TECHNOLOGY-ANALYSIS:

Biomass Energy - Introduction to a Technology Analysis
(Summary)

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Summary

1. BIOMASS AND BIOMASS ENERGY

Biomass consists of any organic matter of vegetable or animal origin. It is available in many forms and from many different sources e.g. forestry products (biomass from logging and silvicultural treatments, process residues such as sawdust and black liquor, etc.); agricultural products (crops, harvest residues, food processing waste, animal dung, etc.); and municipal and other waste (waste wood, sewage sludge, organic components of municipal solid waste, etc). (OECD/IEA Energy Technology Perspectives, 2010).

Biomass is a renewable resource that can be converted to different, intermediate energy carriers or *biofuels*, which on turn can be used to satisfy all final energy uses, i.e. to produce electricity, heat, or fuels for the transport sector. Categorisation of biomass energy is very complex, depending on the wide variety of feedstock, conversion routes, biofuels.

A bioenergy chain, or route, consists of a series of conversion steps by which a raw biomass feedstock is transformed into a final energy product (heat, electricity, or transport biofuel). There are many potential bioenergy chains as a result of the wide range of raw biomass feedstock (wood, grass, oil, starch, fat, etc.) and the variety of possible end-uses. Different conversion technologies have been developed that are adapted to the different physical natures and chemical compositions of feedstock, as well as to the energy service required (heat, electricity, transport fuel). While some routes are straightforward (e.g. direct combustion of forest wood for heat production), others necessitate several pretreatment, upgrading and conversion steps, such as those required for the production of liquid fuels that can be used in an internal combustion engine.

Three main classes of conversion routes can be identified:

- *thermochemical conversion*, by which biomass undergoes chemical degradation induced by high temperature. The main thermochemical routes are combustion, gasification, pyrolysis, and torrefaction which differ mainly in their temperature ranges, heating rate and amount of oxygen present in the reaction.

- *physicochemical conversion* is used to produce liquid fuels (biodiesel or vegetable oil) from oil crop (rapeseed, soybean, Jatropha, etc.) by oil extraction possibly followed by a transesterification or hydrogenation process.

- *biological routes* use living micro-organisms (enzymes, bacteria) to degrade the feedstock and produce liquid and gaseous fuels. Biological routes are numerous, key mechanisms being fermentation from sugar (sugar-cane, sugar-beet, etc.), starch (corn/maize, wheat, etc.) and lignocellulosic (grass, wood, etc.) feedstock, anaerobic digestion (mostly from wet biomass), and the more recent bio-photochemical routes (e.g. hydrogen production using algae), which require the action of sunlight.

Table 1 - Final uses of biofuels.

		biofuels			
				gaseous	
		solid	liquid	biogas, syngas	bio-methane
heat	heating (residential, industry)	++	-	+	o
	process heat (industry)	+	o(C)	+	o
mechanical power	engines (industry)	-	+/++	-	-
	engines (vehicles)	-	+/++	-	++
	engines (airplanes)	-	++	-	-
electricity		o(C)	o(C)	++	-

(++) preferred; (+) well suited; (o) feasible; (-) not well suited; (C) with co-generation.

This implies that almost any final use (heat, electricity, mechanical power) can be obtained through a proper conversion route from almost any biomass feedstock. This has led to the concept of *biorefinery*, i.e. the processing of biomass from any sources into a spectrum of marketable products, including food, feed, chemicals, materials, and energy as fuels, power, and/or heat.

To the purpose of the present study, a simplified categorisation will be used:

- biomass energy for *heat* production (for spatial heating in buildings or as process heat in industries), mainly *solid biofuels* (wood or wood derivatives, with or without pre-treatment or up-grading), or *heat recovery* from other processes such as co-generation (CHP, combined heat and power);

- biomass energy for *transport*, mainly *liquid or gaseous biofuels*, including first-generation biofuels (ethanol or biodiesel from food crops) and second-generation biofuels (ethanol or biodiesel from no-food crops, syndiesel from wood pyrolysis, biomethane from biogas reforming);

- biomass energy for *electricity*, mainly from gaseous biofuels, including biogas from anaerobic digestion, syngas from gasification, and hydrogen from either reforming of biogas / syngas, or direct production from algae.

2. THE EUROPEAN ENERGY STRATEGY

The development of renewable energy sources has been a priority in the political strategy of the European Union since 1997, when the European Council set a target of a 12% share of renewable energy in gross inland consumption by 2010, i.e. doubling the 6% share of 1997.

