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Eco-Efficiency of Pellet Production from Dedicated Poplar Plantations

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Abstract: Biomass, due to its neutrality in terms of greenhouse gas emissions into the atmosphere during its life cycle, is considered an interesting renewable source for energy production as an alternative to the use of more polluting fossil fuels. Among the different wood fuels, pellets are convenient for use in dedicated stoves, and pellet heating systems have a high energy efficiency. The aim of this work was to estimate the economic and global warming potential (GWP100a) generated along the thermal energy supply chain of wood pellets, starting from the production of raw biomass from dedicated poplar cultivations and ending with the use of pellets in stoves by the end-user to produce thermal energy and ash. The Eco-Efficiency Indicator (*EEI*) was used to link the economic and environmental performance for eight proposed scenarios, obtained by combining different levels of mechanisation for poplar harvesting and wood biomass management before arrival at the pellet plant. For the thermal energy produced by the poplar wood pellet, the GWP100a ranged from 1.5×10^{-2} to 2.1×10^{-2} kg CO_2-eq MJ^{-1} for three-year-old plantations and from 1.9×10^{-2} to 2.4×10^{-2} kg CO_2-eq MJ^{-1}, for six-year-old plantations. In terms of eco-efficiency of the baseline scenario (*EEIb*), the most favourable scenarios remain those linked to the use of biomass from three-year-old poplar plantations, with *EEIb* values ranging from 0.31 to 0.60 € $kgCO_2-eq^{-1}$, compared to from 0.29 to 0.36 € $kgCO_2-eq^{-1}$ for pellets obtained from biomass produced from six-year-old poplar plantations. In terms of the Global Eco-Efficiency Indicator (*EEIg*), which also takes into account the positive effect on the reduction of greenhouse gases due to the storage of carbon in the soil by the plantations and the reduction of emissions from avoided fossil fuels, the most favourable scenarios remain those linked to the use of biomass from three-year-old poplar plantations, with *EEIg* values that vary in the range of 0.60 ÷ 1.04 € $kgCO_2-eq^{-1}$, compared to 0.55 ÷ 0.62 € kg CO_2-eq^{-1} for thermal energy obtained using biomass from six-year-old poplar plantations.

Keywords: life cycle assessment; life cycle cost; carbon footprint; biomass; thermal energy; poplar

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1. Introduction

Over the past 30 years, human activities have continuously increased CO_2 emissions due to rising energy demands [1,2]. The increase in atmospheric CO_2 and other greenhouse gases due to the use of fossil fuels represents one of the main environmental concerns today [3]. In this regard, the European Union (EU) has defined a new scenario for a more sustainable future. As part of the European Green Deal, with the Fit For 55% package [4], it has set a climate neutrality objective for the EU by 2050 and an intermediate climate objective of net emissions reduction of greenhouse gases by at least 55% by 2030. Furthermore, the Renewable Energy Directive, RED III [5], has been definitively adopted. The Directive redefines binding renewable energy targets for Member States and accelerates the transition towards cleaner energy sources. The main objective of the new European measure on renewable energy, which modifies the previous Red II Directive [6], is to achieve, by 2030, a percentage of energy coming from renewable sources equal to 42.5% (compared to the previous 32%) of the overall energy mix of the European Union. In the context of reducing the concentration of greenhouse gases in the atmosphere, the use of woody biomass as a resource for energy production becomes a key option due to the neutrality of its CO_2 life cycle [2,7–9]. Remembering also that the use of renewable energy leads to a reduction in energy costs determined by fossil fuels [10]. Despite being an important renewable energy resource, whether derived from dedicated energy crops or not, it is widely recognised that woody biomass is characterised by low energy density, high moisture content, heterogeneous geographical distribution and high transport costs that limit its wider use as an energy source [11–13]. These drawbacks can be overcome by applying a process of densification, or rather pelletisation, to the source woody material, which optimises the use of this solid biofuel as an energy feedstock [14–18], improving storage and facilitating the logistics and supply of power plants and small individual boiler rooms [19–21].

As a result, wood pellets have become the preferred form of biomass for efficient heating, so much so that in Europe, the growth of pellet production and consumption has increased by about 20 percent in the last decade [3]. The global demand for pellets tripled from 2012 to 2020, reaching approximately 50 million tonnes per year [22]. In 2022, pellet production in the EU-27 was 20.6 million tonnes [23].

