Energies **2015**, *8*, 5182-5197; doi:10.3390/en8065182

OPEN ACCESS

energies

ISSN 1996-1073

www.mdpi.com/journal/energies

Article

Sustainability Assessment of a Self-Consumption Wood-Energy Chain on Small Scale for Heat Generation in Central Italy

Stefano Verani [1], Giulio Sperandio [2], Rodolfo Picchio [3,*], Enrico Marchi [4] and Corrado Costa [2]

[1] Consiglio per la ricerca in agricoltura e l'analisi dell'economia agraria (CRA), Unità di ricerca per le produzioni legnose fuori foresta, Via valle della quistione, 27, 00166 Rome, Italy; E-Mail: stefano.verani@entecra.it

[2] Consiglio per la ricerca in agricoltura e l'analisi dell'economia agraria (CRA), Unità di ricerca per l'ingegneria agraria, Via della Pascolare, 16, 00016 Monterotondo, Italy; E-Mails: giulio.sperandio@entecra.it (G.S.); corrado.costa@entecra.it (C.C.)

[3] Department of Science and Technology for Agriculture, Forest, Nature and Energy (DAFNE), Tuscia University, Via S. Camillo De Lellis, 01100 Viterbo, Italy

[4] Department of Agriculture, Food and Forest Systems, Florence University, Via San Bonaventura, 13 50145 Florence, Italy; E-Mail: enrico.marchi@unifi.it

* Author to whom correspondence should be addressed; E-Mail: r.picchio@unitus.it; Tel.: +39-0761-357-400; Fax: +39-0761-357-250.

Academic Editor: Enrico Sciubba

Received: 30 March 2015 / Accepted: 18 May 2015 / Published: 3 June 2015

Abstract: The sustainability of a small-scale self-consumption wood-energy chain for heat generation in central Italy was analyzed from a technical, economic and energetic point of view. A micro-chain was developed within the CRA-ING farm at Monterotondo (Rome, Italy): The purpose of this system was to produce biomass for supplying a heating plant within the CRA-ING property as a substitute for diesel fuel. A poplar short rotation coppice, established with clones AF2, AF6 and Monviso, fed the micro-chain. The rotation was biennial. The average plantation production ($Mg_{d.m.}·ha^{-1}·year^{-1}$) was 10.2, with a maximum of 13.53 for the twin-rows AF2 and a minimum of 8.00 for the single-row Monviso. The economic assessment was based on the Net Present Value (NPV) method and the equivalent annuity cost, and found an average saving of 15.60 €·GJ^{-1} of heat generated by the wood chips heating system in comparison with the diesel heating system over a 10 year lifetime of the thermal power plant. The energy assessment of the poplar plantation, carried out using the Gross Energy Requirements method, reported an energy output/input ratio of 12.3. The energy output/input ratio of the whole micro-chain was 4.5.

Keywords: short rotation coppice; micro-chain; production costs; economic sustainability; energy budget; net present value

1. Introduction

At an international level, the management of forest resources is crucial for both the environment and economic development. The Kyoto Protocol of the United Nation Framework to Combat Climate Change [1], established the terms for a commitment to effectively reduce greenhouse gas emissions. For the first commitment period (2008–2012), the signatory States had to comply both to reduce gas emissions and to increase the terrestrial carbon (C) sink through reforestation and forest management [2]. The global negotiations, aimed at achieving new climate change mitigations and other arrangements after 2012 (the end of the Kyoto commitment period), started in Bali in 2007, continued in Copenhagen in 2009 [3] and will become operative in 2020, as decided in Durban on December 2011. This process will determine the direction and intensity of long-term changes to limit global warming. Proposals for a long-term objective include: (i) an upper bound on global temperature increase of 1.5 or 2 °C; (ii) an upper bound on atmospheric concentrations of CO_2 of 350 or 450 parts per million (ppm); (iii) a long-term goal to reduce global emissions by 50% by 2050 (the so-called "50 by 50" target); (iv) a target date for the peaking of global emissions (and possibly also dates for the peaking of developed and developing country emissions) [4,5]. In this context, the European Union determined the ambitious objectives (European Council 4/2009) addressed for 2020 to: (i) promote energy production from renewable resources + (20%); (ii) reduce energy consumption by 20%; (iii) unilaterally reduce CO_2 emissions with respect to 1990; (iv) substitute 10% of fuel consumption with biofuel.

Nowadays, about 15% of world energy requirement is provided by biomass, of which 13% is consumed by developing countries and 2% by developed countries [6,7]. In Italy, biomass has been receiving increasing attention, although energy crops have not actually been exploited yet on a large commercial scale [8]. Amid the biomass that may be used for energy production, wood shows the greatest potential from both a production and environmental point of view [9–11].

Forest biomass supply can be provided by pre-existing forests or by newly-established plantations, to be managed through Short Rotation Coppice (SRC). This system is indicated as a biomass production system and its future development is encouraged within the framework of the Kyoto protocol (Art. 3.4—Additional activities). The positive effects of introducing energy crop on local employment allow a more sustainable development of rural areas [12]. In Italy, this type of plantations has been adopted since the early 1990s. In fact, the total surface area dedicated to SRC is about 7000 ha, mostly concentrated in the Northern areas, along the Po valley, where the Italian agricultural industry is more developed [13]. In the Central-Southern Italian regions, a few hundred hectares dedicated to SRC have been mainly established in recent years [14]. One of the most critical aspects of the use of woody biomass is its transportation. While burning wood from short rotation can be considered C neutral, transport from the harvesting site to the final users causes CO_2 release into the atmosphere. Biomass transportation on long distances implies extra costs, energy consumption, material loss and complex logistics [15]. It is therefore important to minimize the transport distance and thus facilitate the establishment of short chains [16]. The aim of this study was to analyze the economic and energetic sustainability of a wood-energy chain, where the biomass to feed the heating system was self-produced at a farm in Central Italy.