To this goal, the EU required all Member States to set national targets, and to introduce proper support systems of incentives:

- for the share of renewable energy in electricity (Directive 2001/77/EC);

- for biofuels in all liquid fuels for transport; reference targets were suggested, i.e. a 2% market share (on LHV basis) for biofuels in 2005, and a 5.75% share in 2010 (Directive 2003/30/EC).

In 2005, the Biomass Action Plan proposed the objective of doubling energy production from biomass from 69 Mtoe in 2003 to 150 Mtoe in 2010 and a broad range of measures, including:

- incentives for biomass heating (not included in the above mentioned Directives);

- increased R&D in new technologies, through the creation of an industry-led "biofuel technology platform" focused on the development of the "bio-refinery" concept and of second-generation biofuels.

Directive 2009/28/EC introduced long-term mandatory targets for 2020, and required each Member State to adopt a national renewable energy action plan with related measures in order to ensure their fulfilment. The targets were set by the EU for each Member State so as to reach the overall target share for the entire Union of 20% in 2020 (from 6.8% in 2005). Overall targets were set at 17% for Italy, and 34% for Austria (target for share of energy from renewable sources in gross final consumption of energy, 2020). The actual shares in 2005 were 5.2% and 24.4%, respectively (share of energy from renewable sources in gross final consumption of energy, 2005).

Table 2 - Gross final consumption of energy in Italy and target shares for renewable energy sources (RES) for 2020.

Year	2005([1])			2020		
	All sources	RES		All sources	RES	
	ktoe	ktoe	share,%	ktoe	ktoe	share,%
Heating and cooling	68 501	1 916	2.8	61 185	10 456	17.1
Electricity	29 749	4 847	16.3	32 227	9 631	29.9
Transport	39 000	179	0.5	39 630	2 530	6.4
Total	137 250	6 942	5.1	133 042	22 617	17.0
Transport (10% objective)([2])				33 972	3 445	10.1

([1]) Revision of Italian NREAP referred to average 2006-10 for electricity, and 2005-07 for other ES.
([2]) air and water transport not included in final consumption; contribution of electric vehicles multiplied by 2.5, and second-generation biofuels by 2.0.

Table 3 - Gross final consumption of energy in Austria and target shares for renewable energy sources (RES) for 2020.

Year	2005			2020		
	All sources	RES		All sources	RES	
	ktoe	ktoe	share,%	ktoe	ktoe	share,%
Heating and cooling	13 206	3 213	24.3	12 802	4 179	32.6
Electricity	5 725	3 480	60.8	6 377	4 503	70.6
Transport	8 945	205	2.3	8 414	958	11.4
Total	27 610	6 735	24.4	27 109	9 266	34.2

Following Directive 2009/28/EC, both Italy and Austria adopted their National Renewable Energy Energy Action Plans (NREAPs) in 2010 (Italy, Ministry for Economic Development, 2010; Austria, Federal Ministry of Economy, Family and Youth, 2010). NREAPs included projections and target shares for renewable energy sources (RES) until 2020 in the three sectors of Heating and Cooling, Electricity Generation, and Transport (Table 2, Italy; and

Table 3, Austria). Both Italy and Austria are currently fully in line with the projected trajectories, in all three sectors.

3. SUSTAINABILITY OF BIOENERGY

3.1. INTRODUCTION

During the late 2000s, however, increasing criticism has emerged, including:

- because of competition for land use, biofuels may trigger increases in prices of food commodities, especially in the next future, when global demand of food is projected to increase following the development of China, India and other emerging countries;

- availability of biomass is insufficient to substantially contribute to energy needs in developed countries; EU estimates (EEA, 2006) are that the bioenergy potential in 2030 would represent no more than 15–16 % of projected primary energy requirements;

- therefore, legal targets and financial support of biofuels have led to increased biomass imports (exchanging biomass imports with fossil fuel imports), with no substantial benefits either for the economy or even the domestic agricultural sector, or even to exporting sustainability problems to developing countries;

- conversion of biomass into energy has poor efficiency, particularly for biofuels, owing to high fossil energy inputs during conversion of the feedstock; a consequence of this it that GHG emission savings are much lower than previously maintained (even below 16% for most first-generation biofuels);

- conversion of natural land, including forests and abandoned land, for production of biofuel feedstock, may destroy substantial amounts of accumulated C in the soil and plants, and so increase GHG emissions;

- energy crops increase GHG (N_2O) emissions owing to fertilisers;

- agricultural and forestry residues cannot be fully exploited for energy purpose because they are essential to maintain a high storage of organic C in the soils.

