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Research paper

Thinning in black pine (*Pinus nigra* J.F. Arnold) forests: the economic sustainability of the wood-energy supply chain in a case study in Italy

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ABSTRACT In Italy, black pine has been largely used in reforestation projects in the past. Most of these reforestations are characterized by a high instability, vulnerability, and a limited resistance to atmospheric agents. In this situation, it is crucial to define silvicultural interventions able to increase the ecological stability of black pine stands and at the same time to guarantee the economic sustainability of the wood products obtained. Thinning in black pine forests can provide wood material for energy use. The main aim of the present study was to investigate the economic sustainability of a local wood-energy supply chain applying three different forest management options. The case study was Monte Morello forest, a degraded black pine forest located in Central Italy. The results show that the long-term economic sustainability of the wood-energy supply chain is ensured only when the use of bio-fuel is characterized by high energy efficiency. In addition, the results show that public contributions are fundamental to ensure that silvicultural interventions are realized with a positive economic balance and that to surmount this situation many loggings companies are organizing. Finally, the results highlighted the importance of the quantities of thermal energy sold to ensure the economic and environmental efficiency of the wood-energy supply chain.

KEYWORDS: renewable energy sources, reforestation, wood-energy supply chain, woodchips, bioeconomy, economic sustainability.

Introduction

In the first half of the twentieth century, several fast-growing pioneer conifer species have been widely used in Italy in reforestation projects planned for the restoration of degraded lands and the improvement of slope stability in mountain areas (Cenni et al. 1998). The main objective of these reforestation projects ranged from timber production to soil erosion protection (Marchi et al. 2018). The long-term strategy for the reforested areas was and still is to facilitate the introduction of broadleaved species and the transition toward mixed forests (Cantiani and Chiavetta 2016, Cantiani et al. 2010, Piermattei et al. 2012).

Black pine (*Pinus nigra* J.F.Arnold) was one of the most used species in the reforestation projects because it is a pioneer species. In particular, black pine is easily adaptable to shallow and stony soils, resistant to wind and drought and its management is easy in nursery due to the fast rooting of planted seedlings (Mondino and Bernetti 1998). According to the Italian National Forest Inventory (2005), black pine forests cover 236,467 ha in Italy (Gasparini and Tabacchi 2011), while in Tuscany, black pine forests cover about 20,500 ha.

Generally, black pine forests were realized at high densities to ensure the forest coverage in a short period and multiple thinning should be applied during the rotation period (Marchi et al. 2017). Furthermore, silvicultural interventions influence the transition age from juvenile to mature wood with higher ring density, and with higher wood quality and value (Gutiérrez et al. 2006, Passialis et al. 2004). Unfortunately, due to the high costs of multiple thinning, to the lack of wood products demand, and to the low economic value of the black pine timber the silvicultural interventions have generally been delayed. Currently, these forests are simplified and vulnerable forest systems, characterized by a high instability and a limited resistance to atmospheric agents (Marchi et al. 2018, Cantiani 2016, Seidl et al. 2011).

Against this background, the management of wood stocks and flows, the regeneration of productive resources, the maximization of individual and collective goods and services (e.g., wood production, carbon storage, water flow protection, biodiversity conservation), and the new bio-energy market can be considered good opportunities not only for the economic sustainability of thinning as emphasized by several studies (Sotirova et al. 2019, Ericsson et al. 2004, Conrad IV and Bolding 2011). Therefore, thinned black pine forests can provide raw material for energy use in accordance with the principles of bioeconomy and cascading approach (Paletto et al. 2019).

In 2012, the European Union (EU) adopted the Bioeconomy Strategy for Europe with the aim to ensure economic growth and the fulfilment of social

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needs through a sustainable use of renewable biological resources (European Commission 2012). Recently, in the Updated EU Bioeconomy Strategy (2018) the key role of bioeconomy to build a carbon neutral future in line with the objectives of the Paris Climate Agreement (2015) has been emphasized and promoted among decision makers. Recently, the European Green Deal (2019) considered the decarbonising of the EU energy system as key point to reach climate objectives in 2030 and 2050, while the revised Renewable Energy Directive (2108) emphasized the role of forests to contribute to the decarbonisation of the economy. In accordance with the principles of EU Bioenergy Strategy, the forest-based sector can play a growing role for the future economic development of the EU both through innovative solutions for the production of added value bio-based products (e.g., bio-chemicals, bio-textiles) and through the enhancement of wood fuels (Hänninen and Mutanen 2014, Näyhä et al. 2014, Pieratti et al. 2020). About this last point, wood fuels represent one of the most important renewable energy sources in Europe (61.8% of total renewable energy EU-28) contributing to the reduction of greenhouse gas (GHG) emissions and to economic growth of European mountain and rural areas (Eurostat 2017). In future decades, as evidenced by EU wood project (2010) the EU's forest biomass supply would increase by 11% from 2010 to 2030 (Mantau et al. 2010). In addition, Beurskens et al. (2011) estimated a future increase in the use of wood fuels to satisfy energy demand in EU member countries. The potential increase in the wood fuels use must be managed through the bioeconomy approach rather than through the traditional linear fossil-based economic approach (Biancolillo et al. 2020). Adopting a bioeconomy approach means reviewing all phases of production and paying attention to the entire wood-energy supply chain (Pieratti et al. 2019). According to the MacArthur Foundation (2014), the new concept of wood-energy supply chain should be based on three key principles: (*i*) preserving and increasing natural capital, controlling limited stocks and balancing the flow of renewable resources; (*ii*) optimizing the yield of resources through the circulation of products, components and materials to the maximum usefulness in all the times both in technical and biological cycles; (*iii*) encouraging the effectiveness of the system by revealing and eliminating negative externalities. In addition, it is important to emphasize that for guaranteeing the sustainable management of the biofuels production cycle it is necessary to satisfy the economic efficiency of the production process (Kalt and Kranzl 2011, Czekała et al. 2018).

