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Techno-Economic Modeling of Biomass Pellet Routes: Feasibility in Italy

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Abstract: Wood and agricultural biomass pellets boost the potential as bio-fuels toward power production in tertiary and residential sectors. The production of pellets, however, is a multi-stage process where the supply-processing phases and the overall energy input strongly depend on the characteristics of the input biomass. In this paper, we describe the key features of the market for pellets in Italy, including national production and consumption data, production costs and prices, the available energy conversion systems, and the current regulatory issues. Moreover, we outline the main technical, economic, and end-user barriers that should be addressed in order to foster the growth of Italian pellet production. Additionally, we propose a methodology to evaluate the profitability of the pellet production chain, by assessing the investment and operation costs as a function of the quality of the raw biomass. The approach is applied to a real case study of a small firm producing wooden frames along with dry wood chips as the main by-product, which can be utilized subsequently for pellet production. Moreover, in order to optimize the size of the pellet production plant, further biomass was purchased from the market, including wood pruning and agricultural residues, wood chips from forestry, and uncontaminated residues of wood processing firms. A sensitivity analysis of the main technical and economic parameters (including the cost and quality of raw material, pellet market value, investment and operational costs, and plant lifetime) indicated that the biomass market price considerably affects the profitability of pellet production plants, particularly where the biomass has a high moisture content. Therefore, a 20% increase in the price of biomass with a high moisture content leads to a 60% fall in profitability index, turning it into negative one. This is due in particular to the costs of pre-treatment and drying of biomass, as well as to the lower energy content of wet biomass. As a result, the use of forestry residues with high moisture and high ash content, high costs of collection/transport, and high costs of pre-treatment and drying is not financially competitive.

Keywords: pellet; agricultural residues; wood chips; market

1. Introduction

The global warming impact, the increasing prices of fossil fuel, and the need to produce thermal and electrical energy stimulated the creation of an industry leaning toward energy production by renewable sources. Biomass is a widespread renewable source to provide energy demand in terms of electricity and heat [1–4]. The Renewable Energy Directive 2018/2001/EU (RED II) obligates the

European Union (EU) to raise renewable energy consumption to 32% by 2030 [5]. According to IRENA [6], biomass currently accounts for 14% of the global renewable energy demand, of which almost 70% is utilized for residential applications (e.g., cooking and heating purposes) [7].

Biomass harvesting in some cases faces mechanical difficulties that could be solved by means of accurate studies of a mathematical model that describes the whole machine or parts of it [8,9], as well as the application of new technologies in harvesting machines themselves [10].

The major hurdle to generating renewable energy from biomass is the low bulk density, low energy density, and high moisture content [11–14], which increase biomass transport and handling costs.

The biomass densification process transforming biomass into pellet and briquette can diminish the logistics cost [15].

In recent years, pellets became an important fuel in the production of heat and power in Europe [16]. The consumption of wood pellets grew rapidly during the last decade. The swift increase in the consumption of pellets is mainly due to legislation in several European countries that supports renewable energy [5]. In addition, between 2000 and 2017, global production jumped significantly, particularly in South America, Asia, and Oceania. The contribution of five main areas, i.e., EU 28, North America, Asia and Oceania, and South America, to the global wood pellet production in 2017 accounted for 48%, 32%, 8%, and 2%, respectively [17]. However, in the consumer market, EU 28 is a massive pellet consumer with a 77% of the world's wood pellet consumption [17]. In 2017, European pellet demand experienced a growth of 2.5 million tons, while production raised to 1.4 million tons [17].

Among the top 10 pellet-consuming countries in 2017, Italy took the second position with the consumption of 3.5 million tons in order to meet commercial and residential heat demands [18].

The Italian production of pellets settled, in 2015, about 300 thousand tons, a decrease by 16% from the previous year. The main production sites are Lombardia accounting for 45% of the national supply, followed by Veneto (18%), Friuli Venezia Giulia (16%), and Trentino Alto Adige (8%) [19]. On the other hand, the Italian national demand of pellets was estimated, in 2015, as about 2.25 million tons, experiencing an increase of 35% from the previous year [20], which was met by importing from foreign countries, particularly Austria [21]. The growth of the pellet production industry depends on the economic and energetic efficiency of the pellet plant, which is a function of many variables, namely, woody biomass availability, location, cost of investment, operation and maintenance, plant capacity, logistics, energy costs, and the possibility to locate pellet plants close to a source of low-cost heat for drying purposes (i.e., industrial cogeneration plants), environmental benefits, and financial incentives. Therefore, techno-economic examination of the pellet production systems is essential to evaluate the sustainability of the pelletization schemes and to select key factors affecting its development [22].

