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ANALYSIS OF A MICRO BIOENERGY CHAIN

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Summary

A bioenergy chain, from short rotation coppice (SRC) to a micro district heating network, has been realized in the CRA Research Unit for Intensive wood production of Casale Monf. (AL, Italy). The biomass, harvested by a foragers with header modified, from experimental short rotation coppice trials of poplar, willow, black locust and elm feed an automated boiler system (200 kW). In the winter 2009-2010, 100,6 t of wood chips with humidity ranging from 16 to 39%, are been used. The heating system produced 198,52 MWt. Considering all the chain the cost has been lower than those for diesel heating.

Keywords: bioenergy chain, heating network, SRC.

Introduction

The global growth in energy demand continues; the International Energy Agency predicts energy demand will increase by 40% between 2007 and 2030 (IEA, 2009). The intense and unsustainable use of fossil fuels implies an increasing global environmental impact. The impact of greenhouse gas emissions on global climate change, the increasing oil and natural gas prices, the uncertainty of the political situation and the catastrophic atmospheric events in the areas of production that influence the national security of fossil fuels supply, are driving national and international policies to promote alternative energy sources particularly in developped countries. According to the European Commission climate and energy plan a target of 20% of energy and a specific target of 10% of the energy in transport sector will come from renewable energy sources in 2020 (European Commission, 2008).

To fulfill this requirements, biomass will play an important role. But biomass has to be provided and it can contribute to climate change mitigation only when sustainably produced and used (Ladanai and Vinterbäck, 2010). Biomass for bioenergy come from a wide range of sources: agriculture and forest residues, wet and dry manure, municipal solid waste, industrial wood waste and energy crops. At present, wood is the first source of bioenergy.

To avoid the reduction of the food crops and the forest soil fertility is necessary to increase the cultivation of dedicated energy crops (oil and starch crops, perennial grasses and short rotation forestry or coppices) characterized by high production per hectare and low environmental pressure (EEA, 2006).

However to meet the above mentioned goals, first of all environmental sustainability, a rational thermal utilization of biomass in power plants, both for heat generation and possibly for heat and power cogeneration, is necessary. This objective constitutes a very important target of the European Union and Italian energy policy, in terms of least cost renewable energy exploitation, reduction of CO_2 emissions, energy supply security, social acceptability, energy efficiency and environmental improvement at local level in highly polluted residential areas like the Po valley (CTI, 2006).

In order to study the biomass chain on a small and medium scale, from the energy crop to power plants in 2006 the Italian Ministry of Agricultural, Forestry and Food Policies (MIPAAF) has financed a specific research program ‘Bioenergie’. The activities concerning wood biomass chain are coordinated by the Intensive wood production research Unit of Agricultural Research

Council (CRA-PLF). A micro district heating network, fed with biomass produced by short rotation coppice (SRC), has been realized in the farm of the Research Unit at Casale Monferrato (AL, Italy).

Materials and Methods

The plant is planned to heat four buildings but currently only two are connected: one including offices and guest house (1500 m^3), and the green house (1200 m^3). The connecting pipe has a length of 75 m. The thermal plant (figure 1) includes a boiler Binder mod. TSRF (200 kW of nominal capacity) with an electronic control system, a hot water accumulator tank of 5 m^3, a transport systems for woodchips and ash, a stainless-steel chimney and a woodchips storage silo (40 m^3). The boiler has refractory linings around the walls of the chamber in order to ensure the combustion temperature despite the relatively wet fuel. The boiler has a moving grate burner with hydraulic stoker ram for fuels up to max. 35 % moisture content and an ash content > 1 %. Fuel is metered into the combustion chamber by means of an auger and then distributed along the chamber by the moving grate. The plant is completely automated. The plant's parameters are monitored, displayed, and trend data may be sampled and evaluated for longer periods of time. Air supply and fuel inputs are coordinated to attain the actual heat demand using PLC control and Lambda O2 regulation. When heat demand drops, the unit is operated in part-load mode or is shut down. Fly ash and bottom ash are automatically conveyed into a central ash container, using an auger. Quadruple safety devices prevent any fire reaching the woodchips silo. Thanks to the elevated technological level, the emissions result inferior to the limits fixed by the Italian law (DPCM 8.03.2002).

The fuel is directly produced in farm partly from Short Rotation Coppices (SRC) of different fast growing species using a corn foragers equipped with a modified header, specific for small trees, provided by a contractors and partly from the residues of the cultivation of poplar nurseries and stand using a self propelled chipper available in the farm.

