SUSTAINABILITY ASSESSMENT OF AGRICULTURAL WASTE BIOMASS EXPLOITATIONS

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SUMMARY: Biomass is organic, plant derived material that may be converted into other forms of energy. It is easily produced in almost any environment, regenerated quickly and has a long history of use for direct heating applications. Biomass is the only fuel available for renewable electricity generation. For these reasons, it has gained significant attention as a substitute for fossil fuels. Waste-to-energy plants offer both generation of clean electric power and environmentally safe waste management and disposal. To understand the potential of agricultural waste biomass to contribute more significantly to global electricity generation, an assessment of its potential for sustainable development has been conducted. Special focus on GHG and energy balance, but other environmental impact categories has been paid, as well.

1. INTRODUCTION

The use of biomass to produce electricity has steadily increased by an average of 13TWh per year between 2000 and 2008, while it has maintained its market share of total global generation over the last 20 years at approximately 2% (Evans et al., 2010). There are a total of 62 countries in the world currently producing electricity from biomass. The USA is the dominant producer at 26% of world production, followed by Germany (15%), Brazil and Japan (both 7%). Over 1.59 EJ of biomass were consumed in the EU in 2007. Biomass provided nearly 70% of all renewable energy or 5.4% of the total gross inland energy consumption in that year (EUROSTAT, 2012). The average majority of biomass energy is produced from wood and wood wastes (64%), followed by MSW (24%), agricultural waste (5%) and landfill gas (5%) (Demirbas et al., 2011).

Among the different possible feedstocks, agricultural residues are a wide-spread lignocellulosic biomass source available in almost every country worldwide. At a global scale, available residues are estimated to be 10^{10} Mt, which corresponds to an energy value of 47 EJ (Cherubini and Ulgiatti, 2010). Agricultural field by-products are divided in two categories: herbaceous and woody by-products. Herbaceous by-products are considered to be those crop residues, which remain in the field after the crop is harvested. Their nature is diverse, depending on the crop, method of harvesting, etc. Woody by-products are those produced as a consequence

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of pruning and regenerating orchards, vineyards and olive trees. Usually, herbaceous crops are cultivated on arable land, whereas woody plantations are considered permanent crops (Esteban and Carrasco, 2011).

Nowadays, it is almost universally accepted that our energy production and consumption is key to sustainable development. For example, the United Nations suggests that effective atmosphere-protection strategies must address the energy sector by increasing efficiency and shifting to environmentally benign energy systems (Strong, 1992). In addition to clean energy resources, energy sustainability includes energy carriers that do not contribute to environmental problems through harmful emissions or other impacts.

This paper aims to help understand the potential of agricultural waste biomass to contribute more significantly to global electricity generation by conducting an assessment of its potential for sustainable development.

2. ENERGY CONSUMPTION

After a world primary energy use drop by 1.1% in 2009, which followed years of consistent rise, 2010 has seen an increase of 5.6% (Fig. 1), the highest since 1973. This increase can be attributed to two main factors; the global recovery from the economic downturn in 2008—2009, especially in China and India, and the continuous improvement of the standard of living, mainly in the developing countries of Asia. In 2010:

(i) China's rose by 7% (lowest since 2002), the U.S. rose by 4.8% (notably after a 5% drop in 2009) and India's by 4.2% (lowest in recent years).

(ii) It rose even in all other countries that have in 2008 exhibited a drop, such as the EU, Japan, and Australia (Lior, 2012; U.S.D.O.E., 2011; ENERDATA, 2011).

(iii) Consumption in OECD countries grew by 3.5%, the strongest growth rate since 1984, non-OECD grew by 7.5%. A few smaller OECD countries had slight drops in energy consumption: Norway -3.7% (it is one the highest per person consumers though), Switzerland -2.4% and Greece -2.4% (Lior, 2012; Lior, 2011; Weil RH, 2011).

