion: MTBE (methanol) • plant oils and biodiesels o mechanical conversion (extraction): pure plant oils (PPO) = straight vegetable oils (SVO) (oil crops) o chemical conversion (esterification): biodiesels (plant oil, waste fat and industrial waste) • pyrolysis oils o thermochemical conversion: biocrude, bio-oil (all solid biomass) o thermochemical conversion (thermal depolymerization, hydrous pyrolysis): bio-oil (wet biowaste) o chemical conversion of bio-oil: various synfuels • liquefaction o thermochemical conversion - Fischer-Tropsch (FT) process (indirect liquefaction via synthesis gas to synfuels): diesel, gasolin, kerosene and other synfuels (all solid biomass, black liquor) o thermochemical conversion - Bergius process (direct liquefaction/hydrogenation): various synfuels (all solid biomass) o thermochemical conversion – hydrothermal cracking, HTU process etc. (direct liquefaction): various synfuels (wet biowaste, all solid biomass)
Secondary bioenergy: gaseous fuels	• biogas and landfill gas o biological conversion (AD, anaerobic digestion): methane, hydrogen (biowaste, crops) • synthesis gas and synfuels o thermochemical conversion (gasification) to syngas (wood gas): hydrogen, carbon monoxide, methane (all solid biomass) o thermochemical conversion of syngas to synfuels (FT process): methane, LPG, DME • other o thermochemical, electrochemical and biological conversion: hydrogen (wood, crops, waste, water) o chemical conversion: DME (methane, methanol) o thermochemical conversion: pyrolysis gas (wood, crops)

Table A2. Conversion of primary and secondary biofuels into heat.

Solid fuel combustion	• fixed grate o open fire (3 stones etc.): $P < 10$ kW, $\eta_{th} < 10\%$ o improved cooking stoves: $P < 10$ kW, $\eta_{th} < 40\%$ o modern heating boilers: 5 kW-100 MW, $\eta_{th} < 90\%$ • central heating • district heating o steam generator o electricity/CHP, $\eta_e < 20\%$ • other grate types: 100 kW – 500 MW, $\eta_e < 25\%$ • fluidized bed (BFB and CFB): 1 MW – 500 MW, $\eta_e < 40\%$ • pulverized: 10 MW – 1500 MW, $\eta_e < 45\%$
Solid fuel gasification	with integrated gas combustion • BIGCC: 1 kW – 500 MW, $\eta_e < 50\%$
Liquid fuel combustion	1 kW – 500 MW, $\eta_e < 60\%$
Liquid fuel reforming	with integrated liquid or gas combustion
Gaseous fuel combustion	1 kW – 1000 MW, $\eta_e < 70\%$
Co-firing	conversion into heat together with peat and fossil fuels
Other	Mechanical biopower directly coupled with ground source heat pump (for final heat use): $\eta_{th} < 200\%$

Table A3. Conversion of heat into mechanical power and electricity, and direct conversion of fuels into mechanical power and electricity.

Heat engines	• ICE reciprocating engines o Otto (4-stroke and 2-stroke): 100 W - 10 MW, $\eta_e < 35\%$ o Diesel (4-stroke and 2-stroke): 1 kW - 50 MW, $\eta_e < 45\%$ o Wankel: 1 kW - 500 kW, $\eta_e < 30\%$ • ECE reciprocating engines o Stirling: 50 W - 500 kW, $\eta_e < 50\%$ o steam engine: 10 kW - 1 MW, $\eta_e < 15\%$ • IC turbines o gas turbine (GT): 500 kW - 500 MW, $\eta_e < 45\%$ o microturbine: 10 kW - 500 kW, $\eta_e < 30\%$ • EC turbines o steam turbine (ST): 100 kW - 1500 MW, $\eta_e < 50\%$ o ORC turbine and other vapour turbines: 10 kW - 10 MW, $\eta_e < 25\%$ o hot air turbine, 100 kW-10 MW • Combined cycle (CC, heat engines and fuel cells): 0.5-1000 MW, $\eta_e < 80\%$
Other heat based	• Magnetohydrodynamic energy conversion (MHD) via plasma: $\eta_e < 55\%$ • Thermoelectric effect (Peltier, Seebeck, Thomson): 50 W-1 MW, $\eta_e < 10\% \cdot \eta_C$ • Electron thermotunneling effect: 100 W – 1 MW, $\eta_e < 80\% \cdot \eta_C$ • Thermal photovoltaic (TPV) = Infrared Photovoltaic effect (IR-PV)
Direct conversion	• Fuel cells (FC): 1 W - 5 MW, $\eta_e < 65\%$ o hydrogen FCs o methanol, methane and DME FCs o biological/microbial FCs • Muscle power (human and animal): 10 W – 10 kW, $\eta_m < 20\%$

