1. Biomass Applications

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1.1 Introduction

Biomass-fuelled heating is the oldest and most well established form of energy provision in the world, being inextricably linked with the development of the human race. However, it was largely made redundant by higher energy-density fossil fuels, and its application in modern energy systems, particularly in industrialised nations, has until recently played a declining role. Renewed interest in biomass-fuelled energy systems stems from a number roots. These are dominated by interest in reducing greenhouse gas emissions, the advent of efficient new biomass conversion technologies, and reasonably sustained high fossil fuel prices and high price volatility.

Electricity produced from biomass fuels is considered to be renewable, because carbon dioxide produced by the generation process is sequestered again when the biomass crop (or other biomass source) grows. Although results differ between life cycle analyses of biomass technologies, it is apparent that the technology has the potential for very low life cycle greenhouse gas emissions rates [1-3] or may even achieve more than complete closure of the carbon cycle (i.e. carbon-negative) when chemical absorption of CO_2 is employed [4].

Globally, biomass provides approximately 15% of the primary energy needs. In the EU-15, this figure is reduced to 4% [8]. Bio-electricity production capacity in the EU-15 currently represents approximately 1.4% of total production capacity [6], and is primarily associated with the forestry and wood processing industries. Plants are generally applied as combined heat and power (CHP), where heat produced is utilised in industrial processes or district heating [5].

Biomass technologies related to the production of electricity can be broadly classified into five categories; direct combustion, co-firing, gasification, pyrolysis, and anaerobic digestion. These technologies are fuelled from a variety of feedstocks that can be broadly classified by source (plant or animal) and physical state (solid, liquid or gas). The most common fuel sources are residues from primary biomass production, by-products and wastes from a variety of processes and dedicated plantations [6].

1.2 General Issues on Biomass Technologies

Biomass refers to all non-fossil biological materials which are the direct or indirect products of photosynthesis. The chemical energy stored in biomass may be made available for power production through different processing routes, the optimum technological choice depending on the physical and chemical characteristics of the biomass and the economics of the different production chains. A bioelectricity production chain starts with cultivation of the biomass fuel or its collection as residues or waste products from other operations. Fuel storage, transport and pre-treatment are usually significant logistical and cost components of bioelectricity production. Generation of electricity from biomass may involve direct combustion of the biomass at a thermal power plant or the production of intermediate fuels which are then supplied to power plants. The biomass conversion routes may be classified as thermo-chemical, physio-chemical or biological (Figure 1).

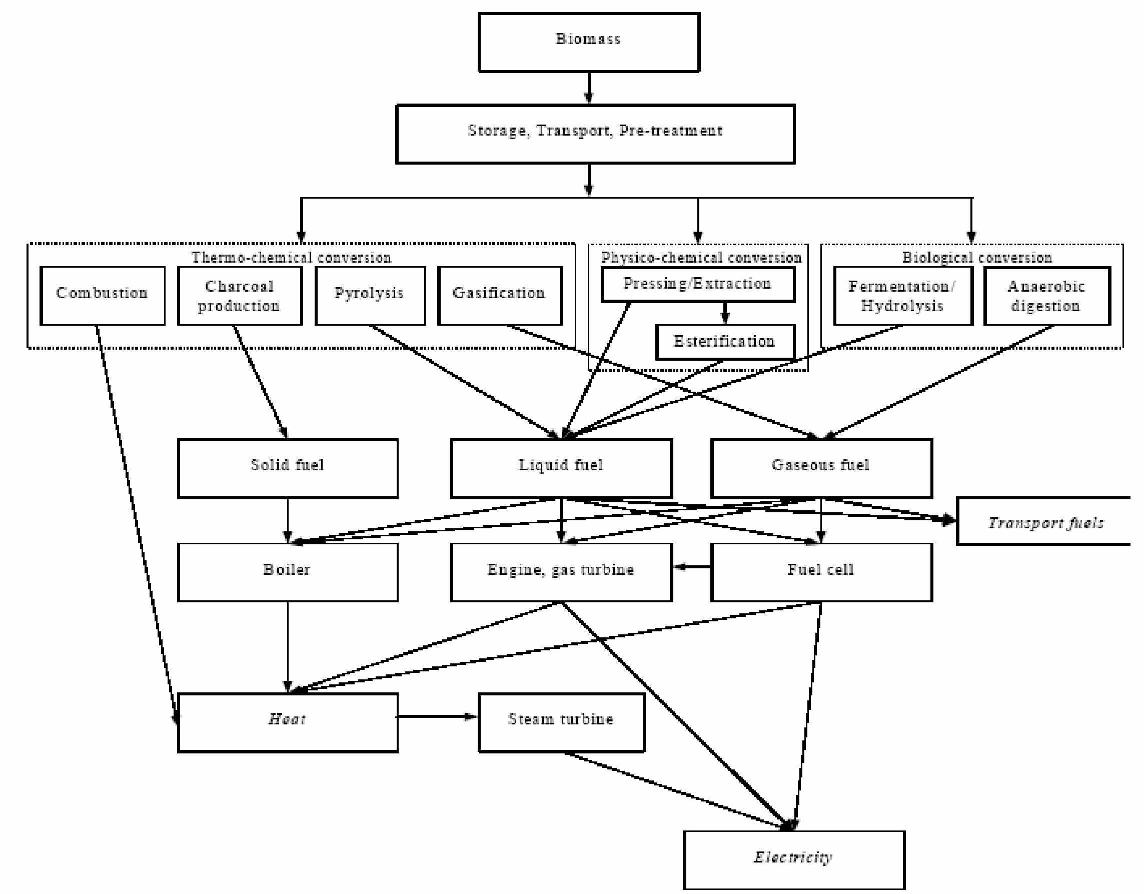

Figure 1: Routes for production of electricity from biomass [6]

1.2.1 Peculiarities

In addition to the environmental benefits of bioelectricity, power production from biomass provides a number of advantages when compared with other forms of renewable electricity production and with fossil-based and nuclear power.