The pellet production process is an extrusion process that involves subjecting previously dried and refined biomass to high pressures and temperatures and compressing it through holes of a few millimetres. The pellet, therefore, comes in a cylindrical form with a diameter of 6–8 mm and an average length of 10–12 mm, which is easy to package and use [24,25]. The starting woody material can be represented by residues from wood processing (sawdust), by wood chips obtained from residues of treetops and forest branches, or even materials derived from the use of dedicated energy systems (SRC) or by residues of agroforestry pruning [9,18,26–29]. Naturally, the transition from raw wood material to pellets involves a production process consisting of several steps that necessarily increases the cost of the finished product. The economic viability of pellet production therefore depends on the cost of the raw material, the type of machinery used in the transformation process, the size of the plants, the pellet market conditions, and so on. However, when the densification process of woody biomass is not fully optimised, pellets are unable to be competitive with fossil fuel sources. This is precisely because the pelletising production process is rather expensive, and although pellets are an energy product with added value, for all the reasons mentioned above with respect to the woody raw material from which they are made, the process itself can be unsustainable [17]. The environmental and economic sustainability of pellet production and use have been analysed in several works. Some studies have focused exclusively on the environmental impact of the pellet production stage [3,29–33]; others have compared pellet production to that of traditional fossil fuels [17,34]. Some studies have assessed the economic sustainability of pellet production [21,35–38], while others have studied the economic and environmental sustainability of the whole process [39–41]. Finally, other authors have carried out economic and environmental analyses of transport from production to consumption areas [35,42–44]. To the best of our knowledge, there are no studies in the literature that have investigated the carbon footprint (CF) and the economic sustainability of the entire wood pellet supply chain from dedicated plantations.

The present research is focused on the evaluation of the economic and environmental sustainability of the pellet supply chain (from cradle to grave) from dedicated poplar plantations in Italy. To this end, an Eco-Efficiency Indicator (*EEI*) was evaluated and calculated as the ratio between the economic net value and the CO_2 emissions released along the pellet production chain. To estimate the cost of wood chips to be used in the pellet production process, in the context of small-scale supply chains, the source of supply of the raw material from which to subsequently produce pellets was represented from wood chips of biomass of poplar plantations of different ages. The overall environmental and economic analysis of the pellet production process was developed on two levels: the first level concerned the analysis of the production processes that lead to the production of wood chips, to be considered as a raw material for subsequent transformation into pellets, and the second level analysed the production processes and plants directly dedicated to the production of pellets, starting from wood chips. The work considered eight scenarios derived from the combination of two poplar production cycles (3 and 6 years), each of which was collected by applying two different levels of mechanisation. For each of the four scenarios derived from the combination of cycles and level of mechanisation, it was considered to produce fresh or partially dry wood chips before delivering them to the pelletising plant. These last two options involve different uses of the pelletising plant, which significantly impacts the wood drying process before pelletising.

2. Materials and Methods

2.1. Goal and Scope

The analysis aims to evaluate the economic and environmental impacts and the Eco-Efficiency Indicator (*EEI*) of utilising wood pellets for thermal energy production over the entire lifecycle. The functional unit used for inventory analysis and impact assessment is the generation of 1 MJ of thermal energy. All energy and mass flows in the inventory are standardised to this functional unit. Figure 1 illustrates the overall system boundaries for the scenarios examined in this research. It encompasses the production of wood chips from Medium Rotation Coppice (MRC), storage, transportation to the pellet plant, pellet production, transportation of pellets to the end-user, and combustion in a small domestic boiler (10 kW). The analysis also accounts for the disposal of ash in landfills.

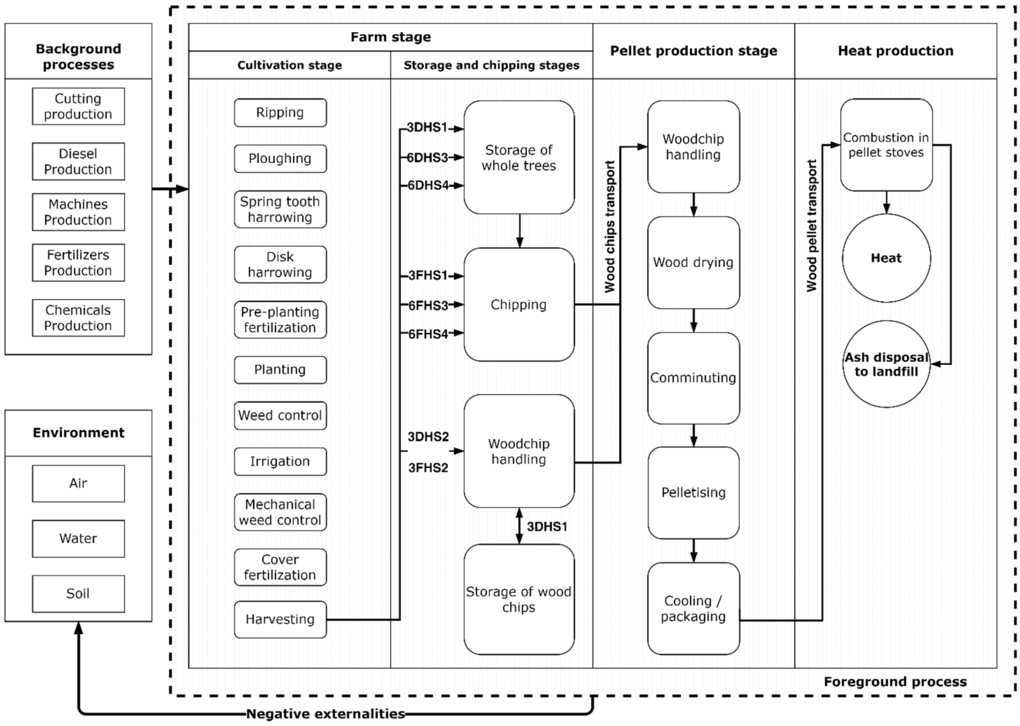

Figure 1. Flow chart depicting the wood pellet supply chains under investigation. The dashed line indicates the system boundary.