APPENDIX B. Bioenergy technology availability matrices.

Values in availability matrices:

- Empty: not technically suitable
- ●: not (yet) available commercially
- ●●: available commercially

Definitions of the user groups are found in chapter 6. Only selected technologies and user groups are presented. Wider lists are available in Appendix A, Tables 4.2-4.3 and Tables 6.2-6.5.

Matrix B1. Bioenergy conversion technology vs. user groups.

	rural households	rural villages	cities	farms	plantations	factories	grid
Biofuel to heat conversion:							
Solid fuel combustion - fixed grate	●●	●●	●●	●●	●●	●●	
- other grate types		●●	●●	●	●●	●●	
- fluidized bed			●●		●●	●●	●●
- pulverized			●●		●●		●●
Solid fuel gasification		●●	●●	●●	●●	●●	●●
Liquid fuel combustion	●●	●●	●●	●●	●●	●●	●●
Gaseous fuel combustion	●●	●●	●●	●●	●●	●●	●●
Electricity and mechanical power production from biofuels:							
Otto	●●	●●		●●	●●		
Diesel	●●	●●	●●	●●	●●	●●	
Wankel	●	●		●			
Stirling	●	●●		●●			
Steam engine		●●		●●	●●	●●	
Microturbine		●●		●●			
Gas turbine			●●		●●	●●	●●
Steam turbine			●●		●●	●●	●●
ORC and other VTs		●●		●●	●●	●●	
Fuel cells	●	●●		●●	●●	●	

Matrix B2. Heat conversion vs. electricity and mechanical power conversion. In case of fuel cells intermediate heat conversion is not needed, but fuel is converted directly.

	Otto	Diesel	Wankel	Stirling	Steam Engine	Micro-turbine	Gas turbine	Steam turbine	ORC	Fuel cells
Solid fuel combustion - fixed grate				●	●●			●●	●●	
- other grate types				●	●●			●●	●●	
- fluidized bed					●			●●	●	
- pulverized					●			●●	●	
Solid fuel gasification	●●	●●	●	●	●	●	●●	●●	●	●
Liquid fuel combustion	●●	●●	●●	●●	●	●●	●●	●●	●	●
Gaseous fuel combustion	●●	●●	●	●●	●	●●	●●	●●	●	●●

Matrix B3. Biofuels vs. conversion to electricity of mechanical power by combustion or directly (fuel cells).

	Otto	Diesel	Wankel	Stirling	Steam engine	Micro-turbine	Gas turbine	Steam turbine	ORC	Fuel cells
Primary biofuels										
- wood and its processing waste				●	●●			●●	●●	
- crops and their processing waste				●	●●			●●	●●	
- biowaste from plants, animals and humans				●	●			●●	●	●
Secondary biofuels: solid										
- mechanical conversion without compression: chips, sawdust, etc.				●	●●			●●	●●	
- mechanical conversion with compression: pellets, briquettes, bales, etc.				●	●●			●●	●●	
- thermal conversion: charcoal				●	●●			●●	●●	
Secondary biofuels: liquid										
- alcohols	●●	●●	●	●	●	●	●	●	●	●
- ethers	●●	●	●	●	●	●	●	●	●	
- plant oils	●	●●	●	●	●	●	●	●	●	
- biodiesels	●	●●	●	●●	●	●	●	●	●	
- synfuels	●●	●●	●●	●●	●	●●	●●	●●	●	
Secondary biofuels: gaseous										
- methane	●●	●●	●	●●	●	●●	●●	●●	●	●
- DME		●●		●	●	●	●	●	●	●
- synthesis gas	●●	●●	●	●	●	●●	●●	●●	●	●
- hydrogen	●●			●	●	●	●●	●	●	●●