Biomass, the energy carrier required at the beginning of a bioelectricity production chain, is available in the form of a very wide number of plant and plant-derived materials occurring all over the world. Technical, economic, social and environmental factors mean that certain types of biomass resources are currently most suitable for bioenergy production. Table 1 provides examples of the main types of biomass resources currently exploited.

Table 1. Examples of biomass resources [21].

Biomass Resource Categories	Examples
Residues from primary biomass production	Wood from forestry thinning and felling residues; straw from a variety of cereal crops; other residues from food and industrial crops such as sugarcane, tea, coffee, rubber trees and oil and coconut palms
By-products and wastes from a variety of processes	Sawmill waste, manure, sewage sludge and organic fractions on municipal solid waste, used vegetable cooking oil
Dedicated plantations	Short rotation forestry crops such as eucalyptus and willow; perennial annual crops such as miscanthus; arable crops such as rapeseed and sugarcane

A key advantage of bioelectricity production is that, unlike many other renewables, it is based on a fuel (biomass), and like fossil-based electricity, it is available on demand. Energy is stored in biomass fuels (provided natural decomposition is avoided) until required by the conversion process. Other forms of renewable electricity do not have this natural storage feature but instead are generated in response to variable environmental conditions such as wind speed or sunlight intensity. Bioelectricity is the only renewable electricity technology that is readily dispatchable.

Because of the diverse range of potential fuels, bioelectricity production chains can involve a complex collection of stakeholders, with potential impacts on the agriculture, agro-industry, forestry and waste management sectors. Power production from biomass can provide additional income streams and boost employment in these sectors. Of particular importance in the EU is the potential for energy crop production, which could provide a much-needed boost to agriculture in many European countries.

Electricity production from biomass does suffer from a number of limitations in comparison with fossil-fuel based electricity. Biomass fuels have lower energy densities than fossil fuels, and are usually available in less convenient forms. Additionally, the relatively high costs of transporting the low energy density and often dispersed feedstock limit the availability of economic feedstock for a given conversion plant and therefore limit the scale of the plants. The smaller scale bioelectricity plants have lower efficiencies than larger fossil-based electricity plants.

1.2.2 Environmental aspects

Production of electricity from biomass can affect the environment in various ways, with potentially significant impacts that range in scope from the local to the global. Local impacts that must be managed include particulate and gaseous emissions from the conversion plant, solid waste (ash) disposal, increased demand for local water resources, noise, odour from some types of feedstock, physical intrusion and increased levels of traffic. On the other hand, some bioenergy production chains also present opportunities for improving local environments through reducing erosion and nutrient run-off from agricultural land, providing an effective disposal route for waste products and even increasing biodiversity. Today the most important environmental benefit of bioelectricity production results from its almost carbon-neutral production cycle, which means that as an alternative to fossil fuel-based electricity, bioelectricity can reduce anthropogenic contributions to global warming.

As a renewable technology, bioelectricity does not depend fundamentally on depletion of primary resources, although some non-renewable resources are used up in any bioenergy production chain. This includes fossil fuel used directly or indirectly in production, transport, and pre-treatment of the feedstock.

If dedicated energy crops are used as feedstock, the environmental impacts of land use change and use of water, fertilizer and other agricultural inputs can be significant. Ploughing up grassland or removing forest cover in order to introduce a new crop releases significant amounts of soil carbon and would generally be discouraged. On the other hand, where perennial energy crops are replacing annual crops, reduced soil disturbance, greater soil cover and therefore reduced erosion result. Soil organic matter, soil carbon and biodiversity are also improved [6]. The use of mineral fertilizers and other agricultural chemicals impacts negatively on the greenhouse gas balance of the bioenergy production chain and could lead to problems of leaching into local water courses. However, short rotation coppice, miscanthus and other favoured energy crops require much lower fertilizer inputs than common agricultural crops and their introduction could therefore be environmentally beneficial. Commercial fertilizer inputs could also be reduced through recycling of nutrients in the ash from the biomass power plant. With high biomass productivities, energy crops tend to have higher water requirements than the vegetation they replace, and energy cropping could therefore reduce the amount of water flowing into rivers and percolating into local ground water, thereby impacting negatively on ecosystems which depend on this water. On the other hand, the high water usage of energy crops may be desirable in areas which are prone to flooding or which have problems related to high water tables [20].

Because the carbon dioxide emitted during conversion of biomass to electricity is matched by that sequestered during biomass growth, life-cycle CO_2 emissions from bioelectricity are very low, with net emissions resulting from use of fossil fuels for cultivation, harvesting, transport and pre-treatment and processing of the biomass fuel. CO_2 emissions from procurement of biomass fuels are also generally lower than from procurement of fossil fuels [10]. Replacement of fossil-fuel-based electricity with bioelectricity therefore results in significant reductions in greenhouse gas emissions.

The levels emissions of other gases and particulates from biomass power plants depend on the fuel, conversion technology, plant operational characteristics and the use of emission reduction measures. Because of the generally low level of sulphur in biomass, SO_x emissions are usually substantially reduced in bioelectricity production compared with coal or oil-based electricity. NO_x production from direct biomass combustion is strongly dependent on thermal NO_x formation, which involves nitrogen in the air, and emissions are therefore comparable to those of fossil fuel combustion. It must be noted that modern fossil fuel-based power plants use very effective methods to ensure that NO_x emissions are maintained below maximum acceptable levels.