Scenarios Analysed

Eight scenarios were analysed in this study. These included four harvesting systems (HS1, HS2, HS3, and HS4) combined with two options of fresh biomass (F) and dehydrated biomass (D) delivered to the pellet mill inlet for both the 3- and 6-year cutting cycles (Table 1).

Table 1. Scenarios description.

Scenarios	Cutting Cycle (Years)	Harvesting	Extraction of Wood Chips or Whole Trees	Handling/ Loading of Wood Chips	On-Farm Drying Stage	Chipping
3DHS1	3	Tree cutting performed with a tractor (59 kW) equipped with a disc saw that cut and arranged the plants on the ground transversely to the running direction	Extraction of the whole trees carried out with a tractor (75 kW) equipped with a front grapple (M.C. = 52%) [45]	-	Field-dried whole trees to a M.C. = 13.6% − D.M. loss = 10% [45,46]	Chipper powered by tractor (177 kW); forestry loader equipped with grapples (75 kW) to load the chipper (Biomass losses 3% [47])
3FHS1					No drying stage (M.C. = 52%)	
DHS2		Modified self-propelled forage harvester (350 kW) equipped with a dedicated cutting head; 2 Tractors (84 kW) with high-sided trailer for transporting wood chips. The harvesting and chipping operations were performed continuously with a single passage of the machine in the field (Biomass losses 0.98%) [48]		Tractor (74 kW) with shovel	Wood chips dried in piles to a M.C. = 34.4% − D.M. loss = 11.9% (average value from [49])	-
3FHS2					No drying stage (M.C. = 52%)	
6DHS3	6	Felling performed by an operator with a chainsaw (3 kW)	Extraction carried out by two operators with a tractor equipped with a winch (70 kW) (M.C. = 54%) [45]	-	Field-dried whole trees to a M.C. = 32% − D.M. loss = 10% [45,46]	Chipper powered by tractor (177 kW); forestry loader equipped with grapples (75 kW) to load the chipper (Biomass losses 3%) [47]
6FHS3					No drying stage (M.C. = 54%)	
6DHS4		Felling and aligning and/or stacking trees curried out by an operator and excavator equipped with a forest shear (69 kW)	Extraction of whole or sectioned trees with a skidder (90 kW) with rear grapple and an operator (M.C. = 54%) [45]		Field-dried whole trees to a M.C. = 32% − D.M. loss = 10% [45,46]	
6FHS4					No drying stage (M.C. = 54%)	

In relation to the different ages of the poplar plantations considered, corresponding to 3- and 6-years old of the stand trees, and therefore, to all the different dendrometric characteristics possessed by the plants at the time of cutting, it was necessary to consider different levels of mechanisation to be used in harvesting, wood extraction, and chipping operations. The different processing systems adopted with different levels of mechanisation applied have also had different impacts on the environment and on the production costs of wood chips. For the first harvesting system (HS1), referring to 3-year cutting cycles, it was possible, at least with reference to the biomass increases found in the CREA-IT poplar plantations, to use a lower level of mechanisation more compatible with the availability of the farm fleet. This involved the use of a low-power tractor (59 kW) equipped at the rear with a disc saw. This machine allowed whole plants to be cut and stacked transversely in the direction of travel. Another tractor (80 kW) equipped with a front grapple then collected the plants and transported them to the processing area. Here the plants were chipped using a chipper powered by a tractor (177 kW). A forestry loader equipped with grapples (75 kW) was used to load the chipper.

As the second harvesting system (HS2), a modified self-propelled forage harvester (350 kW) equipped with a dedicated felling head was applied. In fact, the use of this machine was possible when the diameter at the base of the plants did not reach 15–20 cm, the maximum cutting limit beyond which the machine struggled to operate correctly [50]. During the works, to make the work site efficient, the harvester was supported by two tractors (84 kW each) equipped with high-sided trailers for loading and transporting the wood chips to the unloading site [51].

For the harvesting of the plantation in 6-year cycles, it was instead necessary to resort to a more proper forestry mechanisation. In this case, two other harvesting systems with different levels of mechanisation were applied. The first concerned a motor-manual harvesting system (HS3), also suitable for the availability of machinery at the farm level. An operator with a chainsaw was employed for the felling, two operators and a tractor with a winch were employed for the extraction of whole trees, while, to produce wood chips, two operators were employed to operate a chipper and a loader. The other harvesting system (HS4) involved the application of a higher level of mechanisation with the use of an excavator equipped with forestry shears (69 kW) for felling, aligning, and/or stacking trees. To extract the trees up to the processing area, where the chipping took place, as in the case examined above, a skidder with grapple (85 kW) was used. Except for the HS2, for all the others, the "Whole Tree System" (WTS) was applied, which involves felling trees and stacking them on the fall bed, and then removing them whole using a tractor equipped with a winch, a skidder with grapple or a forwarder with pliers [52]. The harvesting methods that characterise the various scenarios were chosen based on experimental trials of poplar plantation harvesting conducted at the CREA Research Institute in 2023.