Many of these constraints have been taken into account by Directive 2009/28/EC, which set such compelling sustainability requirements as to:

- nearly completely phase out first-generation biofuels after 2018;

- after that, rely almost entirely on second-generation biofuels (lignocellulosic ethanol, FT diesel) which are however, at the moment, still far from being cost-effective in comparison to fossil fuels.

Additionally, fast development of wind power on one side, and energy saving technologies in buildings, have reduced the relative importance of (poorly effective, and suffering from limited feedstock availability) electricity generation from biomass, and even biomass heating (that can be replaced by insulations, passive-house techniques, and heat pumps).

3.2. LAND USE CHANGE AND CARBON STORAGE IN SOILS

As a renewable energy source, biomass energy has the potential of substantially contributing to the objectives of European energy and climate change policy.

Biomass energy is renewable since it derives from solar energy, captured through photosynthesis and continuously stored in plant and animal tissues. The International Energy Agency defines "renewable energy" as "energy derived from natural processes... that are replenished at a faster rate than they are consumed”[1]. Unlike wind and solar energy, biomass can, however, indeed be consumed at a faster rate than it is reproduced. Examples are:

- conversion of natural land, including forests and abandoned land, for production of biofuel feedstock, may destroy substantial amounts of accumulated C in the soil and plants, that it will take years to reproduce;

- removal of agricultural and forestry residues may decrease organic C storage in the soils, and reduce soil fertility.

It is clear that any net destruction of biomass is neither sustainable, or GHG-neutral (indeed, it corresponds to a net release of CO_2 and other GHG gases).

3.3. COMPETITION WITH FOOD

Another difference is that biomass includes food, fodder and materials like wood for construction and furniture. Production of biomass for energy uses may increase competition for land use or other production inputs like fertilisers and water, and so increase market prices and/or reduce availability of food, fodder and no-food biomass-based products.

Finally, the conversion of natural areas for bioenergy production may imply the loss of natural resources such as ecosystems, biodiversity and life forms; or, create environmental risks, e.g. those associated with soil erosion, the control of natural water flows, fire events and similar.

This implies that biomass can be considered as a renewable energy source only to a limited extent, determined by the net production of biomass available after subtracting all food and no-food essential productions, and excluding any areas subjected to environmental risks.

[1] http://www.iea.org/aboutus/faqs/renewableenergy/ ; accessed 21.10.2013.

All this implies that any potential for bioenergy production is limited to those Countries with an excess of agricultural and forestry land (e.g. with substantial food export), and/or with large, unexploited areas with little or no value as natural reserves.

3.4. GHG EMISSIONS AND THE ENERGY RATIO (EROI)

In relation to the global climate change problem, biomass is a potentially "clean" energy source, since any emissions of CO_2 from biomass combustion are balanced by equal amounts of CO_2 absorbed by the plants through photosynthesis, so that the net balance is potentially CO_2-neutral. However, both the production of biomass (tillage, fertilisation, harvesting and processing) and the conversion of feedstock into energy (depending on the conversion route and technology), always require certain amounts of input energy.

The ratio of output energy to input energy has been termed "Energy ratio", or "energy return of investments" (EROI), and is an indicator of the efficiency level of biomass energy production. When the inputs are deriving from fossil fuels, this implies a decrease in the potential reduction in GHG emissions. As an example, an EROI ratio of 1.25 (i.e., 5:4), typical for bioethanol from maize corn (with 100% fossil energy inputs), implies a potential reduction in GHG emissions of only 20%

Table 4 - Energy ratio (EROI; only fossil energy considered in input) and Area efficiency (year's average)(e) for various fuel and electricity sources (Modified from GNAS, 2012).

	EROI		Area efficiency ($W\ m^{-2}$)	
Firewood	10	(a)		
Bioethanol from maize (USA)	1.5	(a)	< 0.3	
Bioethanol from sugar beet	3.5	(a)	< 0.4	
Bioethanol from sugar cane (Brazil)	8	(a)(b)	< 0.5	
Bioethanol from Triticale/maize (combined production) (b)	8	(a)	< 0.3	
Bioethanol (a), methane (a) and electricity from lignocellulose (b)	3		< 0.5	
Bioethanol from switch grass (USA)	5.4		< 0.2	
Bio-butanol	< 1	(a)		
Biodiesel from rapeseed	< 2	(a)	< 0.2	
Biodiesel from algae (h)	< 1	(a)		
Biogas from maize silage (electricity)	1.4		< 0.4	
Biogas from maize silage	4.8	(a)	< 1.1	
Biogas from manure and crop residues	6.3	(a)		
Photovoltaic (Europe) (electricity)	7		> 5	
Wind turbine (Europe) (electricity)	18		2-3	(c)
Nuclear power (electricity)	10-20	(b)		
Hydropower (electricity)	100	(e)		

(a) Combustion energy.
(b) See comment in the text.
(c) Land based standard wind farms; the land between the turbines may be used for agricultural or other purposes.
(e) Average power during 365 days and 24 hours a day.
(h) Curtiss and Kreider (2009).