Matrix B4. Final energy use vs. heat conversion.

	Solid fuel combustion: grate	fluidized bed	pulverized	Solid fuel gasification	Liquid fuel combustion	Gaseous fuel combustion
CHP heat or direct heat - cooking	●●				●●	●●
- domestic hot water	●●	●●	●●	●●	●●	●●
- space heating	●●	●●	●●	●●	●●	●●
- illumination	●●				●●	●●
- cooling	●●	●●	●●	●●	●●	●●
- humidity control	●	●	●	●	●	●
- water purification	●	●	●	●	●●	●●
- drying	●●	●●	●●	●●	●●	●●
- industrial steam	●●	●●	●●	●●	●●	●●
CHP electricity or condensing electricity	●●	●●	●●	●●	●●	●●
Mechanical engine power				●	●●	●●

APPENDIX C. List of abbreviations.

ABFB	Atmospheric bubbling fluidized bed	
ACFB	Atmospheric circulating fluidized bed	
AD	Anaerobic digestion	
BIGCC	Biomass integrated gasification with combined cycle power plant	
BIGGT	Biomass integrated gasification with gas turbine plant	
BFB	Bubbling fluidized bed	
CDM	Clean development mechanism	
CFB	Circulating fluidized bed	
CHP	Combined heat and power production	
DME	Dimethyl ether	
EC	External combustion	
ECE	External combustion engine	
ETBE	Ethyl tertiary-butyl ether	
FAME	Fatty acid methyl ester (one group of biodiesels)	
FAEE	Fatty acid ethyl ester (one group of biodiesels)	
FC	Fuel cell	
FFV	Flexible fuel vehicle	
FT	Fischer-Tropsch process (for making synfuels)	
GHG	Greenhouse gas	
GT	Gas turbine	
HHV	High heating value, the stoichiometric energy content of a fuel	
HTU	Hydrothermal upgrading	
IC	Internal combustion	
ICE	Internal combustion engine	
ICE	Costa Rican national electricity company (el Institutio Costarricence de Electricidad)	
IR-PV	Infrared photovoltaic	
IGCC	Integrated gasification with combined cycle power plant	
LPG	Liquefied petroleum gas (propane and butane)	
MTBE	Methyl tertiary-butyl ether	
NG	Natural gas (mostly methane)	
ORC	Organic Rankine cycle	
P	Power	
PPO	Pure plant oil	
PBFB	Pressurized bubbling fluidized bed	
PCFB	Pressurized circulating fluidized bed	
REE	Rape oil ethyl ester (one type of FAEE biodiesel)	
RES	Renewable energy sources	
RME	Rape oil methyl ester (one type of FAME biodiesel)	
SME	Soy methyl ester (one type of FAME biodiesel)	
ST	Steam turbine	
syn	Synthetic	
UN	United Nations	
VT	Vapour turbine	
μ	Micro	
μT	Micro-turbine	
η	Conversion efficiency	
Subscripts:	e	electric
	m	mechanical
	t, th	thermal
	C	Carnot

APPENDIX D. Case studies in Costa Rica.

D1. Río Azul, electricity production from landfill gas.
D2. Coope Libertad – biogas for energy from coffee prosessing waste water.
D3. Farm Robago – pilot project on electricity generation from biogas.