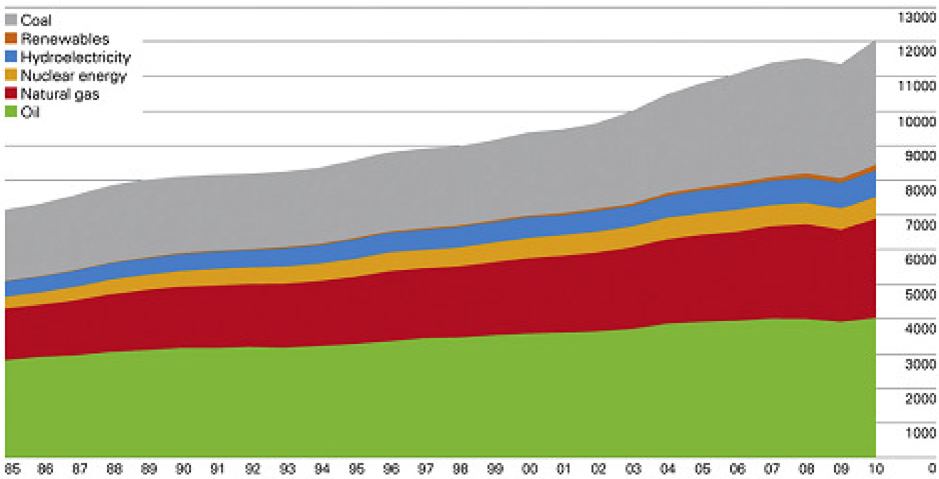

Figure 1. World primary energy consumption 1985-2010 / million tonnes of oil equivalent (Lior, 2012).

As an axiom, energy is essential to economic and social development and welfare enhancing. Unfortunately, the greatest part of the world's energy is currently produced and consumed in unsustainable ways since fossil fuels provide more than 90% of total commercial energy needs, with oil the leading source in the global energy mix (Yuksel, 2008). Achieving a solution to the environmental problems that we face today requires long-term potential actions for sustainable development. In this regard, renewable energy resources are one of the most efficient and effective solutions (Kaya, 2006). Renewable energy sources are natural energy sources which do not have a limited supply. Renewable energy can be used again and again, and will never run out, e.g. solar energy, wind energy, biomass energy, geothermal energy. They are often called alternative sources of energy (Rathore and Panwar, 2007). Renewable energy sources that meet domestic energy requirements have the potential to provide energy services with zero or almost zero emissions of both air pollutants and greenhouse gases. Further, renewable energy system development will make it possible to resolve issues surrounding energy supply reliability and organic fuel economy. Moreover, they can help solve problems of local energy and water supply, increase the standard of living and level of employment of the local population, and ensure the sustainable development of remote regions. In addition, renewable energy sources can help the implementation of the obligations of the countries with regard to fulfilling the international agreements relating to environmental protection (Zakhidov, 2008). Table 1 below, presents a scenario for global renewable by 2040.

Table 1. Global renewable energy scenario by 2040 (Panwara et al., 2011).

	2001	**2010**	**2020**	**2030**	**2040**
Total consumption (million tons oil equivalent)	**10,038**	**10,549**	**11,425**	**12,352**	**13,310**
Biomass	1080	1313	1791	2483	3271
Large hydro	22.7	266	309	341	358
Geothermal	43.2	86	186	333	493
Small hydro	9.5	19	49	106	189
Wind	4.7	44	266	542	688
Solar thermal	4.1	15	66	244	480
Photovoltaic	0.1	2	24	221	784
Solar thermal electricity	0.1	0.4	3	16	68
Marine (tidal/wave/ocean)	0.05	0.1	0.4	3	20
Total RES	1,365.5	1,745.5	2,964.4	4289	6351
Renewable energy source contribution (%)	**13.6**	**16.6**	**23.6**	**34.7**	**47.7**

It is worth emphasising that the development and implementations of renewable energy projects in rural areas can create job opportunities and thus minimizing migration towards urban areas (Bergmann et al, 2008). Harvesting the renewable energy in decentralized manner is one of the options to meet the rural and small scale energy needs in a reliable, affordable and environmentally sustainable way (Reddy and Subramanian, 1980; Ravindranath and Hall, 1995).

Among renewable energy sources, biomass offers good future potential as an energy source, as it can reduce carbon dioxide emissions and directly replace fossil fuels. Biomass is very diverse and includes wood residues, organic wastes, crops residues, crops grown specifically for energy production, animal wastes, black liquor (black liquor is a byproduct of the kraft process, one of the processes used by pulp mills during the production of paper pulp) and municipal solid waste (MSW). However, crop production for energy must be balanced against the need for food, fibre, animal feed, biochemical and soil carbon and forest sinks due to the limited availability of land biomass production.

3. BIOMASS RESOURCES

The new European Union Directive on the promotion of the use of energy from renewable sources (Directive 2009/28/EC), includes a binding target of a 20% share of renewable energy in energy consumption in the EU and differentiated national overall targets by 2020. The use of biomass for transport fuel, heat and electricity production will have to increase substantially. Estimates suggest that biomass will contribute around two-thirds of the renewable energy share in 2020 (European Commission, 2009). Thus, it is imperative that the use of biomass for bioenergy production considers the use of all available resources in a sustainable way, without causing negative impacts.