(i.e., 1 - 4/5), relative to the fossil energy mix used as input.

Table 4 compares the energy ratios of various fuel and electricity sources, including most biofuels.

It can be seen that bioenergy has, in general, a much lower energy ratio compared with Hydropower, (EROI = 100), Wind power (EROI = 18), Solar photovoltaic (EROI = 7), and even Nuclear power (EROI = 10-20). EROI estimates for nuclear power as low as 1 and as high as 50 can be found in the literature (Hall et al., 2008). The estimates are problematic because of the still poorly developed database for the costs of deconstruction and making good the damage caused by catastrophes.

One well-known exception is bioethanol from sugar cane (Brazil); however, the high EROI (= 8) is reached only when bagasse (the residue from sugar cane after it has been crushed to extract the juice) is used as the main energy source for distillation, which is not sustainable because of the resulting loss in soil carbon (Martinelli and Filoso, 2008).

Examples of biofuel conversion routes with high potentials of EROI have been suggested, using heat and electricity generation from biogas for bioethanol distillation:

- first-generation Bioethanol from triticale + maize; maize silage, part of the triticale straw and all the distillation residues are used in a biogas plant to produce electricity and heat for distillation of bioethanol from Triticale grain (Senn et al., 2010);

- Bioethanol, methane and electricity can be produced from maize silage, adding milled maize grains to concentrate the mash and decrease the energy input of distillation; electricity and heat is produced in a biogas plant (Fleischer et al., 2010).

Table 4 shows, however, that the two best bioenergy routes, based on EROI, are:

- wood, or wood-derived products such as pellet or aggregates, for combustion and heating (EROI = 10);

- biogas from wastes (e.g. manure, crop residues) for electricity and heat (EROI = 6.3).

Associated typical GHG reductions are 90% for wood combustion, and 84% for biogas from wastes. It should be remarked that sustainability of biogas production is very much dependent on the feedstock and the final uses. Biogas from maize silage has a lower EROI of 4.8, but only 1.4 if the heat is not being used in a combined heat and electrical power (CHP) process.

4. PROMISING TECHNOLOGIES

4.1. SUSTAINABILITY CRITERIA OF BIOMASS

Based on the above considerations, the promotion of bioenergy should be limited to those forms of bioenergy that:

(a) do not reduce food availability or spur food-price increases due to competition for limited resources such as land or water;

(b) do not have large adverse impacts on ecosystems and biodiversity;

(c) have a substantially (>60-70 per cent) better GHG balance than the energy carriers they replace.

These requirements will have to be carefully checked for the different biomass energy technologies, including all possible alternatives, e.g.: woody biomass used for production of just heat, or combined heat and electrical power; individual household heating systems, or district heating systems; small-scale versus large-scale systems. This will be done in the specific Studies following the present Technology analysis.

The valuable range of services that ecosystems provided to the public will have to be respected in any case. All these items have to be considered when biomass or biomass products are imported for bioenergy purposes. A combined optimization of food and bioenergy production, e.g. through use of animal manures for biogas production or energy capture from biogenic wastes or agricultural residues holds promise for a significant bioenergy production.

With energy generation from agricultural residues, the effects of their removal on soil fertility need to be taken into account when determining sustainable levels of residue use. At present, European cropland soils are losing too much carbon. For sustainability, it is therefore important that in future more residues are ploughed back into the soil.

Finally, when evaluating the GHG emissions of bioenergy, the full suite of emissions (CO_2, N_2O and CH_4) resulting from fertilizer application, from fossil-fuel consumption during production and conversion of the biomass and from manpower for operations all need to be separately addressed and taken into account. Also the effects of direct and indirect land use change on the GHG balance, on ecosystem functions and biodiversity have to be considered.

4.2. BIOMASS FOR COMBUSTION AND HEATING

According to EU projections, biomass will still have the major contribution of 81% of all renewable energy sources (~ 90 Mtoe) for heating and cooling in 2020, of which, solid biomass will provide 81.0 Mtoe. Small-scale, very-low-emissions combustion installations are expected to be available for commercial applications. High efficiency heat & power generation via thermochemical conversion should also penetrate the market by 2020.