2. Materials and Methods

In March 2005, a SRC poplar plantation was established over a 4 ha area within the farm of the Agricultural Engineering Research Unit at the Agriculture Research Council (CRA-ING) (Lat. 42°06’07” N, Long. 12°37’39” E). The site was located on a flat terrain. The soil was clay loam texture and low level of organic matter, nitrogen and phosphorus. Three clones were used: AF2, AF6 and Monviso [17,18]. A transplant machine activated by a 73 kW power tractor, able to operate on single-row and twin-rows, was used to plant the poplar cuttings. This field was separated into two plots of about 2 ha each: One plot was single-row and the other plot was twin-rows. The distance between the rows (either single or twin) was 2.80 m; the distance between the rows forming the twin was 0.75 m. The cuttings were planted along the row with a spacing of 0.50 m. The effective density of the plantation for the single and twin-rows was 7,140 and 10,360 cuttings·ha^{-1}, respectively.

Since the establishment, the growth of the plantation was monitored by measuring the Diameter at Breast Height (DBH) and the height of all the trees in 30 permanent sampling areas, being representative of the entire area. In particular, 18 sampling areas (six for each clone) of 67 m^2 were selected for the single-row plantation and 12 sampling areas (four for each clone) of 57 m^2 were selected for the twin-rows plantation. In the two years following the plantation establishment, the number of sprouts for each stump, wood moisture, bulk density and High Heating Value (HHV) were determined for each of the three clones. Three woody samples were taken from 30 sprouts, randomly selected, for every clone (one at ground level, one at mid-height and one close to the top). After felling, woody samples (5 cm length) were immediately weighed by a scale (Orma model BC16D) and transferred to the laboratory for moisture and wood density determination by using the thermo-gravimetric method (UNI ISO 1985; UNI 1987; UNI EN 2003). Analysis of variance (ANOVA test) was applied to moisture and wood density data. Then, the woody samples were chipped and processed, according to the European Standard UNI EN 14918:2010 “Solid biofuels—Method for the determination of calorific value”, for determining the higher heating value. A sub-sample of 100 g was ground with an Ika Werke MF10B rotating-blade mill equipped with a 0.7 mm sieve, then 1 g of wood dust was selected and compressed into pellets by a Parr manual press. The pellet was burned in a Parr 6200 adiabatic bomb calorimeter. Analysis of variance (ANOVA test) was applied to moisture and wood density data while HHV data were processed using the non-parametric Kruskal-Wallis test [19,20].

On December 2007 the plantation was harvested. For each plot and clone, the curves to determine the height (hypsometric) and the fresh weight as a function of DBH were determined. The hypsometric curves were obtained from 84 observations, while 30 observations were used to determine the fresh weight curves; the two equation models were respectively:

$$Y_H = a + bx - cx^2 \tag{1}$$

and:

$$Y_W = ax^z \tag{2}$$

where Y_H represents the height (m), Y_W represents the fresh weight (kg), x represents the DBH (cm), and z is for single rows: AF2 = 1.9417, for AF6 = 2.2471, Monviso = 2.5201; and for twin rows: AF2 = 2.0125, for AF6 = 2.1929, Monviso = 1.8445.

Economic Analysis

The economic analysis focused on the evaluation of the sustainability of the SRC plantation and on the whole self-consumption wood-energy micro-chain, comparing two heating systems based on wood chip fuel and diesel fuel, respectively. The adopted method was Life-Cycle Cost Analysis (LCCA) [12,21–24].

The length of the period for assessing the performance of two systems was 10 years, indicated as the life period of the Institute's heating plant. The economic analysis started from the year of initial investment to purchase the heating power plant. For the long-term period, the analysis was conducted using financial formulas based on the Net Present Value (NPV) method [22,25–27]. NPV criterion is defined as a sum of present values of annual net incomes earned over the period. In this case, only the costs were considered, for which the parameter calculated was the Present Value of Costs (PVC). The formula is:

$$PVC = \sum_{t=1}^{n} \frac{Ct}{(1+r)^t} + P \tag{3}$$

where:

Ct = total annual costs at the year *t*;

r = real discounted rate (equal to 3%);

t = year (variable from 1 to 10);

P = initial investment cost.

Moreover, based on the PVC, the equivalent annuity method was adopted to calculate the equivalent annual cost (EAC), according to the following formula:

$$EAC = PVC \frac{r(1+r)^t}{(1+r)^t - 1} \tag{4}$$

where:

PVC = Present Value of Costs; *t* = years (variable from 1 to 10); *r* = real discount rate (equal to 3%).

For the wood chip heating system, the initial cost of the heating plant, the annual plant operating costs and the cost of planting, management, harvesting and chipping of the SRC plantation were considered. A productive cycle of 10 years was hypothesized, considering five biannual harvests, even if a cycle of twelve or fourteen years is likely.

The power heating design and logistic provide a technical life of the plant of 10 years. In these 10 years of operation a constant supply of biomass must be delivered. This is possible by managing the plantation in two batches whose planting year differs by one year (Figure 1). This scheme was also the basis to show the cash flow of costs to evaluate the PVC and EAC of the plantation and management of the thermal power plant.

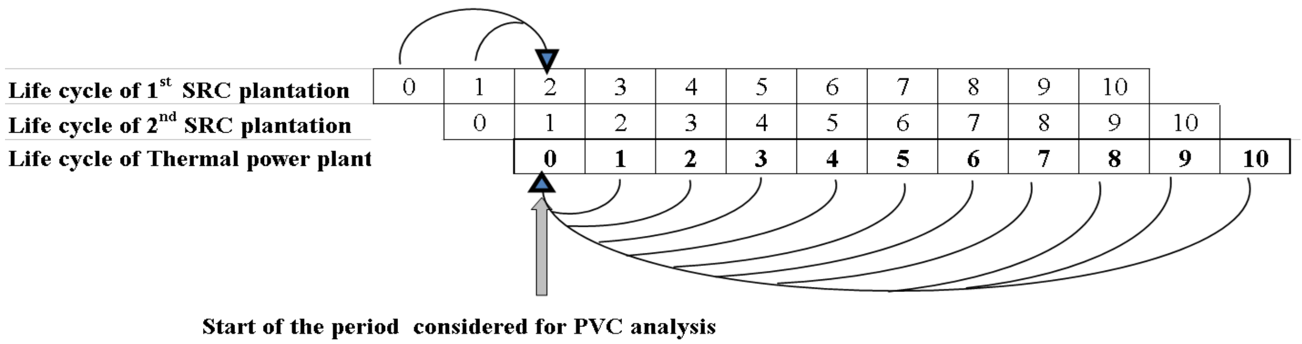

Figure 1. Scheme of the period (in years) considered for the economic evaluation of the Present Value of Costs (PVC) in a wood chip heating system.