Forest biomass supply chain for energy (heat and electricity) production includes many activities such as: in-field harvesting; in-field skidding to the roadside; storage on the road; chipping; loading and unloading the transportation vehicle; transport to the energy plant. The cost of forest biomass delivery to the gate of the energy plant depends on the forest management adopted, the type of forest biomass, on the harvesting methods and tools, on the configuration of the wood-energy supply chain. The delivery cost of different biomass types to energy plants were analysed and compared by Akhtari et al. (2014). The bulk density of the biomass was shown to have high impact on the delivery cost to district energy plants. Bulk density determines transportation and handling costs, which contribute to up to 50% of the total delivery cost (Sultana and Kumar 2011, Akhtari et al. 2014). At the light of the above mentioned considerations, the delivery cost of forest biomass to the gate of the energy plants is an important issue to be verified when developing the wood energy market, taking into consideration that it should be economically competitive with alternative energy sources.

Several studies and surveys have demonstrated that the wood consumption for energy purposes in Italy is much higher than that officially estimated (Gerardi and Perrella 2001, Corona et al. 2007, APAT-ARPA 2008, ARPA Emilia-Romagna 2011). In recent years, two studies came to the conclusion that the assumptions relative to the levels of wood biomass consumption made in the National Renewable Energy Action Plan (NREAP) are strongly underestimated and that it is likely that bioenergy production in 2010 was already higher than 5.25 M_{tep}, which is the target for 2020 (Tomassetti 2010, Pettenella and Andrighetto 2011). This incompleteness and inaccuracy of the informative framework and the lack of solid wood energy market estimations can be major limiting factors to an effective assessment of the real role of wood-energy as a renewable energy sources in the national energy mix. These issues are particularly important in order to be able to provide a coherent regulatory framework to the sector, especially within the perspective of an increased demand for wood biomass energy in Italy, as-well-as in the other European countries, as a consequence of more long-term targets on renewable energy sources promotion (Smith 2015).

Starting from these considerations, the main aims of this study were to investigate the performance of different forest management options and to analyse the economic sustainability of the wood-energy supply chain following the principles of the bioeconomy approach. The research was implemented in a degraded black pine forest in Central Italy (Monte Morello forest, Tuscany region).

Material and methods

Study Area

The study area is Monte Morello forest, a degraded black pine forest involved in the project LIFE FoResMit (Recovery of degraded coniferous Forests for environmental sustainability and climate change mitigation - LIFE14CCM/IT/000905).

The Monte Morello forest, located in Tuscany region, is the result of a reforestation project realized from 1909 to 1980 over an area of 1,035 ha. Currently, Monte Morello forest is an adult Austrian pine (*Pinus nigra* spp. *nigra*) and Calabrian pine forest (*Pinus brutia* Ten. subsp. *brutia*) with sporadic presence of cypress (*Cupressus* spp.), Turkey oak (*Quercus cerris* L.), and manna ash (*Fraxinus ornus* L.) species. The forest is characterized by a living-tree volume of 560 m^3 ha^{-1} and a deadwood volume of 75 m^3 ha^{-1} (De Meo et al. 2017, Paletto et al. 2017) (Fig. 1).

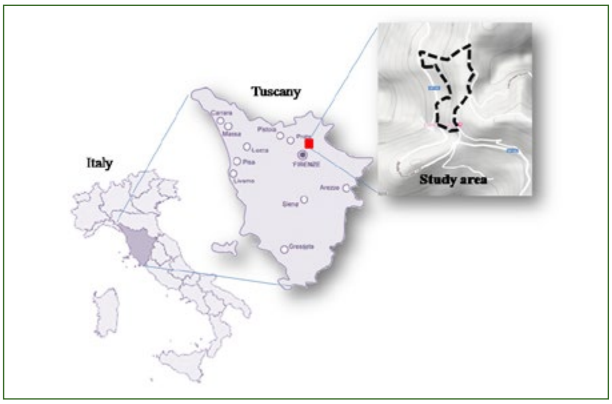
The LIFE FoResMit project tested different silvicultural interventions in even-aged pine forest parcels (about 50-year-old) with the aim to define forest management guidelines for the recovery of degraded black pine forests in the Mediterranean environment. To that end, three forest management options – applied on 15.08 ha overall – have been tested and compared with the aim to analyse the economic impacts on wood-energy supply chain (Cantiani et al. 2016, Cantiani et al. 2017, Marchi et al. 2018):

1. Traditional thinning option (tested on 5.35 ha): all trees of the dominated plan are removed with a reduction in basal area by about 20%. Standing dead trees are also cut down, without removing lying deadwood.
2. Selective thinning option (tested on 4.73 ha): approximately 100 trees per hectare are released. The choice of the trees to be cut is based on a positive selection (thinned 30-40% of basal area) favouring broadleaved species (e.g., Turkey oak, manna ash). During cutting operations, all crown-volume competitor trees are harvested, standing dead trees, and lying deadwood of first decay classes with diameter at breast height (dbh) more than 20 cm are removed.
3. *Status quo* option (tested on 5.0 ha): no silvicultural interventions are applied.