Pellet market evaluation indicates that, although the size and efficiency of the pellet production plant affect investment and operational costs of pellet, the production heavily depends on the physical characteristics of the raw biomass, particularly moisture content, and the need for mechanical pre-treatments [23,24]. Among diverse types of biomass (woody, herbaceous, fruity, or mixtures), raw materials for the pelletizing process in Europe are dominated by secondary feedstocks encompassing any by-products from the wood industry and pruning residues [17,18]. Agricultural residues also massively contribute to pellet production, considering that 102,000 kt of these by-products are annually produced in Europe [25]. Hence, some studies focused on different feedstocks to produce pellet. Carone et al. [26] carried out an assessment of technical factors influencing the quality of pellet produced from olive pruning residues and other agricultural waste, by means of an experimental set-up. Sánchez et al. carried out a cost evaluation of the pellet production chain from agri-food and wood industries in Spain. In this study, the cost of pelleting was affected by business fee, biomass transport, profit margin (15%), and pellet transport [27]. Hoefnagels and Junginger investigated the economic potential of wood pellet production from secondary forestry residues to find an optimal size of pellet plant [28]. They showed that optimal size depends on the location and feedstock supply assumptions.

Sultana and Kumar developed a multi-criteria assessment model for large biomass heat and power generation plants. They also revealed the importance of environmental, economic, and technical factors in decision-making regarding five pellets, each produced from a different sustainable biomass feedstock, i.e., wood, straw, switchgrass, alfalfa, and poultry litter [29]. In other research [30], Sultana et al. investigated minimum production cost and optimum plant size for pellet plants fed by agricultural biomass residue from wheat, barley, and oats. Three scenarios involving minimum, average, and maximum yields of straw were considered for developing a techno-economic model. Results showed that the total cost of pellet production is highly affected by field cost and transportation cost. To the best of our knowledge, there is a lack of studies on the effects of raw material characteristics on the investment costs of pellet production. Therefore, this research focuses on the assessment of the influence on pellet production plants in terms of the investment and operational costs of different biomass typologies and supply chains. To this end, operational indices, net present value (NPV), payback time (PBT), and profitability index (PI) are applied. In addition, the uncertainty impact of the key physical, chemical, and economic characteristics of the raw biomass on each indicator is quantified by sensitivity analysis. The target audiences of this study are potential investors interested in the pellet production sector, as well as policymakers evaluating the optimal scale of pellet plants to foster growth of the pellet production sector and biomass supply companies investigating the relationship between the quality and price of the biomass.

2. Legislative Framework for Biomass Pellets

Pellets are classified according to their physical and chemical properties. These properties affect the possibilities of pellet use in energy conversion technologies. For instance, a comparatively low amount of dust and ash in the pellet is an important factor for small heating systems, while larger power systems can cope with higher amounts of dust and ash. Other important parameters include durability, surface smoothness, and resistance to swelling. In Table 1, the main physical–chemical characteristics of pellets are shown, according to European Committee for Standardization (CEN) standards.

Table 1. Pellet physico-chemical characteristics [31].

Parameters	Effects
Chemical Characteristics	
Elements	
CI	Emission of dioxynes and furanoids, corrosion issues
	Emission of NOx, HCN, N_2O
N	Emission of SOx
S	Corrosion issues, low melting point of ashes
K	High melting point of ashes, pollutants in exhaust fumes
	High melting point of ashes, pollutants in exhaust fumes
Mg, Ka, P	
Heavy Metals	
Composition of Ashes	Polluting emissions, ash disposal issues
Physical Characteristics	
Moisture	Storage issues, Low Heating Value (LHV), auto-combustion
Density	Transport and storage issues, combustion properties
Pellet Size	Fluidity, transport safety, production of dust
Mechanical Durability	Changes in pellet quality, leakage

In order to foster the development of the pellet market, the European Committee for Standardization (CEN) issued a set of procedures for the characterization of solid bio-fuels (EN

14961, TC335, EN 17225) and for the quality certification of the bio-fuels (EN 15234), including pellets. Table 2 outlines the regulatory quality standards set within different nations.

Table 2. Quality standards for pellets in different EU Countries and in the USA.

Parameter	Austria (1)	Sweden (2)	Germany (3)	USA (4)
Size (mm)	3 < D < 4L ≤ 100	L = 5D	-	-
Density (kg/m^3)	-	≤500	-	≤639
Durability (%, <3 mm)	-	≤1.5	-	≤0.5
Energy Density (MJ/kg)	≤18.0	≤16.9	17.5–19.5	-
Moisture (% mass)	≤12	≤10	≤12	-
Ashes Content (% mass)	≤0.5	≤1.5	≤1.5	≤1
Sulfur (% mass)	≤0.04	≤0.08	≤0.08	-
Nitrogen (% mass)	≤0.3	-	≤0.3	-
Chlorine (% mass)	≤0.02	≤0.03	≤0.03	-
Additives (glues)	Not allowed	To be declared	-	-

Notes: (1) ONORM M 7135 [32], 2 categories for wood (pellet) and bark (briquettes). (2) SS 187120[33], three groups, having L = 4D, L = 5D, and L = 6D. (3) DIN 51731[34], five categories having L between 5 and 30 cm. (4) Pellet Fuel Institute [35], two categories (standard and premium), having ash content between 1% and 3%.