Scarlat et al. (2010) argues that important amounts of agricultural crop residues are available in the EU, estimating them at an average of 1530 PJ/year, which can be used for bioenergy production in a sustainable way. Important amounts of crop residues are available in France, Germany, Romania, Spain, Italy, Hungary, Poland, etc. However, Scarlat et al. (2010) results show large spatial and temporal variations at EU27 level, especially for Mediterranean countries and New Member States. Scarlat et al. (2010) further concluded that in the EU27, the share of agricultural residue in final energy consumption could reach 3.2% on average, ranging from 2.3% to 4%, depending on the availability of residues in different years. The share in final energy consumption in EU27 varies from country to country, depending on the resource and internal energy consumption, reaching up to 14% in Hungary, 13% in Romania and Bulgaria and even up to 7% in Denmark and 5.7% in France. As can be deduced from Table 2, 364.50 Tg y^{-1} of forest and agricultural residues are estimated as 'potential resources' in the 11 EU countries considered (77% of the EU 27 territory) and Norway. After the application of technical and environmental restrictions, the available resources are calculated to be 205.33 Tg y^{-1} (56.33% of the estimated biomass potential). Most forest biomass is located in Northern EU considered (63.07% of the potential and 62.95% of the available resources) whilst most of the agricultural residual biomass is in Southern EU countries (52.69% and 55.18% respectively, for potential and available resources). Globally, the biomass resources are very similar (30.83% of the total available biomass is in Southern EU countries) (Scarlat et al., 2010).

As mentioned previously, among the different possible feedstocks, agricultural residues are a widespread lignocellulosic biomass source available in many countries. Available residues are estimated to be 10^{10} Mt worldwide, corresponding to an energy value of 47 EJ (Gabrielle and Gagnaire, 2008). Among them, cereal residues are the largest source (about 3.8×10^{9} tons), making up two thirds of the total available amount (Lal, 2008). Therefore, crop residues are considered possible renewable biomass sources in countries with large available land area. However, there is an ongoing debate on the effective possibilities of crop residue removal from agricultural field, since such removal affects processes like soil organic matter turnover, soil erosion, crop yields, N_2O emissions from soils and others. The effects from the collection of crop residues are strongly affected by local conditions (climate, soil type, crop management) and are described in several papers (Cherubini and Ulgiati, 2010; Lal, 2008; Lal et al, 1998; Lal, 2005). By contrast, LCA implications in terms of environmental impacts due to straw removal are still uncertain: there are few references on these effects in the literature and the patterns are not consistent across references (Gabrielle and Gagnaire, 2008).

Table 2. Biomass resources estimated in the evaluated countries (adapted by Esteban et al, 2011).

Country	Forest Potential Available MARV			Agricultural Potential Available MARV		
	Tg yr^{-1}	Tg yr^{-1}	Mg ha^{-1} y^{-1}	Tg yr^{-1}	Tg yr^{-1}	(Mg ha^{-1} y^{-1})
Sweden	20.68	10.43	0.49	5.93	3.11	4.19
Finland	13.59	6.94	0.23	3.08	1.12	1.9
Germany	9.54	4.27	0.26	67.34	42.56	6.85
Norway	8.6	4.33	0.46	1.85	0.83	0.26
Austria	5.26	2.63	1.08	6.25	3.79	5.00
Poland	4.11	2.05	0.29	28.09	10.36	2.87
Denmark	0.74	0.37	0.88	12.99	8.17	5.80
SUBTOTAL	**62.52**	**31.02**	**-**	**125.53**	**69.94**	**-**
France	13.43	7.75	0.63	78.39	49.81	4.24
Spain	10.55	4.77	0.44	26.22	12.84	1.23
Italy	7.49	4.01	0.53	25.44	16.94	2.35
Greece	2.90	1.09	0.53	7.42	4.82	2.09
Portugal	2.23	0.64	0.29	2.38	1.70	0.96
SUBTOTAL	**36.60**	**18.26**	**-**	**139.85**	**86.11**	**-**
TOTAL	**99.12**	**49.28**	**-**	**265.38**	**56.05**	**-**

4. BIOENERGY

Bioenergy is renewable energy made available from materials derived from biological sources (Banosa et al., 2011). Biomass power plants exist in over 50 countries around the world and supply a growing share of electricity. European countries are expanding their total share of power from biomass, such as Austria (7% of the renewable energy generation), Finland (20%), and Germany (5%) (Renewables, 2010). Trends include growing use of solid biomass pellets, use of biomass in building-scale or community-scale combined heat and power plants, and use of biomass for centralized district heating systems (Renewables, 2010). The sustainability of electricity generation from biomass must be assessed according to the key indicators of price, efficiency, greenhouse gas emissions, availability, limitations, land use, water use and social impacts.