In the study area, 1,814 m^3 of wood volume have been removed (772 m^3 in the parcels managed with traditional thinning and 1,042 m^3 in the parcels managed with selective thinning). The silvicultural interventions were performed according to the Full Tree System or Whole Tree System with the involvement of two fixed workers in the felling trees phase and another two workers in the harvesting phase. The equipment used were two medium-speed saws Stihl MS180, two tractors (engine power 74.0 kW) equipped with forest gripper. Wood materials were chipped by a chipper (500 HP engine power) mounted on a Timberjack Oy model forwarder Timberjack 1110D, and two workers (Paletto et al. 2018). Finally, the transport of woodchips has been carried out through semi-trailer with a capacity of 85-90 cubic meters (28-30 tons of fresh woodchips).

The harvested wood volume – 1,814 m^3 corresponding to 120.3 m^3 ha^{-1} – were totally allocated to the woodchips production to feed a combined heat and power plant (CHP) located 12 km from the Monte Morello forest. CHP was built in 2009 on an area of about 1,300 m^2, with a total output of 5.9 MW, which supplies a 6.5 km district heating network (thermal power fed into the grid of 3.5 MW) and a production of electricity by using organic fluid turbine (ORC) of nominal power equal to 800 kW_{el}. CHP uses exclusively local biomass, coming from territories located within a radius of 40 km for an average annual quantity of about 12,000 tons/year. CHP supplies approximately 1,500 public and private users including 630 apartments, a private sports area, the municipal swimming pool, and some public and school buildings. The district heating network consists of a pair of buried and insulated pipes run by hot water (supply temperature 90-95 °C and return 70 °C) with a loss of temperature around 1-2 °C km^{-1}.

Figure 1 - Sampled plantations.



Methodology

In the international literature, there are few studies focused on the evaluation of economic efficiency of wood-energy supply chain (Madlener and Bachhiesl 2007, Trishkin et al. 2017, Paolotti et al. 2017). Among the Italian studies, Boatto et al. (2003) realized a production costs analysis for the cereal supply chain, while Fagarazzi and Tirinnanzi (2016) evaluated the economic efficiency of bioenergy supply chains in Tuscany region (Italy).

In accordance with the study conducted by Fagarazzi and Tirinnanzi (2016), the present study is based on estimating the unit production costs of the various production phases, on the identification of purchase prices for forest products and the subsequent estimation of safety margins compared to the market price of woodchips. In particular, economic sustainability for the logging company can be verified by estimating the safety margin between the market price of woodchips and unit production costs (*Sm1*). The economic sustainability of the energy conversion process is verifiable with the estimation of safety margin between the market price of woodchips and the break-even price of the woodchips purchase (*Sm2*), as follows:

$$c \longrightarrow Pm \longrightarrow Pbep$$

$$Sm1 = \frac{Pm - c}{Pm} \qquad Sm2 = \frac{Pbep - Pm}{Pm} \qquad [1]$$

Where:

c = unit production cost of woodchips (ex-works – in the energy production company)

Pm = woodchips market price

Pbep = Break Even Point price of woodchips for the energy production company

Sm1 = Safety margin compared to the woodchips price for the logging company

Sm2 = Safety margin compared to the woodchips price for the energy production company

Sm1 indicates the maximum decrease in the market price of woodchips (%), capable of guaranteeing the coverage of production costs for the logging company. *Sm2* indicates the maximum increase in the market price of woodchips (%), capable of guaranteeing the coverage of the production costs of the energy production company (thermal, electric, or thermo-electric). It is important to highlight that the safety margins of the two operators in the wood-energy supply chain is directly related to the guarantees of long-term economic sustainability of the supply chain (Fagarazzi and Tirinnanzi 2016).

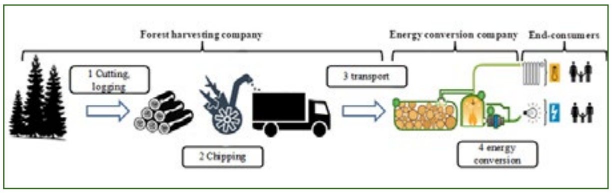
Thanks to the evaluation of the cost items and the market prices of woodchips, it is possible to calculate the stumpage value of the silvicultural interventions (traditional thinning and selective thinning). The unit production costs of each phase of the woodchips production process was analysed. As argued by Paletto et al. (2017), four phases of the woodchips production process correlated with sustainability indicators were identified and considered (Tab. 1 and Fig. 2).