The boiler needs woodchips with a water content (w) inferior to 35%. The high moisture content of wood fuel at the harvest (Table 1) imposes a long period of natural drying. Woodchips were stored in the farm center, 1.5 km from the boiler (figure 2), partly indoor (open shed) and partly outdoors but covered with a TOPTEX fabric cover. They were piled to an height of maximum 4-5 m and during heating period, every 7-20 days they are moved with a wheel loader from storage area to the boiler feeding system (silos).

Table 1. Casale Monferrato (Italy). Woodchips water content (w%) at the harvest.

Species	w%
Poplar	49,4÷59,2
Willow	45,8÷59,2
Black locust	35,9÷50,5
Siberian elm	48,7÷54,0

Since heating plant has been realized in the autumn 2008 but it started to heat only in winter, to calculate the energetic, environmental and economic balances only the period October 15th 2009 – April 30th 2010 has been considered, at present the only period of complete heating.

The total amount of woodchips used in the period 2009-2010 was obtained only by SRC and it was around 100 tons with average water content of 23%, ranging from 16 to 38%.

For the calculation of the energetic, environmental and economic balances, experimental SRC of four species: poplar, willow, black locust and elm have been considered. The SRC were established in spring 2002, all the data are referred to a standard plantation with surface of an hectare. The poplar and willow SRC had a planting density of 8333 trees per hectare, black locust 7500 and elm 10000 trees per hectare. The plantation were coppiced at the end of the second, fourth, seventh and ninth year. All the actual management practices, carried out in the first 9 years of rotation for the four plantation considered, are reported in the Tables 2, 3, 4 and 5.

Table 2. Casale Monferrato (Italy). Annual management practices for cultivation of poplar SRC.

Management practice					**year**				
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Establishment									
Ploughing	1	-	-	-	-	-	-	-	-
Harrowing	1	-	-	-	-	-	-	-	-
Fertilization	1	-	-	-	-	-	-	-	-
Planting	1	-	-	-	-	-	-	-	-
Herbicide treatment	1	-	-	-	-	-	-	-	-
Weed control post planting									
Harrowing	4	1	2	1	1	1	1	1	1
Herbicide treatment	1	-	1	-	-	-	-	1	-
Pest control									
Crysomela populi	1	-	2	-	1	-	-	-	-
Iphantrhia americana	-	-	-	-	-	-	-	-	-
Chryptorrhinchus lapathy	1	-	-	-	-	-	-	-	-
Fertilization post planting	-	-	-	-	-	-	-	-	-
Irrigation (sprinkler)	1	4	3	1	1	-	-	-	-
Harvesting	-	1	-	1	-	-	1	-	1
Clearing	-	-	-	-	-	-	-	-	-

Table 3. Casale Monferrato (Italy). Annual management practices for cultivation of willow SRC.

Management practice					**year**				
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Establishment									
Ploughing	1	-	-	-	-	-	-	-	-
Harrowing	1	-	-	-	-	-	-	-	-
Fertilization	1	-	-	-	-	-	-	-	-
Planting	1	-	-	-	-	-	-	-	-
Herbicide treatment	1	-	-	-	-	-	-	-	-
Weed control post planting									
Harrowing	4	1	2	1	1	1	1	1	1
Herbicide treatment	1	-	1	-	-	-	-	1	-
Pest control									
Crysomela populi	1	-	2	-	1	-	-	-	-
Iphantrhia americana	-	-	-	-	-	-	-	-	-
Chryptorrhinchus lapathy	-	-	-	-	-	-	-	-	-
Fertilization post planting	-	-	-	-	-	-	-	-	-
Irrigation (sprinkler)	1	4	3	1	1	-	-	-	-
Harvesting	-	1	-	1	-	-	1	-	1
Clearing	-	-	-	-	-	-	-	-	-

Table 4. Casale Monferrato (Italy). Annual management practices for cultivation of black locust SRC.

Management practice				**year**					
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Establishment									
Ploughing	1	-	-	-	-	-	-	-	-
Harrowing	1	-	-	-	-	-	-	-	-
Fertilization	-	-	-	-	-	-	-	-	-
Planting	1	-	-	-	-	-	-	-	-
Herbicide treatment	1	-	-	-	-	-	-	-	-
Weed control post planting									
Harrowing	4	1	2	1	1	1	1	1	1
Herbicide treatment	-	-	1	-	-	-	-	1	-
Fertilization post planting	-	-	-	-	-	-	-	-	-
Irrigation (sprinkler)	-	2	1	1	1	-	-	-	-
Harvesting	-	1	-	1	-	-	1	-	1
Clearing	-	-	-	-	-	-	-	-	-

Table 5. Casale Monferrato (Italy). Annual management practices for cultivation of Siberian elm SRC.

