Development and Evaluation of a New Advanced Solid Bio-Fuel and Related Production Process

Gabriele Di Giacomo*‡, Luca Taglieri*

*Department of Industrial Engineering, University of L'Aquila

gabriele.digiacomo@univaq.it, luca.taglieri@univaq.it

‡ Corresponding Author; Gabriele Di Giacomo, Department of Industrial Engineering, University of L'Aquila, via Giovanni Gronchi, I-67100, L'Aquila, Italy, +39 0862 434 225, gabriele.digiacomo@univaq.it

Received: 14.01.2013 Accepted: 24.03.2013

Abstract- An advanced solid bio-fuel along with a suitable process for its production at industrial scale was developed and analyzed. This new product, similar in the shape to woody pellet, can be obtained not only by wood or woody material but also by uncontaminated agro-industrial vegetable wastes. It is characterized by high density, low mixture content, and good calorific value. All these desirable properties were obtained by compressing and heating the raw materials, previously chopped and mixed, at temperature significantly higher than that used for drying but smaller than that used for the pyrolysis of woody material. The compression and heating condition of biomass were set within the range that partial decomposition of a portion of the biomass and thermal hardening of hemicelluloses is induced, 115-230 °C and 8-25 MPa. The measured lower heating value of the new solid bio-fuel is in the range between 18 and 20 MJ/kg and its specific net renewable energy content is significantly higher than that of traditional woody pellet. This last result along with a number of environmental impacts of the new solid bio-fuel was quantified using an LCA methodology.

Keywords- Solid Bio-Fuels, Renewable Energy, Biomass.

1. Introduction

The total world energy consumption (TWEC) on 2008 amounted to 474×10^{18} J [1], obtained for more than 80% from combustion of fossil fuels (coal, oil and natural gas) [2,3]. In 2009, for the first time in 30 years, there was a reduction of 1.1% of TWEC in comparison with the previous year, as a consequence of the economic crisis in the USA, EU and other developed countries [4].

The solar radiation arriving yearly on the earth is almost 4 orders of magnitude larger than the TWEC [5] and significantly higher with reference to the residual energy resources derived from fossil fuels [6]. Currently, renewable energy, consisting of energy produced and/or derived from sources infinitely renovated (hydro, solar, wind) or generated by combustible renewables (sustainably produced biomass) [7], contributes to the TWEC for less than 20% [6]. Starting with this scenario it appears reasonable to expect that renewable energy, which is strictly related to the solar radiation, will contribute more and more in satisfying the growing TWEC, provided that new advanced technologies will be developed and applied in order to meet all the requirements of the modern way of living as consolidated in developed countries. In future energy scenarios an important role has been addressed to bioenergy considering that biomass, under certain conditions [8], can be considered carbon neutral and less contaminant in comparison to fossil fuels; consequently, GHG emissions and other pollutants can be significantly reduced [9]. In this contest, the potential contribution of solid biofuels to the TWEC has been estimated to about 11% [10] and, in particular areas, this value can arrive to 25% [11,12] or more. There are already a variety of consolidated modern solid biofuels made using chopped or densified milled wood and sawdust as raw material, used for both electrical and heat production for industrial and heating purposes. Among these, the most popular and marketed solid biofuel is the woody pellet [13]. It has been pointed out that biofuel pellets can also be produced using mixtures of waste materials from the agricultural-food industry: pruning residues, straw and bran of rice and cereals, grape pomace, biomasses herbaceous and fibrous generated in the processes of producing juices of fruits and/or horticultural products, and many others [14-18]. The total yearly availability of these materials is very big [19-21]. In this case, only the grinding, the natural drying and the densification are not sufficient, while more sophisticated upstream and downstream processing of raw materials are required to obtain biofuel pellets with satisfactory physical, chemical and mechanical properties [22]. Among these, torrefaction (a kind of mild pyrolysis) between 200 °C and 300 °C is the most diffused and promising technology [21,23-25]. However, the joint effect of pressure and temperature on processing mixed agro-industrial wastes (MAW) for producing high quality biofuel pellets is interesting [26-28]. The main purpose of this work is the development of a mixed biomass derived biofuel pellet (MBDP) having better physicochemical and environmental impact in comparison to traditional woody pellets (WP). To this purpose, the minimally processed (MP) raw materials were treated into a pressurized and heated reactor in order to study the combined effect of pressure, temperature, residence time and ratio between wood and biomass herbaceous and fibrous. An additional purpose of the research is the development of a process and the identification of a set of optimal operating parameters for the industrial production of MBDP.