2.2. Life Cycle Inventory (LCI)

2.2.1. Cultivation Stage of the Experimental Poplar Plantation

The analysis was developed based on the results of the biomass production of poplar groves for energy use, carried out at the Centro di Ricerca Ingegneria e Trasformazioni Agroalimentari of the CREA (Consiglio per la Ricerca in Agricoltura e l'Analisi dell'Economia Agraria), located in Monterotondo (Rome), central Italy (42°6′2.63′′ N; 12°37′37.36′′ E). The types of experimental plantations used to produce biomass were characterised by different durations of the cutting cycles, i.e., 3 and 6 years out of a whole production period of 18 years. The planting originally had a density of 7140 plants per hectare, single row with a planting distance of 2.8 m between rows and 0.5 m between cuttings [53,54]. The poplar clones used were AF2 (*Populus* × *canadensis* Moench), AF6 (*Populus nigra* L. × *Populus* × *generosa* A. Henry) and Monviso (*Populus* × *generosa* A. Henry × *Populus nigra* L.) [55]. The plantation was established in 2005 on a flat area of about 4.5 hectares. The area is located near the alluvial valley of the Tiber River, which has produced alluvial deposits consisting of fine sandy silt and fine sediments derived from erosion and reworking of the deposits and soils of the slopes [56]. The classification of the soil was silty-clayey type with low organic matter and phosphorus content [57].

The processes were evaluated over a standard year, during which each agricultural stage received a frequency equal to the average occurrence over eighteen years. Each operation was assessed based on primary data collected during the years of experimental fields at the CREA institute (machinery requirements, fuel consumption, fertilisers, and chemicals used). To fill in the gaps where data were not readily accessible, the Ecoinvent 3 dataset within the SimaPro 8.0.1 software (PRé Sustainability B.V., Utrecht, The Netherlands) was used, which provided the necessary secondary data (cuttings production, emissions from diesel engines, as well as heavy metal and atmospheric emissions from various sources, such as tyre abrasion and fertiliser application). Emissions associated with the utilisation of fertilisers and herbicides were determined by the scientific software EFE-So (version 2.0.0.6; Fusi and Fusi), in accordance with the methodology proposed by [58]. The calculation of carbon dioxide emissions stemming from urea fertilisation followed the method described in reference [59]. Furthermore, the assessment of herbicide emissions into the atmosphere, surface water, and groundwater was conducted utilising the PestLCI v.2.0 model (as described in reference [60]).

To plant the poplar groves, it was first necessary to proceed with the preparation of the soil by deep ripping and superficial ploughing, fertilisation (basal application over the entire field), and harrowing and mechanised planting of the poplar cuttings. Subsequently, nitrogenous covering fertilisation and post-plant mechanical treatments were carried out to contain weeds. The stumps were removed after 18 years of planting.

As regards the annual management of poplar plantations, in addition to the weeding carried out annually, the most important and expensive operation was represented by the harvesting and chipping of the biomass produced, performed with different mechanised systems in relation to the cutting cycles adopted. Two reference scenarios were used for the production cycles: (1) scenario with cutting every 3 years for 6 biomass harvesting cycles and (2) scenario with cutting every 6 years with 3 harvesting cycles in 18 years. The economic and environmental analyses were conducted for both types of scenarios, each assuming a constant average annual increase in biomass production per hectare equal to about 10 Mg DM ha^{-1} $year^{-1}$ or about 21.3 Mg ha^{-1} $year^{-1}$ of fresh biomass. This represents the average production observed over the years for the reference plantations [53]. Figure 2 shows the production of fresh biomass considered in the economic and environmental analyses relating to the two cutting cycles of the poplar plantations.

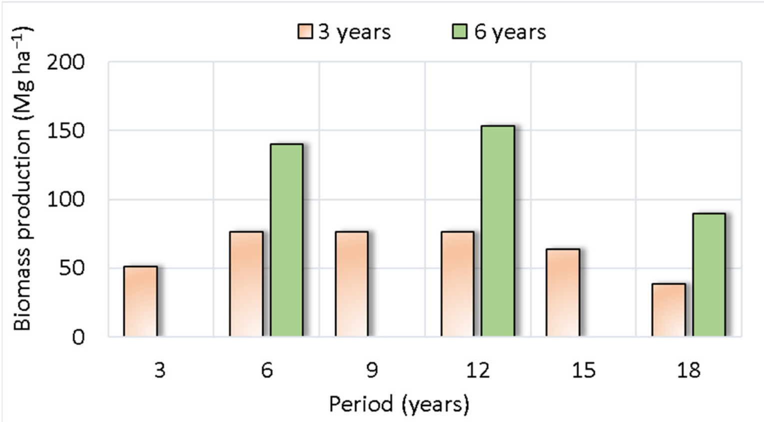

Figure 2. Production of fresh biomass obtainable over 18 years from poplar plantations divided according to the cutting cycle applied (every 3 and 6 years).

The agricultural activities planned in the 18-year crop cycle and the techno-economic data considered are reported in Table S1 of the Supplementary Materials, according to Sperandio et al. [61]. Furthermore, specific technical and economic data on the harvesting operations stated in Table 1 are given in Tables S2 and S3 of the Supplementary Materials.