Management practice					**year**				
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Establishment									
Ploughing	1	-	-	-	-	-	-	-	-
Harrowing	1	-	-	-	-	-	-	-	-
Fertilization	1	-	-	-	-	-	-	-	-
Planting	1	-	-	-	-	-	-	-	-
Herbicide treatment	1	-	-	-	-	-	-	-	-
Weed control post planting									
Harrowing	2	1	2	-	2	-	-	1	-
Herbicide treatment	-	-	1	-	-	-	-	-	-
Fertilization post planting	-	-	-	-	-	-	-	-	-
Irrigation (sprinkler)	1	4	3	1	1	2	1	1	2
Harvesting	-	1	-	1	-	-	1	-	1
Clearing	-	-	-	-	-	-	-	-	-

Figura 1. Casale Monferratio (Italy) The thermal plant. On the right: the boiler Binder mod. TSRF (200 kW of nominal capacity) and on the left the hot water accumulator tank of 5 m^3

Figura 2. Casale Monferratio (Italy). On the right: Storage of chips in open shed and on the left the silo of thermal plant.

The study of energy and environmental sustainability was carried out following the guidelines of ISO 14040 and 14044 (ISO 2006). The energy and environmental analyses were made through the development of LCA methodology, using the software GEMIS (Global Emission Model Integration System, 4.6 version), implemented by setting the boundaries of the system according to the specific SRC energy chains.. GEMIS, developed from the German Oko-Institute (Institute of Applied Ecology), is a life cycle analysis program and a database for energy, material and transport systems. In its calculation of environmental impacts the software includes the total life cycle, i.e. material used for construction, waste treatment and fuel delivery. GEMIS facilitatedthe assessment of environmental analyses by valuating the results as aggregated indicators (Oko-Iinstitute, 2007). The first step was to define the goal and scope of the study as well as the system boundaries. The scope was to find the most economic and environmentally sustainable supply chain to produce hot water for a micro heat district. One MJ of thermal energy produced was the functional unit chosen to compare the different supply chains. The four SRC supply chains were compared to diesel and natural gas supply chains to quantify the annual emission reduced. The indexes Cumulated Energy Required (CER) and Cumulated Material Required (CMR were used to evaluate the energy efficiency of the chains. Using CER, it is possible to determine the total energy resources used (renewable and non-renewable primary energy), and with CMR, the amount of raw material required, in the supply chain, to obtain the product or service. Data used for yield, amount of fertilizers, water, pesticide and herbicides , fuel consumption and electricity have been validated through comparison with literature and experimental field data obtained within the 'Bioenergy' project. The SRC crop life cycle was divided in two phases; agricultural and energy conversion. The yield of the 4 crops harvested was obtained by the average calculated over a 9 year period of SRC rotation. The same was made for all inputs and emissions considered. The data inventory of the agricultural phase did not take into account all the impacts associated with the production of cuttings to be transplanted, utilization of lubricants, plant buildings and human works. Moreover, the direct emission of machines due to diesel consumption have been modeled without taking into account the transportation of the material used. The output (thermal energy) and inputs (electricity and construction material) of the conversion phase were considered the same for all four SRC crop supply chains. Furthermore, through GEMIS, the following environmental aspects were assessed:

- the global warming potential (GWP): that is the mass-based equivalent of the radiative forcing of green house gases (GHG), based on the specific forcing of CO2 therefore, it is expressed in CO2 equivalents. Because GHG (CO_2, CH_4, N_2O, SF_6, PFC, HFC) have different atmospheric residence times, the GWP is determined as an integral over a period of time. Usually, GWP data refer to a time horizon of 100 years (Oko institute, 2008).

The CO_2 equivalents of all GHG are calculated by the following formula:

$GWP_{equi} = \sum (e_i * GWP_i)$

e_i = mass of GHG "i" in kg
GWP_i = global warming potential of emission "i", in [kg/kg]

Table 6. Acidification potential (AP) of acid air pollutant expressed in SO_2 equivalents.

