Biomass for Heat and Power

Highlights

- **Process and Technology Status –** On a global scale, biomass supplies more than 1% of the electricity demand, i.e. some 257 TWh per year (IEA, 2009a). Based on up-to-date combustion technologies, biomass and waste also supply approximately 4.5 EJ (105 Mtoe) of direct heat to the industrial and residential sectors, and 2 to 3 EJ (47 to 70 Mtoe) of heat from combined heat and power (CHP) plants (IEA, 2008). These estimates do not include traditional biomass combustion mostly used in developing countries. In the IEA countries, the use of combustible renewables (especially solid biomass) has a significant impact on the energy balance of countries and regions with abundant primary resources such as the European Nordic countries, Austria, and Switzerland while the use of biogas is increasing in Germany, the Netherlands, the United Kingdom, and Italy (IEA, 2009a). Power generation and CHP based on biomass and waste, as well as on biomass co-firing in coal-fired power plants, are also rapidly growing. In Germany, for instance, the growth of biomass-based CHP amounted to 23% per year in the period 2004-2008 (Fritsche et al, 2009) and state-of-the-art plants are characterised by high-performance steam parameters and efficiency. The capacity of biomass CHP plants varies considerably. Biogas anaerobic digestors are usually associated to gas-fired engines for heat and power generation with electrical capacity from tens of kW_e up to a few MW_e. Biomass-fired power plants and CHP plants have capacities ranging from a few MW_e up to 350 MW_e. Small and medium-size CHP plants are usually sourced with locally available biomass. Large CHP plants and coal/biomass co-firing power plants require biomass sourcing from a wide region and/or imported wood or forestry residues. Biomass CHP plants are mature technologies while biomass integrated gasification combined cycles (BIGCC), which offer high technical and economic performance, are currently in the process of entering the market, following the industrial demonstration phase.
- **Costs –** The investment costs of biomass CHP and power plants with capacities of up to 50 MW_e are between \$3,000 and \$6,000/kW_e (US\$2008). The annual operation and maintenance cost (O&M) of the CHP plants is approximately \$100/kW_e. The incremental investment cost and the annual O&M cost of biomass co-firing in coal-fired power plants are approximately \$335/kW_e and about \$12/kW_e, respectively. The investment costs of anaerobic digestors with gas-engines for CHP are in the range of \$3,000 to \$5,000/kW_e, with annual O&M cost of about \$ 300/kW_e.
- **Potential & Barriers –** Biomass-based CHP or power generation is widely used in regions that have ample fuel wood resources, forestry or agricultural residues. A business plan including the cost of the biomass resource collection and logistics is needed to ensure that CHP or power generation from solid biomass is economically viable. For large-scale biomass co-firing in coal-fired power plants, the location close to a large harbour is economically important. Biomass use in CHP plants may compete with other, non-energy uses of agricultural residues such as straw, or with wood processing industry (i.e. pulp and paper) in the case of forestry residues. Increasing competition between different markets may increase the price of biomass. Large-scale use of biomass for power generation or co-firing may raise sustainability issues and limit the potential of biomass CHP and co-firing technologies.

Process and Technology Status – In the IEA countries, the use of solid biomass for heat and power generation, including combined generation, started during the 1970s, in the wake of the oil crises. Currently, on a global scale, biomass supplies more than 1% of the electricity demand, i.e. approximately 257 TWh per year (IEA, 2009a). Along with waste, biomass also supply approximately 4.5 EJ (105 Mtoe) of direct heat to the industrial and residential sectors, and between 2 and 3 EJ (47 to 70 Mtoe) of heat from combined heat and power plants (CHP). In Europe, the use of biomass is significant in regions with ample biomass resources, e.g. the Nordic countries, Austria, and Switzerland (IEA, 2009b). The status of major biomass technologies is highlighted in Figure 1.

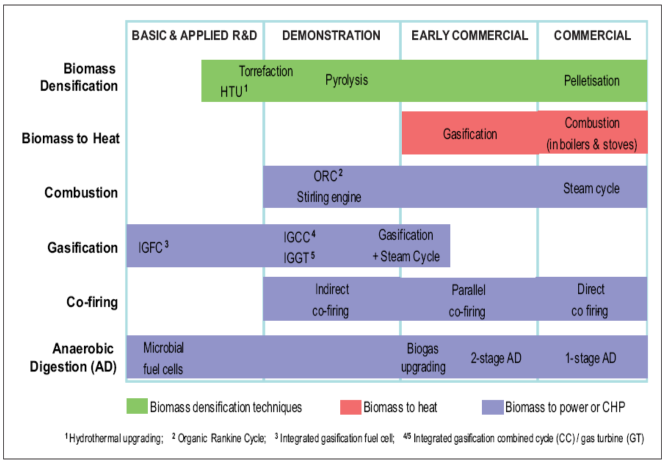


Fig. 1 - Status of major biomass technologies (IEA Bioenergy, 2009)

- **Biomass-based power generation and CHP –** Biomass-fired power and CHP plants can be characterised by the boiler technology. **Water-cooled vibrating grate (VG)** boilers (Figure 2) are an established technology for power generation from wood residues. Based on natural circulation, these boilers are designed to burn low-heating-value (LHV of about13.8 MJ/kg) wood residues, with 30% humidity.