2. Materials and Methods

Both the wood waste (WW) that biomass herbaceous and fibrous (BHF) were taken from local farmers and stored in open flat containers, one for each kind of biomass. The WW was naturally dried and grounded, when necessary, and then intimately mixed with different amounts, from 0 to 60% by weight, of BHF taken from the vessel where were stored for about one week. The resulting mixture was charged in the heated reactor shown in Figure 1, which can be manually pressurized to a predetermined desired value.

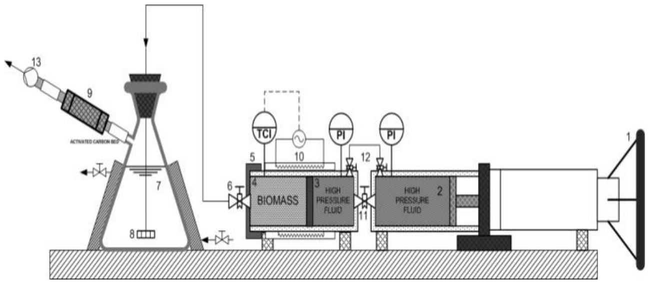

Fig. 1. Schematic diagram of the laboratory scale heated and pressurizing reactor used for developing the new solid bio-fuel.

As can be seen there is a vessel (4) where the biomass can be charged, heated electrically, 10, and pressurized using a manual pump, 1and 2, to the desired values. For proper operation of this device, an additional piston was inserted between the pressuring fluid and the biomass. The reactor 3, 4, 5, 6 and 10, can be easily opened and closed by using the cover 5. The residence time can be changed as necessary and temperature and pressure inside the reactor are continuously monitored; in addition, the temperature is fixed at some predetermined value and automatically controlled. As a consequence of heating and pressurization the biomass is dried and densified; at the same time small amounts of organic compounds and of water are released and collected, for the most, and quantified in the refrigerated vessel 7, equipped with a diffuser 8. The uncondensed portion of this stream is adsorbed from the activated granular carbon inside the ampoule 9 and subsequently analysed together with the solution into the vessel 7, in order to identify the composition and quantify the whole stream leaving the reactor during the whole time of duration of an experimental test.

Both the reactor vessel (0.1 L) and the pump were made of stainless steel 316 L, while the refrigerated vessel (0.6 L) used to collect water and the condensable vapours coming from the reactor, was made of glass. The glass bulb containing the activated carbon is connected to the glass vessel 7, and to the vacuum system 13, by two small pieces of silicon tube that were sealed at the end of each experiment. The glass bulb containing the activated carbon is connected to the glass vessel 7 and to the vacuum system 13 by two small pieces of silicon tube that are sealed at the end of each experiment. Then, the adsorbed organic compounds are recovered by breaking the bulb and by washing the activated carbon with an organic solvent. The resulting liquid solution, along with the liquid solution in the vessel 7, were in turn analyzed using standard procedure and a GC equipped with FID and thermal conductivity detectors, while the amount of steam collected in the vessel 8 was determined by weighing the solution before and after each experiment. Finally, the reactor was cooled and opened in order to take the solid bio-fuel from the inside and to measure its residual moisture content using the Karl Fischer METTLER TOLEDO method, its LHV using a standard Mahler bomb, and its density. Several experimental tests were made in order to find the influence and the applicable ranges of the process parameters on the characteristics of the final product. In particular, accounting for literature results [15,26] and after few preliminary tests, the following ranges for the experimental parameters were selected:

- Temperature, from 115 °C to 230 °C;
- Pressure, from 8 MPA to 25 MPa;
- BHF /WW ratio, from 0% to 60%;
- Reaction time from 0.5 h to 6 h.

It is worth to emphasize that this range of temperature covers three typical different intervals: a) the nonreactive drying, where there isn't any changes in chemical composition, other than the mixture content; b) the reactive drying where initiates changes in chemical composition and colour; c) the destructive drying usually called torrefaction where alterations in chemical composition and colour is significant [15]. Furthermore, the above selected range of pressure is all above the operating pressure of the wet torrefaction [27] to obtain higher value of density.