As shown in Table 1, for the first three phases of the woodchips production process, the economic sustainability of the silvicultural interventions is well represented by the stumpage value and the corresponding stumpage price (Carbone and Savelli 2010, Accastello et al. 2017). It is important to underline that the stumpage value is traditionally referred to the roadside, without transport costs. In addition, many logging companies are also involved in the chipping phase (2) and transport phase (3) of the product up to the energy plant. In this case, a key aspect is to evaluate the stumpage value ex-works (at the biomass energy plant) in order to calculate all activities related to the logging company.

Table 1 - Phases of the woodchips production process and indicators of economic sustainability.

Phases	Economic sustainability indicators
Cutting and logging	Indicator of silvicultural intervention efficiency (Stumpage value)
Chipping	
Transport	
Energy conversion	Indicator of efficiency in log-term period (Break-even point Price to reset the Net Present Value of investment)

Figure 2 - Phases of the woodchips production process and indicators of economic sustainability.



The stumpage value (eq.1) of thinning has been calculated as the difference between the revenues of the processed products and the production phases costs (Brun and Blanc 2017):

$$Sv = R - C \qquad [2]$$

Where

Sv = stumpage value (€)

R = revenues obtained from the sale of harvested wood (€)

C = total costs including operative costs and generale costs (€)

As argued by several authors (Neri and Piegai 2007, Fabiano and Piegai 2007, Spinelli et al. 2003), total processing costs included marking selected trees for cutting and testing. Revenues deriving from the sale of the harvested wood (woodchips), are based on both the national and local market: 47 € per tons of fresh matter (f.m.).

In the Monte Morello forest, the amount of wood removed is equal to 697.9 tons f.m. by selective thinning and 517.1 tons f.m. by traditional thinning.

For evaluating the economic efficiency of energy conversion (last phase in Tab. 1), the Break Even Point price (*Pbep*) of woodchips was used. It allows the long-term economic sustainability of the energy conversion system in relation to the biofuel market prices in the local supply chain. *Pbep* represents the purchase price of the biofuel that allows balancing the annual costs deriving from the investment in energy conversion system (e.g., combined heat and power plant) with the revenues obtained from the sale of electricity and thermal energy. Considering a certain discount rate[1], *Pbep* is the price *p* that set at

1 In our study discount rate is equal to 1.5 %.

zero Net Present Value (*NPV*) according to the following equation (eq.2):

$$NPV = \sum_{t=0}^{n} \frac{(R_t^E + R_t^T)}{(1+r)^t} - \sum_{t=0}^{n} \frac{C_t}{(1+r)^t} \quad [3]$$

Where:

NPV = Net Present Value of the energy conversion system

R_t^E = Revenues obtained per year t from the sale of electricity

R_t^T = Revenues obtained per year t from the sale of thermal energy

C_t = Total costs per year t

n = Lasting in years

Ct is defined as follow:

$$C_t = \sum_{j=1}^{j} (C_1^t + C_2^t + \ldots + C_m^t + C_j^t) \quad [4]$$

Where:

C_j^t = Cost of the *j-th* productive factor per year t

C_m^t is defined as follow:

$$C_m^t = (Pbep\ Qaa) \quad [5]$$

Pbep = Break Price Even Point for the purchase of woodchips

Qaa= Average annual quantity of woodchips purchased from the energy

The *Pbep* corresponds to the price that makes *NPV* = 0

Results and Discussion

The results concerning the thinning implemented in the Monte Morello forest show a productivity of 1.6 t h^{-1} (or 75 h ha^{-1}) for the cutting phase, while for the logging phase increased to 2.4 t h^{-1} (or 50 h ha^{-1}). The wood chipping and transport phases have a productivity of 10.1 t h^{-1} and 20 t h^{-1} respectively (Paletto et al. 2018).

To compare our results with the national literature, we analysed other studies that estimated the production costs for wood-energy supply chain.

In the present research, we used the mean costs derived from literature as “ordinary” costs for comparison with data obtained from our case study. The unit costs of the various production phases obtained from ten other studies were discounted and used to estimate the “ordinary” costs (Spinelli et al. 2003, Spinelli et al. 2006, Neri and Piegai 2007, Fabiano and Piegai 2007, Negrin and Francescato 2009, Zuccoli Bergomi 2009, Baldini et al. 2010, Sperandio 2014, Prada et al. 2015, Verani et al. 2015). The results show the following rage of costs for each phase: cutting from 6.5 € to 12.1 € t f.m.$^{-1}$; logging from 15.8 € to 23.6 € t f.m.$^{-1}$; chipping from 7.5 € to 16.1 t f.m.$^{-1}$; and transport 5.6 € to 13.7 € t f.m.$^{-1}$. Taking into account the low range of values, it possible to consider these costs as representative of the ordinary conditions for thinning in coniferous forests with an age between 40 and 60 years.

Based on the hourly productivity of the various operations carried out in the Monte Morello forest, and the costs of the various production factors (workforce, vehicles, equipment, etc.), the unit costs of the various production phases were calculated. In Table 2 the unit production costs of Monte Morello and ordinary costs derived from literature are compared.

Table 2 shows that in the wood-energy supply chain of Monte Morello the unit cost of transport is particularly low compared with ordinary conditions, due to the short distance of the roadside and from the CHP (12 km). Total production cost amount to 43.3 € t f.m.$^{-1}$. Considering that the transport conditions were particularly favourable compared to the average values found in the sector, production cost is consistent with costs recorded in similar supply chains (from 35.4 € t f.m.$^{-1}$ to 65.5 € t f.m.$^{-1}$).