In Italy, in accordance with legislative decree 152/2006, the only kind of raw material allowed toward the production of pellets is biomass derived from mechanical processes applied within agriculture and forestry production, pruning residues, and lumber-mill by-products from raw wood.

Following requirements for the development of a voluntarily certified pellet quality certification in Italy, the Pellet Gold system, including a brand statement and quality assurance, was recently developed by AIEL (Associazione Italiana Energia dal Legno) [36]. The procedure Pellet Gold involves a series of tests, performed according to stringent quality parameters. The process to obtain and maintain a certificate of quality involves audits in companies, with sampling, testing, and process control. The fundamental assumption is that the pellet product is composed of virgin wood not contaminated with paints, additives, or other chemical adhesives. The requirements to Pellet Gold are similar to those indicated by the more stringent regulations CEN/TS 14961 [37], DIN plus, and ONORM M 7135, and they are aligned to the limits set by the Pellet Fuel Institute (PFI) [35].

On 21 July 2011, Italy adopted the European standard (EN 14961-2) to define the quality characteristics of pellets for non-industrial use. This standard was updated in 2014 (UNI EN ISO 17225:2014), which includes a series for pellets from woody biomass and another one for pellets from non-woody biomass. The standard introduces three quality classes:

- Class A1, which corresponds to a higher quality, and maximum ash content of 0.7%;
- Class A2, characterized by an ash content of 1.5%;
- Class B, characterized by a maximum ash content of 3.5%, which can be produced either from sawdust by the cortex, destined to centralized plants of greater dimensions, for commercial or pseudo-industrial application.

Since March 2012, the certificate Pellet Gold ensures compliance with UNI EN 17225-2. Therefore, companies certified must deal with the ash content of the pellets from their product. In addition to conforming to the European Pellet Gold certification, the determination of formaldehyde content and radioactivity was supplemented as criteria for the manufacturer. Technical specifications and the classification of wood-based pellets from woody biomass, as well as those for non-industrial applications, are indicated in Table 3.

Table 3. Pellet quality standard according to UNI EN ISO 17225-2.

Features	Category					
	A1 Tree Trunks and/or Untreated Wood without Bark (No Additives)	**A2 Tree Trunks and/or Untreated Wood without Bark (No Additives)**		**B Forestry Wood, Wood Processing By-Products, Used Wood**		
Diameter D (mm) and Length L (mm)	D = 6–8 L = 3.15–40	D = 6–8 L = 3.15–40	8 ± 0.5	6 ± 0.5	8 ± 0.5	From D > 10 ± 1.5 To D < 25 ± 1.0
Moisture (%)	10	10		10		18
Ashes (%)	0.7	1.5		3		To be declared
Durability (%)	1	1		1		To be declared
Additives (%)	Not allowed	To be declared (1)		To be declared (1)		To be declared (1)
Sulfur (%)	0.05	0.05		0.05		To be declared
Nitrogen (%)	0.3	0.3		0.3		To be declared
Chlorine (%)	0.03	0.03		To be declared		To be declared
Density (kg/m^3)	620–720	620–720		620–720		550
LHV (MJ/kg)	16.9	16.9		16.2		To be declared

(1) Permissible additives (glues) are maize starch, raw vegetable oil extracted from purely mechanical pressing, molasses, and natural paraffin. No artificial substances are allowed. The nature and quantities of additive must be declared.

3. Biomass Pellet Routes and Agro-Pellet Main Issues

Figure 1 outlines the phases of the pellet production process. In this section, these phases are shortly discussed, in order to highlight the main technical barriers of the pellet chain and to define the costs assumed in the successive economic assessment.

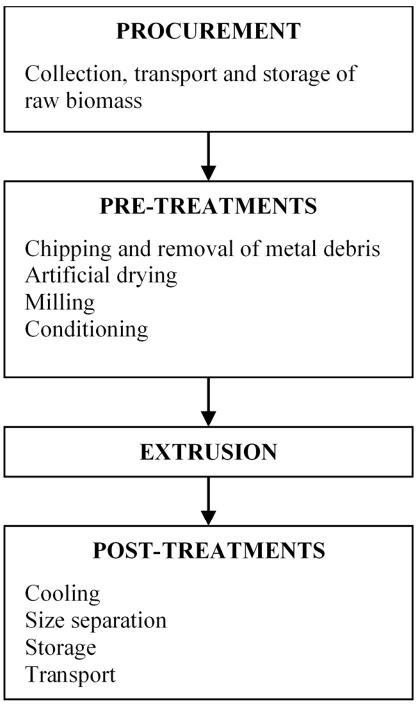

Figure 1. Phases of the pellet production process.