Figure 1 foresees the establishment of two plantations of equal surface area. To ensure immediate activation of the heating system, it is necessary that the biomass obtained from a two year-old plantation is available. With the biomass necessary to feed the heating plant being hypothesized as constant, the annual biomass requirement derives from the alternate harvesting of the two SRC plantations. In this way it is possible to produce wood chips (in spring) 6–8 months before the heating plant seasonal start (in autumn), when the wood chips have lost moisture and are more suitable for burning in the boiler.

For the economic analysis, the costs of the two years before the start of the evaluation period were cumulated using the following multiplicative factor (f):

$$f = (1 + r)^z \quad (5)$$

where:

r = real discount rate (equal to 3%); z = year (variable from 0 to 2).

The biomass production was considered as constant for all the harvests and equal to the average production actually obtained by the experimental plantation at the first harvest. The SRC plantation surface needed for the total wood chip supply was estimated by the above-mentioned production and in relation to the annual average requirement of thermal energy. In addition, an average loss of 10% of raw material was considered due to the storage of the stacked trees before their use in the thermal power plant.

All the sustained actual costs during the first three years (observed data) and the estimated costs for the years until the end of the productive cycle, were considered. At the end of the productive cycle (after five harvests at year 10), the costs of stump grinding and ground restoration for agricultural use were added [28]. The costs of plantation (deep scarification, ploughing, fertilization, harrowing, purchase cuttings and mechanized transplantation) and management (chemical weeding post-planting, nitrogen fertilization, hoeing, irrigation, harvesting and ground restoration) over the whole period of

10 years, were reported according to [18]. The costs were calculated as the average between the single- and the twin-row typology of plantation. For the economic analysis, in addition to the operating costs, an annual cost of land use equal to € 500 was considered. This value represents the average of market values deduced from rent contracts of similar typology of land in Central Italy [29].

The analysis was conducted considering constant prices throughout the whole period. The analysis of machine costs was carried out using an analytic methodology [30]. Finally, a sensitivity analysis was conducted to assess the effect of a change in fuel cost (diesel and wood chip) on the PVC value for two heating systems.

3. Results

3.1. The Plantation

The ANOVA test showed a significant difference in wood density among the clones (p-value < 0.0001); Tukey's *post-hoc* test highlighted three groups: Clone AF2, 280.19 ± 4.14 $kg_{DM}\cdot m^{-3}$; AF6, 324.57 ± 4.81 $kg_{DM}\cdot m^{-3}$; Monviso, 345.76 ± 5.78 $kg_{DM}\cdot m^{-3}$; average of the three clones, 316.66 ± 4.09 $kg_{DM}\cdot m^{-3}$. Within each clone, the differences among the sample position (base, middle and top) were not significant (p-value = 0.075).

The average moisture content for AF2, AF6 and Monviso clones at single-row were 51.6%, 52.7% and 53.4%, respectively, and at twin-rows were 53.3% 53.4% and 53.9%, respectively. No significant differences were noted (p-value = 0.168). Table 1 reports the equations to determine height (m) and weight (kg) in relation to DBH for each clone and plantation typology (single and twin-rows).

The fresh mass per hectare was calculated from the equations reported in Table 1. In detail, for every clone and plantation system, the fresh weight of the sprout with average DBH has been multiplied by the average number of sprouts per hectare (Table 2) (single-row stand: AF2 = 27,704; AF6 = 31,095; Monviso = 25,616; and for the twin-rows stand: AF2 = 29,400; AF6 = 25,299, Monviso = 17,944).

Table 1. Equations to determinate height (m) and weight (kg) as a function of DBH for each clone and plantation typology (single- and twin-rows).

Plantation Typology	Clone	Equations for the Fresh Weight Determination Y (Weight, kg); X (DBH, cm)	Equations for the Height Determination Y (height, m); X (DBH, cm)
SINGLE-ROW	AF2	$Y = 0.2523X^{1.9417}$ $N = 30$ $R^2 = 0.8395$	$Y = -0.1173X^2 + 1.6438X + 1.1859$ $N = 84$ $R^2 = 0.889$
	AF6	$Y = 0.1705X^{2.2471}$ $N = 30$ $R^2 = 0.8356$	$Y = -0.0513X^2 + 1.0314X + 2.0117$ $N = 84$ $R^2 = 0.6401$
	MON	$Y = 0.136X^{2.5201}$ $N = 30$ $R^2 = 0.9616$	$Y = -0.2267X^2 + 2.4337X + 0.0714$ $N = 84$ $R^2 = 0.8273$
TWIN-ROWS	AF2	$Y = 0.2187X^{2.0125}$ $N = 30$ $R^2 = 0.9203$	$Y = -0.1734X^2 + 2.0691X + 0.7885$ $N = 84$ $R^2 = 0.8416$
	AF6	$Y = 0.1888X^{2.1929}$ $N = 30$ $R^2 = 0.6346$	$Y = -0.2107X^2 + 2.3785X + 0.1379$ $N = 84$ $R^2 = 0.6681$
	MON	$Y = 0.3359X^{1.8445}$ $N = 30$ $R^2 = 0.9038$	$Y = -0.2317X^2 + 2.5318X + 0.1766$ $N = 84$ $R^2 = 0.8292$

Table 2. Poplar SRC plantation characteristics.