Table 2 - Unit production costs and prices of woodchips.

		Type of wood-energy supply chain	
		Monte Morello forest	Ordinary conditions
General costs Functioning costs Transaction costs € t^{-1}	Cutting	11.4	6.5 – 12.1
	Logging	15.9	15.8 – 23.6
	Chipping	11.1	7.5 – 16.1
	Transport	4.9	5.6 – 13.7
Total production Cost (€ t^{-1})		43.3	35.4 – 65.5
Market prices € t^{-1}	Roadside price	15	30
	Ex-works price		
	Ex-dock price	47	68

To estimate the stumpage value in ordinary conditions, it was also necessary to verify the purchase prices of the woodchips. The results show that the roadside price (15 € t f.m.$^{-1}$) and ex-works price (47 € t f.m.$^{-1}$) are lower than those found under ordinary conditions, this fact influencing the stumpage values of wood-energy supply chain of the Monte Morello forest (Table 3). In fact, both types of thinning show a particularly negative stumpage value (roadside): -2,195 € ha^{-1} for selective thinning and -1,438 € ha^{-1} for traditional thinning. The value is negative also under ordinary conditions, with -364 € ha^{-1} for selective thinning and -239 € ha^{-1} for traditional thinning.

On the other hand, Table 3 shows that the stumpage value of ex-works energy conversion is positive for traditional and selective thinning both in the Monte Morello case study and under ordinary conditions. The results also show that both in selective and traditional thinning, the material obtained from harvesting operations is used exclusively to produce woodchips. Therefore, the differences in value between selective thinning (163 € ha^{-1}) and traditional thinning (106 € ha^{-1}) are only related to the difference in cubic meters obtained from the two types of thinning. In fact, 772 m^3 were obtained in the parcels managed with traditional thinning, while 1,042 m^3 in the parcels managed with selective thinning.

Tas regards the economic efficiency of the energy conversion system, Table 4 shows the results of the investment evaluation for the Monte Morello wood-energy supply chain. The evaluation was made using production costs obtained from direct investigation through interviews with the local logging companies, and with the market prices of fuels and energy.

The results show that there are problems related to the economic inefficiency of the investment.

Taking 15 years as the average working life of the CHP, the results are negative (NPV of the investment is equal to -969,707 € over 15 years).

When analysing the *Pbep* of woodchips needed to set at zero the NPV of the investment, it is possible to note that its maximum value should be fixed in 41 € t f.m.$^{-1}$. Therefore, it is not compatible with the production costs of the wood-energy supply chain (equal to 43.3 € t f.m.$^{-1}$). In these conditions, the safety margins Sm_1 and Sm_2 cannot be evaluated either.

To guarantee a positive financial balance (return on investment), the working life of the CHP should be at least 17.2 years; with a working life of 20 years, the NPV becomes positive (1,279,302 €).

Another important factor that can guarantee high economic efficiency of the wood-energy supply chain is the quantity of electrical and thermal energy sold. Under current conditions, all electricity produced is sold for the management of the electricity network,

Table 3 - Production costs and stumpage values.

	Monte Morello forest		Ordinary condition		Unit
Type of thinning	Selective	Traditional	Selective	Traditional	
Thinning surface	4.73	5.35	4.73	5.35	Ha
Total production	698	517	698	517	Tons f.m..
Average production	148	97	148	97	Tons f.m. ha^{-1}
Cutting costs	7,956	5,895	6,481	4,802	€
	1,682	1,102	1,370	897	€ ha^{-1}
Logging costs	11,167	8,273	13,759	10,195	€
	2,361	1,546	2,908	1,905	€ ha^{-1}
Roadside total costs	19,123	14,168	20,240	14,997	€
	4,043	2,648	4,278	2,802	€ ha^{-1}
Management, administrative and monitoring costs	956	708	1,012	750	€
Costs of contract, tree marking, testing, tax	628	465	1,256	931	€
Interest value	143	106	152	112	€
Harvested wood value (roadside)	10,469	7,757	20,937	15,513	€
	2,213	1,449	4,425	2,898	€ ha^{-1}
Stumpage value (roadside)	-10,382	- 7,691	- 1,724	- 1,277	€
	-2,195	- 1,438	- 364	-239	€ ha^{-1}
Chipping costs	7,747	5,740	8,253	6,115	€
	1,638	1,073	1,744	1,142	€ ha-1
Transport costs	3,420	2,534	6,709	4,971	€
	723	474	1,418	929	€ ha-1
Total costs (ex-works / ex-dock)	32,017	23,721	37,623	27,876	€
	6,769	4,434	7,954	5,211	€ ha^{-1}
Harvested wood value (ex-works / ex-dock)	32,801	24,304	47,457	35,163	€
	6,933	4,540	10,033	6,572	€ ha^{-1}
Stumpage value (ex-works / ex-dock)	784	582	9,834	7,287	€
	163	106	2,079	1,362	€ ha^{-1}

Table 4 - Current condition cash flow energy conversion system (phase 4): 23% thermal Energy sold.