Biomass produced electricity generally provides favorable price, efficiency, emissions, availability and limitations but often has unfavorably high land and water usage as well as social impacts (Evans et al, 2010). The use of biomass as a source of energy has been further enhanced in recent years and special attention has been paid to biomass gasification. Agugliaro (2007) proposed the use of vegetable biomass from greenhouse residues to produce electrical energy by the gasification process. Due to the increasing interest in biomass gasification, some models that explain the design, simulation, optimization and process analysis of gasifiers have been presented, including gasification models based on thermodynamic equilibrium, kinetics and ANN (Puig-Arnavat et al., 2010). Biogas, a byproduct of fermenting solid and liquid biomass, can be converted by a combustion engine to heat, power, and transport (Renewables, 2010). Madlener (Madlener et al., 2009) performed a multi-criteria study with the aim of evaluating the performance of a large number of agricultural biogas plants in order to determine their relative performance in terms of economic, environmental, and social criteria and corresponding indicators.

The potential of biomass to contribute to reductions in greenhouse gas (GHG) emissions, to improved energy security and to rural diversification and development, is recognised the world over (Elghali et al., 2007). Several bioenergy policies such as the Brazilian Biofuel Law, the Indian Biofuel Policy, the U.S. Renewable Fuel Standard, and European policies such as the Renewable Energy Directive, Strategy on Biofuels and the Biomass Action Plans, push the implementation of energy derived from biomass. These policies are a source of increasing concern due to questions over the sustainability of large-scale bioenergy crop production. Potential negative impacts include direct and indirect land use change (Searchinger, 2008; Lapola, 2008; IEA Bioenergy, 2009; Schubert et al., 2009) and biodiversity loss (Lee and Elsam, 2008; Hennenberg et al, 2010), availability of water resources (Berndes, 2002; Gerbens-Leenes et al., 2009a; 2009b), rising agricultural commodity prices and threats to food security (De Fraiture et al., 2008; Wakker, 2005; Tilman et al., 2009; Pimentel et al., 2009; ActionAid, 2010; Wolf et al., 2003; Cotula et al., 2008). These risks have to be weighed against the potential benefits, which as already mentioned, include improved greenhouse gas balances, employment and income generation, rural development, conversion of conventional industries and increased security of energy supply (Richert and Sielhorst, 2006; Verweij and Maarek, 2006; Energy Transition, 2008).