The typical power plant capacity is in the order of 10 MWe. **Bubbling fluidised bed combustion (BFBC)** boilers (Figure 3**)** for solid biomass and other feedstock are also a proven and commercial option, but continued improvements in CHP technology have made available

Please send comments to Paul Lako, Author (lako@ecn.nl), and to
Giorgio.Simbolotti@enea.it and Giancarlo Tosato (gct@etsap.org) (Project Co-ordinators)

a new generation of plants that offer advanced steam parameters and high efficiency. In the BFBC boilers, the ascending air speed is sufficiently high to maintain the bed in a state of fluidisation, with a high degree of mixing, but it is low enough to make most of the solid particles lifted out of the bed fall back. The result is a dense bed with uniform temperature and burning char, and rather small over-temperatures. The dense part of the fluidised bed has a void fraction that is near to minimum fluidisation requirement. Within the dense part of the bed, a bubble phase exists, with a low content of solids. The bubbles formed from air in excess rise through the dense phase. As in gas-liquid systems, the bubble flow in the fluidised bed induces solids transport and mixing in the dense region. The upward velocity of air/combustion gases is 2 – 3 m/s, and bed heights are 0.5 to 1.5 m. Solid materials mostly stay in the well-stirred bed, although small particles will leave the bubbling bed and be thrown up into the freeboard region. Cyclones and other particulate removal equipments are used to collect them before the flue gas is channelled to the heat recovery systems. Coarse bed material is also withdrawn from the bottom of the bed to maintain high sulphur-capture capacity and to avoid ash contamination which might cause bed agglomeration (PowerClean, 2004).

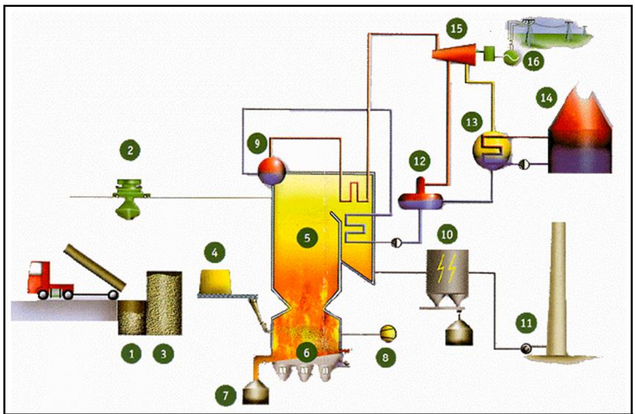
Circulating fluidised bed combustion (CFBC) boilers offer a further option for biomass-fired CHP. In CFBC, a distinction between the bed and the freeboard area is no longer applicable. A large fraction of the particles rises up from the bed and is re-circulated by a cyclone. The circulating bed material is used for temperature control in the boiler. The choice between BFBC and CFBC depends *inter alia* on the fuel used. CBFC boilers are used in large CHP or power plants, with capacity of hundreds of MW_e, but they may also be competitive in smaller biomass-fired plants (Figure 4, SEI 2005). They also are the technology of choice for large biomass- or coal-fired CHP plants (Figure 5, EPRI, 2008). Table 1 presents the technical features – including electric and thermal (heat/steam) capacity – of selected biomass-fuelled CHP and power plants in Europe, mostly based on wood, forestry residues, or waste wood. Approximately 10% of the plants in Table 1 have a capacity of more than 100 MW_e, 70% have a capacity between 10 and 100 MW_e, and 20% is in the range of 2 to 10 MW_e. Biomass-based CHP has successfully been applied in e.g. Germany (RWE, 2009). The optimal size of the biomass CHP plants appears to be around 20 MW_e taking into account the optimal size of the biomass sourcing area (< 50km) and the number of truck loads per day (< 50). Plants with a capacity of 7 to 20 MW_e are used for CHP (in Germany), whereas power plants with a capacity of 50 to 65 MW_e are used solely for power generation (UK).

Figure 6 shows the electric efficiency by feedstock of biomass CHP and power plants presented in Table 1. Biomass-fuelled plants with capacities of 25 MW_e or more usually have advanced steam parameters and high efficiencies. For example: the straw-fired, VG-

Tab. 1 - Technical features of biomass CHP or power (Several literature and internet sources)

Country	Operator	Start year	Tech. option	Electric eff.	Capacity	
				[%]	MW_e	MW_{th}
Belgium	A&S	2010	N/A	N/A	24	
Denmark[a]	Dong	2009	BFBC	29.9	35	85
Finland	Salmi	2002	N/A	28.3	13.6	28
Finland	Fortum	2010	CFBC	23.2	25	50
Germany	RWE	2002	VG	16.5	8.7	
Germany	RWE	2004	CFBC	19.4	20	65
Germany	RWE	2005	N/A	26.6	20	23
Germany	RWE	2009	N/A	19.0	8	30
Germany	RWE	2012	N/A	N/A	7	30
France	Solvay	2010	N/A	N/A	30	
Hungary	DBM	2009	VG		19.8	
Hungary[a]	BHD	2010	N/A	31.5	49.9	
Ireland	Balcas	2005	BFBC	16.0	2.4	10
Ireland	IBS	2004	VG	16.1	1.83	3.5
NL	RWE	2002	BFBC	29.9	25	
Portugal	N/A	1999	VG	26.5	9	
Spain[a]	EHN	2003	VG	32.0	25	
UK[a]	EPR Ely	2000	VG	32.0	38	
UK	Semb	2007	BFBC	29.5	30	10
UK	E.On	2008	BFBC	31.3	43.9	
UK	Eco2 Ltd	2009	VG	N/A	13.8	
UK	Prenergy	2011	N/A	36.0	350	
UK	RWE	2012	N/A	N/A	50	
UK	E.On	2011	N/A	N/A	25	
UK	Eco2 Ltd	2011	VG	N/A	40	
UK	RWE	2011	N/A	N/A	65	
UK	Helius	2012	N/A	N/A	100	
UK	E.On	2013	N/A	N/A	150	
UK	MGT	2012	N/A	N/A	295	
UK	RES	2015	N/A	N/A	100	
TOTAL					**1,626**	

a) Based on straw instead of wood as fuel.