Pollutant	AP
NO_x	0.696
HF	1.601
HCl	0.878
H_2S	0.983
NH_3	3.762

- acidification potential (AP): that is the result of aggregating acid air emissions (SO_2, NO_x, HCl, HF, NH_3, H_2S), is expressed in SO_2 equivalents (. The SO_2 equivalents express the acidification potential (= AP) and are calculated from the molecular weights and the protone bindings potential of the respective emissions (by definition AP = 1 for SO_2). The algorithm used to calculate the AP through GEMIS is:

AP_{equi} is determined as $\sum (e_i * AP_i)$

e_i = mass of emission "i" in kg
AP_i = acidification potential of emission "i", in [kg/kg]

Table 7. Tropospheric ozone precursor potentials (TOPP) of pollutant.

Pollutant	**TOPP**
NO_x	1.220
NMVOC	1.000
CO	0.110
CH_4	0.014

- the relative tropospheric ozone precursor potentials (TOPP) that is the mass-based equivalent of the ozone formation rate from precursors, measured ozone precursor equivalents (CO, CH_4, NMVOC, NO_x). The TOPP represents the potentially formation of near-ground (tropospheric) O_3 which can cause summer smog.

The algorithm used to calculate the OPP_{equi} through GEMIS is:

$$OPP_{equi} = \sum (e_i * OPP_i)$$

e_i = mass of emission "i" in kg
OPPi = ozone precursor potential of emission "i", in [kg/kg]

At farm level the Green House Gas (GHG) balances for each crop included the estimates of the CO_2 uptake by the aboveground biomass and the CO_2, CH_4 and N_2O emitted, considered all in CO_2 equivalents, (IPCC, 2002) during management practices. Carbon sequestration in the soil is not considered.

CO_2, CH_4 and N_2O emissions and energy used by machinery and equipment utilized (ploughing, harrowing, planting, harvest, irrigation, fertilizers, herbicides and pesticides sprayed) were calculated considering diesel oil consumption and national emission factors (ANPA, 2002) were then applied.

Energy utilized and GHG emission for machinery and equipment construction, based on data from Fiala and Bacenetti (2009) were considered for the time of use. For planting material, fertilizer, herbicides and pesticides emissions which occurred during their production were considered, on the basis of the energy consumption and the actual amounts used in the field (Tedeschi et al., 2005).

Soil N_2O efflux (considered as CO_2 equivalents) were assumed equal to the 1.25% of the N input in soil (Tedeschi et *al*. 2005).

The economic assessment of the entire micro bioenergy chain has enabled to consider the sustainability of the use of biomass in energy production, in this case for chip-fed boiler for residential buildings and greenhouses for vegetable production. Production costs of wood chips and management of the boiler are taken into account. The following is an economic balance of the various production processes of the wood-energy chain and a comparison with the diesel heating system previously utilized. The comparison was made assuming, for the diesel central heating, the same rated power possessed by a biomass heating boiler (200 kW).

The economic evaluation related to the production of biomass was carried out as described above and based on plantations in which they were detected and calculated in financial terms the costs of all procedures and products used in each year of the duration of the crop, 9 years and 4 harvesting. After the last coppice it is assumed that the trials were concluded, the energy plantation is removed and the soil return to conventional cropping. For the harvesting of biomass has been adopted a system of simultaneous cutting and chipping in the field and transport of wood chip in the storage area of the farm. The main economic parameter determined was the average cost of wood chip production (Table 8). This cost was calculated using a financial analysis based on the discounting of flows of annual cost (price 2010).

Table 8. Costs for every practice of poplar, willow, black locust and siberian elm SRC.

	Poplar €/ha	**Willow €/ha**	**Black locust €/ha**	**Siberian elm €/ha**
Establishment				
Ploughing	84	84	84	84
Harrowing	43	43	43	43
Fertilization	1.125	1.125	-	1.125
Planting	2.028	2.028	2.472	3.362
Herbicide treatment	193	193	127	127
practices post planting				
Harrowing	50	50	53	53
Herbicide treatment	245	242	122	243
Pest control	45	36	-	-
Fertilization post planting	-	-	-	-
Irrigation (sprinkler)	190	190	293	188
Harvesting	529	712	687	814
Clearing	500	500	600	500

Results

The actual biomass productions of the four SRC plantations are reported in Table 9.

Table 9. Casale Monferrato (Italy). Actual yields of SRC in the first four biennial or triennial harvesting cycle, expressed as dry weight (DW) in odt·ha^{-1}·year^{-1}.