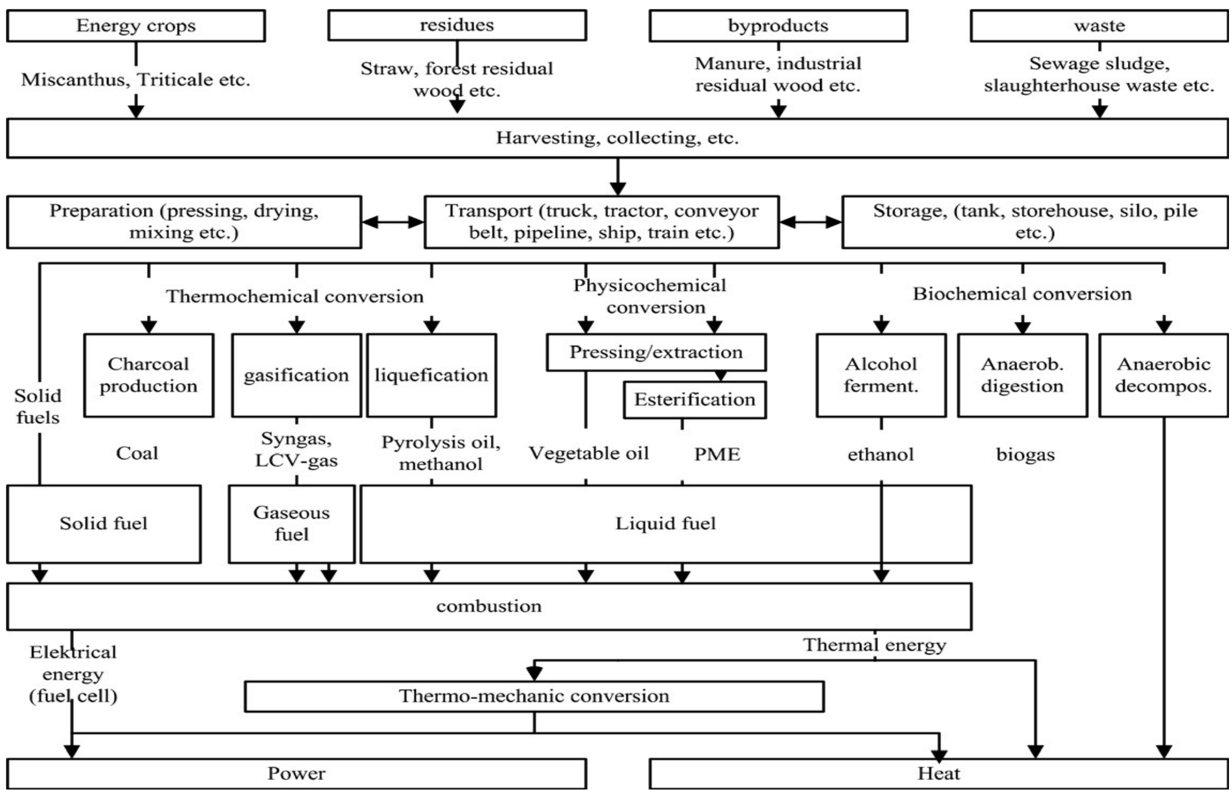

Figure. 2. Overview of renewable energy production from organic substrates (Kaltschmitt et al., 2004).

Therefore, the environmental, social and economic impacts of bioenergy development needs to be assessed carefully before deciding whether and how this industry should be developed, and what technologies, policies and investment strategies should be pursued. In this context, some governments and institutions started developing sustainability tools and standards to evaluate the environmental, social and economic performance of biomass energy production. At the same time, companies are willing to integrate more sustainable strategies in their energy management and are looking for practical and reliable sustainability assessment tools to assess different energy system possibilities. However, the high variability in biomass sources, conversion technologies and contexts complicate such assessments (Baelemans and Muys, 1998).

5. BIOENERGY UTILIZATION AND CARBON DIOXIDE EMISSION

Carbon neutral, frequently mentioned in bioenergy use means that carbon dioxide emitted from bioenergy utilization is compensated by planting to reach the purpose of environmental protection, without aggravating the overall greenhouse effect. Emission of carbon dioxide from bioenergy consumption is almost equivalent to the amount absorbed by plants from the atmosphere through photosynthesis during their growth (Li et al., 2009). A conclusion on the balance of absorption and emission of carbon dioxide can be obtained on the base of substance balance of biomass. However, there is no doubt that utilization of bioenergy affects atmospheric carbon flow cycle, the regional carbon source and sink. Additional energy input (usually fossil energy) to bioenergy production also affects carbon dioxide emission.

As mentioned previously, biomass encompasses vegetation and energy crops, as well as, biosolids, animal, forestry and agricultural residues, the organic fraction of municipal waste and certain types of industrial wastes. Its appeal is due to its potential worldwide availability, its conversion efficiency and its ability to be produced and consumed on a CO_2-neutral basis. The production of second-generation biofuels obtained by waste biomass is actively supported globally to avoid the direct and indirect effects that stem from the energetic utilization of energy crops (OECD, 2007), and further support effectively waste management policies. Waste-to-energy plants offer both generation of clean electric power and environmentally safe waste management and disposal. Many research efforts document the current and potential role of biomass in the future global energy supply (e.g. Parikka, 2004; Yamamoto et al., 2001). Theoretically, the total bio-energy contribution (combined in descending order of theoretical potential by agricultural, forest, animal residues and organic wastes) could be as high as 1100 EJ, exceeding the current global energy use of 410 EJ (Hoogwijk et al., 2003). Berndes et al (2003) analyses and syntheses earlier studies on the subject, further reinforcing the arguments in favour of the potential of biomass in the future global energy supply. However, a careful analysis of all the related literature reveals that there is no consensus regarding the biomass potential among the researchers, but rather their assessments differ strongly.

5.1 Biomass power generation and carbon dioxide emission

Concerning biomass power generation, research and development (R&D) has concentrated heavily on biomass pyrolysis and gasification techniques. The Finnish Tam Perret Power Company is in the process of establishing a waste wood gasification power plant, while the Swedish Energy Center is planning to build a power plant based on biomass gasification and combined cycle power generation technique to dispose of abundant local bagasse (Panwara et al., 2011). In the USA, more than 350 biomass power generation plants have been built (Cao et al., 2009).