YEAR	% sold energy	0	3	6	9	12	15
Incomings							
Electric energy sold	100%	-	1,288,000	1,288,000	1,288,000	1,288,000	1,288,000
Thermal energy sold	23%	-	649,500	649,500	649,500	649,500	649,500
Regional capital financing (measure 3.2 DocUp 2005) amounting to 10% of total costs		739,000					
TOTAL INCOMINGS		739,000	1,937,500	1,937,500	1,937,500	1,937,500	1,937,500
Costs							
Thermal energy pipeline, buildings and methane substations realization		4,500,000					
Combined heat and power system		4,500,000					
Insurance		-	40,000	40,000	40,000	40,000	40,000
Methane for thermal sub-stations		-	83,640	83,640	83,640	83,640	83,640
Self-consumed electric energy		-	174,000	174,000	174,000	174,000	174,000
Electric energy for system functioning		-	8,971	8,971	8,971	8,971	8,971
System maintenance		-	150,000	150,000	150,000	150,000	150,000
Wood chips acquire		-	587,500	587,500	587,500	587,500	587,500
Ash disposal		-	65,475	65,475	65,475	65,475	65,475
Water consumption		-	10,000	10,000	10,000	10,000	10,000
Labour cost		-	230,000	230,000	230,000	230,000	230,000
TOTAL COSTS		9,000,000	1,349,586	1,349,586	1,349,586	1,349,586	1,349,586
NET CASH FLOW		- 8,261,000	587,914	587,914	587,914	587,914	587,914
Discounted cash flow		- 8,261,000	562,232	537,672	514,185	491,724	470,244
WOOD CHIPS MARKET PRICE ex works (€ t f.m.$^{-1}$)	47.0						
Discount rate	1.5%						
NPV investment at 15 years	- 969,707						
NPV investment at 17 years	- 49,965						
NPV investment at 20 years	1,279,302						

while only 23% of thermal energy produced is sold[2]. If at least 50% of the thermal energy would be sold, it would be possible to achieve the economic efficiency of the supply chain (Tab. 5).

The NPV of the investment with a duration of 15 years would be equal to 8,667,801 € and the time for return on investment should be 7.1 years. In this case, the *Pbep* of the woodchips purchased from the combined heat and power plant would be 99 € t f.m.$^{-1}$. This hypothesis would guarantee the long-term stability of the wood-energy supply chain. Even, in case of an increase in market prices, the manager would have a wide margin of security with respect to price.

If the purchase price of woodchips would be equal to the ordinary price (68 € t^{-1}), the Sm_2 would be 45.6%. The market price of biofuel could therefore increase by 45.6% without compromising the economic efficiency of the energy conversion system.

In the present study, to verify if the harvesting activities were sustainable, it was referred to the stumpage value, while to verify the sustainability of the energy conversion system, it was identified the Break Even Point price (*Pbep*) of ex-works woodchips. The sustainability of the entire supply chain has been verified in relation to two safety margins (Sm_1 e Sm_2) that link the unit production costs c (€ t f.m.$^{-1}$) of the biofuel with the *Pbep* (€ t f.m^{-1}) of the energy conversion system.

The results show a contrasting framework in which the long-term economic sustainability of the wood-energy supply chain is guaranteed only in case of high energy efficiency in the use of biofuel. Fur-

2 The remaining 77% thermal energy is dissipated into the atmosphere with external air cooler

Table 5 - Better condition cash flow energy conversion system (phase 4): 50% thermal Energy sold.

YEAR	% sold energy	0	3	6	9	12	15
Incomings							
Electric energy sold	100%	-	1,288,000	1,288,000	1,288,000	1,288,000	1,288,000
Thermal energy sold	50%	-	1,428,900	1,428,900	1,428,900	1,428,900	1,428,900
Regional capital financing (measure 3.2 DocUp 2005) amounting to 10% of total costs		739,000					
TOTAL INCOMINGS		739,000	2,716,900	2,716,900	2,716,900	2,716,900	2,716,900
Costs							
Thermal energy pipeline, buildings and methane substations realization		4,500,000					
Combined heat and power system		4,500,000					
Insurance		-	40,000	40,000	40,000	40,000	40,000
Methane for thermal sub-stations		-		83,640	83,640	83,640	83,640
Self-consumed electric energy		-	174,000	174,000	174,000	174,000	174,000
Electric energy for system functioning		-	8,971	8,971	8,971	8,971	8,971
System maintenance		-	150,000	150,000	150,000	150,000	150,000
Wood chips acquire		-	587,500	587,500	587,500	587,500	587,500
Ash disposal		-	65,475	65,475	65,475	65,475	65,475
Water consumption		-	10,000	10,000	10,000	10,000	10,000
Labour cost		-	230,000	230,000	230,000	230,000	230,000
TOTAL COSTS		9,000,000	1,349,586	1,349,586	1,349,586	1,349,586	1,349,586
NET CASH FLOW		- 8,261,000	1,367,314	1,367,314	1,367,314	1,367,314	1,367,314
Discounted cash flow		- 8,261,000	1,307,585	1,250,466	1,195,842	1,143,604	1,093,648
WOOD CHIPS MARKET PRICE ex works (€ t f.m.$^{-1}$)	47.0						
Discount rate	1.5%						
NPV investment at 15 years	8,667,801						
NPV investment at 17 years	10,806,849						
NPV investment at 20 years	13,898,331						