1 Pit
2- Crane
3 - Silo
4 - Hopper
5 - Boiler
6 - Grate
7 - Ashtrays
8 - Fans
9 - Holdfast
10 – Electrostatic precipitator
11 - Chimney
12- Desgasifier
13 - Condenser
14 – Refrigerator tower
15 - Turbine
16 - Generator

Fig. 2 – Plant scheme with VG boiler (Almeida, 2000)

Please send comments to Paul Lako, Author (lako@ecn.nl), and to
Giorgio.Simbolotti@enea.it and Giancarlo Tosato (gct@etsap.org) (Project Co-ordinators)

boiler, 25-MW_e power plant at Sangüesa, Spain, generates steam at 92 bar/542°C, with 32% efficiency; a similar 35-MW_e plant at Fynsværket (Denmark) works at 112 bar/540°C, with 29.9% efficiency; the wood-fired, BFBC boiler, 30-MW_e power plant at Teesside (UK) works at 92 bar/482°C, with 29.5% efficiency; a similar 44-MW_e power plant at Steven's Croft (UK) produces steam at 137 bar/537°C, with 31.3% efficiency. Electric efficiency, however, is not the only appropriate performance indicator. For example, in Table 1, ten CHP plants with capacities of between 2 and 30 MW_e, have electric efficiency of about 25%, thermal efficiency of 50% and overall efficiency of around 75%. As far as air emissions is concerned, biomass CHP plants have to comply with strict emission limits. Emissions from specific power plants are provided in Table 2 along with the emission limits in the EU.

■ Co-firing of biomass in coal-fired power plants

Biomass co-firing in coal-fired power plants offers significant advantages: it is highly efficient, approximately between 36% and 44%, depending on the efficiency of the coal-fired unit (39% - 46%); coal-fired power plants have coal access facilities, which may also facilitate biomass supply; they also have advanced flue gas cleaning equipments, which in some cases may obviate separate cleaning for biomass. According to IEA-ETSAP TB E01 (Coal-Fired Power), today's maximum efficiency of a pulverised coal-fired power (PC) plants is around 46%, with potential for reaching 50% or more by 2020. Respective figures for integrated gasification combined cycles (IGCC) are 46% and 52% (see also Figure 7)). Because of the smaller size, neither biomass power plants nor biomass integrated gasification combined cycles (BIGCC) can attain efficiency as high as co-firing. The BIGCC technology also requires significant RD&D before its full commercialisation (2020). However, biomass co-firing in coal power plants requires significant boiler retrofitting, as well as specific equipment and space for biomass logistics, and tailoring of flue gas cleaning equipment (i.e. electrostatic precipitator, flue gas desulphurisation, and de-NO_x, if applicable), especially if significant amounts of biomass are co-fired. NO_x emissions in coal/biomass co-firing depend significantly on the emission reduction technology, e.g. separated overfire air (SOFA - Moulton, 2009), or NO_x selective catalytic reduction (SCR). Blasiak (2008) reports NO_x emissions of 150 – 300 mg/Nm^3, equivalent to 400 – 800 gNO_x/MWh. For a retrofitted coal-fired power plant in Poland, NO_x emissions are less than 200 mg/Nm^3, equivalent to 500 g NO_x/MWh (Higgins et al, 2009). Biomass co-firing may reduce NO_x emissions compared to coal as biomass has a lower nitrogen content. Figure 8 summarises the co-firing technology options, which include direct co-firing, indirect co-firing and parallel co-firing, in particular: **Direct Co-firing** with pre-mixed biomass and coal, co-milling and co-firing (route 1 & 5); **Direct Co-firing** with pre-milled biomass to the coal firing system or furnace (route 2 & 3); **Indirect co-firing** with biomass gasification and fuel gas combustion (route 4); and **Parallel co-firing** with biomass combustion in a separate combustor and boiler, and utilization of the steam within the coal steam and power generation systems.

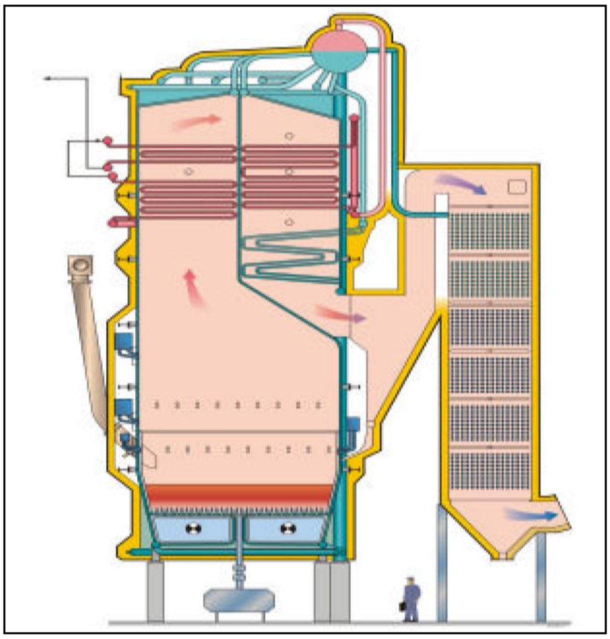


Fig. 3 - Scheme of bubbling fluidised bed combustion boiler (Niemelä and Westerlund, 2003)

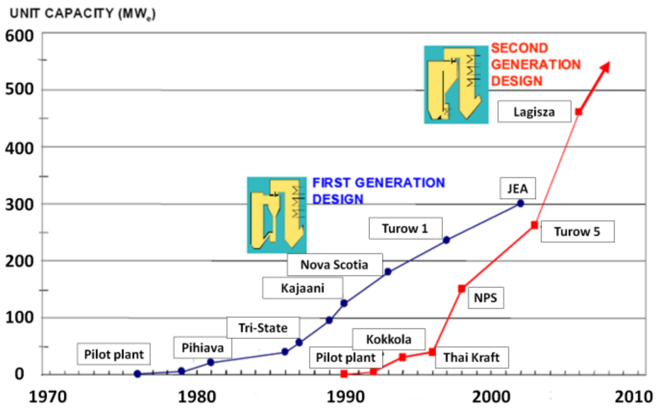


Fig. 4 - Size of CFBC boilers (Venäläinen, 2003)