Research on carbon storage in poplar plantations has shown that the amount of carbon stored varies depending on factors such as tree species, thinning regime, and management patterns. Dewar and Cannell [62] found that poplar plantations on fertile land can store carbon rapidly in the short term, while Meifang et al. [63] highlighted the influence of clone type on carbon sequestration capacity. Fang et al. [64] further emphasised the importance of planting density, with higher densities leading to greater biomass production and carbon storage potential. Garten et al. [65] added that changes in plant traits and nitrogen fertilisation can also impact soil carbon sequestration. These studies collectively suggest that the carbon storage in poplar 3- and 6-year cut medium-rotation forestry can be influenced by a range of factors, and further research is needed to determine the specific amount stored in these scenarios. Garten et al. [65] also provided insights into the predicted annual rate of soil carbon accrual at the end of the fourth rotation of hybrid poplar: the authors observed significant heterogeneity in soil carbon sequestration in poplar plantation, varying between 23 to 93 g C m^{-2} y^{-1}, contingent upon fertiliser application rates, aboveground biomass yield, and dead root decomposition dynamics. In the present study, carbon sequestration was not considered in the baseline scenarios and for the calculation of the eco-efficiency (*EEIb*), but the global Eco-Efficiency Indicator (*EEIg*) was calculated also considering a conservative minimum soil carbon sequestration as observed by Garten et al. [65], corresponding to 23 g C m^{-2} y^{-1} (84.3 g CO_2−eq m^{-2} y^{-1}), equivalent to -4.77×10^{-3} kg CO_2−eq MJ^{-1} in order to assess the improvement in eco-efficiency.

2.2.2. Chipping and Storage

Whole trees, once felled, can be left to dry in the field. Field drying was considered in scenarios 3DHS1, 6DHS3, and 6DHS4. After a few months of drying, when the moisture content of the whole tree wood had decreased (see Table 1 for biomass losses and moisture content considered in each scenario), the biomass was chipped and transported to the pellet plant. For the 3FHS1, 6FHS3, and 6FHS4 scenarios, the chipping stage was considered directly, so the whole trees were chipped directly and transported to the pellet plant. For the 3DHS2 and 3FHS2 scenarios, a modified self-propelled forage harvester equipped with a special cutting head and two tractors with high-side trailers for chip transport was considered (Table S1). In the 3FHS2 scenario, the chipped fresh biomass was loaded into a truck and transported directly to the pellet plant. For the 3DHS2 scenario, the biomass was stored in piles on the farm for the initial drying process and, after a few months, loaded onto a truck and transported to the pellet plant. Table S4 of the Supplementary Materials provides technical and economic information regarding the chipping stage.

2.2.3. Transportation Stage

Transportation data were taken from the Ecoinvent v.2.0 database. The transport of chips from the farm to the pellet plant was assumed to be 50 km, carried out by an average fleet with a capacity of 10–28 Mg. The calculation was based on a round trip (full and empty). Pellets in 15 kg plastic bags were assumed to be transported 10 km by van (<3.5 Mg of load) to the end-user. Table S5 in the Supplementary Materials provides technical and economic information on the transportation stage.

2.2.4. Pellet Production Stage

The production process that leads to the production of wood pellets, the so-called pelletising, is a technique of densification of incoherent materials initially adopted by the animal feed industry. Limited data concerning the conversion of wood biomass into pellets are available in the existing literature, particularly with regard to individual processes [66]. Consequently, to address the lack of data, a collaboration was established with an Italian pelleting facility to ascertain the mass and energy flows across various stages of the process. The process consists of various stages: procurement of the raw material; evaluation and analysis of the source material; drying, refining, conditioning, addition of additives, pelletising, cooling, screening, packaging and storage, transport, and use. The initial biomass, therefore, before entering the production process, must be analysed and selected, since the greater or lesser quality of the pellet depends on the quality of the raw material. The water content, dimensions of the material, and presence of certain quantities of certain elements that could create problems in the subsequent pellet combustion phase (silicon, chlorine, magnesium) are very important. The wood species of origin of the material used is also extremely important, as is the percentage of bark present, which can negatively affect the quality of the final product [11,66–70].

However, the water content remains the most important element for which the drying phase represents a fundamental aspect of the production process. The most suitable water content to feed the pelletising process of the incoming material must be between 10% and 14% [71–74]. This drying process must be carried out in special dryers of various types and functions (rotating drums and belts).

The original material must undergo refining with the elimination of non-woody foreign materials that could hinder the production process and damage the machinery, such as earthy residues, metal particles, small stones, and other elements. The process is carried out inside a refiner with a knife mill, which leads to the production of materials with a particle size suitable for the subsequent pelletisation process. If the qualitative characteristics of this material are not considered suitable, it is necessary at this stage to mix the material with permitted natural additives characterised by their binding capacity. Water can be used, but lignin and starch can also be added in quantities not exceeding 2% by weight, which manages to improve the quality of the finished product, especially in terms of durability [71,72,75,76]. The pressing phase of the material in the pelletiser represents the main operation in which the product undergoes a physical-mechanical transformation and is transformed into pellets with their own shape, size, and density [71,72,77]. The diameter of the holes in a metal grid into which the sawdust is pushed under pressure characterises the size of the pellets, which can vary from 3 to 25 mm in diameter, with lengths ranging from 5 to 40 mm.