2.1. Energetic Balance and Environmental Impact

An unavoidable verification in the production of solid biofuels is to quantify the sustainability, namely the amount of the net renewable energy, and the main environmental implications to be compared with the use of coal. In fact, to make a solid modern biofuel with a modern technology, one must consider the fossil energy “invested” in the building of plants, machineries, roads, and others required durable goods, and the fossil energy consumed for the collection, the transportation, and the operation of the plant.

Using all these information, the energetic balance allows to quantify a variety of indicators such as EROEI (energy returned on energy invested), EPBT (energetic pay-back time), NREV (specific net renewable energy value), and others related to additional aspects of environmental impacts. In this study this was done using the LCA (life cycle assessment) methodology [8,28,29]. In particular, the commercial LCA software package SimaPro7.0 [29] was used to make a comparison between MBDP and WP assuming that: a) the non-renewable energy “invested” is practically the same in both cases; b) the whole processes used for the industrial production of MBDP and WP are quite similar. The only significant difference is in the extrusion section because when producing MBDP, temperature, pressure and residence time are quite higher and, consequently, the fossil energy required for a unit amount of MBDP is about 15% higher than that required for the same quantity of WP.

2.2. Industrial Process

Figure 2 shows the block diagram of the process developed for the industrial production of the solid biofuel obtained at laboratory scale.

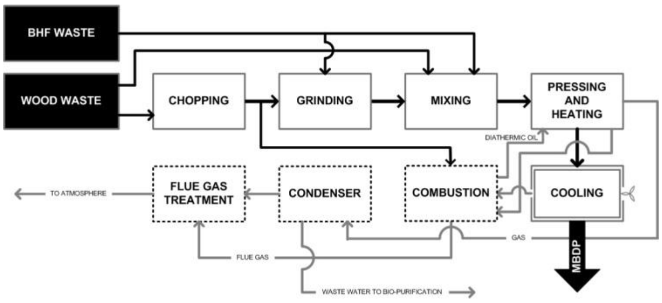

Fig. 2. Block diagram of the process proposed for the industrial production of MBDP.

As can be seen this process proposed for the industrial is made of several sections, including extrusion and cooling of MBDP, heat recovery, and purification of flue gas deriving from the combustion of a portion of lingo-cellulosic biomass. However, since only virgin wood is burned, the flue gas purification section is actually a treatment finalized to remove small amount of solid particulate. It can also be observed that a portion of the lingo-cellulosic biomass is fed directly to the mixer, as in the case of sawdust. Similarly, the BHF waste are fed directly to the mixer, considering that this kind of material is usually friable.

The process can be operated in a continuous mode provided that the extruder is made with pressure resistant but porous walls in order to allow water and other volatile organic compounds to be separated from the solid MBDP.

3. Results and discussion

All the raw experimental results obtained at laboratory scale using the apparatus and the procedure described above are reported in Table 1. In addition, Figures 3 and 4 show the behaviour of LHV, yield, and density of MBDP as function of temperature, pressure and BHF/WW ratio. The forth independent variable-the reaction time-is strongly related to geometry and volume of the reactor other than to operating procedure and heating system. For the laboratory apparatus used in this work it was found that a residence time in the range between 0.5 h and 1 h can be considered satisfactory and, consequently it was fixed to 1 h for all the tests reported in Figure 3 and in Figure 4. As can be seen from Figure 3 LHV is almost independent from P, while the influence of T is about 3% and that of BHF/WW ratio is about 10%; furthermore, the yield is almost independent from P and BHF/WW ratio, while the influence of T is stronger, in particular with T higher than 200 °C. As can be seen from Figure 4 the density is almost independent from the BHF/WW ratio, while is strongly influenced from T and P. As result of all the above considerations and of the additional experimental tests reported in Table 1, the following set of operating parameters was selected:

- T = 200 °C;
- P = 20 MPa;
- BHF/WW = 0;
- Reaction time = 1 h.

Table 2 shows the physical and chemical properties of MBDP obtained under these condition, for comparison with those of a traditional WP. Furthermore, under these conditions, the residual moisture content in the solid biofuel was about 2%, and the sample had the shape of the reactor, was not friable and brown in the colour. Using a material balance made after the measurements of the quantity and the composition of the adsorbate on the activated carbon taken from the glass bulb, along with the quantity and the composition of the organic matter condensed in the glass vessel, it was found that the whole organic matter lost was lower than 3.5%.

Table 2. Comparison between the average value of some physical and chemical properties of MBDP (obtained under optimal o perating conditions) and those of traditional WP.