Liang and Fan (2004) quantified the carbon dioxide emission from fire coal by determining consumption of coal in thermal power generation, substituted by biomass renewable energy. Yang and Ma (2006) calculated the net reduction of carbon dioxide using UNFCCC's accounting formula from uniform baseline methodology of the approved landfill gas project. The benefit of GHG reduction in landfill gas power generation was also analyzed in their studies. However, more attentions should be paid to bioenergy's ability to reduce the reliance on limited fossil energy for three sectors including heat, power and transportation fuels, which are all big energy consumers.

5.2 Gasifier based power generation system

Gas turbines cannot be fired directly with biomass, because the biomass combustion products would damage the turbine blades. However, by first gasifying the biomass and cleaning the gas before combustion, it is feasible to operate gas turbines with biomass fuels. Figure 3 is a schematic representation of a biomass-integrated gasifier (BIG)/gas turbine (GT) combined cycle, a leading first generation candidate for BIG/GT systems (Williams and Larson 1996). This process gives higher efficiency of electricity production in a gaseous power plant than in the classic power plant during the combustion of biomass and steam cycle. Besides, this process enables considerably lower emission of harmful gases and particles. For this biopower option based on gasification, the size of the biopower plant is 75MW and total efficiency would be n = 36%. An estimation of the cost of this type of power plant has been given at 2750$/kW, with electricity costs approximately 0.03$/kWh (Afgan et al., 2007).

Bhattacharya et al. (2001) conducted a study on a multi-stage hybrid biomass–charcoal gasification to produce low tar content gas for engine application using coconut shell as a fuel as shown in. Engine generator efficiency at dual fuel operation was lower than that of diesel fuel operation, with the experimental system, achieving an engine-generator efficiency of 14.7% and a maximum electrical power output (11:44 kWe) with 81% of the total energy input coming from producer gas. Maximum electrical power output for dual fuel operation was about 79% of that for diesel fuel operation.

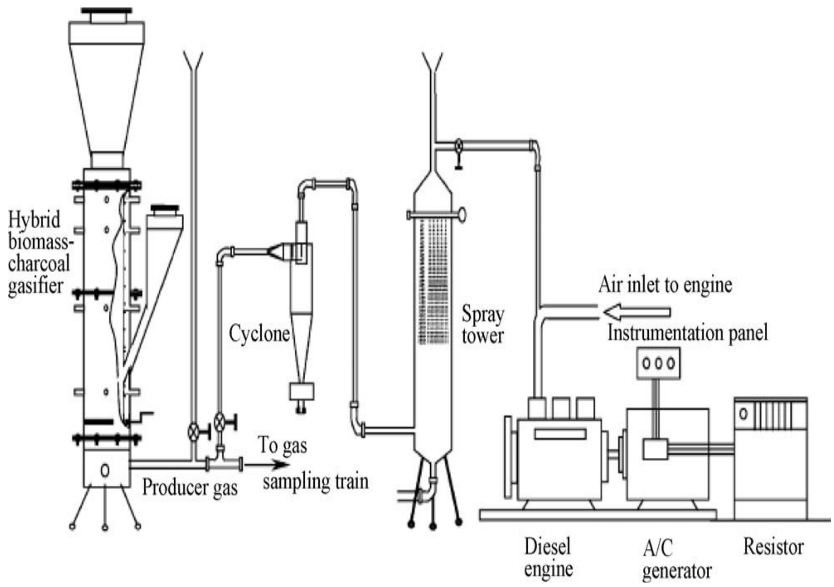

Figure 3. A biomass-gasifier/gas turbine combined cycle (Panwara et al., 2011).

5.3 Biogas utilization

The production of biogas through anaerobic digestion offers significant advantages over other forms of bioenergy production. It has been evaluated as one of the most energy-efficient and environmentally beneficial technologies for bioenergy production (Weiland, 2010). For the production of biogas it is possible to use several different raw materials and digestion technologies. This variety, coupled with the diverse fields of application for the biogas and digested product, results in great differences in the environmental performance among the potential biogas systems. Among the raw materials are organic wastes from households and the food industry, dedicated energy crops, and agricultural waste products, such as crop residues and manure (Borjesson and Berglud, 2006).