D1. Río Azul, electricity production from landfill gas

The first landfill gas energy project in the Central America and Caribbean is in operation in landfill Río Azul in San José, the capital of Costa Rica. The project was enabled by the Clean Development Mechanism of Kyoto protocol. Contract of carbon emission reductions was made with the Dutch government. The landfill started operation in 1973. It receives waste from 12 municipalities in the Metropolitan Area. The landfill stays in operation until 2007. The landfill contains about 5 million tons of waste with an average composition of 50% organic materials and a potential to produce about 200 m^3 of landfill gas per ton of waste.

Figure 1. Electricity generation unit under construction in Río Azul in July 2004.

During most of the operation time waste was deposited on the landfill without any technical criteria; no biogas ventilation, no leachate collection or treatment. However, there have been some passive landfill gas emissions control; the landfill gas is vented through 122 chimneys, which were constructed during the filling.

The idea of the project is to reduce methane emissions from the landfill and at the same time utilize the energy content of methane in order to produce electricity. The current Costa Rican legislation does not require landfill operators to flare nor to recover landfill gas for use and treatment. The only requirement is to vent the landfill gas (e.g. passive emissions control) in order to reduce the risk of explosion and hazardous concentration of toxic gases. Thus, this project means a new kind of practice to be introduced to Costa Rica with the help of the CDM.

Construction or the project started in November 2003 and commercial electricity production is expected to start in August 2004. The construction will be performed by Corporate Group SARET and a British firm Combined Landfill Projects (CLP), with experience on similar projects, will act as technical supervisor. Three major suppliers /subcontractors will also participate: Caterpillar will supply the gas engines and related electro-mechanical equipment, Grampiam-Organics the gas pump and flare, and Roype S.A., a local subcontractor, will drill the wells. The project will be operated by SARET, acting as project owner. CNFL (Compañía Nacional de Fuerza y Luz) will buy the produced electricity from SARET.

The plant will have a capacity to produce about 3.5 MW of electricity. The operation time will be 10 years (2004-2013), but if gas production continues the operation time will be extended. Landfill gas production on the site is estimated to be about 2 000m^3/h and the carbon emission reduction potential is about 2.1 Mtons CO_2^{eq}. Emission reduction contract with the Dutch government is made for about 1/3 of this amount in order to insure the ability to meet the contract.

The system consists of recollection of the gas, including pipelines and pumps, electricity generation unit, with 4 generators, a flaring unit and an electricity distribution system (Figure 2).

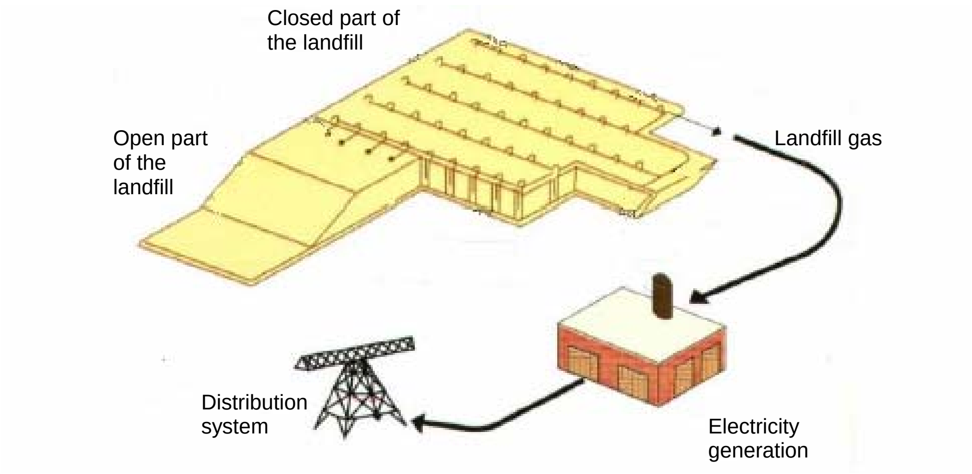

Figure 2. Schematic figure of the landfill gas collection and electricity generation (Vargas and Bach 2003).