Cropping System	Clone	Stumps (n·ha^{-1})	Sprouts (n·stump^{-1})	Sprouts (n·ha^{-1})
Single row	AF2	6926	4	27,704
	AF6	6219	5	31,095
	MON	6404	4	25,616
Twin row	AF2	8800	3	26,400
	AF6	8433	3	25,299
	MON	8972	2	17,944

From the fresh mass data, with the results of moisture analysis and wood density, the dry biomass per hectare was estimated for each clone within each plantation typology (Figure 2). The results of the 4 ha examined, highlighted an average dry matter production of 10.2 Mg·ha^{-1}·year^{-1}. The maximum value was observed for the AF2 clone at twin-rows (13.53 t·ha^{-1}·year^{-1}), while the minimum value was recorded for the Monviso clone at single-row (8.00 t·ha^{-1}·year^{-1}).

Figure 2 also shows the variation of the production, over the first three years of activity, for the three clones in the two plantation typologies. The highest values of average diameter, height and fresh weight of each clone, was observed in the twin-rows plot.

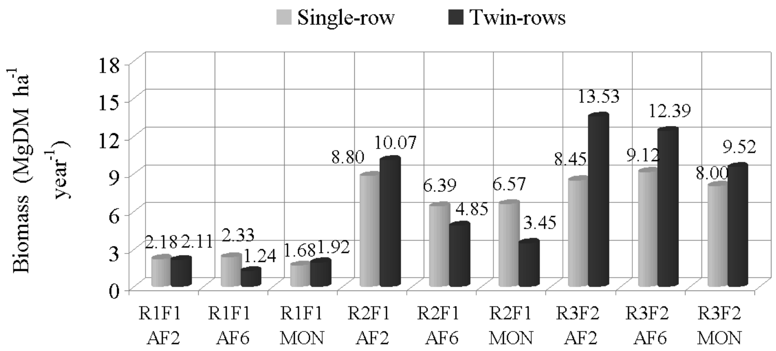

Figure 2. Biomass production (Mg_{DM}·ha^{-1}·year^{-1}) of clones AF2, AF6 and Monviso, planted at single- and twin-rows, during three growing seasons (R = roots, S = stem, R1F1 = first year, R2F1 = second year, R3F2 = third year).

In the twin-rows, the AF6 clone showed the largest diameter (3.00 cm), while AF2 and Monviso showed an average value of 2.98 cm and 2.84 cm, respectively. In the single-row, the average value of DBH for AF6, AF2 and Monviso were 2.29 cm, 2.42 cm and 2.48 cm, respectively. The average height for the single-row plot was equal to 4.42 m (ranging between 4.21 and 4.71 m), while for the twin-rows plot it was higher (+22.6%) with a value of 5.42 (ranging between 5.32 and 5.58 m). The average sprout mass for the twin-rows was 2.12 kg (ranging between 1.97 and 2.31 kg), while for the single-row it was 1.28 kg (ranging between 1.24 and 1.34 kg).

3.2. Economic Aspects

The evaluation referred to the maximum thermal demand of the CRA-ING buildings during a service period equal to 1500 h·year^{-1}, 10 h·day^{-1}, with a total production of thermal energy of 1004.40 GJ·year^{-1}. The amount of wood chips needed for the annual management of the heating system and other elements used in the economic assessment are shown in Tables 3 and 4.

Table 3. Technical elements for the calculation of the machine costs.

Description	Tractor 210 kW + Ripper/Plow	Tractor 60 kW + Fertilizer Spreader	Tractor 60 kW + Disc Harrow	Tractor 73 kW + Transplanter	Tractor 80 kW + Circular Saw Cut Trees	Tractor 80 kW + Gripper	Tractor 95 kW + Forestry Chipper	Tractor 95 kW + Stump Grinding
Purchase price (€)	122,000	37,500	40,700	57,000	43,500	41,600	90,000	65,000
Salvage value (€)	23,920	7020	7660	10,920	8220	7840	17,520	12,520
Life time (year)	10	10	10	10	10	10	10	10
Average Annual Investment (€/year)	76,544	22,464	24,512	34,944	26,304	25,088	56,064	40,064
Total time (h)	10,080	10,080	10,080	10,080	10,080	10,080	10,080	10,080
Scheduled hours (h/year)	1680	1680	1680	1680	1680	1680	1680	1680
Productive hours (h/year)	1008	1008	1008	1008	1008	1008	1008	1008
Machine utilization coefficient	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Daily machine utilization (h/day)	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8
Engine Power (kW)	210	60	60	73	60	80	95	95
Interest rate	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Fuel consumption (L/h)	33.56	6.97	9.59	10.60	10.46	12.78	19.32	16.56
Lubricants consumption (L/h)	0.78	0.37	0.37	0.41	0.37	0.43	0.47	0.47
Fuel price (€/L)	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20
Lubricant price (€/L)	9.00	9.00	9.00	9.00	9.00	9.00	9.00	9.00
Change tyres coefficient	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15
Load factor	0.55	0.40	0.55	0.50	0.60	0.55	0.70	0.60

The initial investment cost and the annual management costs of the two heating systems are reported in Tables 5 and 6. The cost of self-produced wood chips is not reported in Table 4 because its value derives from the management costs of the SRC poplar plantation and is included in the economic evaluation of the wood chip production during the whole cycle of 10 years.

Table 4. Average plantation and management costs (€·ha^{-1}), on the productive cycle of the SRC plantation (10 years).

Operations	Cost (€·ha^{-1})
Plowing, fertilizing, harrowing and planting cost (initial investment)	2995.00
Post-plantation management cost (1th year)	840.00
Plantation management cost (2nd, 4th, 6th, 8th, 10th year)	170.00
Plantation management cost (3rd, 5th, 7th, 9th year)	265.00
Harvesting and chipping cost (2nd, 4th, 6th, 8th, 10th year)	747.50
Stump grinding (cycle end, 10th year)	300.00
Benefit land (from 1st to 10th year)	500.00

Table 5. Principal elements used to calculate the consumption of the fuel and the costs of the different heating systems.