Parameter	MBDP	WP
Density (kg/m^3)	1276	650
Residual moisture content (%w)	2	10
LHV (MJ/ton)	20000	17000

It is of some interest to point out that the above mentioned result was obtained using always the same WW material (olive oil pruning, naturally dried in the laboratory for at least 6 months, and milled just before starting the experimental run, with the same laboratory mill), and the same BHF, naturally dried in the laboratory for a week (waste of mixed horticultural products taken from a minimally processed food (MPF) and carrot juice local production plant). It is reasonable to expect that changing the nature of the raw materials the results can also change a little.

Table 1. Raw experimental results obtained with the laboratory reactor, varying T, P, BHF/WW ratio, and reaction time inside the range indicated above for each independent variable.

Test	Charge	Process parameters			Product			
	BHF/WW (kg/kg)	T (°C)	P (MPa)	ϴ (h)	LHV (MJ/kg)	Yield (%)	Moisture content (%w)	Density (kg/m^3)
1	0	115	8	1	19.2	89.0	4 ±0.5	921
2	0.60	115	8	1	16.9	87.6	4 ±0.5	925
3	0	115	20	1	19.1	88.9	4 ±0.5	985
4	0.60	115	20	1	17.0	87.7	4 ±0.5	988
5	0	115	25	1	19.1	88.8	4 ±0.5	993
6	0.60	115	25	1	16.9	87.8	4 ±0.5	996
7	0	200	8	1	19.8	80.5	2 ±0.5	1043
8	0.60	200	8	1	17.7	79.0	2 ±0.5	1047
9	0	200	20	1	20.0	81.0	2 ±0.5	1276
10	0.60	200	20	1	17.8	79.6	2 ±0.5	1281
11	0	200	25	1	19.9	81.0	2 ±0.5	1280
12	0.60	200	25	1	17.9	79.7	2 ±0.5	1282
13	0	230	8	1	20.2	77.0	2 ±0.5	1051
14	0.60	230	8	1	18.0	73.0	2 ±0.5	1060
15	0	230	20	1	20.1	77.5	2 ±0.5	1280
16	0.60	230	20	1	17.9	74.1	2 ±0.5	1288
17	0	230	25	1	20.2	77.4	2 ±0.5	1281
18	0.60	230	25	1	17.9	74.3	2 ±0.5	1290
19	0	200	20	0.5	18.8	81.4	5 ±0.5	1215
20	0.60	200	20	0.5	16.5	79.8	5 ±0.5	1220
21	0	200	20	6.0	20.0	80.5	2 ±0.5	1277
22	0.60	200	20	6.0	17.5	79.3	2 ±0.5	1280
23	0.15	200	20	1	19.2	80.4	2 ±0.5	1277
24	0.30	200	20	1	18.6	80.1	2 ±0.5	1279
25	0.45	200	20	1	18.1	79.8	2 ±0.5	1280

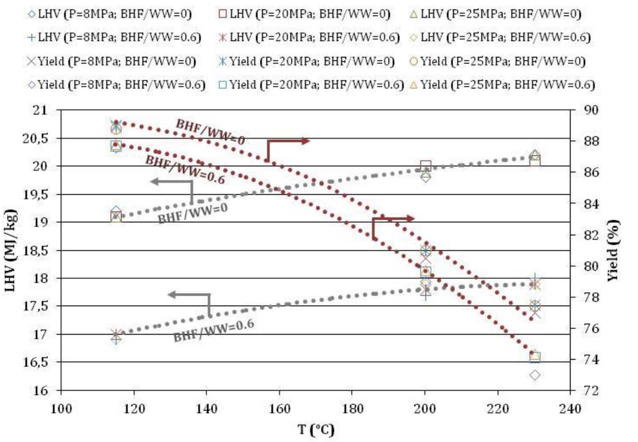

Fig. 3. Behaviour of LHV and yield of MBDP as function of temperature, pressure and BHF/WW ratio.