With good planning, design and management of the entire bioelectricity production chain, it is usually possible to limit any negative environmental impacts to satisfactory levels.

1.3 Description of Biomass technologies

1.3.1 Biomass Direct Combustion and Co-Firing

Biomass direct combustion is generally based on the Rankine cycle, where a steam turbine is employed to drive the generator. This type of system is well developed, and available commercially around the world. Most bioelectricity plants today are direct-fired [11]. In direct combustion, steam is generated in boilers burning solid biomass which has been suitably prepared (dried, baled, chipped, formed into pellets or briquettes or otherwise modified to suit the combustion technology). Direct combustion technologies may be divided into fixed bed, fluidized bed and dust combustion (Figure 2).

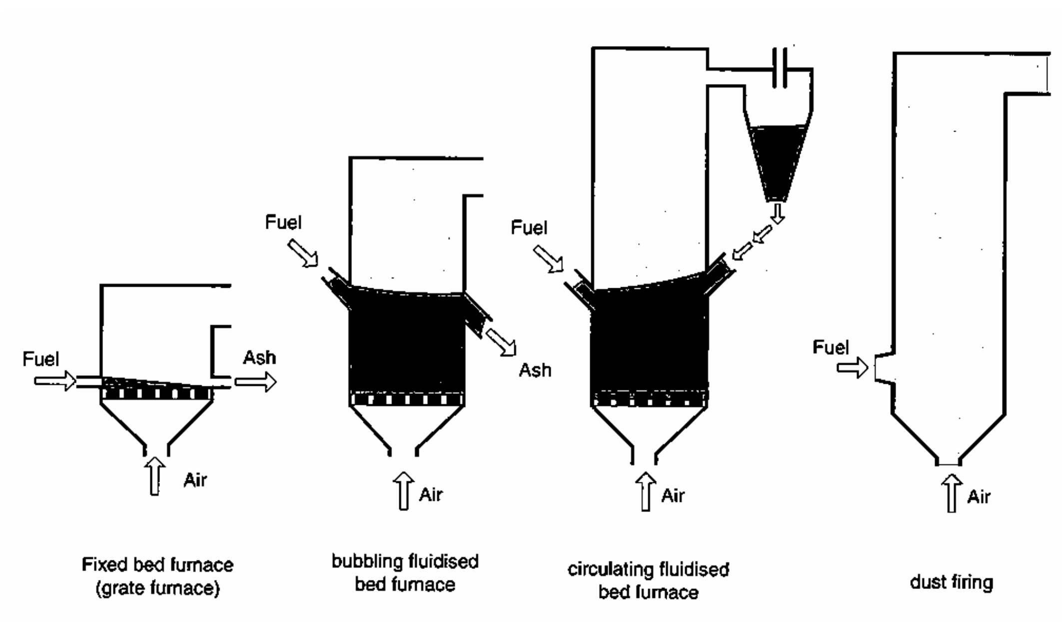

Figure 2: Direct combustion technologies [10]

In fixed bed systems, the biomass fuel burns in a layer on a grate which moves to transport the fuel through the furnace towards ash removal. Fixed bed technologies are reliable and generally have relatively low investment costs compared with other direct combustion technologies. However, a given fixed bed boiler design can usually handle only a limited range of biomass fuel types.

In fluidised bed boilers, the fuel burns in a constantly mixing suspension of hot, inert, granular bed material (usually silica sand or dolomite) into which combustion air enters from below. Because of the very effective mixing achieved, fluidised bed plants are very flexible in their ability to burn different biomass fuel types, although the fuel particle size must be relatively uniform. Fluidised bed systems have high investment and operating costs.

In dust combustion, fuel in the form of small particles such as sawdust or fine wood shavings is injected along with air into the combustion chamber, and combustion takes place with the fuel in suspension.

Fluidised bed systems are rapidly becoming the preferred technology for larger systems (>10MW_e) because of their superior combustion characteristics. Biomass direct combustion plants are typically relatively small, usually less than 100MW_e [6]. With higher capital and operating costs than other direct combustion systems, fluidised bed systems are normally only considered for applications with capacity over about 20 MW_{th}. Dust combustion systems are available for thermal capacities between 2 and 8 MW [10]. The smaller scale of biomass direct combustion systems leads to generally higher unit costs and lower plant efficiencies compared with large-scale fossil fuel plants.

Biomass co-firing refers to the combustion of a mixture of fossil fuels such as coal and biomass fuels. Biomass proportions in co-firing range from a few percent up to approximately 40%, although most existing commercial projects are in the range of 3 to 5% by mass. Most biomass co-firing today is practiced on pulverised coal boilers, at power stations with capacities in the range 50-700MW_e. Co-firing is a very attractive option for producing electricity from biomass because it takes advantage of the large investment, established power generation infrastructure and higher efficiencies of existing large-scale power plants while requiring comparatively low investment costs to include a fraction of biomass in the fuel. Because of the lower nitrogen and sulphur contents in biomass compared with coal, and the virtually CO_2-neutral nature of biomass-to-power production chains, biomass co-firing can be a very effective method for reduction of NO_x, SO_x and greenhouse gas emissions from fossil-fuelled power plants.

The options for implementing biomass co-combustion in pulverised coal power stations may be divided into three categories:

In **direct co-firing**, the appropriately prepared biomass is fed directly into the coal furnace. There are a number of ways in which this may be done. The simplest approach involves blending the biomass with coal on the fuel pile and providing the mixed fuel as input to the coal mills before supply to the boiler's coal feeding system. This method is generally used at low biomass blend percentages. Alternatively, the biomass fuel preparation and feeding may be handled by a separate system which then feeds the prepared biomass to the coal burners or to separate, dedicated burners.