The bulk density can vary from 550 to 700 kg m^{-3} and is considered the main indicator of the quality of the pellet, together with the particle size distribution of the pellet [68]. The pellet density and shelf life are influenced by the physical and chemical properties of the raw materials, temperature, and pressure applied during the pelleting process [78]. The temperature of the outgoing pellets can vary from 70 °C to 90 °C due to the frictional heat generated during the extrusion phase. Subsequently, to ensure hardening and further loss of water, the product is cooled to 20 °C in a counterflow cooler. At the end of this phase, the pellets can undergo the packaging process, subsequent storage, and transport to their destination.

The cost of the pelletising process was calculated, taking into consideration a pelletising plant with a production capacity suitable for small-scale energy supply chains. The costs of the input raw material (chips) refer to the results obtained in reference to the eight scenarios reported in Table 1; the plant is considered to have a constant production capacity of 500 kg h^{-1} for a total annual pellet production of 3840 Mg y^{-1}. The main elements considered for the economic analysis of the pelletising process, divided into single-process phases, are reported in Table S6 of the Supplementary Materials. The values of each parameter for the different operational phases contribute to determining the operating costs of the final production indicated. Regarding the costs incurred in the plants, some elaborations were carried out on what was found in the bibliography [79,80], which showed a reduction in the cost per product unit of the pellet as the size and production yields of the plant. Outlined in Table S6 of the Supplementary Materials are distinct sections of the facility, along with the corresponding technical and economic information.

2.2.5. Combustion and Ash Disposal

The final aspect under consideration involves the management of ashes, with an assumed ash content of 2.78% (±0.09%) and 1.82% (±0.23%), equating to 1.96 Mg and 1.27 Mg of ashes per functional unit for 3-year and 6-year cut cycle respectively [46]. These ashes were not considered as by-products suitable for use as potassium fertiliser, as suggested by Fantozzi and Buratti [81], but as a more realistic approach that considers ashes disposed of in landfills after domestic use of the pellets by the end-user. The electrical power required for the water circulation pump and the screw pellet extractor was estimated at 93 W, equating to a consumption of 0.0012 kWh per MJ. The biogenic CO_2 emitted by burning pellets in the home boiler was not included in the analysis. According to the Ecoinvent v.2.0 database, to produce 1 MJ of heat from diesel, 0.0886 kg CO_2-eq MJ^{-1} is generated. The thermal energy from the pellets reflects a certain amount of fossil fuel avoided, and the corresponding amount of CO_2-eq is not emitted. This was calculated as the difference between the CO_2-eq emitted by the diesel supply chain and that emitted by the pellet supply chain per MJ of thermal energy produced. This difference in CO_2-eq (avoided emissions) was used to calculate the global eco-efficiency (*EEIg*) of the eight pellet supply chains.

2.3. Environmental Life Cycle Impact Assessment Method

A life cycle assessment (LCA) was conducted to evaluate the environmental impact of producing heat from poplar wood pellets from resource extraction to waste disposal using a cradle-to-grave approach. The assessment evaluated a CF of 1 MJ of thermal energy generated by a pellet stove at the end-user level. SimaPro 8 software (Prè Consultant, Amersfoort, The Netherlands) was used to convert greenhouse gas emissions into CO_2 equivalents (CO_2-eq) using 100-year global warming potential coefficients (GWP100a v1.02).

2.4. Economic Assessment Method

The economic analysis of the entire pellet production chain, starting from the production of biomass from dedicated poplar groves, requires considering the entire production cycle of the biomass and its transformation first into wood chips and then into pellets. For this reason, this study considered all the costs and impacts derived from the planting of poplar, from the cultivation over the years, from the harvesting, from the transformation into wood chips, from the transport to pelletising plants, and finally, from the transport of the pellets to the end-users. The economic analysis aimed at calculating the costs per hour and per hectare of all operations conducted on the poplar plantation (planting, hourly management, biomass harvesting, and production of wood chips) was carried out by applying an analytical methodology [82]. The overall hourly operating costs of the machines and equipment used in the different scenarios proposed were calculated and divided into fixed costs (depreciation, taxes, insurance, and general expenses) and variable costs (maintenance and repairs, energy consumption). In addition to these costs, the costs necessary for the workers employed were considered. The economic analysis was based on the Life Cycle Cost (LCC) methodology, which uses the Net Present Value (*NPV*) calculation technique. LCC is a method that provides an economic analysis of operations and production processes within a product or service supply chain. This approach is linked to the ISO 14040 standard considered for LCA, and the same system boundaries described for the latter were considered. The discount and interest rates applied were 0.0356 and 0.05, respectively, according to official indications for the year 2023 in Italy [83].