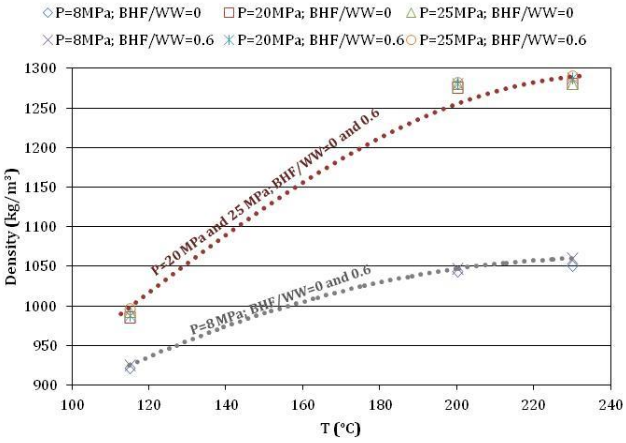

Fig. 4. Behaviour of density of MBDP as function of temperature, pressure and BHF/WW ratio.

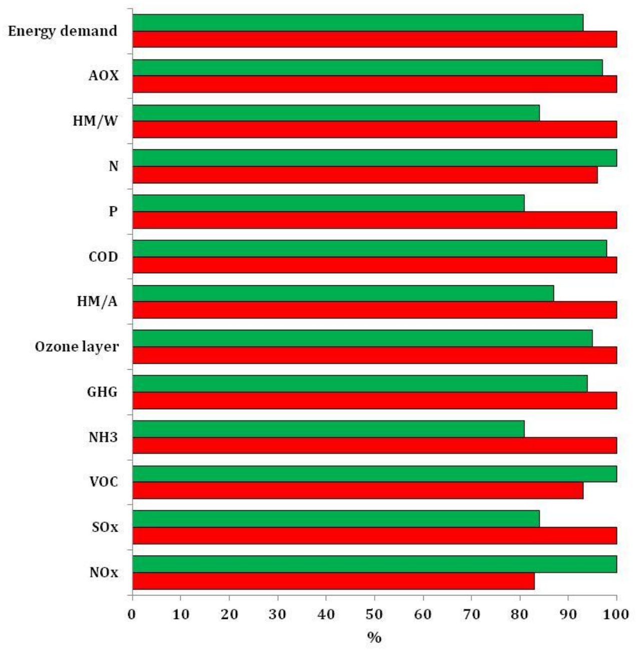

Fig. 5. Environmental impact of MBDP (red) in comparison to WP (green).

4. Conclusion

A new solid bio-fuel named MBDP, which can be produced using woody material mixed with other waste biomass from agricultural and agrifood activities was developed as alternative to traditional woody pellet. Its technical feasibility was proved experimentally at laboratory scale using a small device built for this purpose. The main advantages of MBDP in comparison to traditional WP is that the first is characterized by a residual moisture content less than 2% and its density is about 1280 (kg/m^3. Consequently its LHV for the same volume is significantly higher.

A continuous process for the industrial production of MBDP was developed and described as block diagram, and a set of optimal operating conditions was identified: T= 200°C; P = 20 MPa; 0% of the BHF to WW ratio, and 1 h of reaction time.

Finally, the results show that the MBDP is significantly better (5%) than traditional WP in terms of net renewable energy value, NREV, while it is comparable to WP in terms of the environmental impact.

Acknowledgements

We appreciate the opportunity to be of service to the Italian Government who provided the RIA funding for this study.

References

[1] BP Statistical Review of Word Energy, 31 July 2006, reetrived 24 October 2009.

[2] ET2010:46, Swedish Energy Agency, Energy in Sweden, 2010.

[3] Faaij, A., Modern Biomass Conversion Technologies, “Mitigation and Adaptation Strategy for Global Change, Vol 22, pp 343-375, 2006.

[4] ENERDATA, Yearbook 2012: Global Energy Market.

[5] EEM08, 5th International Conference on the European Electricity Market, Lisbon, 20-30 May 2008.

[6] BP Statistical Review of Word Energy, June 2010.

[7] FAO Forest Department Wood Energy Programme, Unified Bioenergy Terminology (UBET), December 2006.

[8] The Asian Biomass Handbook. A Guide For Biomass Production and Utilization, The Japan Institute of Energy, Shina Yokoyama Ed. January 2008.

[9] Li, J. And Hu, R., Sustainable Biomass Production for Energy in China, Biomass and Bioenergy, Vol 25, pp 483-499, 2003.

[10] IEA Bioenergy, Benefits of Bioenergy, IEA Bioenergy:ExCo2007, 2007.

[11] Di Giacomo, G. and Taglieri, L., Renewable Energy Benefits with Conversion of Woody Residues to Pellets, Energy, Vol. 34, pp 724-731, 2009.