Tab. 2 - Emissions of biomass CHP (Grainger Sawmills, 2009; Almeida, 2000; Bioenergy, 2005				
Air pollutant mg/m_0^3	Ennisk., IRL Wood resid	Mortágua Portugal Wood	Ely, UK Straw	EU limit (IPPC)
NO_x	168 [a]	340 [b]	<300 [b]	500 [c]
SO_x	N/A	300 [b]	<300 [b]	N/A
CO	45[a]	200[b]	<250[b]	200[c]
Particles	2.7[a]	100[b]	<25[b]	50[c]

a Monitoring results of 2008 (Enniskeane, Ireland).
b Guaranteed or design parameter.
c Enniskeane plant limits (IRL) (Grainger Sawmills, 2009).

■ Anaerobic digestion of wet biomass with CHP -

Anaerobic digestion for biogas production from wet biomass is a small-scale biomass CHP application.

Figure 9 shows the stages from *wet biomass* to bio-methane. The use of biogas is gaining importance in Germany, the Netherlands, the United Kingdom, and Italy (IEA, 2009). Biogas may also be upgraded to be mixed with natural gas and used in natural gas grids or to power vehicles as compressed natural gas (CNG). Also, anaerobic digestion of wet manure and co-digestion of wet manure along with agricultural residues may be economically viable for the generation of heat and power using internal combustion gas engines. Figure 10 shows the electric and thermal efficiencies of anaerobic digestion CHP in the Netherlands.

COSTS – The investment cost of **biomass-based CHP and power generation** depends upon several parameters such as the feedstock used (e.g. wood, straw, waste, etc.), the boiler technology (VG, BFBC, or CFBC); the capacity of the plant (MW_e) and the kind of plant service (CHP or solely power generation). Based on Table 1, Figure 11 shows the investments costs of biomass CHP and power plants with capacities of up to 50 MWe. The investment costs of biomass-based CHP plants are between \$3,000 and \$6,000/kW_e (typically, some \$4000/kW_e in 2008). Operation and maintenance (O&M) costs are in the order of \$100/kW_e per year. (Almeida, 2000; Bioenergy 2005; Prenergy, 2006).

Table 3 summarises several data on **biomass co-firing in coal power plants** (VTT, 2007; EUBIA, 2007; DoE, 2004; TNO, 2005; KEMA, 2008; Drax, 2009; Atwood, 2004; EESI, 2009). Based on these studies, co-firing involves an incremental investment cost for the coal-fired power plant of about \$335/kW_e. The annual O&M cost is approximately \$12/kW_e. According to (Pfeiffer and Van de Ven, 2009), biomass-based power and biomass co-firing would have a target generation cost of 50 – 70 €/MWh, which is equivalent to 75 – 100 \$/MWh.

The investment costs for **anaerobic digestion with gas engines-based CHP** as derived from various studies (Fig. 12), range from \$3,700 to \$5,300/kW_e, with a typical value of \$4,500/kW_e in 2008. According to McDannel (2009), investment costs range from \$1,700 to \$3,000/kW_e, with the upper value representing a typical figure for the US (California) market. Investment costs of \$3,000/kWe for digestion CHP plants refer to rather large-size plants with capacity of 1.0 - 1.5 MW_e (Fig. 12). Average O&M costs for anaerobic digestion plants with CHP are in the order of \$300/kW_e per year.

An estimate of current and projected power generation costs from biogas-fired CHP plants, including cost reductions due to larger commercialisation and technology learning is provided in Figure 13 (RWE, 2009). While the 2008 generation cost is estimated at about \$190/MWh, the cost in 2020 is estimated at approximately \$150/MWh.

WATER CONSUMPTION & WITHDRAWAL – for biomass-based power generation water consumption and withdrawal varies dependent upon the type of technology and cooling system. Dry cooling systems consume and withdraw the least amount of water (consumes 35 gallons/MWh and withdraws zero) relative to other cooling systems such as Once-through (consumes 300 gallons/MWh; withdraws 20,000-50,000) and Tower (consumes 235-965 gallons/MWh; withdraws 500-1,460) systems. Table 3 shows the ranges of water consumption and withdrawal factors for these different cooling systems in biomass-based power generation plants.

Table 3 – Water consumption and withdrawal factors for power plants using biomass technologies (Sources: Meldrum et al., 2012; Macknick et al., 2011; Zhai et al., 2011; NETL, 2009; Tzimas, 2011; EPRI, 2011)

Plant type	Cooling system	Water consumption (gallons/MWh)	Water Withdrawal (gallons/MWh)
Biopower	Dry	35	-
	Pond	300-480	300-600
	Once-through	300	20,000-50,000
	Tower	235-965	500-1460

POTENTIAL & BARRIERS – The biomass energy market offers a significant growth potential. In the Reference Scenario of the World Energy Outlook 2009 (IEA, 2009a), global biomass-based power generation is assumed to increase from 259 TWh in 2007 to 840

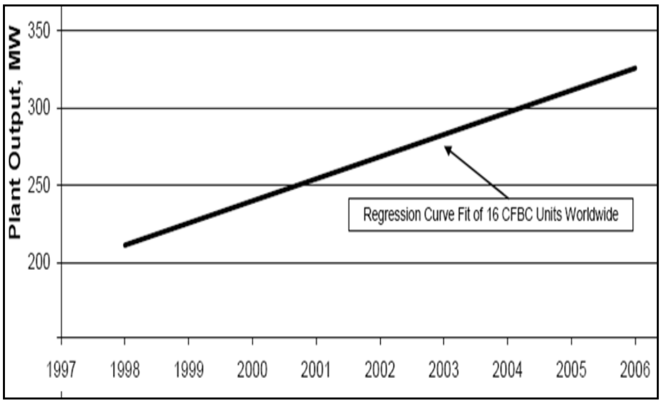


Fig. 5 - Progression of CFBC unit size based on 16 units worldwide (EPRI, 2008)