3.1. Biomass Supply

This phase includes the collection, transport, and storage of biomass to the collection point; green wood is mechanically removed, and pruning residues are air-dried.

3.2. Biomass Pre-Treatments

This phase includes the mechanical processes such as converting wood into wood chips (except when starting from sawdust), the removal of ferrous material, drying, milling, and conditioning. The wood chips are typically dried in heaters fed with conventional fuel, although sometimes the heaters use wood chips as fuel. The most common driers use rotating drums with flow of air, in which the wet biomass does not stick to the drum surfaces and over-heating is minimized. If the biomass can withstand contact with the combustion products, the simplest and cheapest system is a direct-heating drier, in which the wet biomass is in contact with hot combustion gases. Alternatively, the wet biomass can be dried using hot air. The dried biomass is further milled to obtain wood chips with average length of 3 mm and to homogenize the end product. The most common mills use rotating hammers, and the material is shifted through the machine using compressed air. Sometimes, the secondary milling is bypassed by a simple tilted-plane mechanical size selector. The pre-conditioning involves exposure of the biomass to an appropriate mix of environmental conditions (temperature, moisture, length of exposure time) to optimize its behavior in the subsequent extrusion. A common pre-conditioning process exposes the biomass to rapid heating using hot water vapor, with the effect of softening the wood chips and obtaining a partial decomposition of starch and cellulose in simpler sugars, which allow easier compacting. The short time of exposure to hot vapor minimizes significant increases in the moisture content of the biomass. Additives (such as molasses, starch, fats, oils, glues, etc.) aimed at improving biomass quality and extrusion behavior can be added to the raw feed during this phase [38,39].

3.3. Extrusion

This phase involves the physical production of the pellet by applying mechanical pressure on the biomass through a suitable holed plate, to obtain pellets with diameters in the 2–12 mm range and heights in the 12–18 mm range. The main technical parameters of the pelletizer are as follows: canal geometry, number and speed of pressurizing drums, ratio between diameter and length of canals, and distance between drum and holed plate. The devices may use a vertical cylindrical holed drum or a plane plate.

3.4. Post-Treatments

These phases include cooling, selection of pellet size, collection, and storage in silos or sacks for subsequent sale. The cooling phase is critical for the stabilization of the product, since, during the extrusion, the pellets reach comparatively high temperatures (90–95 °C) and are typically obtained via forced exposure to air at room temperature. Pellets with a non-standard size are mechanically removed to minimize development of dust in the storage areas.

4. Methodology for the Economic Evaluation

The economic evaluation is carried out by calculating the net present value (NPV) and profitability index (PI) of the investment. Subsequently, a sensitivity analysis is performed considering following parameters: biomass moisture content, pellet market value, cost of raw biomass, and average biomass transport distance.

The cost of investment ($C_{Investment}$) is calculated as follows:

$$C_{Investment} = C_{pell} + C_{dry} + C_{chip} + C_{store} + C_{inst} + C_{eng}, \quad (1)$$

where C_{pell} is the cost of pelletizing the plant, C_{dry} is the cost of drying the plant, C_{chip} is the cost of pre-treatment processes, C_{store} is the cost of storage, C_{inst} is the cost of plant installation, and C_{eng} is the plant engineering cost.

The annual operation and maintenance costs ($C_{Operation}$) are calculated as follows:

$$C_{Operation} = C_{biomass} + C_{transport} + C_{drying} + C_{electricity} + C_{personnel} + C_{maintenance} \text{ (€/year)}, \quad (2)$$

where $C_{biomass}$ is the cost of raw biomass, $C_{transport}$ is the cost of transport, C_{drying} is the biomass drying cost, $C_{electricity}$ is the cost of electricity, $C_{personnel}$ is the personnel cost, and $C_{maintenance}$ is the maintenance cost. Details on each parameter are outlined below.

$$C_{biomass} = \sum\nolimits_{j=1}^{m} P_{A,j} \times Q_{B,j} (\text{€/year}), \quad (3)$$

where m is the number of times of biomass feeding in the plant, $P_{A,j}$ is the purchase price of the j-th biomass feed (€/t), and $Q_{B,j}$ is the amount of the j-th biomass feed (t/year).