Indirect co-firing involves separate gasification of the biomass to produce a low calorific value fuel gas which is then burnt in the coal-fired boiler furnace. The gasifier is usually of the air-blown, atmospheric pressure, circulating fluidised bed type. Indirect co-firing avoids risks to burner and boiler operation associated with direct combustion, but is more expensive than direct co-firing and is currently only available for wood fuels [9].

In **parallel co-firing**, biomass is combusted in a separate boiler and the steam produced is fed to a coal-fired power station where it is upgraded to the higher temperature and pressure conditions of the large coal plant. The overall efficiency of conversion from energy in biomass to electrical energy is thereby increased. In an alternative form of parallel co-firing, the flue gases from combustion of biomass in a separate combustion chamber are fed into the boiler of the coal power plant [12]. The need for a separate biomass combustion installation in parallel co-firing leads to higher costs.

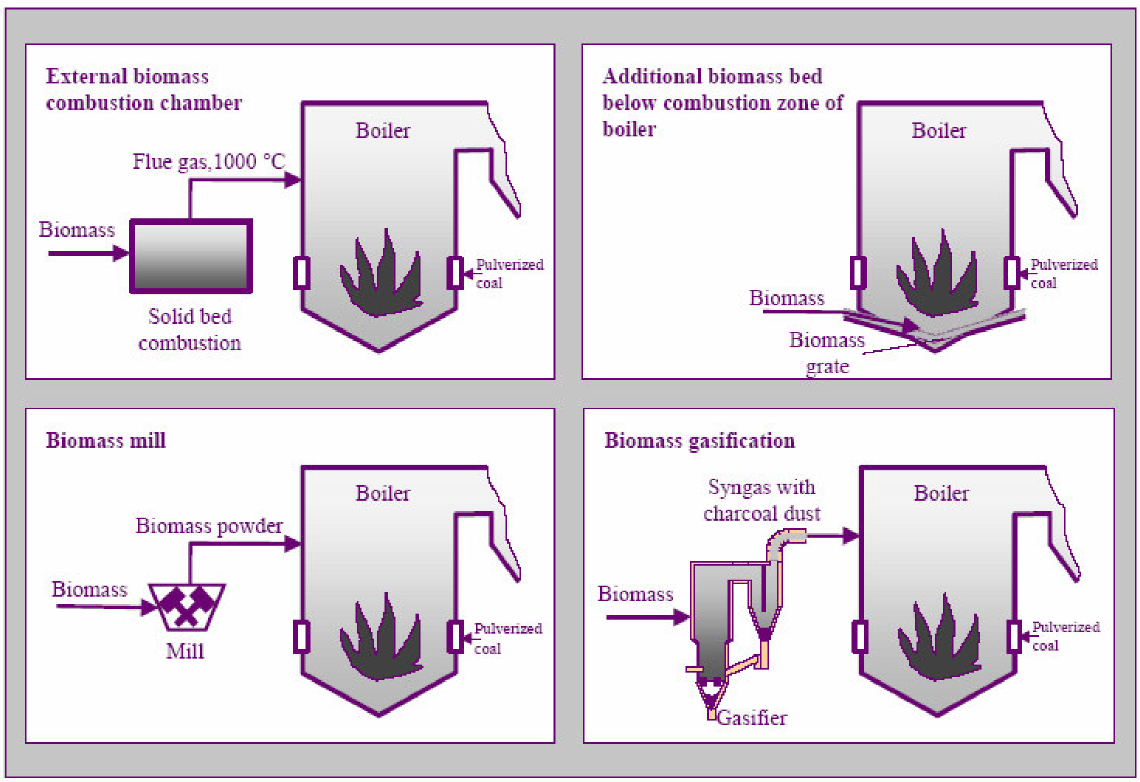

Figure 3: Methods for co-firing biomass with pulverized coal. Clockwise from upper left: parallel co-firing with flue gases from biomass combustion fed to coal-fired boiler; direct co-firing with separate biomass combustion on grate; indirect co-firing; direct co-firing with separate biomass feed and burner [12]

1.3.2 Biomass Gasification

Gasification is the conversion by partial oxidation at elevated temperature of a carbonaceous feedstock into a gaseous fuel. The product gas is a mixture of hydrogen, carbon monoxide, methane, carbon dioxide, water vapour, and small quantities of heavier hydrocarbons. The oxidising medium is normally air, oxygen or steam. Inorganic residues and an oil-tar fraction are also produced in the process. The product gas generally has a heating value between one tenth and half that of natural gas, depending on the composition of the biomass input and the gasification process employed. This gas may be burnt in boilers or, after cleanup to remove tars, may be used as a fuel in engines or gas turbines. It can also be reformed to produce fuels such as methanol or hydrogen. Gasification enables the production of bioelectricity using modern aeroderative gas turbines, giving relatively high efficiency (compared with Rankine cycle systems) and low unit costs at the modest scales of biomass systems. Gasification also provides a route for small scale, decentralised bioelectricity production using gas engines.

A number of gasifier designs have been demonstrated for use with biomass. These can be categorised as either fixed bed or fluidised bed (Figure 4). In the updraft gasifier, the biomass is fed into the top of the unit and moves slowly downward as it goes through the different stages of the gasification process, with ash emerging at the bottom of the reactor. Air is fed through from the bottom through a grate. Just above the grate, air comes into contact with hot char and combustion occurs. The resultant hot gases rise and heat the biomass further up, causing pyrolysis in that layer. The gases released rise further and dry the incoming biomass in the top layer, before exiting the gasifier at the top. This type of gasifier produces significant amounts of tars in the fuel gas and is not suitable for applications using gas engines or gas turbines.