	Harvesting cicle number and cycle length (year)			
Species	**1(2y)**	**2 (2y)**	**3 (3y)**	**4 (2y)**
Poplar	6,0	9,0	10,0	7,5
Willow	6,0	16,0	14,0	14,8
Black locust	11,6	12,4	12,2	14,4
Siberian elm	6,6	12,9	12,9	14,3

The GHG balance of the four bioenergy crops has been reported in Table 10, while energy balance in Table 11. The source and sink have been evaluated for the first four rotations (2-3 years). To obtain a complete and correct balance is necessary to consider the whole life cycle of the plantation (12-15 years); but 9 nine years represent a good approximation. The balance is highly positive for each plantation.

A detailed description of the GHGs emissions per each management operation and each crop have been reported in Figure from 4, 5 and 6. The inputs include direct (fuel and material utilized) and indirect costs (machinery construction and fertilizer, herbicides and pesticides production).

The most part of the energetic inputs are concentrated in the establishment phase of poplar, willow and Siberian elm SRC; while they are diluted during the time in black locust SRC because this plantation wasn't fertilized.

Table 10. GHG balance in t CO_2eq.·ha^{-1}·rotation^{-1}: source (So), sink (Si) and rotation (Rot) length in year for perennial crops.

Crop	So	Si	Rot
Poplar	6,16	137,5	9
Willow	6,70	221,9	9
Black locust	3.99	205,5	9
Siberian elm	7,41	200,2	9

Table 11. Energy balance in GJ · ha^{-1} ·rotation^{-1}: source (So) and sink (Si) and rotation (Rot) length in year for perennial crops.

Crop	So	Si	Rot
Poplar	56,8	1312,5	9
Willow	65,3	2023,0	9
Black locust	48,1	1961,8	9
Siberian elm	73,9	1911,4	9

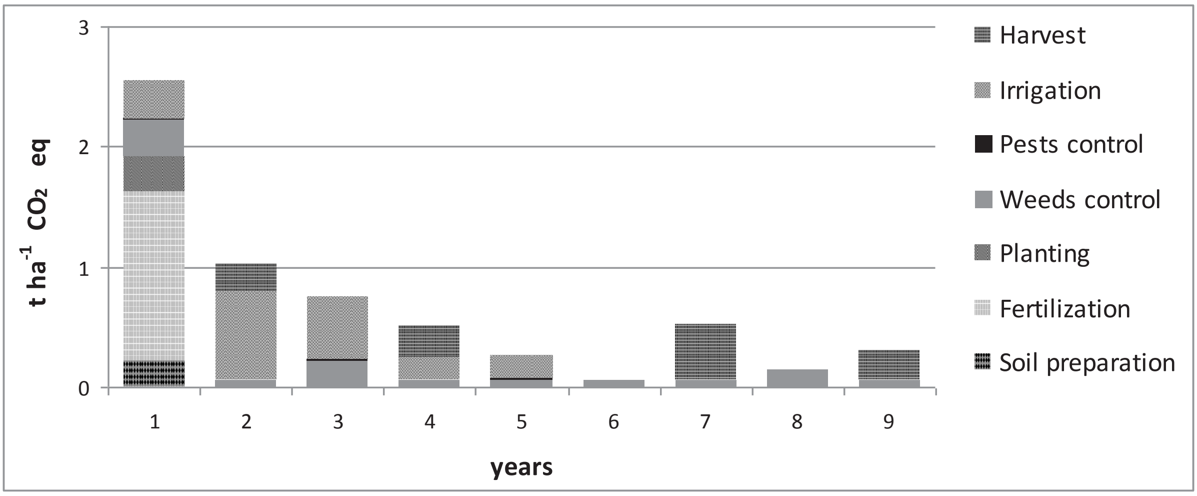

Figure 3. Casale Monferrato (Italy). GHG emission for each management operation in poplar and willow SRC.