At regional level, targets for Friuli Venezia Giulia are particularly demanding in the Heating and cooling sector, with a projected increase of 193 ktoe, i.e. +536% in 2020 relative to 2005. Woody biomass from forestry for combustion has the advantages:

(a) it does not reduce food availability;

(b) does not have large adverse impacts on ecosystems and biodiversity;

(c) has a substantially (i.e., approx. 90%) better GHG balance than the energy carriers it replaces (i.e. oil and natural gas); this is reflected by the very high EROI of approx. 10.

However, the following problems should be considered:

(a) biomass energy may compete for availability of wood that may be used in the construction, building and furniture sectors; this can indeed spur price increases in these commodities, due to competition for limited resources such as forest land;

(b) increased wood supply from regional forests can have adverse impacts on ecosystems and biodiversity, which need to be carefully assessed; this may also reduce the sustainable supply of woody biomass, compared to the potential yearly production of forests;

(c) increased wood combustion may worsen air quality, especially because of an increase in gaseous emissions such as particulate matter (PM), carbon oxide (CO), and nitrogen oxides (NOx);

(d) the very good GHG balance (90% reduction) and EROI (approx. 10) are typical only when woody biomass is used for combustion, i.e. space heating in buildings; GHG balances and EROI should be carefully assessed and evaluated depending on the type of installation (small-scale, individual households versus large-scale, district-heating systems), and type of final energy production (heating only versus combined heating and power, CHP).

On the other side, the targeted reduction in consumption for heating and cooling can also be obtained using energy saving technologies for the building sector, especially insulation, heat pumps, and heat storage. A combination of heat production from small-scale, individual-household installations (such as biomass stoves and boilers) with energy saving techniques may make it possible to reach the above regional targets even with limited availability of biomass, owing to either competition for the same feedstock from several economic sectors (energy, wood industry) or to ecological limitation in the employment of the biomass resource.

Based on the above considerations, the most promising technologies for biomass combustion are:

- technologies that may improve agricultural and forest practices to make them more efficient and better for the environment, with a focus on improving the logistics of biomass supply from crop residues and other additional unexploited biomass sources;

- development of cost-efficient, high-quality and high-energy-content fuels from various biomass sources – e.g. via pre-treatment (biochar for example), blending, compacting, etc.;

- technologies that increase system efficiency of and reduce emissions (e.g. particulate emissions) from stoves, boilers and CHP plants from micro to large scale.

4.3. Biogas from Agricultural and Municipal Wastes

The installed bio-electricity capacity in EU-27 according to the NREAPs is expected to reach more than 43 GW in 2020, of which 30 GW from solid biomass plants, 11 GW from biogas plants and 2 GW from liquid biofuel plants.

Bio-methane from biomass can be a gradually increasing substitute for natural gas. Bio-methane, as long as it undergoes a purification process to comply with the methane grid specifications, can be mixed at any ratio with natural gas avoiding double investment into a parallel bio-methane distribution network.

Increased biogas and biomethane production may contribute to the regional targets for Friuli Venezia Giulia in the electricity sector, where the expected increase for 2020 the target is 64 ktoe, i.e. +43% of total electricity.

Electricity production from biogas has the advantages:

(a) it does not reduce food availability, if it derives from animal, agricultural, industry and food wastes; on the contrary, use of food or forage crops as feedstock (e.g., maize silage) may trigger food-price increases due to competition for limited land, and should be avoided;

(b) does not have large adverse impacts on ecosystems and biodiversity, if the same conditions are fulfilled, and additionally if the digestate produced at the final stage of the process can be safely used as an organic fertiliser, without any adverse effects on crops and animals, and with the effect of preserving the carbon content of soils;

(c) has a substantially (i.e., approx. 80%) better GHG balance than the energy carriers it replaces (i.e., natural gas); this is reflected by the high EROI of approx. 4.8; however, this is true only if 100% of the heat is re-used (for electricity production only, EROI is around 1.4, and GHG reduction is below 30%).

Based on the above considerations, promising technologies are those that:

- produce high biogas yields using just residual feedstock, i.e. animal wastes, crop residues that cannot be used as forages, food wastes and so on;

- ensure that all the heat produced during electricity generation is being re-used for space heating or process heating in industries;

- produce a very stable digestate, without any adverse effects owing to the residual bacterial content either to the crops (esp. forage crops) where the digestate is distributed, or the animals;

- the amounts of digestate distributed as fertiliser should also ensure that the carbon stock in agricultural soils is properly preserved and possibly increased;

- improve the security and safety of installations, i.e. preventing any risks from explosions and such;

- ensure the production and distribution of bio-methane on a cost-to-cost competition basis with existing fossil alternatives.