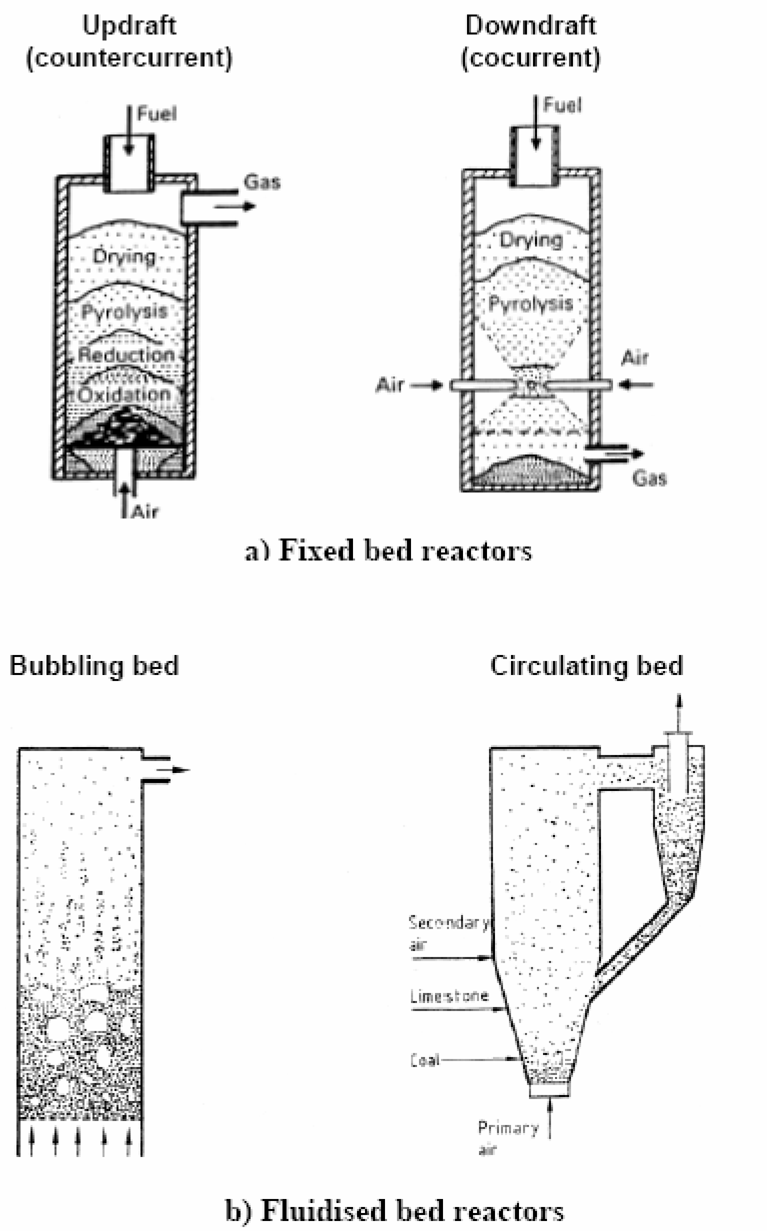

Figure 4: Basic principles of main biomass gasifier types [13]

In the downdraft gasifier, the biomass and air move in the same direction, and the product gas leaves the reactor after passing through the hot zone. Temperatures of around 1000°C in the hot zone cause cracking of some of the tars in the gas, and the product gas from downdraft gasifiers usually have low tar content.

In fluidised bed gasifiers, biomass particles undergo drying, pyrolysis and gasification in a hot, fluidised mixture with inert bed material and air. The fluidised bed process enables good heat transfer between the gas and solid phases, and the high temperatures involved also provide some cracking of tars in the gas. Circulating fluidised bed gasifiers employ more turbulent mixing than bubbling fluidised bed systems, and use cyclones to separate solid particles from the gas stream before returning them to the bottom of the riser section. Fluidised bed gasifiers have higher throughput capacities than fixed bed gasifiers and have less stringent requirements for fuel type (they can process mixtures of woody and herbaceous fuels) or condition (they can process reasonably wet biomass).

Much recent development activity has focused on fluidised bed systems and system coupling with combined cycle gas and steam turbines (Figure 5). For combined cycle applications, pressurised fluidised bed gasifiers avoid the need to compress the fuel gas prior to burning it in the combustion chamber of the gas turbine. However, pressurised gasifier systems are more complex and costly than atmospheric systems. Biomass Integrated Gasification Combined Cycle (BIGCC) systems can achieve efficiencies of up to 50% for electricity production, although at this demonstration and early commercialisation stage capital costs are high [6].