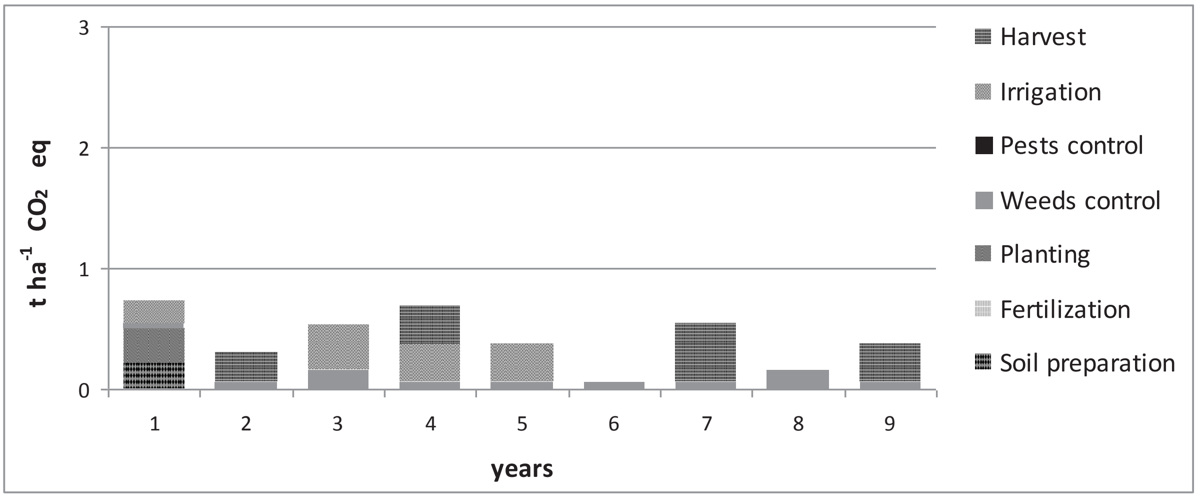

Figure 4. Casale Monferrato (Italy). GHG emission for each management operation in black locust SRC.

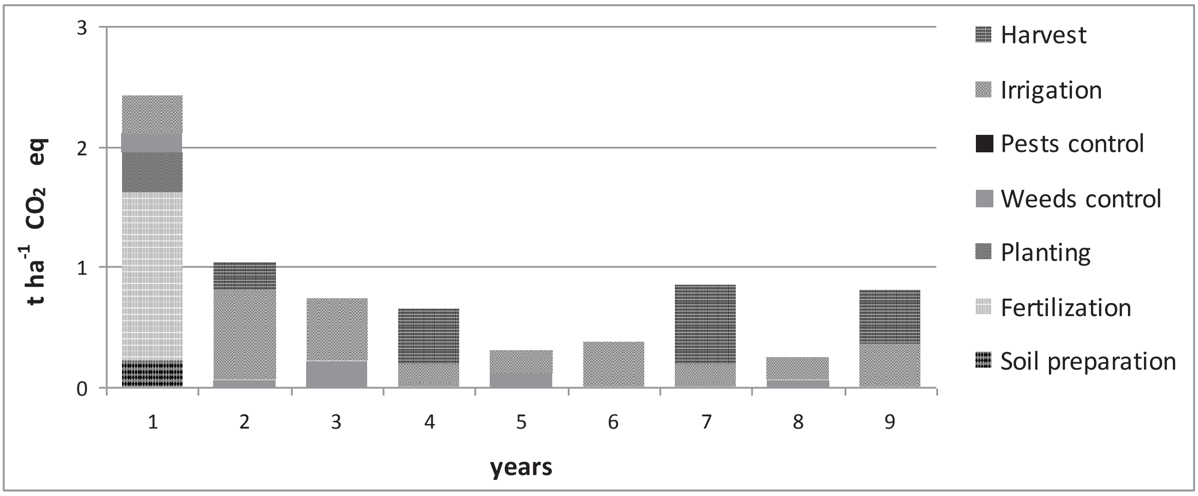

Figure 5. Casale Monferrato (Italy). GHG emission for each management operation in siberian elm SRC.

Table 12. Cumulated Energy Required (MJ) to produce 1 MJ of thermal energy.

Supply chain	Sum	non renewable	renewable	other
Blacklocust SRC	1,642700	5,16E-01	1,103491	2,33E-02
SiberianElm SRC	1,643982	5,17E-01	1,103508	2,33E-02
Willow SRC	1,672190	5,44E-01	1,103581	2,45E-02
Poplar SRC	1,705846	5,78E-01	1,103699	2,42E-02
Natural gas	1,328637	1,327245	5,23E-04	8,69E-04
Diesel	1,546744	1,538786	7,58E-03	3,80E-04

The impact of the emissions from biomass is modest, having in average a consumption of only 0,54 MJ per MJ of hot water produced compared to 1,54 MJ/MJ of diesel and 1,33 MJ/MJ of natural gas (Tables 12 and 13).

The CO_2 equivalent emitted for the production of 1 MJ of hot water by the SRC supply chains was assessed as 3,65 kg·y^{-1} on average (Table 14). The best result was obtained from the Black Locust SRC supply chain with 0,354 kg CO_2·MJ$^{-1}{}_{hotwater}$·y^{-1} while the Willow SRC supply chain produced the most CO_2 with 0,376 kg CO_2·MJ$^{-1}{}_{hotwater}$·y^{-1} . The major cause of CO_2 and N_2O emissions are due to tillage operations (45%) and for CH_4 , the raw material extraction (68%).