The pellet production ($Q_{Pellets}$) is equal to

$$Q_{Pellets} = Q_{max} \times i_U \times H. \text{ (t/year)}, \quad (4)$$

where Q_{max} is the maximum production capacity of the plant (t/hour), i_U is the production load factor, H is the annual production time (hours/year).

The number of production hours per year is calculated by

$$\mathrm{H} = \mathrm{n_{shifts}} \times 8 \times 12 \times \mathrm{d_{working}}, \quad (5)$$

where $\mathrm{n_{shifts}}$ is the number of daily shifts (each lasting 8 h), and $\mathrm{d_{working}}$ is the number of working days per month.

The amount of biomass requisite to produce $Q_{Pellets}$ also depends on the moisture content of both the raw biomass and the final pellet, according to

$$Q_{Pellets} = \sum_{j=1}^{m} \left(\frac{1 + m_{pellet}}{1 + m_{j-biomass}} \right) \cdot Q_{B,j} \text{ (t/year)}, \quad (6)$$

where m_{pellet} is the pellet moisture content, and $m_{j\text{-}biomass}$ is the j-th biomass moisture content.

If a portion of raw biomass is utilized to dry the remaining biomass, the biomass drying cost (C_{drying}) is equal to

$$C_{drying} = \sum_{j=1}^{m} \left(m_{j-biomass} - m_{pellet} \right) \cdot k_{drying} \cdot P_{A,j} \cdot Q_{\ B,\,j} \text{ (€/year)}, \quad (7)$$

where k_{drying} represents a dimensionless coefficient, equivalent to the additional mass of raw biomass (kg) needed to decrease the moisture content of 1 kg of biomass by one percentage point. The value of the coefficient also depends on the efficiency of the drying plant.

The cost of electricity is equal to

$$C_{electricity} = P_{electricity} \cdot \left(E_{pellet} \cdot Q_{Pellets} + \sum_{j=1}^{m} E_{chip,j} \cdot \overline{Q_{B,j}} \right) \text{ (€/year)}, \quad (8)$$

where: $P_{electricity}$ is the price of electricity (€/MWh), E_{pellet} is the electricity needed during the pre-loading, conditioning, extrusion, cooling, and size selection phases of the pellet production chain (MWh/t), $E_{chip,j}$ is the electricity needed during the mechanical pre-treatment of the j-th raw biomass feed, and

$\overline{Q_{B,j}}$ is the mass amount of *j*-th raw biomass feed undergoing mechanical treatments, with the net of biomass amounts used for drying purposes.

$$\overline{Q_{B,j}} = Q_{B,j} \cdot \left[1 + k_{drying} \cdot \left(m_{j-biomass} - m_{pellet}\right)\right] \text{ (t/year)}. \quad (9)$$

The cost of transport is equal to

$$C_{transport} = c_{transport}\left(\sum_{j=1}^{m} d_j \overline{Q_{B,j}}\right) \text{ (€/year)}, \quad (10)$$

where $c_{transport}$ is the cost of transport (€/t·km), and d_j is the average transport distance of *j*-th raw biomass feed (km).

The personnel cost is equal to

$$C_{personnel} = n_{unit/shift} \cdot n_{shifts} \cdot c_{unit} \text{ (€/year)}, \quad (11)$$

where $n_{unit/shift}$ is the number of personns employed for each shift, n_{shifts} is the number of daily shifts (each lasting 8 h), and c_{unit} is the annual per-unit cost of personnel.

The maintenance costs are equal to

$$C_{maintenance} = (C_{pell} + C_{dry} + C_{chip}) \cdot k_M, \quad (12)$$

where k_M is a coefficient reflecting the ordinary and extraordinary maintenance costs for plants and machinery.

The total revenues are equal to

$$\text{Revenues} = P_{pellet} \times Q_{pellets} \text{ (€/year)}, \quad (13)$$

where P_{pellet} (€/t) is the market value of pellets.

The total costs (costs of goods sold + overheads and interests) are equal to

$$Costs_{total} = \frac{C_{I-year} + C_{Operation}}{Q_{pellets}} \text{ (€/t·year)}, \quad (14)$$

where $C_{I\text{-year}}$ is the annual financial charge, equal to

$$C_{I-year} = \frac{C_{Investment} \cdot r}{1 - (1/(1+r))^n} \text{ (€/year)}, \quad (15)$$

where r is the annual real discount rate, and n is the lifetime of the plant (year).