thermore, it is evidenced a dynamism of the activities carried out by the logging company which, to guarantee some phases of the production process, tend to implement new activities with higher added value. Specifically, the data of Table 3 highlight that in the traditional and selective thinning the stumpage value is negative, both in Monte Morello and referring to the average production costs under ordinary conditions. In this case, the purchase price of the raw material proposed by the intermediary plays a crucial role. This price is always very low and equal to 15 € t f.m.$^{-1}$ in Monte Morello and 30 € t f.m.$^{-1}$ in the ordinary conditions. This situation evidences that only the forest districts which can benefit of public contributions for the execution of agricultural-environmental interventions could be in production. To overcome this situation, many logging companies are moving towards direct supply to the energy production company, also considering the chipping and transport phases to the customer (Triplat et al. 2013, Hetsch 2007). This allows a greater marginality to the energy production company which, although having to equip itself for these new activities (chippers and lorries), manages to achieve positive economic results. In fact, the data relating to the stumpage value ex-works or ex-dock show positive values, especially when referring to the ordinary conditions. In this case, the results evidences that logging company can get higher prices for the woodchips and that investing in this new market have expanded their production capacity (Halaj and Brodrechtova 2018). It is also important to show that these companies require the processing of large quantities of wood products to amortize the new chipping and transport equipment and consequently are forced to work even outside their forest sites (Fagarazzi and Tirinnanzi 2016).

Concerning the long-term economic sustainability of the CHP, the woodchips *Pbep* analysis reveals the presence of long-term sustainability issues. *Pbep* under current conditions is in fact equal to 41 € t f.m.$^{-1}$, while biofuel production costs are 43.3 € t f.m.$^{-1}$. Therefore, they are not compatible. When comparing the *Pbep* with ordinary production costs from 35.4 € t f.m.$^{-1}$ to 65.5 € t f.m.$^{-1}$, the economic unsustainability of this wood-energy supply chain is even more clear. In these conditions, the safety margins Sm_1 and Sm_2 cannot be evaluated. It was observed that the sustainability of this investment needs a working life higher than the ordinary, able to balance of account.

In order to clarify the correlation between thermal energy sold and *Pbep*, the sensitivity analysis of investment was performed (Jovanovic 1999, Borgonovo and Peccati 2004, Talavera et al. 2010). In this case, the effect of two parameters of the investment – the woodchips price and the discount rate – were considered. During the life of the CHP system, the selling price of electric and thermal energy, as-well-as the insurance, system maintenance, ash disposal, water consumption and labour cost can consider fixed (Tab. 6). For this type of economic investment, the significantly uncertainties of results could be determinate by the variation of the woodfuel price and the variation of the rate of time preference. Sensitivity analysis can be seen as a generalization of break-even analysis (Schmidt and Wright 1996), but in this case, the analysis was repeated several times and each time varying one of the input parameters (e.g., percentage of thermal energy sold). In this way, it was possible plot the change in present worth versus percentage change in each parameter (percentage of thermal energy sold and discount rate).

Table 6 and 7 show the change of *Pbep* in relation to the variation of thermal energy sold and discount rate.

The results show that the percentage of thermal energy sold has a decisive influence on the final result (*NPV* of investment). Low percentages of thermal energy sales correspond low *Pbep* of woodchips purchase. Observing Table 7, the results show that for very low percentage (5-15%) small increases in the sale of thermal energy produce a substantial increase of *Pbep*. With a discount rate of 1.5%, an increase in sales of thermal energy from 5 to 10% produces an increase of *Pbep* equal to 294%. This increase then gradually decreases to reach 12% of the increase of *Pbep* for a thermal energy sold of 45-50%.

In addition, the results of the present study underline the importance of the amount of electrical and thermal energy sold, to guarantee the economic efficiency of the wood-energy supply chain (Raj et al. 2011, Sitas et al. 2019). A critical aspect is the amount of thermal energy sold to the end-consumers. Currently, the electricity produced is totally sold to the manager of the electric network, while only 23% of the thermal energy produced is sold.

Finally, to demonstrate the importance of thermal energy sales to improve the economic and environmental performance of the wood-energy supply chain, the sale of 50% of thermal energy was assumed. With this hypothesis of new investment, the results show that the *NPV* with ordinary working life plant (15 years) increases and the payback period is reduced to only 7.1 years. Under these conditions,

Table 6 - Sensitive analysis of Price of Break Even Point (euro/ton f.m.) in relation to the thermal Energy sold and discount rate.