Table13. Detailed non renewable energy resource balance SRC supply chains (MJ).

Supply chain	Black locust SRC	Poplar SRC	Siberian elm SRC	Willow SRC
Coal (hard)	112,62*10^{-3}	117,86*10^{-3}	112,69*10^{-3}	119,19*10^{-3}
Lignite	31,681*10^{-3}	32,309*10^{-3}	31,787*10^{-3}	31,769*10^{-3}
Natural gas	15,144*10^{-3}	18,547*10^{-3}	15,601*10^{-3}	16,112*10^{-3}
Nuclear	31,474*10^{-3}	32,411*10^{-3}	31,616*10^{-3}	31,655*10^{-3}
Oil	325,02*10^{-3}	376,78*10^{-3}	325,48*10^{-3}	345,36*10^{-3}
Total non renew.	515,94*10^{-3}	577,90*10^{-3}	517,17*10^{-3}	544,09*10^{-3}

The CO_2 saved (Table 14) by the SRC supply chains in comparison with fossil fuel supply chains to produce hot water in the studied micro heat district resulted in average about 29 t $CO_{2\ saved}$ ·y^{-1} in comparison with natural gas and 55,8 t $CO_{2\ saved}$ ·y^{-1} in comparison with diesel.

Table14. GHG balance of the supply chains and quantity of CO_2 saved by use of chips-based fuel in comparison with diesel and natural gas-based fuel.

Supply chain	CO_2 eq	CO_2	CH_4	N_2O	Chips vs Diesel	Chips vs Natural gas
		(kg CO_2 *MJ^{-1}*y^{-1})			(t $CO_{2\,saved}$ *y^{-1})	
Blacklocust	3,54E-02	3,38E-02	5,88E-05	9,00E-07	5,66E+01	2,96E+01
Siberian Elm	3,55E-02	3,38E-02	5,89E-05	9,09E-07	5,65E+01	2,95E+01
Willow	3,76E-02	3,59E-02	6,27E-05	9,60E-07	5,50E+01	2,80E+01
Poplar	3,75E-02	3,57E-02	6,26E-05	9,93E-07	5,51E+01	2,81E+01
Natural gas	7,68E-02	7,19E-02	1,90E-04	1,48E-06	2,70E+01	-
Diesel	1,15E-01	1,11E-01	1,04E-04	4,17E-06	-	-2,70E+01

The LCA results for the acidification and the ozone formation potential impact category are shown in Table 15. The natural gas systems in this impacts category were associated with the lowest environmental impacts (TOPP 1,35E-04 kg*MJ^{-1}*y^{-1}; 7,35E-05 kg*MJ^{-1}*y^{-1}). The diesel system was the most environmentally impacting cause of high emission of NO_x. Wood chips fuel based systems showed an average potential acidification of 4,14E-04 kg*MJ^{-1}*y^{-1} and TOPP of 6,59E-04 kg*MJ^{-1}*y^{-1}.

Table15. Tropospheric ozone precursor potentials (TOPP) and acidification potential (AP) of the wood chips, diesel and natural gas based-fuel supply chains. (kg*MJ^{-1}*y^{-1}).

Supply chain	TOPP equivalent	SO2 equivalent
Blacklocust SRC	6,53E-04	3,95E-04
SiberianElm SRC	6,55E-04	3,96E-04
Willow SRC	6,63E-04	4,61E-04
Poplar SRC	6,64E-04	4,04E-04
Natural gas	1,35E-04	7,35E-05
Diesel	1,51E-03	1,28E-03

For the economic evaluation at first the average annual costs of production were determined. The average cost per unit of product has been obtained considering the annual production, the values are reported in Table 16.

Table 16. Costs of plantations (€·ha^{-1}), and determination of the average production cost of wood chips on a production cycle of 9 years, 4 harvesting and final clearing.

	Poplar	Willow	Black locust	Siberian elm
Total costs (9 years €· ha^{-1})	9.321,90	10.000,84	8.654,19	12.168,76
Mean annual costs (€· ha^{-1}·$year^{-1}$)	1.035,77	1.111,20	961,58	1.352,08
Mean production (t· ha^{-1}·$year^{-1}$)	18,33	26,59	20,68	21,86
Water content %	54,50	51,70	40,00	46,00
Mean cost (€·t^{-1})	56,49	41,79	46,50	61,85
Mean cost 22% w (€·t^{-1})	90,30	66,79	74,32	98,85
Mean cost dry matter (€·t^{-1})	124,29	86,51	77,50	114,53

Table 17. Chips composition and mean costs of chips at harvest, at boiler silos and oven dry.