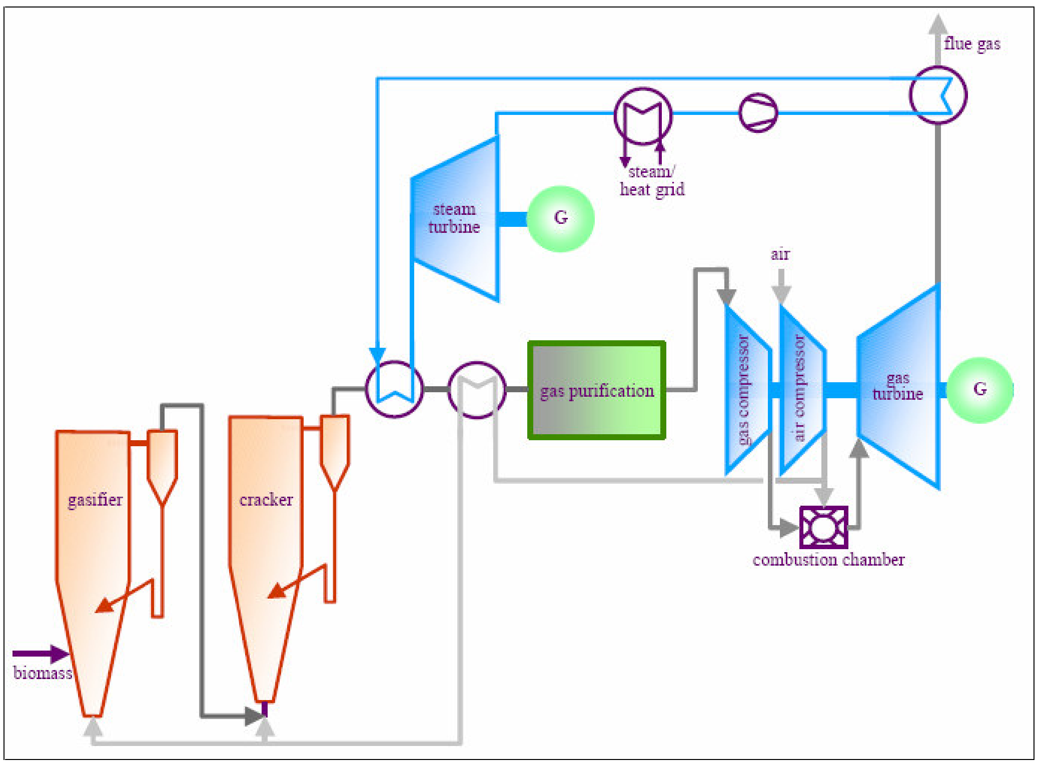

Figure 5: Biomass gasification combined cycle (BGCC) system schematic [12]

1.3.3 Biomass Anaerobic Digestion

Anaerobic digestion is a biological process that converts solid or liquid biomass to a gas in the absence of oxygen. The product gas (biogas) is a mixture of methane and carbon dioxide, with small proportions of other gases. Any solid or liquid waste residues can be used as compost and fertilizers. Anaerobic digestion is a very effective method of treating high moisture content organic wastes, and many implementations of anaerobic digestion are driven by waste management needs, with biogas as a valuable by-product. Feedstocks suitable for anaerobic digestion include sewage sludge, agricultural and industrial organic wastes, animal by-products (categories 2 and 3) and the organic fraction of municipal solid wastes (MSW) [15].

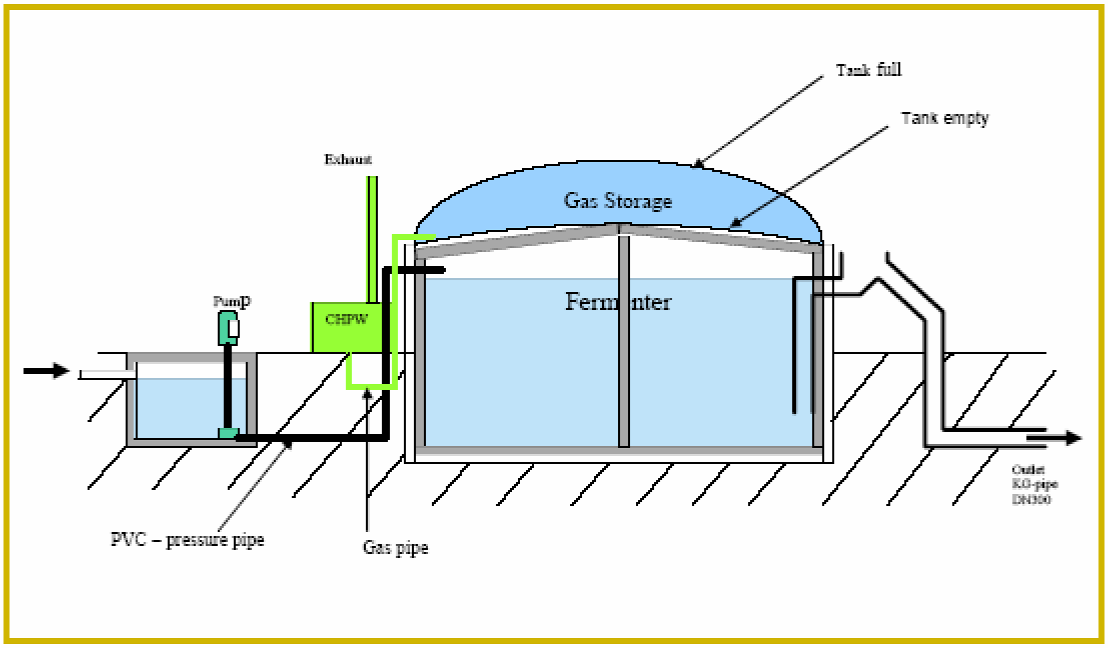

Figure 6: Agricultural waste digester design commonly used in Europe [13]

Biogas contains 60-70 % methane and 30-40 % carbon dioxide by volume, and has a lower heating value of value of 18-29 MJ/m^3 (pure methane has a lower heating value of 36 MJ/ m^3) [16]. Typically between 20% and 40% of the heating value of the feedstock is contained in the biogas [17]. For electricity production, biogas is commonly burnt in internal combustion engines, which may include heat recovery for combined heat and power production. Electrical capacities range from tens of kW_e to several MW_e [15]. Biogas may also be burnt in gas turbines; at larger scales, combined cycle systems may be economically justified.