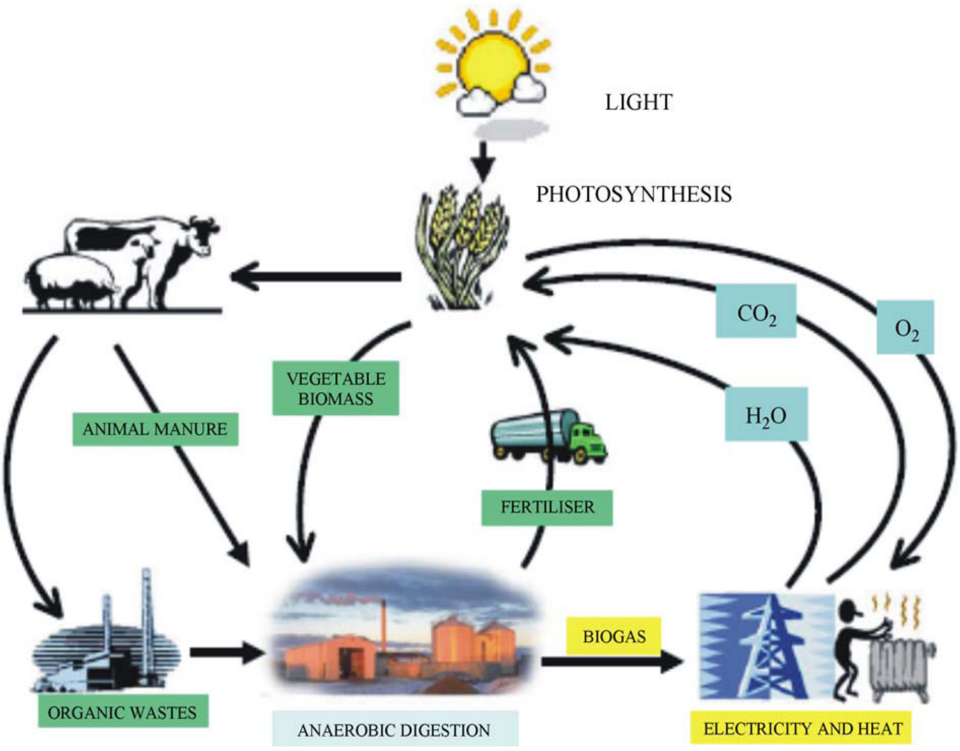

Figure 4. Schematic representation of the sustainable cycle of anaerobic co-digestion of animal manure and organic wastes (Al Seadi, 2002).

The largest resource is represented by animal manure, slurries, and organic waste streams. Dedicated agricultural crops and crop residues are also a promising feedstock as are grasses (e.g. straws from wheat, rice, and sorghum) or silage maize. The increasing interest in animal manures and slurries is due to the many co-benefits that derive from their energy exploitation. When untreated or poorly managed, animal manure becomes a major source of air and water pollution. Nutrient leaching, mainly nitrogen and phosphorous, ammonia evaporation and pathogen contamination are some of the major threats. Moreover, from the climate change perspective, the animal production sector is responsible for 18% of the overall greenhouse gases emissions in CO_2 equivalent (Holm-Nielsen et al., 2009). The energy use of manure contributes to decreases in water, soil and air pollution, while pathogens population possibly present in the manure are reduced (Sorensen B, 2004). Moreover, the digestate, the final residue of AD, can be used as soil amendment, for fertigation or as a colloidal humus (Tambone, 2009; Tani et al., 2006).

For a medium-sized biogas project, the calculation method of carbon dioxide reduction is on the base of a complete life cycle of the whole project, including emissions from both production and utilization (Su et al., 2002). Wang (1999) and Zhang et al. (2005; 2008) estimated carbon dioxide emissions from both biofuel and biogas combustion, applying empirical equation on the base of industrial emission factors. Liu et al. (2008) following the calculation method recommended by IPCC, estimated the energy saved and GHG reduction as a result of biogas utilization in order to analyze the total reduction of GHG emission in each province and autonomous regions in China and predicted significant reductions of GHG (Liu et al., 2008).

5.4 Hydrogen as fuel

Most H_2 is currently produced from non renewable sources such as oil, natural gas, and coal (Zhang et al., 2006). Thermochemical conversion processes such as pyrolysis and gasification of biomass have considerable potential for producing renewable hydrogen, which can help in the exploitation of biomass resources, and the development of a highly efficient, clean way for large-scale hydrogen production. Further, such development has the added benefit of lessening dependence on insecure fossil energy sources (Demirbas, 2006). However, at present, all existing technologies are too costly to be practicable. As it can be seen from Fig. 5, there are two main routes available for producing hydrogen from biomass: thermochemical and biochemical.