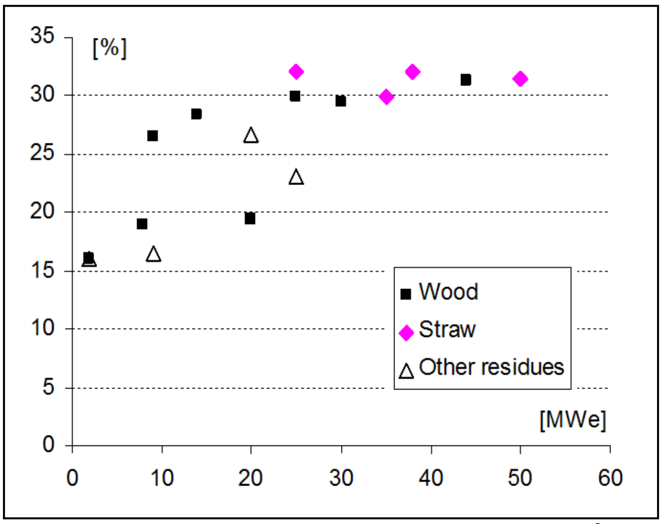


Fig. 6 - Electric efficiency of biomass CHP (Tab. 1)

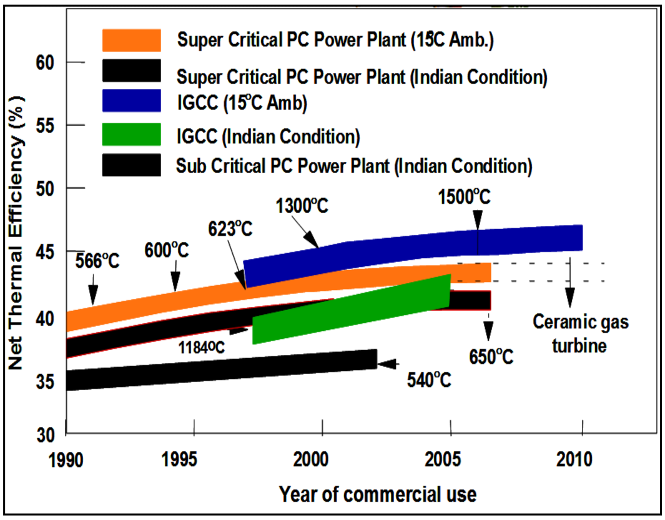


Fig. 7 - Generation efficiency of coal-based power generation technologies (BHEL, 2008)

Tab. 3 - Characteristics of coal co-firing power plants					
Country /region	Electric capacity[a]	Electric efficiency	Investment cost		Source
	MW_e	%	M$	$/kW$_e$	
Finland				458	VTT
Europe		35 – 40		381	EUBIA
USA	15		4.5	298	DoE
NL				318	TNO
UK	400		120[b]	300	KEMA
Europe		37.5		259	Atwood
Average				335	

a. The electric capacity refers to biomass co-firing.
b. Incl. rail unloading and biomass handlingrax, 2009).

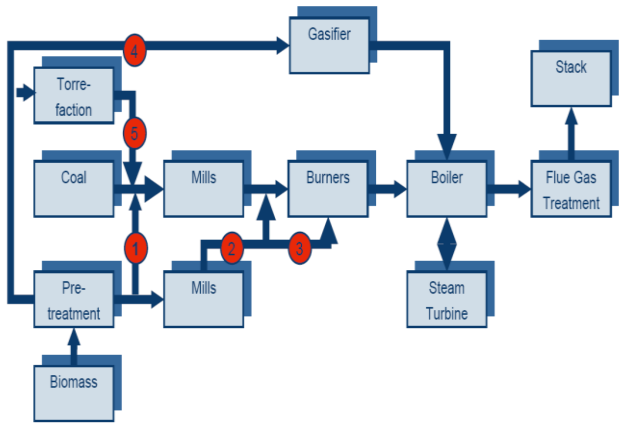


Fig. 8 - Co-firing options (Cremers, Livingston, 2009)

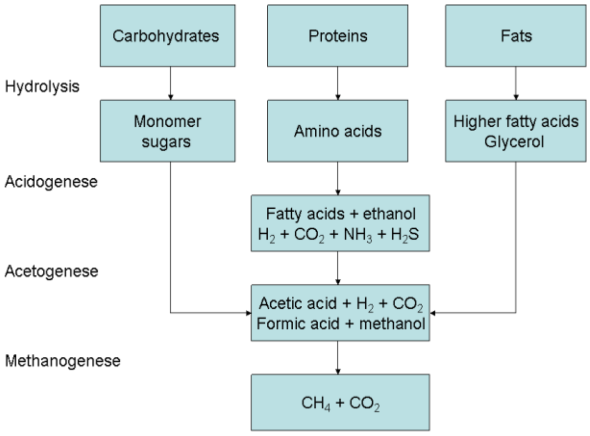


Fig. 9 - Wet biomass anaerobic digestion (HAS, 2003)

TWh in 2030 (a growth rate of 5%/a). In Germany, the current technical potential of biomass is about 1200 PJ/a, and biomass might cover up to 8% of Germany's primary energy demand (Thrän, 2009). However, several barriers exist against the widespread use of biomass for heat and power generation. Logistics costs of feedstock collection may reduce the biomass technology potential (RWE, 2009). Biomass feedstock