Elements	Wood Chips Heating System	Gas Oil Heating System
Burnig power (kW)	232	207
Power yield (kW)	186	186
Performance (%)	80	90
Gross thermal energy produced (GJ·year^{-1})	1252.80	1116.00
Net thermal energy produced (GJ·year^{-1})	1004.40	1004.40
Fuel consumption (Mg·year^{-1})	85.22	26.13
Service period (h·year^{-1})	1500	1500
Wood chips moisture (%)	30%	
Fuel cost (€·Mg^{-1})	-	1490.00
Average biomass production (Mg_{DM}·ha^{-1} year^{-1})	10.2	
Theoretical biomass quantity (Mg_{DM}·year^{-1})	65.59	
Theoretical surface of SRC (ha)	6.43	
Loss percentage for biomass storage (%)	10	
Real necessity of biomass (Mg_{DM}·year^{-1})	72.15	
Real necessity of SRC surface (ha)	7.7	

Table 6. Annual cost elements related to the two heating systems considered in the economic comparison and total annual cost of management.

Cost Elements	Wood Chips Heating System (C)			Diesel Heating System (D)		
	Quantity	Price (€)	Value (€)	Quantity	Price (€)	Value (€)
Initial investment cost (€)	1.00	60,300.00	60,300.00	1.00	16,900.00	16,900.00
Maintenance (h·year^{-1})	66.53	13.00	864.88	4.44	13.00	57.72
Repair (€·year^{-1})			603.00			169.00
Fuel consumption (M30) (kg·year^{-1})	85,224.49	(*)	(*)	26,138.28	1.49	38,946.04
Wood chips handling and loading (h·year^{-1})	71.65	35.00	2507.65			
Electric energy consumption (kWh·year^{-1})	12,375.00	0.12	1485.00	6825.00	0.12	819.00
Insurance and service agreements (€·year^{-1})			301.50			84.50
Direction, administration, control (h year^{-1})	14.00	13.00	182.00	3.00	13.00	39.00
Total annual cost (€·year^{-1})			5944.14			40115.26

(*) The wood chips cost is determined in relationship with the production costs of the SRF plantation.

The results of the financial calculations are reported in Figures 3–6. Figure 3 shows the variation of PVC during the period. The value was higher for diesel (D) than for wood-chip (C) from the fourth year on, and the total difference, considering the whole period, is equal to € 156,703.28. Figure 4 reports the EAC value and the saving of C with respect to D. The average annual saving amounts to € 18,370.41 considering the whole period.

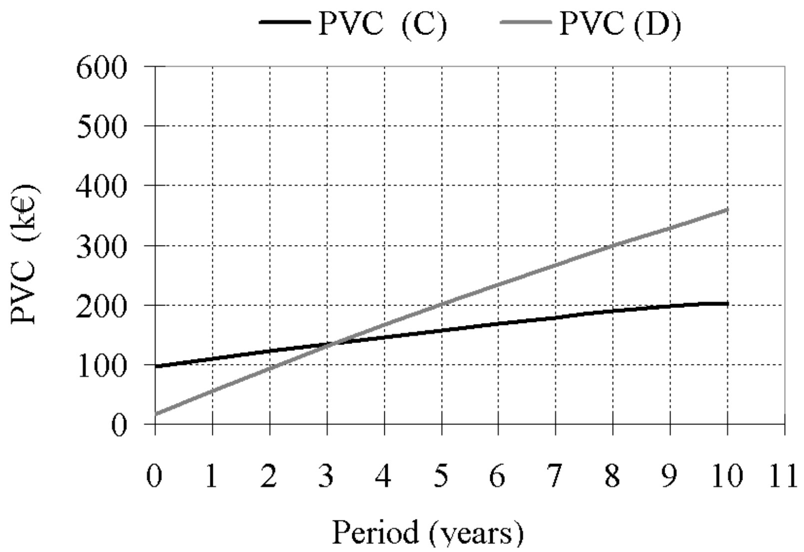

Figure 3. Variation of the Present Value of Costs (PVC) of the two heating systems (C = wood chips heating system; D = Diesel heating system) in relationship with the period duration.

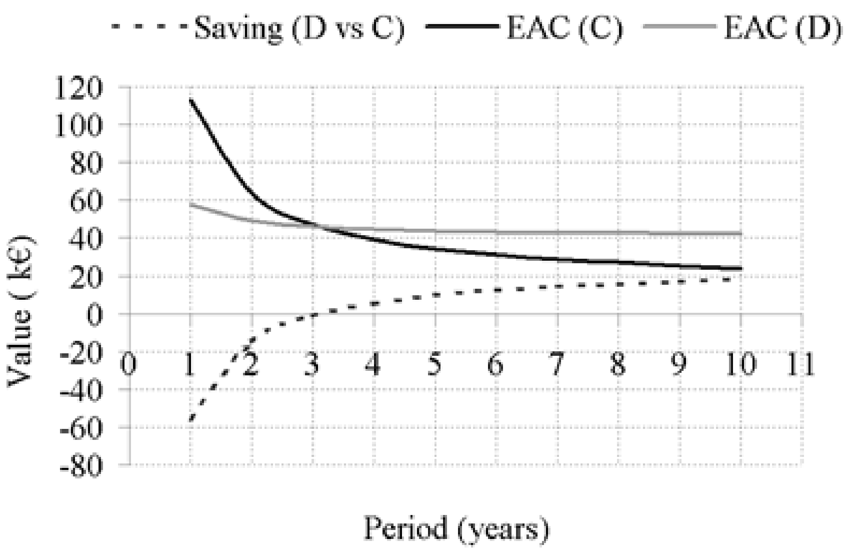

Figure 4. Variation of the Equivalent Annual Cost (EAC) for the different heating systems in relationship with the duration of the management period (C = wood chips heating system; D = Diesel heating system) and saving of C *vs.* D.