The *NPV* (net present value) of the investment is

$$NPV = \sum_{i=1}^{n} \frac{CF_i}{(1+r)^i} - C_{Investment} \text{ (€)}, \quad (16)$$

where CF_i is the cash flow generated at the *i*-th year, and it is equal to

$$CF_i = (Revenues - C_{Operation}) \text{ (€/year)}. \quad (17)$$

The profitability index (*PI*) is calculated according to

$$PI = \frac{NPV}{C_{Investment}}. \quad (18)$$

5. Application to the Case Study

The economic evaluation was carried out for a firm producing door and window frames in laminated wood. This firm generates 3000 t/year of waste virgin wood residues, characterized by a small size and 13–15% moisture content. A small portion of this biomass (500 t/year) is currently used as bio-fuel to meet heat demand within the production site, while the remaining portion is considered as waste and disposed. The evaluation was aimed at assessing the economic viability of employing the waste biomass for pellets production. The analysis was carried out within four scenarios:

- In the base case, pellets are produced using by-products of the wood industry, similar to those available in-house by the firm under exam; however, in this scenario, they are purchased externally.
- In this scenario, all the waste virgin wood residues available in-house by the firm (and conveniently mixed with other similar biomass sourced locally, where appropriate) are used for the production of pellets.
- In this scenario, the waste virgin wood residues available in-house by the firm are mixed with other wood residues having a higher moisture content.
- In this scenario, the waste virgin wood residues available in-house by the firm are mixed with lumber mill residues and pruning residues, which all require suitable mechanical pre-treatments, before the drying and extrusion phases.

Tables 4 and 5 outline the technical and economic input parameters, as well as investment and operating costs considered within the four scenarios. In particular, Table 4 reports the technical and economical parameters which are constant within the four scenarios, while Table 5 reports the parameters varying across the different case studies. The pellet market value is intended as the pellet selling price to the retailer, excluding transport costs, assuming a final selling price for the end user of 220 €/t and considering the income for the distributor of the pellet.

Table 4. Technical and economic parameters held constant within the four scenarios.

Parameters	Unit	Value
Maximum production capacity Q_{max}	t/hour	1.25
Production load factor i_U	%	80
Hourly production capacity Q	t/hour	1
Number of daily shifts n_{shifts}	-	2
Number of annual production hours H	hours/year	3840
Annual pellet production Q_{pellet}	t/year	3840
Pellet moisture content m_{pellet}	%	12
Cost of transport $c_{transport}$ (1)	€/t·km	0.15
Drying coefficient k_{drying} (2)	-	0.015
Price of electricity $P_{electricity}$	€/MWh	150
Electricity needed per t of pellet E_{pellet} (3)	MWh/t	0.15
Annual cost of personnel c_{unit}	€/year·person	20,000
Maintenance coefficient k_M (4)	%	10
Lifetime of the plant n	years	8
Real discount rate r	%	5
Pellet market value P_{pellet}	€/t	135

(1) The quoted value is an average of the fares charged by the Italian Road Transport Operators' Association, relating to a distance of 100 km and a load of 20 t (see: www.confartigianatotrasp.com); (2) The value is obtained by considering an average consumption of 0.3 kg of biomass with 32% moisture content in order to dry 1 kg of biomass with 12% moisture content; (3) According to Reference [40]; (4) Average value for maintenance costs of the drying plant and machinery for chipping and extrusion [41].

Table 5. Technical and economic parameters varying across the four scenarios.

Parameters	Unit Scenario	Values A	B	C	D
Biomass amount (1)	t/year	4070	2420	2420	2420
Biomass price (1)	€/t	35	0	0	0
Moisture content (1)	%	14	14	14	14
Average transport distance (1)	Km	60	0	0	0
Electricity needed for chipping (1) (*)	MWh/t	0.02	0.02	0.02	0.02
Biomass amount (2)	t/year	0	1800	3300	3300
Biomass price (2)	€/t	0	35	30	25
Moisture content (2)	%	0	18	50	50
Average transport distance (2)	km	0	60	60	60
Electricity needed for chipping (2) (*)	MWh/t	0	0.02	0.02	0.065
Personnel units per shift	units	2	2	2	3

(1) Biomass feed available in-house by the firm; (2) Biomass feed sourced/purchased externally by the firm; (*) Authors' elaboration, based on average values of energy required for chipping and in relation to the quality of raw biomass, size of chipping machinery, and quality of the extruded material [42].

In Tables 6 and 7, the investment and operational costs for each scenario are reported. As seen, operation and maintenance (O&M) costs in case A are high because of the cost of biomass, while, in cases C and D, they are higher than in case B, due to the need to reduce the initial moisture content of the raw biomass from 50% to 12%. Furthermore, in case D, the raw biomass needs to undergo a pre-chipping phase, prior to being dried, which leads to an increase in investment costs and requirement for one additional personnel unit.

Table 6. Investment costs for the chosen scenarios.