The gas collection system consists of wells with 30 cm diameter. They are drilled to about 5 meters from the bottom of the landfill. The wells are distributed over the total landfill area. Pipes are inserted into the wells to collect the gas, and the pipes from different wells are connected to a primary pipe that leads to suction pump and finally to the electricity generation unit.

The collected landfill gas flows through separators and filters before entering the electricity generation unit in order to remove condensates. The capacity of the pumping system is about 2 500 m^3/h, while the estimated gas production is 2 000 m^3/h. Excess gas is burned in an enclosed flare. The capacity of the flare is enough to burn all the pumped gas in case the engines are turned off.

The electricity generation unit consists of four Otto engines (G3516) leased from Caterpillar. Each engine has 925 kW_e capacity. The engines are made specifically to resist corrosion caused by landfill gas.

Fact box Río Azul

Electricity production capacity	4 × 925 kW_e
Estimated landfill gas production	2000 m^3/h
Methane content in the gas	40-70 %
Carbon emission mitigation potential	2.1 Mtons CO_2^{eq}
Carbon emission mitigation contract	0.79 Mtons CO_2^{eq}
Operation time	2004-2013

The gas collection system has encountered some problems during the construction phase and some of these still need to be solved. First, the landfill has no proper structure, thus it was impossible to know what was deposited and where. This made it difficult to place the wells in most suitable places for methane extraction. Second, since the landfill has no active leachate collection system, leachate resting inside the landfill structure is being pumped together with landfill gas. In addition, leachate causes a risk of collapse in the landfill, when voluminous masses of liquid are removed from inside the landfill.

In July 2004 the methane extraction was 50% of the estimated and leachate caused still problems. Of the 105 installed methane extraction wells, only 60 were in use due to leachate problems.

Figure 3. Landfill site with pipes for gas collection.

Reference:

Vargas L. and Bach M. O. 2003. La biomasa en Costa Rica: una fuente limpia para la generacion de electricidad. International seminar on bioenergy and sustainable rural development. 5th LAMNET project workshop – Mexico 2003.

D2. Coope Libertad – biogas for energy from coffee prosessing waste water

Coffee processing facility Coope Libertad near San Jose, the capital of Costa Rica, has installed an anaerobic bioreactor to treat waste waters produced in coffee processing. The biogas produced in the bioreactor is utilized for energy production to cover some of the energy needs of the facility. The background of the case is in the changes made to the environmental legislation in Costa Rica and the increasing environmental demands by coffee consumers.


Figure 1. Coffee plant in Turrialba.

Previously the coffee sector in Costa Rica utilized significant amounts of water: about 3-6 m^3 per fanega (production unit, about 100 pounds of gold coffee). In year 1992 targets were set to reduce the contamination generated by the coffee sector by about 80% during the next five years. The main means to do this were: water recycling, separation of larger solid particles from the water, dry transportation of the pulp, dry de-pulping and treatment of residual waters. The treatment of residual waters could be done by utilizing aerobic or anaerobic treatment systems.

Figure 2. The Coope Libertad plant.

In Coope Libertad, an anaerobic treatment system for the pulp waste water was installed in addition to water use minimizing. The core idea behind this choice was the desire to explore the possibility to produce electricity from biogas and cut the electricity costs during peak hours of consumption. The solid pulp waste is composted behind the plant, and the composted material is sold. The water consumption was reduced from 4 m^3 to 0.3 m^3 per production unit and chemical oxygen demand (COD) in the outlet was reduced from 12,000 mg/l to 200 mg/l after the introduction of the treatment system (Table 1). Production in the plant decreased from 120,000 production units to 100,000 units but the quality was improved increasing the price of the coffee.

Table 1. Changes in the production system after reducing the water consumption and introducing the anaerobic waste water treatment system.