		Wet chips at harvest		Chips at boiler		Dry chips	
Species	%	t	€·t^{-1}	t	€·t^{-1}	t	€·t^{-1}
poplar	52,96	85,15	56,49	53,27	90,30	41,15	124,29
willow	28,91	46,49	41,79	29,09	66,79	22,47	86,51
black locust	16,28	26,17	46,50	16,37	74,32	12,65	77,50
siberian elm	1,85	2,98	61,85	1,86	98,85	1,44	114,53
total	100,00	160,78	51,02	100,59	81,54	77,70	105,57

Table 18. Analysis of the technical characteristic and cost comparison of management of the two heating systems (wood chips and oil).

	Units	**Chips**	**Diesel**
Building Volume	m 3	3.500	3.500
Energy demand unit	W/m 3	0,01	0,01
Annual utilization	h	4.614	4.614
Annual gross energy output	kWh/anno	198.520	198.520
Plant power	kW	200	200
Annual average efficiency	%	80,0	90,0
Calorific power of the fuel (LHV)	kWh/kg	3,25	11,86
Annual fuel consumption	t/anno	100,59	17,86
Investment cost	€	104.670	40.000
Fuel unit cost	€/kg	0,082	1,50
Fuel cost per thermal energy unit produced	€/kWh	0,041	0,135
Annual fuel cost	€	8.202,60	26.787,16
Other annual costs (ownership,.maint.cost)	€	8.422,00	2.743,27
Annual total cost	€	16.624,60	29.530,43
Unit cost of energy produced	€/MWh	83,74	148,75

In short, the results of financial analysis (Table 19) show the total costs of plantation, each one with 9 years rotation length, that range from 8.654 € to 12.169 €, corresponding to an average annual cost of cultivation that ranges from 962 Euro per hectare for black locust to Euro 1.352 per hectare for the Siberian elm. The average cost per unit of product with a 22% moisture content is about 82 €/t (about 106 €/t dry) (Table 17). These values were compared with diesel in Table 18.

In order to meet the annual requirement of thermal energy demand in 4.614 hours of operation (198.5 MWh), with an average efficiency of the boiler around 80%, there were burned about 100 tonnes of wood chips with an average moisture content around 22%, or about 18 tonnes of diesel (in this case with a boiler efficiency of 90%). The initial investment costs for the purchase and installation of boilers can be amortized over a period of 20 years of technical life of the thermal plant.

The advantage of using chips instead of diesel amounted to approximately € 12.900,00 per year (annual total costs) as showed in Table 18.

Discussion

At field level GHG and energy balance showed a positive results but we still need to consider the effect of land use change on soil Carbon content.

SRC can be considered a good carbon sink but considering other work (Facciotto et *al*. 2010) there's a strong variability in productions (and in C sequestration) due to the different soils, water availability and management too.

Based on our results, and in agreement with Henkel et *al*. 2009 we suggest that wood chip system is the best choice in terms of the effects on global warming. However, the trade-off is high impacts in categories other than GHG emissions, especially when compared to natural gas based systems (Henkel et *al*. 2009). In general, the impacts of local emissions are quite high, due to high emissions of pollutants other than GHG. For this reason, ecological performance would be improved by better wood chips combustion systems; especially with respect to NOx emissions. But the boiler used in our micro district heating plant respects the constraints of the European, national and local (Piemonte Region) regulations adopting the stricter emission limits.

The environmental benefits of our micro district heating plant include:

- elimination of the emissions of the obsolete heating boilers feed by fossil fuel, distributed in the four building (currently only two);
- rationalization of the chain and minimization of the transportation impact;
- contribution to the reduction of GHG emission.

The economic analysis emphasizes the sustainability of chip-fed system for the production of thermal energy. The wood chips represents the main energy cost, while other costs correspond to the electric energy for pumping water in the pipe and for other minor auxiliary equipment of the boiler.

The final result shows that the use of self-produced chips leads to an average savings in operating costs of heating the CRA-PLF of around 71 Euro per MWh of thermal energy produced: the cost of wood chips is 83,74 Euro per ton while the cost of diesel is 148,75 Euro. In relation to the thermal requirements of the plant, the surface of SRC required to have a constant supply of the boiler range from a minimum of 6 (willow) to a maximum of 9 hectares (poplar), according to the productivity of the four species considered.

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