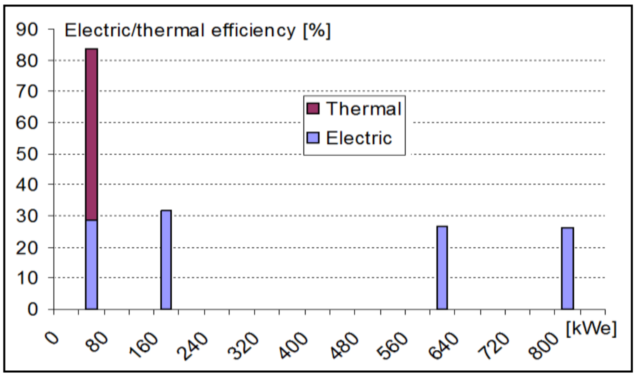


Fig. 10 – Gas-engines efficiency for CHP generation from anaerobic digestion biogas in the Netherlands (Tilburg, 2008, ODE-VI, 2005, HAS, 2003)

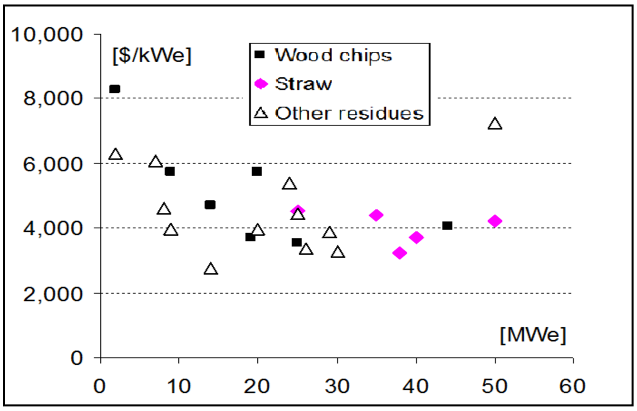


Fig. 11 - Biomass-based CHP investment cost (Tab. 1)

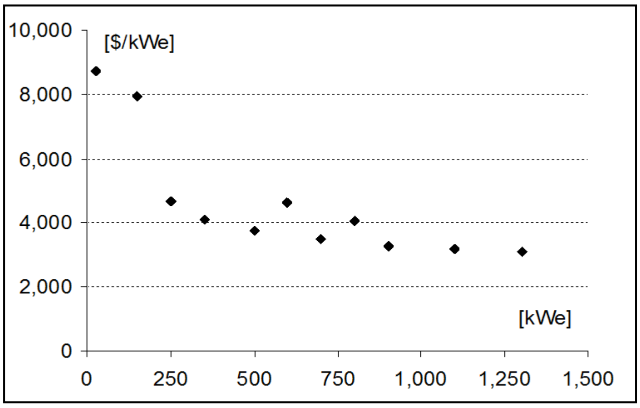


Fig. 12 - Anaerobic digestion with CHP investment cost (Tilburg, 2008; Boerderij, 2005; ODE-Vl, 2005; HAS, 2003; DLV, 2006)

must be available in reasonable quantities within an acceptable distance to make this technology economically viable. In addition, other high value-added, non-energy uses of biomass may compete with the energy production. For large-scale biomass co-firing in coal-fired power plants, a location near a large deep-water harbour is an important advantage for the economic competitiveness (Hunton & Williams, 2009).

As far as biomass co-firing is concerned, the Ontario State in Canada offers an example of shifting from coal to biomass as the government has mandated to phase out coal use by 2014. As a consequence, the main electricity generating company in Ontario focuses on converting coal-fired power stations to biomass. Technical and non-technical issues to be considered include the impact of biomass use on the equipment and the operation, the sustainable supply with minimal impact on other resource users, transportation, storage and processing issues, and pricing of both biomass and the resulting renewable electricity (Pfeiffer and van de Ven, 2009). In some countries (e.g. United Kindom, the Netherlands, Italy) an extensive use of biomass for power generation, CHP and co-firing has to meet sustainability criteria as it implies large-scale import of biomass feedstock.

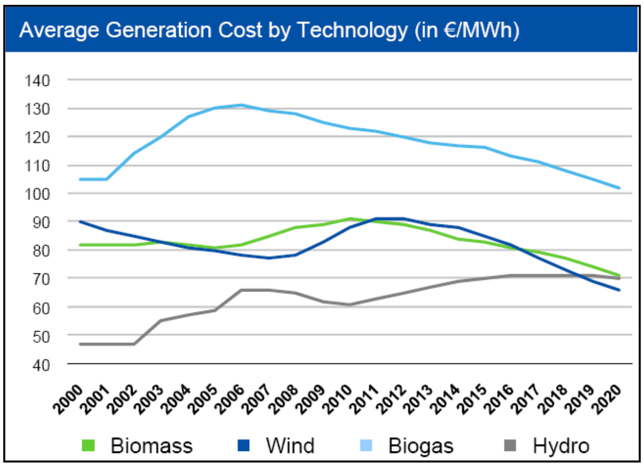


Fig. 13 - Average generation cost of a few renewable energy technologies (RWE, 2009)

Please send comments to Paul Lako, Author (lako@ecn.nl), and to
Giorgio.Simbolotti@enea.it and Giancarlo Tosato (gct@etsap.org) (Project Co-ordinators)