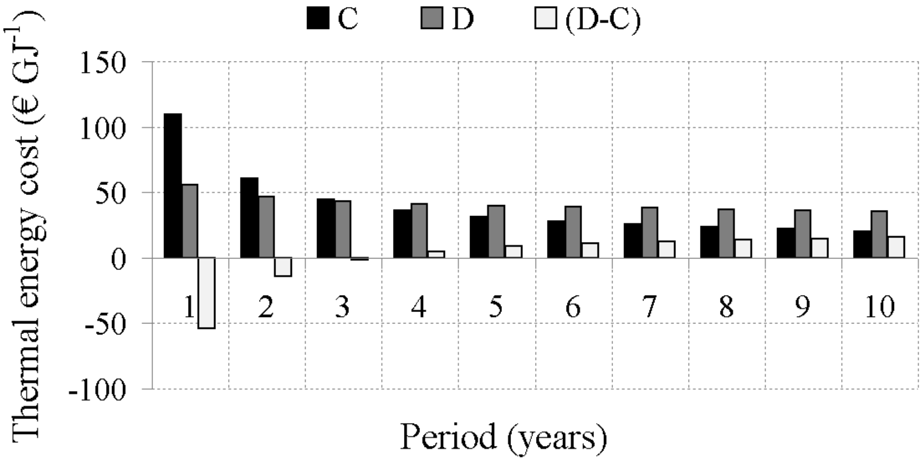

Figure 5. Variation of the thermal energy production cost (€·GJ^{-1}) of the wood chips system and the diesel system, during the considered period. The differences between the two systems (C = wood chips heating system; D = Diesel heating system) was reported (saving of C *vs.* D).

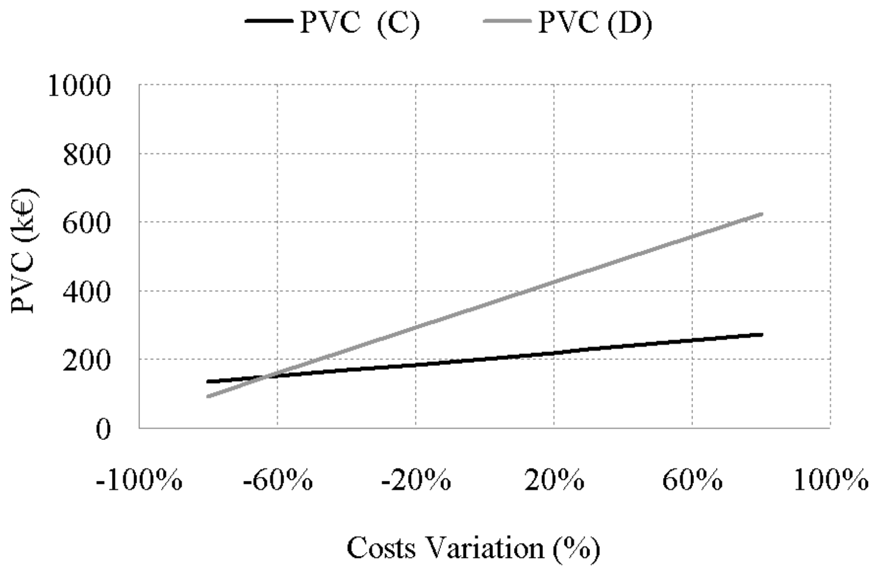

Figure 6. Sensitivity analysis related to the variation of the PVC of the two heating systems (C = wood chips heating system; D = Diesel heating system), in relationship with the variation percentage of the gas-oil price and wood chips production cost.

Figure 5 shows the comparison between the wood-chip system and the diesel system, referring to the same thermal energy power yield (186 kW), for the production of 1 GJ of thermal energy. Considering the whole period, self-consumption wood-energy is economically more advantageous than the diesel system with an average production difference of 15.60 €·GJ^{-1}.

A sensitivity analysis was carried out in relationship with the diesel price variation and wood chip production costs. This analysis underlines that, over the period of 10 years, the diesel heating system was economically advantageous when the reduction in the diesel price was more than 60% with respect to the actual market level (Figure 6).

3.3. Energy Aspects

For the energy output, in terms of HHV the differences among clones were not-significant (p-value = 0.325). For this reason, the HHV value considered was 20.45 $MJ \cdot kg^{-1}_{DM}$ (Table 7). The direct input (Table 8), considering the whole plantation life (10 years) was 118 $GJ \cdot ha^{-1}$. The indirect input considering the whole plantation life (10 years) was 51 $GJ \cdot ha^{-1}$. The total average energy input considering the whole plantation life (10 years) was 169.7 $GJ \cdot ha^{-1}$. The total energy output value, calculated as the average of three clones, was 2079.5 $GJ \cdot ha^{-1}$. The output was represented by the effective annual energy demand (calculated on the HHV_{DM} basis) of the CRA-ING buildings (1475.47 $GJ \cdot year^{-1}$). The energy budget, referring to the plantation management, showed a good output/input index (12.3), with a total demand for human labor to 593.1 $h \cdot ha^{-1} \cdot man^{-1}$. The energy budget, in terms of the whole self-consumption micro-chain, considered the energetic inputs of boiler in the total productive cycle (10 years) (Table 9), showed an output/input index equal to 6.7.

Table 7. Energetic outputs of total productive cycle of plantation ($GJ \cdot ha^{-1}$) (1: Clone AF2, single row; 2: Clone AF6, single row; 3: Clone Monviso, single row; 4: Clone AF2, twin rows; 5: Clone AF6, twin rows; 6: Clone Monviso, twin rows).

Harvesting Cycle	Output						
	1	2	3	4	5	6	Average
1° cycle	345.6	373.0	327.2	553.4	506.8	389.4	415.9
2° cycle	345.6	373.0	327.2	553.4	506.8	389.4	415.9
3° cycle	345.6	373.0	327.2	553.4	506.8	389.4	415.9
4° cycle	345.6	373.0	327.2	553.4	506.8	389.4	415.9
5° cycle	345.6	373.0	327.2	553.4	506.8	389.4	415.9
Total	1728.0	1865.0	1636.0	2766.9	2533.8	1946.8	2079.5

Table 8. Energetic inputs of total productive cycle of plantation ($GJ \cdot ha^{-1}$) (1: Clone AF2, single row; 2: Clone AF6, single row; 3: Clone Monviso, single row; 4: Clone AF2, twin rows; 5: Clone AF6, twin rows; 6: Clone Monviso, twin rows).