1.3.4 Future Biomass Technologies

1.3.4.1 Biomass Pyrolysis

Biomass pyrolysis is the thermal decomposition of biomass in the absence of oxygen. The products of decomposition are solid char, a liquid known as bio-oil or pyrolysis oil and a mixture of combustible gases. The relative proportions of solid, liquid and gaseous products are controlled by process temperature and residence time, as indicated in Table 2. In recent years there has been much research interest in fast pyrolysis of biomass, in which production of bio-oil is maximised. Flash pyrolysis, which uses higher temperatures and shorter residence times than fast pyrolysis, is similarly aimed at maximising bio-oil production, with bio-oil yields of 75-80%. Bio-oil has a lower heating value of about 16MJ/kg and after suitable upgrading, can be used as fuel in boilers, diesel engines and gas turbines for electricity or CHP generation. As a liquid with higher energy density than the solid biomass from which it is derived, bio-oil provides a means of increasing convenience and decreasing costs of biomass transport, storage and handling. Bio-oil production also offers the important advantage of separating fuel production from power generation, enabling independent operation of both processes at the most economical scales.

Table 2: Phase makeup of biomass pyrolysis products for different operational modes

Mode	Conditions	Liquid	Char	Gas
Fast Pyrolysis	Moderate temperature, short residence time particularly for vapour	75%	12%	13%
Carbonisation	low temperature, very long residence time	30%	35%	35%
Gasification	high temperature, long residence times	5%	10%	85%

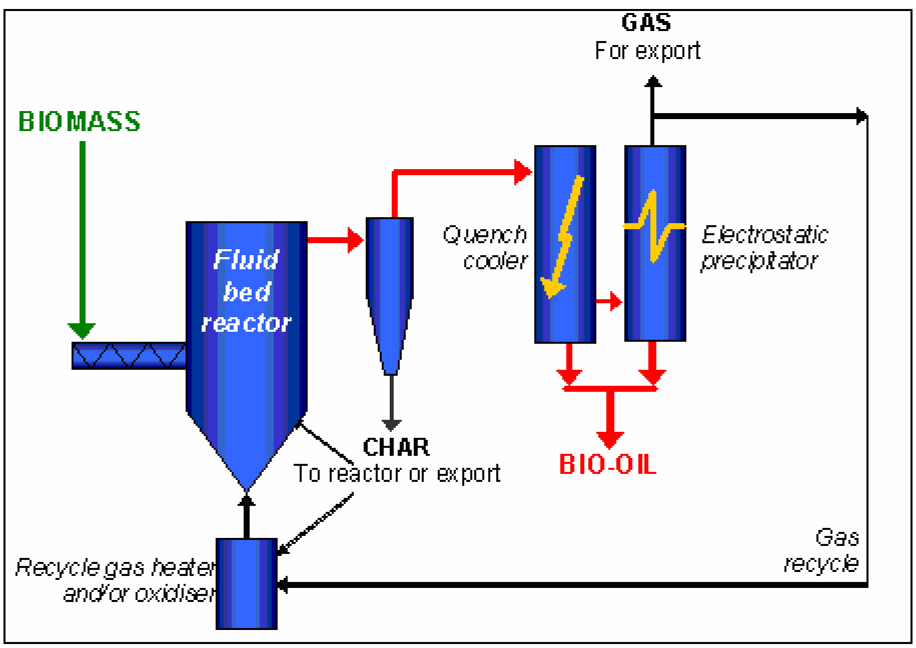

Figure 7: Fast pyrolysis process [18]

1.4 Present Biomass Market

Biomass electricity production is slowly expanding in Europe, with widely varying levels of installed capacity and production. In 2002, installed bioelectricity in the EU-15 was about 6300 MW, or about 1.4% of total installed electricity generating capacity [6]. The greatest installed capacities were in Sweden and Finland, where bioelectricity installed capacity represented 4.6 and 8.1% of total installed electricity generating capacity respectively (Figure 8). Bioelectricity capacity more than doubled in the EU-15 between 1990 and 2001. While bioelectricity capacity and production are relatively low in the newer member states of the EU, the Joint Research Centre of the EU reports that between 1997 and 2001, electricity production from biomass grew by 102 % in four new member states Czech Republic, Hungary, Poland and Slovakia [9]. Altogether, the countries of the EU-25 generated over 39 TWh of bioelectricity in 2002 (Table 3).

In 2001, 54% of bioelectricity production in Europe was from solid biomass, mainly wood. 76.6% of this production was in combined heat and power plants, with the remaining 23.4% from electricity-only plants. The capacity for electricity from solid biomass grew by 5.2% annually between 1990 and 2000. The majority of solid biomass electricity plants are based on direct combustion, with the use of co-firing increasing in the UK, Denmark, Finland, Sweden and other countries.