The formula used to calculate the *NPV* was as follows (1):

$$NPV = \sum_{i=1}^{n} \frac{(Ri - Ci)}{(1+r)^{i}} + I_0 \tag{1}$$

where *NPV* is the Net Present Value (in €) of the whole supply chain calculated for a period of n years; r is the discount rate; Ri and Ci are the revenues and costs, respectively, referring to the ith year; and I_0 is the value of the initial investment for the purchase and installation of the pellet plant, including dryer, refiner, pelletiser, and cooler-packager.

To determine Ri, the annual value of pellet production was considered, taking into account the average market price of pellets for the year 2023. The average market price of category A1 pellets for 2023 was equal to 6.19 € per 15 kg bag. Since the quality of poplar wood pellets considered in the study is a category A2, as reported by [46], the average market price considered in the analysis was 20% lower than the A1 price and equal to 4.95 € per 15 kg bag, or 333 € Mg^{-1}.

The Ci, however, was obtained from the sum of all the annual costs relating to the management of the poplar plantations and all the annual management costs relating to the pelletising plant. For these cost items, all expenses relating to the operation of the machinery and the necessary labour were considered, i.e., the costs of depreciation of agricultural machinery, repairs and maintenance, fuel and electricity consumption, lubricants, taxes, and overheads. The annual costs relating to the loading and transport of wood chips from the poplar groves to the pellet plant and the loading and transport of pellets in 15 kg bags from the production plant to the end-users were added to the previous costs.

The annual equivalent value (*AEV*), expressed in € $year^{-1}$, was obtained from the *NPV* using the following Formula (2):

$$AEV = NPV \times \frac{(1+r)^{n} \times r}{[(1+r)^{n} - 1]} \tag{2}$$

2.5. Economic and Environmental Indicators

The analysis of the efficiency of the entire pellet production chain was carried out by jointly applying the LCA and the LCC methods. The analysis focused on the calculation of three main indicators of efficiency:

- Value Added per unit of Product (*VAP*), expressed in € kg^{-1} of pellet;
- Value Added per unit of Energy produced (*VAE*), expressed in € MJ^{-1};
- Eco-Efficiency Indicator (*EEIb*) of the baseline scenario production chains, expressed in € $kgCO_2-eq^{-1}$.

The *VAP* was obtained by applying the following Formula (3):

$$VAP = \frac{AEV}{P} \tag{3}$$

where:

AEV is the annual equivalent value (in € $year^{-1}$); *P* is the annual pellet production (in kg $year^{-1}$).

The *VAE* was calculated by applying the following Formula (4):

$$VAE = \frac{AEV}{E} \tag{4}$$

where:

AEV is the annual equivalent value (in € $year^{-1}$); *E* is the amount of pellet energy obtained by multiplying $P \times LHV$, where *LHV* is the Low Heating Value (in MJ kg^{-1}).

The evaluation of the *EEIb* in this study was based on a methodology that relates the results relating to economic efficiency with those relating to the environmental impact [36,84]. Reference is made to the thermal energy produced by the poplar wood pellet supply chain, starting from the production of the raw material (biomass) obtained from the planting and management of dedicated poplar plantations over a period of 18 years. To calculate the *EEIb*, the following formula was applied (5):

$$EEIb = \frac{VAE}{GWP} \tag{5}$$

where:

EEIb is the Eco-Efficiency Indicator of the whole production chain expressed in € $kgCO_2-eq^{-1}$; *VAE* is expressed in € MJ^{-1}; *GWP* is the value of the environmental impact of the whole production chain per MJ of thermal energy produced, expressed in kg CO_2-eq MJ^{-1}.

In order to evaluate the positive effects exerted by the reduction of CO_2 emissions into the atmosphere due to both the storage of carbon in the soil during the life cycle of poplars and to the emissions avoided in terms of fossil fuels, for each scenario, a global Eco-Efficiency Indicator (*EEIg*) was calculated separately by using the following Formula (6).

$$EEIg = EEIp + EEIa \tag{6}$$

where:

EEIg is the global Eco-Efficiency Indicator of the whole production chain expressed in € $kgCO_2-eq^{-1}$; *EEIp* is the Eco-Efficiency Indicator obtained by Formula (5) of the baseline scenarios; *EEIa* is the additional Eco-Efficiency Indicator due to the positive environmental effects mentioned above. The *EEIa* was obtained using the following Formula (7):

$$EEIa = \left| \frac{SCV}{GWP} + \frac{AFV}{GWP} \right| \tag{7}$$

$$SCV = SOCs \times p \tag{8}$$

$$AFV = (GWD - GWP) \times p \tag{9}$$

where:

SCV = Soil Carbon Value (€ MJ^{-1});

SOCs = Sequestered soil organic carbon into the soil due to the rotation forestry cultivation as CO_2-eq per MJ of thermal energy produced by poplar wood pellets (23 g C m^{-2} y^{-1} [65], equivalent to -4.77×10^{-3} kg CO_2-eq MJ^{-1});
AFV = Avoided fossil fuel (diesel) value (€ MJ^{-1});
GWD = GWP100a of diesel supply chain (kgCO_2-eq MJ^{-1});
GWP = GWP100a of heat produced by wood pellets from the poplar cultivation supply chain (baseline scenario—kgCO_2-eq MJ^{-1});
p = market price of CO_2 assessed based on the European Union Emissions Trading Scheme (EU ETS), which is a system for exchanging greenhouse gas emission quotas aimed at reducing emissions in the most energy-intensive sectors in the European Union. In the third quarter of 2023, this market price was 84.2 € MgCO_2-eq^{-1} [85].