Operation	Direct Input		Indirect Input		Total Input	References
	1, 2, 3	4, 5, 6	1, 2, 3	4, 5, 6	Average	
Plowing, harrowing, mineral fertilization, plantation and top dressing	14.1	13.8	5.4	5.2	19.3	
Pre-emer. herbicides, inter row cultivation—1° year	4.7	1.9	0.5	0.5	3.8	
Pesticides application, harvesting—2° year	19.6	19.6	9.2	9.2	28.8	
Mineral fertilization, harvesting—4° year	19.4	19.4	9.0	9.0	28.4	[25]
Mineral fertilization, harvesting—6° year	19.4	19.4	9.0	9.0	28.4	[25]
Mineral fertilization, harvesting—8° year	19.4	19.4	9.0	9.0	28.4	[25]
Mineral fertilization, harvesting—10° year	19.4	19.4	9.0	9.0	28.4	[25]
Stumps removal	3.9	3.9	0.3	0.3	4.2	[25]
Total	119.9	116.8	51.4	51.2	169.7	

Table 9. Energetic inputs of boiler, total productive cycle (10 years).

Source input	Direct Input (MJ)	Indirect Input (MJ)	Total Input (MJ)
Boiler inputs	606,375	212,520	818,895
Buildings for boiler and stocking	0	123,060	123,060
Boiler structure and plant, assembly and disassembly	9255.6	3036	12,291.6
Total	615,630.6	338,616	954,246.6

4. Discussion and Conclusions

Although the concept of forest sustainability has a long tradition [31], the notion of sustainable forest and plantation management has shifted from sustained wood yield and steady forest cover to increasing diversity of goods, benefits and ecosystem values demanded by society [32]. This approach developed from the concept of sustainable development (from the Rio de Janeiro Conference held in 1992) which had been presented in a three dimensional aspects—*i.e.*, Economic, Environmental and Social. Both forests and wood plantations have been added to the international agenda because of concerns about the sustainable use of forest ecosystems, e.g., regarding biodiversity and its economic and social contribution to the development of local communities [33]. This work contributes to this issue demonstrating the economic and energetic sustainability of a self-consumption wood-plantation energy micro-chain in a local research community.

The results highlighted the economic and energetic sustainability of the self-consumption wood-energy micro-chain during the considered life cycle of a poplar SRC (10 years), with biannual cycle and constant biomass production of 10.2 $Mg \cdot ha^{-1} \cdot year^{-1}$. In terms of produced SRC biomass, we obtained lower values when compared with the ones obtained in similar works in Italy [34,35].

From an economic point of view, the analysis emphasized that the wood chip heating system had advantages with respect to the diesel heating system. The estimated saving using the thermal energy produced was 56.7 $€ \cdot MWh^{-1}$, corresponding to 15,820 $€ \cdot year^{-1}$, referring to a net annual thermal energy produced of 279 MWh. The economic analysis was conducted using the constant prices method [22,24,26,27], and did not include the annual changes in energetic costs factors such as wage or oil price. This latter, particularly in Italy, are very variable because strongly influenced by government taxes [27].

From the energetic point of view, the output/input ratio agreed with that found in similar work in Italy [26]. Considering the whole self-consumption micro-chain, only one energetic unit was consumed per every 6.7 energetic units of production. This result cannot be obtained by the use of fossil fuels [9]. The use of wood biomass in a self-consumption micro-chain model may be a valid alternative to the conventional heating systems. as demonstrated in this case study.

Acknowledgments

This work was developed within the COFEA project funded by the Italian Ministry of Agriculture Food and Forest Politics. The present work was developed within the third year of Ph.D. activity of Giulio Sperandio (Ph.D. course in 'Science and Technology for the Forestry and Environmental Management', DAFNE, Tuscia University).

Author Contributions

All authors contributed equally to the work.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. UNFCCC. *Report of the Conference of the Parties on its' Third Session, Kyoto from 1 to 11 December 1997*; The United Nations Framework Convention on Climate Change: New York, NY, USA, 1998. Available online: http://www.unfccc.de (accessed on 1 December 2014).
2. Schulze, E.D.; Valentini, R.; Sanz, M.J. The long way from Kyoto to Marrakesh: Implications of the Kyoto Protocol negotiations for global ecology. *Glob. Change Biol.* **2002**, *8*, 505–518.
3. Whalley, J.; Walsh, S. *Bringing the Copenhagen Global Climate Change Negotiations to Conclusion*; CESIFO Working Paper; CESIFO Group: Munich, Germany, 2008; p. 2458.
4. Bodansky, D. The Copenhagen Climate Change Conference: A Post-Mortem. Available online: http://www.indiaenvironmentportal.org.in/files/SSRN-id1553167.pdf (accessed on 27 September 2011).
5. Picchio, R.; Spina, R.; Sirna, A.; Monaco, A.L.; Civitarese, V.; del Giudice, A.; Suardi, A.; Pari, L. Characterization of woodchips for energy from forestry and agroforestry production. *Energies* **2012**, *5*, 3803–3816.
6. Johansson, J.; Lundqvist, U. Estimating Swedish biomass energy supply. *Biomass Bioenergy* **1999**, *17*, 85–93.
7. Picchio, R.; Maesano, M.; Savelli, S.; Marchi, E. Productivity and energy balance in the conversion into high forest system of a Quercus cerris L. coppice in Central Italy. *Croatian J. For. Eng.* **2009**, *1*, 15–26.
8. Pantaleo, A.; Pellerano, A.; Carone, M.T. Potentials and feasibility assessment of small scale CHP plants fired by energy crops in Puglia region (Italy). *Biosyst. Eng.* **2009**, *102*, 345–359.
9. Matthews, R.W. Modelling of energy and carbon budgets of wood fuel coppice systems. *Biomass Bioenergy* **2001**, *21*, 1–19.
10. Yoshioka, T.; Aruga, K.; Nitami, T.; Sakai, H.; Kobayashi, H. A case study on the costs and the fuel consumption of harvesting, transporting, and chipping chains for logging residues in Japan. *Biomass Bioenergy* **2006**, *30*, 342–348.
11. Heinimo, J.; Junginger, M. Production and trading of biomass for energy—An overview of the global status. In Proceedings of the 15th European Biomass Conference & Exhibition, Berlin, Germany, 7–11 May 2007; pp. 2949–2956.
12. Testa, R.; di Trapani, A.M.; Foderà, M.; Sgroi, F.; Tudisca, S. Economic evaluation of introduction of poplar as biomass crop in Italy. *Renew. Sustain. Energy Rev.* **2014**, *38*, 775–780.
13. Spinelli, R.; Nati, C.; Magagnotti, N. Harvesting short-rotation poplar plantation for biomass production. *Croatian J. For. Eng.* **2008**, *29*, 129–139.