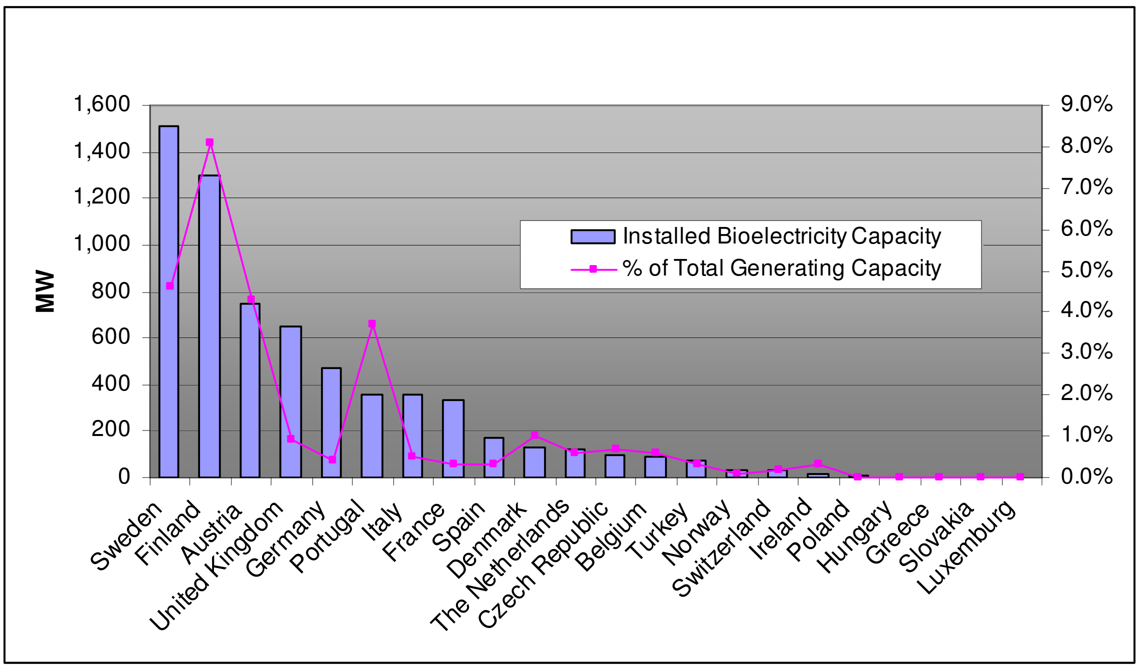

Figure 8: Bioelectricity installed capacity in OECD Europe in 2002 [6]

Table 3: Bioelectricity production in the EU in 2002 [19]

	Total Bio-electricity Production (GWh)	Bio-electricity Production as % of Total Electricity Consumption
Austria	2,068	3.5%
Belgium	718	0.9%
Denmark	2,257	6.4%
Finland	8,453	10.1%
France	3,444	0.8%
Germany	4,735	0.9%
Greece	79	0.2%
Ireland	81	0.3%
Italy	2,480	0.8%
Luxemburg	61	1.0%
The Netherlands	2,538	2.3%
Portugal	1,620	3.6%
Spain	3,829	1.8%
Sweden	4,729	3.2%
United Kingdom	870	0.2%
Cyprus		0.0%
Czech Republic	543	0.9%
Estonia	-	
Hungary	76	0.2%
Latvia	32	0.5%
Lithuania	4	0.05%
Malta	0	0.0%
Poland	560	0.5%
Slovakia	155	0.6%
Slovenia	73	0.6%
Norway	297	0.2%
EU-15	37,962	1.5%
New EU Member States	1,443	0.5%
EU-25	39,405	1.4%

Electricity production from biogas was 7.5 TWh or 19.6 % of total bioelectricity production in the EU-15 in 2001. The United Kingdom was the biggest biogas electricity producer in the EU, generating 2.9 TWh of electricity from biogas in 2001. Germany and Italy also generate significant amounts of electricity from biogas (2.0 TWh and 0.7 TWh respectively in 2001). Among the new Member States, Czech Republic is the largest producer of electricity from biogas (133 GWh in 2001) [9].

1.5 Future Development

Apart from generally smaller-scale operations which are based on negative or low-cost waste or by-product feedstocks, bioelectricity production is not economically competitive with large-scale fossil fuel-based electricity without economic incentives. As bioenergy production increases, high yielding purpose-grown biomass feedstocks and more efficient and economical conversion processes will be required to assure the competitiveness and material contribution of bioelectricity production. The dispersed nature and low energy density of biomass feedstock will continue to be a challenge in relation to the scale of dedicated bioelectricity plants and therefore their economic performance. Table 4 gives indicative efficiencies and capital costs of bioelectricity in 2002 and 2020.

The greenhouse gas reduction potential of bioelectricity and the potential economic benefits to rural communities are likely to be the most important drivers of bioelectricity production in the medium term. Development of the bioelectricity sector will be critically dependent on the existence of a favourable policy framework. With relatively high unit costs and the need for assured, reliable supplies of biomass feedstock over the lifetime of any new conversion plant, tax or other incentives recognising the environmental and rural development benefits of bioelectricity will be required for further development and increased competitiveness of the sector.

Table 4: Capital costs and efficiencies of bioelectricity technologies [6]

Power generation technology	Capital cost €/kW$_e$ (2002)	Capital cost €/kW$_e$ (2020)	Electrical efficiency	Cost of electricity (2020)[2]
Existing coal – co-firing	250	250	35-40%	€0.024-0.047/kWh
Existing coal – parallel firing	700	600	35-40%	€0.034-0.059/kWh
Existing natural gas combined cycle – parallel firing	700	600	35-40%	€0.034-0.059/kWh
Grate/fluidized bed boilers + steam turbine[1]	1500-2500	1500-2500	20-40%	€0.057-0.14/kWh
Gasification + diesel engine or gas turbine[1]	1500-2500	1000-2000	20-30% (50kW$_e$-30MW$_e$)	€0.050-0.12/kWh
Gasification + combined cycle	5000-6000	1500-2500	40-50% (30 MW$_e$-100MW$_e$)	€0.053-0.10/kWh
Wet biomass digestion + engine or turbine	2000-5000	2000-5000	25-35%	€0.052-0.13/kWh
Landfill gas + engine or turbine	1000-1200	1000	25-35%	€0.026/kWh
Pulverised coal – 500 MW$_e$	1300	1300	35-40%	€0.048-0.050/kWh
Natural gas combined	500	500	50-55%	€0.023-

cycle – 500 MW_e				0.035/kWh

[1]Smaller scale systems will be characterized by the higher costs and lower efficiencies indicated in the value ranges. Larger scale systems will be characterized by the lower costs and higher efficiencies indicated in the value ranges.

[2]15% discount rate; biomass fuel cost between €2 and 4/GJ except for digestion and laqndfill gas plants where fuel cost assumed to be zero; coal cost €1.6/GJ; natural gas cost between €1.5 and €3/GJ. The cost of electricity is calculated for supply of electricity only and the supply of combined heat and power could reduce the electricity cost significantly.

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