Table 4 – Summary Table: Key Figures and Data for Biomass-based Technologies

Technical Performance	Typical current international values and ranges		
Energy input	Biomass		
Output	Electricity		
Technologies	Biomass CHP **BP**	Anaerobic digestion CHP **ADCHP**	Co-firing in coal-fired power plant, **CBP** (retrofit)
Electric efficiency, %	16 – 36	26 – 32 (eff. gas engine)	36 – 44
Total efficiency in case of CHP, %	40 – 85	40 – 85 (eff. gas engine)	Not applicable
Construction time, months	Minimum 18; Typical 24; Maximum 30		
Technical lifetime, yr	25		
Load (capacity) factor, %	76 – 91	75 – 80	80 – 90
Max. (plant) availability, %	93	80	90
Typical (capacity) size, MW_e	50	0.5 (0.3 – 10)	100
Installed (existing) capacity, GW_e	30	4	10
Average capacity aging	Differs from country to country.		
Environmental Impact			
CO_2 and other GHG emissions, kg/MWh	Negligible	Negligible	Negligible
SO_2, g/MWh	30 – 60		
NO_x, g/MWh	60 – 65		≤400 – 800
Particulates, g/MWh	11 – 24		
Solid waste (fly ash), kg/MWh	0.07 – 0.08		
By-products			
Costs (US$ 2008)			
Investment cost, including interest during construction, $/kW)	3,000 – 6,000	3,700 – 5,300	250 – 450
O&M cost (fixed and variable), $/kW/a	100	300	12
Fuel cost, $/MWh	30 – 50	40 – 60	30 – 50
Economic lifetime, yr	20		
Interest rate, %	10		
Total production cost, $/MWh	100 – 130	140 – 200	75 – 105
Market share	~ 1	<<1	<<1

Data Projections	**2010**			**2020**			**2030**	
Technology	BP	ADCHP	CBP	BP	ADCHP	CBP	BP	ADCHP
Net Efficiency (LHV)	32	32	40	35	33		38	35
Investm. cost, incl. interest during construction, $/kW	3,750	4,500	335	3,100	3,700	300	2,75 0	3,300
Total production cost, $/MWh	110	160	90	100	140	85	90	130
Market share, % of global electricity output	~ 1	<<1	<<1	1–2	~ 1	~ 1	~ 3	~ 2

References & Further Information

1) Almeida, T. (2000): The analysis report of plant № 13. CBE, Altener, 2000.
2) http://ec.europa.eu/energy/res/sectors/documents/final_reportsaltener_afbnet/part2_cofiring/final_plant_reports/plant_no_13.pdf.
3) Atwood, T. (2004): European Biomass Technology Overview. Global Greenlife Institute, USA, 2004.
4) http://biomass.ucdavis.edu/materials/forums%20and%20workshops/f2004/f2004_Atwood.pdf.
5) BHEL (2008): Advanced Clean Coal Technology – Perspectives for India. Bharat Heavy Electricals Ltd (BHEL), India, 2008.
6) http://www.igeos.pl/doc/coaldialogue/WEC-Coal_Slides.ppt#443,1,Slide 1.
7) Bioener (2005): Sangüesa power plant. Bioener ApS, Valby, Denmark, 2005
8) http://www.bioener.dk/data/media/bioener_side19_20.pdf.
9) Boerderij (2005): Boerderij/veehouderij, 16 augustus 2005, p. 24.
10) http://www.boerderij.nl/upload/292763_672_1177318003155-Volop_beweging_in_vergistersmarkt.pdf.
11) Blasiak, W. (2008): Fuel switch from fossil to 100 % biomass on PC boiler. POWER-GEN Europe, 3-5 June 2008, Milan, Italy.
12) http://www.nalcomobotec.com/files/PowerGen_Europe_2008_Biomass_Cofiring.pdf.
13) Cremers, M.F.G. (2009): IEA Bioenergy Task 32 – Technical status of biomass co-firing. KEMA, Arnhem, the Netherlands, 11 August, 2009. http://www.ieabcc.nl/publications/09-1654%20D4%20Technical%20status%20paper%20biomass%20co-firing.pdf.
14) DLV (2006): Kansen voor mestvergisting. DLV Plant bv, Wageningen, oktober 2006. http://library.wur.nl/ebooks/1840841.pdf.
15) DoE (2004): Biomass Cofiring in Coal-Fired Boilers. Department of Energy (DoE), DOE/EE-0288, USA, 2004.
16) http://www.nrel.gov/docs/fy04osti/33811.pdf.

Please send comments to Paul Lako, Author (lako@ecn.nl), and to
Giorgio.Simbolotti@enea.it and Giancarlo Tosato (gct@etsap.org) (Project Co-ordinators)