14. Verani, S.; Sperandio, G.; Tarchi, M. Piantagioni dedicate da biomassa. Analisi GIS nella regione Lazio. *Sherwood* **2009**, *157*, 41–45.
15. Hamelinck, C.N.; Suurs, R.A.A.; Faaij, A.P.C. International bioenergy transport costs and energy balance. *Biomass Bioenergy* **2005**, *29*, 114–134.
16. Spinelli, R.; Magagnotti, N. Wood Extraction with farm tractor and sulky: Estimating productivity, cost and energy consumption. *Small Scale For.* **2012**, *11*, 73–85.
17. Verani, S.; Sperandio, G.; Savelli, S. Produttività e costi per l'impianto meccanizzato. *Alberi Territ.* **2005**, *2*, 25–30.
18. Di Matteo, G.; Sperandio, G.; Verani, S. Field performance of poplar for bioenergy in southern Europe after two coppicing rotations: Effects of clone and planting density. *iForest* **2012**, *5*, 224–229.
19. Sprent, P.; Smeeton, N.C. *Applied Nonparametric Statistical Methods*, 3rd ed.; Chapman & Hall/CRC: London, UK, 2001; p. 461.
20. Lo Monaco, A.; Todaro, L.; Sarlatto, M.; Spina, R.; Calienno, L.; Picchio, R. Effect of moisture on physical parameters of timber from Turkey oak (Quercus cerris L.) coppice in Central Italy. *For. Stud. China* **2011**, *13*, 276–284.
21. Fuller, S.K.; Petersen, S.R. *Life-Cycle Costing Manual for the Federal Energy Management Program*, 1995 ed.; Office of Applied Economics: Gaithersburg, MD, USA, 1995; p. 222.
22. Rushing, A.S.; Kneifel, J.D.; Lippiatt, B.C. *Energy Price Indices and Discount Factors for Life-Cycle Cost Analysis*; National Institute of Standards and Technology of the U.S. Department of Commerce Technology Administration: Gaithersburg, MD, USA, 2010; p. 64.
23. Juurma, M.; Polder, A. Energy efficiency aspects in wood production value chain. In Proceedings of the 10th International Symposium: Topical Problems in the Field of Electrical and Power Engineering, Parnu, Estonia, 10–15 January 2011; pp. 10–15.
24. Sgroi, F.; di Trapani, A.M.; Foderà, M.; Testa, R.; Tudisca, S. Economic assessment of Eucalypts (spp.) for biomass production as alternative crop in Southern Italy. *Renew. Sustain. Energy Rev.* **2015**, *44*, 614–619.
25. Sieglinde, K.F.; Petersen, S.R. Life-cycle costing manual for the federal energy management program. *NIST Handb.* **1996**, *135*, 222.
26. Manzone, M.; Airoldi, G.; Balsari, P. Energetic and economic evaluation of poplar cultivation for the biomass production in Italy. *Biomass Bioenergy* **2009**, *33*, 1258–1264.
27. Menesatti, P.; Canali, E.; Sperandio, G.; Burchi, G.; Devlin, G.; Costa, C. Cost and waste comparison of reusable and disposable shipping containers for cut flowers. *Packag. Technol. Sci.* **2012**, *25*, 203–215.
28. Picchio, R.; Verani, S.; Sperandio, G.; Spina, R.; Marchi, E. Stump grinding on poplar plantation: Working time, productivity, and economic and energetic inputs. *Ecol. Eng.* **2012**, *40*, 117–120.
29. INEA. *Annuario DELL'Agricoltura Italiana*; Istituto Nazionale di Economia Agraria: Roma, Italy, 2012; Volume LXV, p.553.
30. Miyata, E.S. *Determining Fixed and Operating Costs of Logging Equipment*; General Technical Report NC; North Central Forest Experiment Station: St. Paul, MN, USA, 1980; p. 55.
31. Wiersum, K. 200 years of sustainability in forestry: Lessons from history. *Environ. Manag.* **1995**, *19*, 321–329.

32. Paivinen, R.; Lindner, M.; Rosen, K.; Lexer, M.J. A concept for assessing sustainability impacts of forestry-wood chains. *Eur. J. For. Res.* **2012**, *131*, 7–19.
33. Facciotto, G.; Mughini, G. Modelli colturali e produttività della selvicoltura da biomassa. *L'Inf. Agrar.* **2003**, *59*, 95–98.
34. Bonari, E. Risultati produttivi del pioppo da biomassa. *Terra Vita* **2005**, *45*, 69–73.
35. Mareschi, L.; Paris, P.; Sabatti, M.; Nardin, F.; Giovanardi, R.; Manazzone, S.; Scarascia Mugnozza, G. Le nuove varietà di pioppo da biomassa garantiscono produttività interessanti. *L'Inf. Agrar.* **2005**, *61*, 49–54.