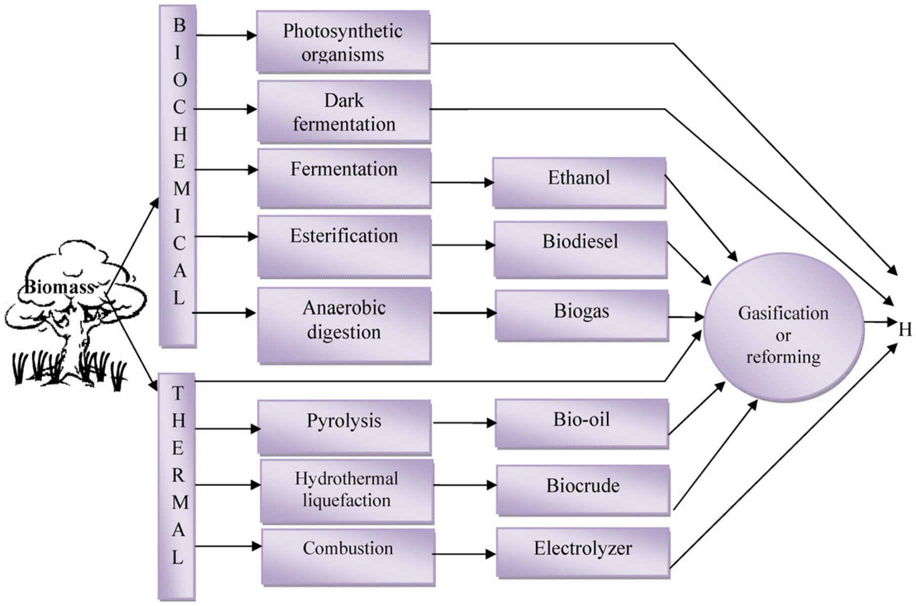

Figure 5. Routes by which hydrogen can be produced from biomass (Abbasi and Abbasi, 2010).

Hydrogen energy systems, including fuel cell systems, appear to provide an effective option for enhancing sustainability. Although it is becoming a more cost effective energy carrier, in part due to the changing costs of producing such energy sources (bio-energy crops, collection and handling of agricultural or forest residues, etc.), it is unlikely that production processes will yield significant reductions in costs, at least in the short to medium term (Dincer and Rosen, 2011). Hydrogen fuel technologies constitute alternatives to conventional fossil-fuel energy technologies and are more efficient, environmentally benign and sustainable. Thus, hydrogen fuel cell systems can assist broadly in efforts to improve energy sustainability, contributing to energy needs in both developing and industrialized countries and in both rural and urban environment.

Investigations have been reported of the potential for providing a sustainable energy system using hydrogen energy (Dunn, 2002) and its role in avoiding climate change and related problems has been described (Scott, 2007). Afgan and Carvalho (2004) describe multicriteria assessments of hydrogen systems, accounting for performance, environment, market and social criteria. The advantages of hydrogen fuel cell system in terms of sustainability include high efficiency, facilitation of use of renewable energy sources, compatibility with renewable energy carriers, environmentally benign compared to conventional energy systems, flexibility in terms of applications, almost unlimited source of the material basis for the fuel, operation flexibility due to the small-scale nature of such systems and the decentralized type of energy systems they constitute, short time duration to implement and adaptability to changes in energy demand.

6. CONCLUSIONS

Energy is essential to economic and social development and welfare enhancing. Unfortunately, the greatest part of the world's energy is currently produced and consumed in unsustainable ways. Fossil fuels provide more than 90% of the world's total commercial energy needs, with oil the leading source in the global energy mix. Achieving a solution to the environmental problems that we face today requires long-term potential actions for sustainable development. In this regard, renewable energy resources are one of the most efficient and effective solutions.

Biomass can offer a good alternative energy source as it can help reduce carbon dioxide emissions and directly replace fossil fuels. Among the different possible feedstocks, agricultural residues are a widespread lignocellulosic source available in most countries. One of its great advantages is that it can offer greater potential for positive environmental, economic and social impacts than most other renewable energy technologies. It is important therefore in assessing bioenergy systems to take account of not only technical, but also environmental, economic and social parameters on a common basis.

As research in bioenergy develops, the understanding of the relationship between bioenergy and environment becomes more and more rational and objective. The use of biomass as a source of energy has been further enhanced with particular attention gasification. The production of biogas through anaerobic digestion offers significant advantages over other forms of bioenergy production. Hydrogen's importance as a sustainable energy carrier results from the fact that it can be used as a fuel with high efficiency, generally causes little or no environmental impact when used and can be produced from a flexible array of energy resources. Many suggest that a hydrogen economy can help ensure economic and social sustainability, once costs are reduced to the point of being competitive with conventional technologies.

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