	Original	**Current**
Production	120,000 qq*/year	100 000 qq/year
Water consumption	4 m^3/qq	0.3 m^3/qq
Outlet COD	12,000 mg/l	200 mg/l

* 1qq=100 pounds of gold coffee

Figure 3. Gold coffee sacks ready for sales.

A 400 kW_e power production system was installed but is not in use anymore. It was meant to be able to cover the electricity needs during peak hours but gas production was overestimated. Also, the gas storage capacity is insufficient. Currently the biogas is led to a boiler and co-combusted with coffee husks and firewood to produce heat for coffee drying.

Figure 4. Boiler for biogas and coffee husks to generate heat for coffee drying.

Major drawback of the anaerobic waste water treatment system is that it is far more expensive than aerobic lagoon system. Thus, aerobic treatment is the favored treatment system. Only 10 of the 98 Costa Rican coffee processing plants have chosen the anaerobic treatment system. Coope Libertad is currently the only one making use of the energy content of the formed biogas.

D3. Farm Robago – pilot project on electricity generation from biogas

ICE, the Costa Rican national electricity company, has a pilot project in electricity generation from biogas in a farm Robago situated in the Pacific Central in Costa Rica in the province of Puntarenas in San Rafael. The project is aimed for finding out a suitable biogas production system for Costa Rican farms. Biogas production offers an interesting possibility to meet the waste treatment requirements by the state and at the same time reduce the electricity costs.

The farm Robago has 250 hectares of land. It concentrates mainly on livestock breeding for both milk and meat production and also chicken breeding. These activities are accompanied by some sugar cane and mango cultivation and pig breeding. Actual electricity consumption in the farm activities is about 4300 kWh/month.

Two simple unheated soft cover bioreactors are installed at the farm. The bioreactors are fed daily with manure produced by 100 cows during the 8 hours of milking (560 kg manure/day). The biogas production is about 40 m^3/day. The retention time in the reactors is 20 days. Mixing is done manually with the help of a hand wheel (Figure 1).

Figure 1. One of the bioreactors in the farm.

The produced biogas is led from the reactors to a dual-fuel diesel engine. The capacity of the diesel engine is 30 kW_e and the engine uses 70% of biogas and 30% of diesel oil as fuels. The electricity is used to operate ventilation and feeding systems for chicken and the milking equipment. The current system is sufficient to provide the electricity needed during milking and some hours of ventilation. The engine is provided by ICE for 4 years of demonstration. The bioreactors were invested by the farmer and after the demonstration project is over the farmer will buy the engine from ICE. Pay-back time for the investments is 4 years.

In the farm an LPG Otto engine, capable of utilizing biogas only, was also tested. Electricity production capacity of the engine was 25 $kW_{e.}$ However, the engine was not feasible in practice; in order to function properly, it required constant surveillance by an engineer. Thus the farmer utilizes rather the diesel engine.

Figure 2. Dual-fuel Diesel engine for electricity generation.

In the future, the farm is planning to increase the biogas production in order to be completely self-sufficient in electricity production. This will be done by starting to utilize pig and chicken manure alongside with the cow manure.

The digested manure is a good fertilizer and it fulfills the requirement for BOD level (not suspended solids) for depositing. It also helps to control flies and bad odors and reduces the amount of bacteria in the manure.

ICE is currently offering consultation services for farms interested in biogas production. There have been several interested farms and some new installations are already under construction. Even if the farm would not be large enough for the electricity production from biogas to be feasible, it can still be possible to use the biogas for water heating or other purposes in the farm.

Table 1. Technical information.

Amount of animals	100
Amount of bioreactors	2
Capacity of bioreactors	43 m^3
Approximate biogas production	40 m^3/d
Hydraulic retention time	20 d
Type of the plant	Dual-fuel Diesel
Capacity of the plant	30 kW_e
Electricity generation (70% biogas, 30% diesel)	4000 kWh/month
Electricity consumption in the farm	4300 kWh/month

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