17) Drax (2009): Drax signs contract with Spencer for supply of biomass co-firing infrastructure. Drax, UK, 2009.
18) http://www.draxgroup.plc.uk/media/press_releases/?id=69889.
19) EESI (2009): Biomass Cofiring: A Transition to a Low-Carbon Future. Environmental and Energy Study Institute (EESI), Washington DC, USA, 3009. http://www.eesi.org/files/cofiring_factsheet_030409.pdf.
20) EUBIA (2007): Capital costs and efficiencies of principal bioelectricity and competing conversion technologies. European Biomass Industry Association (EUBIA), 2007. http://www.eubia.org/189.0.html.
21) EPRI (2008): Program on Technology Innovation: Integrated Generation Technology Options. Electric Power Research Institute (EPRI), Palo Alto, California, USA, page 4-3. http://mydocs.epri.com/docs/public/000000000001018329.pdf.
22) Fritsche et al (2009): IEA Bioenergy Task 40: Country Report Germany. IEA Bioenergy Programme, IEA, Paris, July 2009. http://www.biogaspartner.de/fileadmin/biogas/Downloads/Studien/DBFZ_OEkoInstitut_Studie_BioenergieDeutschland_2009.pdf.
23) Grainger Sawmills (2009): 2008 Annual Environmental Report. Grainger Sawmills Ltd, Enniskeane, Ireland, March 2009.
24) http://www.epa.ie/licences/lic_eDMS/090151b2802a392a.pdf.
25) HAS (2003): Mestvergisting op boerderijniveau - Vergunningverlening en haalbaarheid van vergisting van mest en biomassa. HAS Kennistransfer, in opdracht van NOVEM, 's Hertogenbosch, the Netherlands, January 2003.
26) http://www.mestverwerken.wur.nl/Info/Bibliotheek/pdf/MestvergistingOpBoerderijniveau.pdf .
27) Higgins, B., et al (2009): Biomass Co-firing Retrofit with ROFA for NO_x Reduction at EdF-Wrocław Kogeneracja. Energy Efficiency and Air Pollutant Control Conference, Wroclaw, Poland, 2009
28) http://www.nalcomobotec.com/files/Mobotec_Wroclaw_Biomass_Cofiring.pdf.
29) Hunton & Williams (2009): Renewable Energy Quarterly, Volume IV, June 2009, pp. 9-11.
30) http://www.hunton.com/files/tbl_s47Details/FileUpload265/2585/renewable_energy_quarterly_vol4_june2009.pdf.
31) IEA (2008): Energy Technology Perspectives 2008. International Energy Agency (IEA), Paris, June 2008.
32) IEA (2009a): World Energy Outlook 2009. IEA, Paris, 2009.
33) IEA (2009b): IEA Scoreboard 2009 - 35 Key Energy Trends over 35 Years. IEA, Paris, 2009.
34) http://www.iea.org/journalists/ministerial2009/fs_scoreboard.pdf.
35) IEA Bioenergy (2009): Bioenergy: a Sustainable and Renewable Energy Source – Status and prospects review. IEA, Paris, 2009.
36) http://www.ieabioenergy.com/
37) KEMA (2008): Co-firing high percentages – new chances for power stations (KEMA). IEA Workshop, Geertruidenberg, the Netherlands, October 21, 2008. http://www.ieabcc.nl/meetings/task32_Amsterdam2008/cofiring/Marcel%20Cremers.pdf.
38) Livingston, W.R. (2009): The direct co-firing of biomass at high co-firing ratios. Doosan Babcock Energy, presented at Hamburg, Germany, June 2009. http://www.ieabcc.nl/meetings/task32_Hamburg2009/cofiring/06%20Livingston.pdf.
39) McDannel, M. (2009): Digester Gas-Fired Combined Heat and Power: Technologies and Challenges. California Energy Commission Workshop July 23, 2009.
40) http://www.energy.ca.gov/2009_energypolicy/documents/2009-07-23_workshop/presentations/11_Los_Angeles_County_Sanitation_Districts_Mark_McDannel.PDF.
41) McDannel, M. (2008): A Megawatt Made is a Million Dollars Earned: Energy Production from Digester Gas. Innovative Energy Management Workshop December 16, 2008.
42) http:// ww.epa.gov/region09/waterinfrastructure/training/energy-workshop/docs/Amegawatt.pdf.
43) Moulton, B.W. (2009): Principles of Burner Design for Biomass Co-Firing. 34th International Technical Conference on Coal Utilization & Fuel Systems Clearwater, FL, USA, May 31, 2009
44) http://www.fwc.com/publications/tech_papers/files/TP_FIRSYS_09_02.pdf.
45) Niemelä, K., and Westerlund, K. (2003): Experience of fluidised bed technology for biomass plants in different applications and development towards new applications in RDF burning. PowerGen Conference, Düsseldorf, Germany, 6 – 8 May, 2003.
46) http://www.fwc.com/publications/tech_papers/files/TP_CFB_03_01.pdf.
47) ODE-VI (2005): Biogas - haalbare kaart voor duurzame landbouw. ODE Vlaanderen, 2005.
48) http://www.ode.be/images/stories/Brochures/bmg_fo_biogas_051201.pdf.
49) Pfeiffer, E., Ven, M., van de (2009): Developments in fluid bed combustion and gasification. IEA, Hamburg, 30th of June, 2009.
50) PowerClean (2004): Fossil fuel power generation - State-of-the-art. Report prepared by the PowerClean R, D&D Thematic Network, 30th July 2004. http://www.irc.ee/6rp/valdkonnad/P6/energia/Powerclean_state_of_the_art_final.pdf.
51) Prenenergy (2006): Port Talbot Renewable Energy Plant - Environmental Statement. PrenergyPower, UK, 05 October 2006.
52) http://www.prenergypower.com/nontechnicalsummary.pdf.
53) RWE (2009): Fact Book Renewable Energy. RWE, Germany, April 2009.
54) http://www.rwe.com/web/cms/mediablob/de/315844/data/179662/55988/rwe/verantwortung/RWE-Factbook-Renewable-Energy-April-2009-englisch-.pdf .
55) SEI (2005): Co-firing with biomass. Sustainable Energy Ireland (SEI), Dublin, Ireland, 2005.
56) http://www.sei.ie/Renewables/REIO_Library/Biomass/CoFiringwithBiomassFinalfnl.pdf.
57) Thrän, D. (2009): CHP based on biomass - technologies and potential. Institut für Energetik und Umwelt, Leipzig, Germany, 2009. http://www.zukunftsenergien.de/hp2/eu-project/downloads/thraen-paper.pdf.
58) Tilburg, X., van, et al (2008): Technisch-economische parameters van duurzame elektriciteitsopties in 2009-2010 - Eindadvies basisbedragen voor de SDE regeling. ECN-E—08-090, ECN, Petten, December 2008.
59) TNO (2005): WP 2B Co-processing and co-firing. TNO (the Netherlands), Heidelberg, Germany 11-12 May, 2005.
60) Venäläinen, I., and Psik, R. (2003): 460 MW_e Supercritical CFB Boiler Design for Łagisza Power Plant. Foster Wheeler Energia Oy, Finland, February 2003. http://www.fwc.com/publications/tech_papers/files/TP_CFB_03_02.pdf.
61) VTT (2007): Co-firing techniques for wood and coal — Review of the various co-firing concepts in Europe. VTT, Finland, 2007
62) http://www.unece.org/timber/workshops/2007/belgrade/Presentations/oravainen2.pdf
.

Please send comments to Paul Lako, Author (lako@ecn.nl), and to
Giorgio.Simbolotti@enea.it and Giancarlo Tosato (gct@etsap.org) (Project Co-ordinators)