Discount rate (%)	Thermal Energy sold (KWh/yr) - & - Total thermal energy sold respect produced (%)										
	-	1,100,000	2,200,000	3,300,000	4,400,000	5,500,000	6,600,000	7,700,000	8,800,000	9,900,000	11,000,000
	0%	5%	10%	15%	20%	25%	30%	35%	40%	45%	50%
1.0%	N.E.	5.5	16.1	26.7	37.3	47.9	58.6	69.2	79.8	90.4	101.0
1.5%	N.E.	3.6	14.2	24.8	35.4	46	56.6	67.2	77.7	88.3	98.9
2.0%	N.E.	1.7	12.3	22.9	33.5	44	54.7	65.3	75.7	86.3	96.8
2.5%	N.E.	N.E.	10.3	20.9	31.4	41.9	52.6	63.1	73.6	84.1	94.6
3.0%	N.E.	N.E.	8.3	18.8	29.2	39.8	50.3	60.9	71.5	81.9	92.4
3.5%	N.E.	N.E.	6.2	16.9	27.2	37.7	48.2	58.7	69.4	79.6	90.1
4.0%	N.E.	N.E.	4.1	14.6	25	35.4	46.1	56.4	67.2	77.4	87.8
4.5%	N.E.	N.E.	2	12.4	22.9	33.1	43.7	54	64.9	75.2	85.5
5.0%	N.E.	N.E.	N.E.	10.2	20.6	31	41.4	51.8	62.3	72.7	83.1
5.5%	N.E.	N.E.	N.E.	8	18.1	28.7	39.2	49.7	59.9	70.3	80.6
6.0%	N.E.	N.E.	N.E.	5.7	16.1	26.4	36.8	47.1	57.5	67.8	78.2
6.5%	N.E.	N.E.	N.E.	3.4	13.7	24.1	34.4	44.7	55	65.3	75.7
7.0%	N.E.	N.E.	N.E.	1.1	11.4	21.7	32	42.3	52.5	62.8	73.1

Table 7 - Sensitive analysis of "variation" of Price of Break Even Point (euro/ton f.m.) in relation to the "variation" of thermal Energy sold and discount rate.

	Thermal Energy sold (KWh/yr) - & - Total thermal energy sold respect produced (%)										
Discount rate (%)	-	1,100,000	2,200,000	3,300,000	4,400,000	5,500,000	6,600,000	7,700,000	8,800,000	9,900,000	11,000,000
	0%	5%	10%	15%	20%	25%	30%	35%	40%	45%	50%
1.0%			193%	66%	40%	28%	22%	18%	15%	13%	12%
1.5%			294%	75%	43%	30%	23%	19%	16%	14%	12%
2.0%			624%	86%	46%	31%	24%	19%	16%	14%	12%
2.5%				103%	50%	33%	26%	20%	17%	14%	12%
3.0%				127%	55%	36%	26%	21%	17%	15%	13%
3.5%				173%	61%	39%	28%	22%	18%	15%	13%
4.0%				256%	71%	42%	30%	22%	19%	15%	13%
4.5%				520%	85%	45%	32%	24%	20%	16%	14%
5.0%					102%	50%	34%	25%	20%	17%	14%
5.5%					126%	59%	37%	27%	21%	17%	15%
6.0%					182%	64%	39%	28%	22%	18%	15%
6.5%					303%	76%	43%	30%	23%	19%	16%
7.0%					936%	90%	47%	32%	24%	20%	16%

the *Pbep* of the woodchips purchased by the energy conversion company is higher than the unit production cost of Monte Morello (43.3 € t^{-1}) and of ordinary conditions (from 35.4 € t f.m.$^{-1}$ to 65.5 € t f.m.$^{-1}$). In these cases, there are safety margins with respect to the very large price both for the energy conversion company (45.6%) and for the forest harvesting company (around 36%).

Conclusions

Based on the results of the present study, we can assert that a rational and efficient organization of wood-energy supply chain is the starting point for commercial enhancement of bioenergy products considering the bioeconomy and cascading approach. Market allocation of all energy production (domestic, industrial, and public utilities) can allow for environmental and economic improvement of local wood-energy supply chain. In this way, the local supply chains will be able to contribute to the achievement of the objectives set by the European Green Deal aimed to decarbonize the EU energy sector by 2050. In addition, the local wood-energy supply chains will increasingly play a key role to ensure sustainability as established by the revised Renewable Energy Directive (Renewable Energy – Recast to 2030 - RED II). The RED II encourages production of biomass raw materials that "are produced under circumstances that avoid Indirect Land Use Change (ILUC) effects, by virtue of having been cultivated on unused, abandoned or severely degraded land or emanating from crops which benefited from improved agricultural practices". Therefore, the energy valorisation of wood residues (e.g., tops, twigs, branches) derived from silvicultural interventions in the degraded forests can be considered an interesting option in accordance with the principles of RED II, while the realization of new reforestation projects with the primary objective of bioenergy production should not be considered a viable option. Regarding Monte Morello case study, as-well-as other planted pine forests in Italy, this forest represents a transition to a mixed forest type through natural regeneration, attributed to native species. This gradual substitution can be encouraged by thinning providing mainly wood material for energy use due to the low quality of raw materials obtainable. Even if energy wood harvesting is evaluated as one of the main products of these stands, high quality wood production might be successfully obtained through suited forest management actions. The wood products valorisation has not been considered in the present case, but the results showed that to increase the economic viability is necessary to adopt an active forest management based on improvement felling. Monte Morello forest should be thinned out every 10-15 years to improve the ecological characteristics of the stand and to promote natural regeneration. Besides, if a part of the wood volume harvested is delivered for high quality products such as packaging or poles, higher values are expected in terms of income from timber sales.

In this rapidly changing context, the raw material produced by thinning in reforested areas can be considered an interesting energy resource to be used locally. In addition, these silvicultural interventions applied in the reforested areas generate multiple benefits from the environmental point of view such as an increase in hydrogeological stability, in recreational attractiveness and in the level of biodiversity.

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