Investment Costs (1000 €)								
Scenario	**A**		**B**		**C**		**D**	
C_{pell}	420	57%	420	57%	420	52%	420	45%
C_{dry}	30	4%	30	4%	100	12%	100	11%
C_{chip}	40	5%	40	5%	40	5%	150	16%
C_{store} (1)	200	27%	200	27%	200	25%	200	22%
C_{inst} (2)	30	4%	30	4%	30	4%	30	3%
C_{eng} (3)	20.7	3%	20.7	3%	22.8	5%	26.1	3%
Total	740.7	100%	740.7	100%	812.8	100%	926.1	100%

Notes: (1) Including cost of land, building, and storage facilities; the salvage value of the storage facilities accounts for 60% of the investment cost, and this value was accounted for as lump sum income generated in the last year of the expected operating life of the plant; (2) Authors' elaboration, based on two technicians employed for 30 working days and charging 500 €/person·day; (3) Authors' elaboration, based on design costs as 5% of the investment costs, net of installation costs.

Table 7. Operation and maintenance (O&M) costs for the chosen scenarios.

Operation and Maintenance Costs (1000 €/year)								
Scenario	**A**		**B**		**C**		**D**	
$C_{biomass}$	138.3	40%	55.8	23%	63	20%	52.5	14%
$C_{transport}$	36.6	11%	16.2	7%	29.7	10%	29.7	8%
C_{drying}	4.1	1%	5.2	2%	35.9	12%	29.9	8%
$C_{electricity}$	38.1	11%	38.6	16%	43.1	14%	65.3	18%
$C_{personnel}$	80	23%	80	32%	80	26%	120	33%
$C_{maintenance}$	49	14%	49	20%	56	18%	67	18%
Total	346.1	100%	246.7	100%	307.7	100%	364.4	100%

6. Results

The key results are shown in Table 8. The most convenient situation is indeed that outlined in scenario B, where the availability of abundant and good-quality biomass at zero cost results in a pellet production cost of 94 €/t, a PI of 1.53, and a PBT (payback time) lower than three years.

Table 8. Results of the financial analysis. PBT—payback time; NPV—net present value; PI—profitability index. Total production cost excludes row biomass supply cost

Scenario		A	B	C	D
Production cost	€/t	44.6	45.0	56.0	73.5
Total production cost	€/t	120.0	94.1	112.9	132.2
Cash flow	k€/year	172.2	271.7	210.7	154.0
PBT	Year	4.3	2.7	3.9	6.0
NPV	k€	492.7	1135	669.3	189.1
PI	-	0.67	1.53	0.82	0.20

According to scenario A, all raw biomass (having the same characteristics of the by-product available as firm by-product of the normal production cycle) is sourced externally at a cost of 35 €/t (excluding transport costs). Consequently, the cost of production rises to 120 €/t, while the PI drops to 0.67, and the PBT is higher than four years.

In case C, where externally sourced wet biomass is used as integrating feed for the biomass internally available, the economic values are worse than those of case B, because of the need to dry the wet biomass.

Scenario D is the least convenient of all, with a cost of production of 132 €/t, PI of 0.2, and PBT of six years; this is due to the extra costs related to the pre-treatments required for the raw biomass. Figures 2–5 outline the results of the sensitivity analysis associated with moisture content, average transport distance of raw biomass, pellet market value, and annual maintenance coefficient.

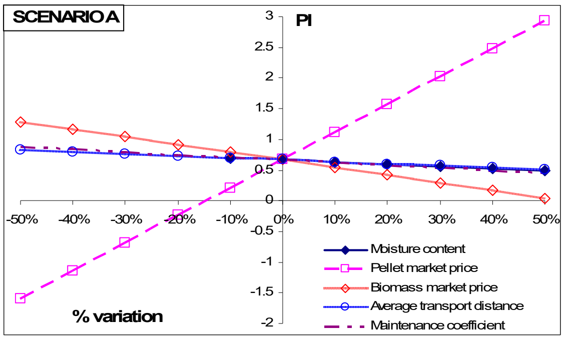

Figure 2. Sensitivity analysis on PI values for scenario A.

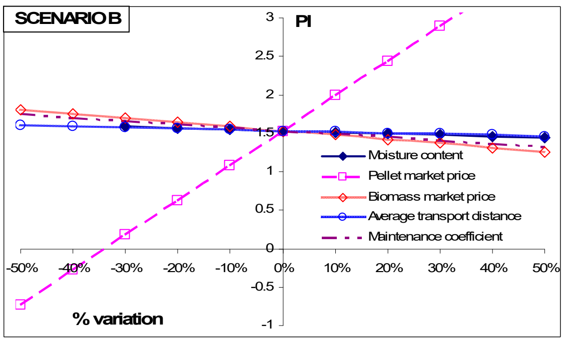

Figure 3. Sensitivity analysis on PI values for scenario B.