[12] Di Giacomo, G., Taglieri, L., Wood and Wood Waste (RLB) as Significant Resource to Improve the Energy Balance as well as the Environmental Quality of a Green Region of EU: Demonstration and Stimulating Actions Involving Proper Regional Sites. Interreg IIIC, RegEnergy: Feasibility Study; 2007.

[13] Sikkema, R., Steiner, M., Junginger, M., Hiegi, W., Hansen, M.T., Faaij, A., The European Wood Pellet Markets: Current Status and Prospects for 2020, Biofuels, Bioproduct & Biorefining, doi: 10.1002/bbb.277, 2011.

[14] Stelte, W., Holm, J.K., Sanadi, A.R., Barsberg, S., Ahrenfeldt, J.,Henriksen, U.B., Fuel Pellet from Biomass: the Importance of the Pelletizing Pressure And Its Dependency On The Processing Conditions, Fuel, Vol 90, issue 11, pp 3285-3290, 2011.

[15] Deutmayer, M., IEA Bioenergy Task 40, Possible Effect of Torrefaction on Biomass Trade, June 2012.

[16] Obidziński, S., Analysis of Usability of Potato Pulp as Solid Fuel, Fuel Processing Technology, Vol 94, Issue1, pp 67-74, 2012

[17] Obidziński, S., Pelletiation Process of Postproduction Plant Waste, Int. Agrophys., doi: 10.2478/v10247-012-0040-8, Vol 26, pp- 279-284, 2012.

[18] Stelte, W., Fuel Pellets from Biomass, Processing, Bonding, Raw Materials, Ph.D. Thesis, Danish National Laboratory for Sustainable Energy, Technical University of Denmark, ISBN: 978-87-550-3955-1, 2011.

[19] UNEP, Division of Technology, Industry and Economics International Environmental Technology

Centre Osaka/Shiga, Converting Waste Agricultural Biomass into a Resource, Compendium of Technologies, Japan, 2009.

[20] Vasen, N.N., Agri-pellets: Perspective of Pellets from Agricoltural Residues (How to Heat at Low Cost), Proceeding of European Pellets Conference, 2-3- March, Wels, Austria, 2005

[21] Tumuluru, J.S., Hess, J.R., Boardman, R.D., Wright, C.T., Westover, T.L., Formulation, Pretreatment, and Densification Options to Improve Biomass Specifications for Co.Firing High Percentages with Coal, Industrial Biotechnology, doi:10.1089/ind.2012.0004, Vol 8, 2012.

[22] Tumuluru, J.S., Wright, C.T., Kenny, K.L., Hess, J.R., A Review on Biomass Densification Technologies for Energy Application, INL/EXT-10-18420, 2010.

[23] Bergman, P.C.A., Kiel, J.H.A., Torrefaction for Biomass Upgrading, Proceeding of 14th European Biomass Conference & Exhibition, Paris, France, 2005.

[24] Bridgeman, T.G., Jones, J.M., Shield, I., Williams, P.T., Torrefaction of Reed Canary Grass, Wheat Straw and willow to enhance solid fuel qualities and Combustion Properties, Fuel, Vol 87, pp 844-856, 2008.

[25] Van Der Stelt, M.J.C., Gerhauser, H., Kiel, J.H.A., Ptasinski, K.J., Biomass Upgrading by Torrefaction for the Production of Biofuels: a Review, Biomass and Bioenergy, Vol 35, pp 3748-3762, 2011.

[26] Linning, W.A.III, Is Densified Biomass Fuel from Agro-Forestry Waste a Sustainable Energy Option?, Theses and Dissertations, Mechanical Engineering, University of Kentucky, 2012.

[27] Yan, W., Hasting, J.T., Acharjee, T.C., Coronella, C.J., Vasquez, V.R., Mass and Energy Balance of Wet Torrefaction of Lignocellulosic Biomass, Energy Fuels, Vol 24, issue 9, pp 4738-4742, 2010.

[28] Cherubini, F., Bird, N.D., Cowie, A., Jungmeier, G., Schlamadinger, B., Woess-Gallasch, S., Energy and Greenhouse Gas-based LCA of Biofuel and Biofuel and Bioenergy Systems: Key Issues, Range and Recommendations.

[29] Fantozzi, F., Barbanera, M., et al., Life Cycle Analysis of Wood Pellet from SRC Through Direct Measuring of Energy Consumption, Proceeding of 14th European Biomass Conference and Exibition, Biomass for Energy, Industry and Climate Protection, Paris,17-21 October, 2005.