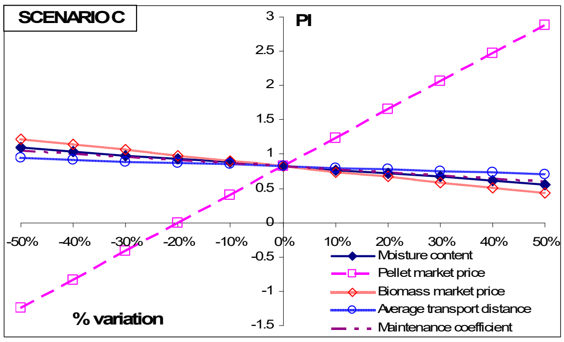

Figure 4. Sensitivity analysis on PI values for scenario C.

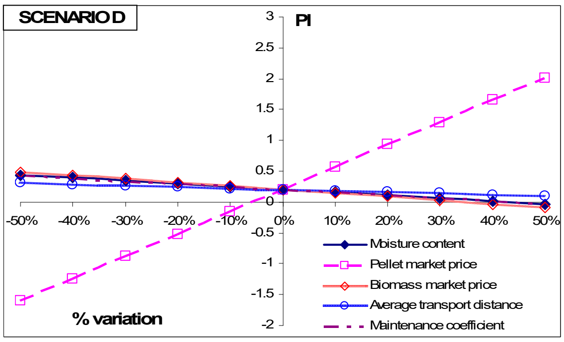

Figure 5. Sensitivity analysis on PI values for scenario D.

The sensitivity analysis allows drawing the following considerations:

- The market value of pellets is the parameter with the highest impact on the PI. The PI becomes negative for pellet prices of 115, 90, 108 and 127 €/t within scenarios A, B, C, and D, respectively.
- The biomass market price significantly affects the PI, particularly in cases A (where all biomass is sourced externally) and D (where the biomass has a high moisture content). Variations of ±20% in the price of biomass result in variations of the PI of ±36%, ±7%, ±20%, and ±60% within scenarios A, B, C, and D, respectively. In scenario A, the PI becomes negative if the price of biomass is higher than 54 €/t.
- An increase in the moisture content of the raw biomass results in a decrease of the PI, since more biomass is needed, and the costs of drying and transport all correspondingly increase. A variation of ±20% in the moisture content results in variations of the PI of ±10%, ±2%, ±12%, and ±50% within scenarios A, B, C, and D, respectively.
- A variation of ±20% in the average transport distance of the raw biomass results in variations of the PI of ±18%, ±4%, ±10%, and ±45% within scenarios A, B, C, and D, respectively. Notably, a reduction of the transport costs by zero results in an increase in PI by about 46%.

7. Conclusions

This paper describes the state of the art and the Italian regulation related to the Italian market for wood pellets. The phases of the pellet production chain are outlined, and a detailed financial appraisal model is put forward with the aim of assessing the financial viability of undertaking the production of pellets. The financial model is applied to an existing firm whose main products are wood door and window frames, which has a sizeable by-product of good-quality biomass (small wood residues) that could be used to manufacture wood pellets. The analysis is carried out within four scenarios, which reflect the main biomass supply options currently available to the firm managers; for each scenario, the NPV, PI, and PBT indices are calculated, and then a sensitivity analysis is carried out, assessing the impact of variations in the main parameters over the PI of the investment.

Based on the hypotheses of this study, it appears that the use of logging residues and bark is not financially competitive, due to the comparatively high costs of pre-treatment and drying. The most promising business opportunities for pellet production lie where an existing high-quality biomass by-product is added to a limited amount of low-moisture and low-cost biomass. It should be noted that, to the author's knowledge, this is one of the first researches comparing the pellet production costs with different biomass supply chains; thus, it is difficult to compare economic profitability and cost figures with previous studies. Moreover, further analyses should be carried out to optimize in an integrated manner the biomass collection area, the biomass processing/pelletization location and sizing, and the technologies for the final energy conversion to match the end users' demand, as already proposed in previous researches focused on sustainable energy systems in urban and peri-urban areas [43,44]. Such approaches could also be linked to the assessment of biomass energy potentials, in order to explore how to best use the resources of the territory in distributed vs. centralized processing and conversion plants, using intermediate bio-fuels (such as pellet) to improve the energy balances, the conversion efficiency, and the logistics of the routes; an example of this approach was proposed in Reference [45], for a case study of the Puglia region.

Finally, further researches should be devoted to the assessment of the potential market segments in the industrial, residential, commercial, and rural sectors, where different typologies of pellet could be used, considering the trade-offs between high-quality/high-cost pellet (from selected woody biomass) and low-quality/low-cost biomass (from agricultural or forestry residues), which could be better used in industrial applications and large-scale combustion/gasification plants able to manage the lower quality of the biofuel, in comparison to domestic stoves or heating plants for the commercial sector.

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