3. Results and Discussion

The study presents a comparative analysis of economic evaluation (€ MJ^{-1}) and greenhouse gas emissions (GWP100a) (kg CO_2-eq MJ^{-1}) of thermal energy produced by poplar wood pellet supply chain across eight scenarios. Each scenario represents a unique combination of the four harvesting systems and wood biomass management.

3.1. Life Cycle Impact Assessment

This study demonstrated that the 3DHS1 scenario exhibited the most sustainable outcomes, with a GWP100a of 15 gCO_2-eq MJ^{-1}. The 6FHS4 scenario, with a 37% increase in emissions compared to 3DHS1, is more impactful in terms of global warming potential (Table 2). Furthermore, scenarios that included a pre-drying process resulted in a substantial reduction in emissions. Specifically, it was observed that field pre-drying in the 6-year cutting cycles resulted in a 17% reduction in emissions and in the 3-year cutting cycle carried out by forage harvesters (3DHS2 and 3FHS2) by 18%, within the same harvesting system. A 28% reduction in emissions was observed only for disk saw-cutting systems, where trees were cut and dried in the field (3DHS1). Indeed, as evidenced by Civitarese et al. [45], trials of natural field drying of 3-year-old whole poplar plants revealed a significant reduction in moisture content from 53% to 13.6% over a six-month period. These data were utilised in the calculation of the 3DHS1 scenario, thereby eliminating the need for an artificial drying process at the pelletising plant stage. This resulted in a reduction in energy consumption at the pelletising plant, with a corresponding reduction in CO_2 emissions of 48% compared to the pelletising plant stage of the 3FHS1 scenario. The "baseline" results obtained in the present study are less than what was observed by Kabir and Kumar [86] in their cradle-to-grid evaluation of pellets produced from whole trees (84 gCO_2 MJ^{-1}), while pellets from forest residues resulted in an emission of 68 gCO_2 MJ^{-1}. In a cradle-to-gate study of the pellet supply chain from wood chips, found values ranging from 18 to 41 gCO_2 MJ^{-1}.

Table 2. CF of thermal energy generated by poplar wood pellets in stoves at the end-user (Baseline scenario, kg CO_2-eq MJ^{-1}).

Wood Pellet Phases	3DHS1	3FHS1	3DHS2	3FHS2	6DHS3	6FHS3	6DHS4	6FHS4
Cultivation stage	3.53×10^{-3}	3.43×10^{-3}	4.28×10^{-3}	3.89×10^{-3}	5.16×10^{-3}	4.82×10^{-3}	5.76×10^{-3}	5.39×10^{-3}
Chipping phase at the landing site	1.81×10^{-3}	1.75×10^{-3}	0.00×10	0.00×10	2.4×10^{-3}	1.74×10^{-3}	2.4×10^{-3}	1.74×10^{-3}
Woodchip storage and handling at the farm stage	0.00×10	0.00×10	8.52×10^{-4}	1.09×10^{-3}	0.00×10	0.00×10	0.00×10+00	0.00×10+00
Woodchip transport to the pellet plant	1.2×10^{-3}	1.74×10^{-3}	1.32×10^{-3}	1.75×10^{-3}	1.26×10^{-3}	1.72×10^{-3}	1.25×10^{-3}	1.72×10^{-3}
Pellet production stage	5.81×10^{-3}	1.11×10^{-2}	7.77×10^{-3}	1.11×10^{-2}	8.4×10^{-3}	1.21×10^{-2}	8.06×10^{-3}	1.21×10^{-2}
Wood pellets transport to the end-user	2.00×10^{-3}	2.00×10^{-3}	2.00×10^{-3}	2.00×10^{-3}	1.98×10^{-3}	1.98×10^{-3}	1.98×10^{-3}	1.98×10^{-3}
Pellet boiler management	8.36×10^{-4}	8.41×10^{-4}	7.81×10^{-4}	8.41×10^{-4}	8.20×10^{-4}	8.20×10^{-4}	8.07×10^{-4}	8.07×10^{-4}
Heat—domestic pellet stove (Total)	1.50×10^{-2}	2.09×10^{-2}	1.70×10^{-2}	2.07×10^{-2}	1.93×10^{-2}	2.32×10^{-2}	1.99×10^{-2}	2.37×10^{-2}

At the cultivation stage, the CF of the different scenarios varied due to the differing environmental impacts of the harvesting methods and drying treatments (Figure 3). The emissions per MJ of energy produced were slightly different for the same harvesting system scenarios. This aspect is related to the functional unit considered and the flow of biomass in the different phases. The quantity of biomass harvested from the field to produce one megajoule (MJ) of thermal energy from wood pellets varies according to the harvesting and storage logistics employed, which influences the moisture content and biomass losses along the supply chain. During the field stage, the drying biomass has a greater impact. However, if the system boundary is extended from the cradle to the grave, the energy saved during the natural drying process produces an important emission reduction in the following supply chain stages.

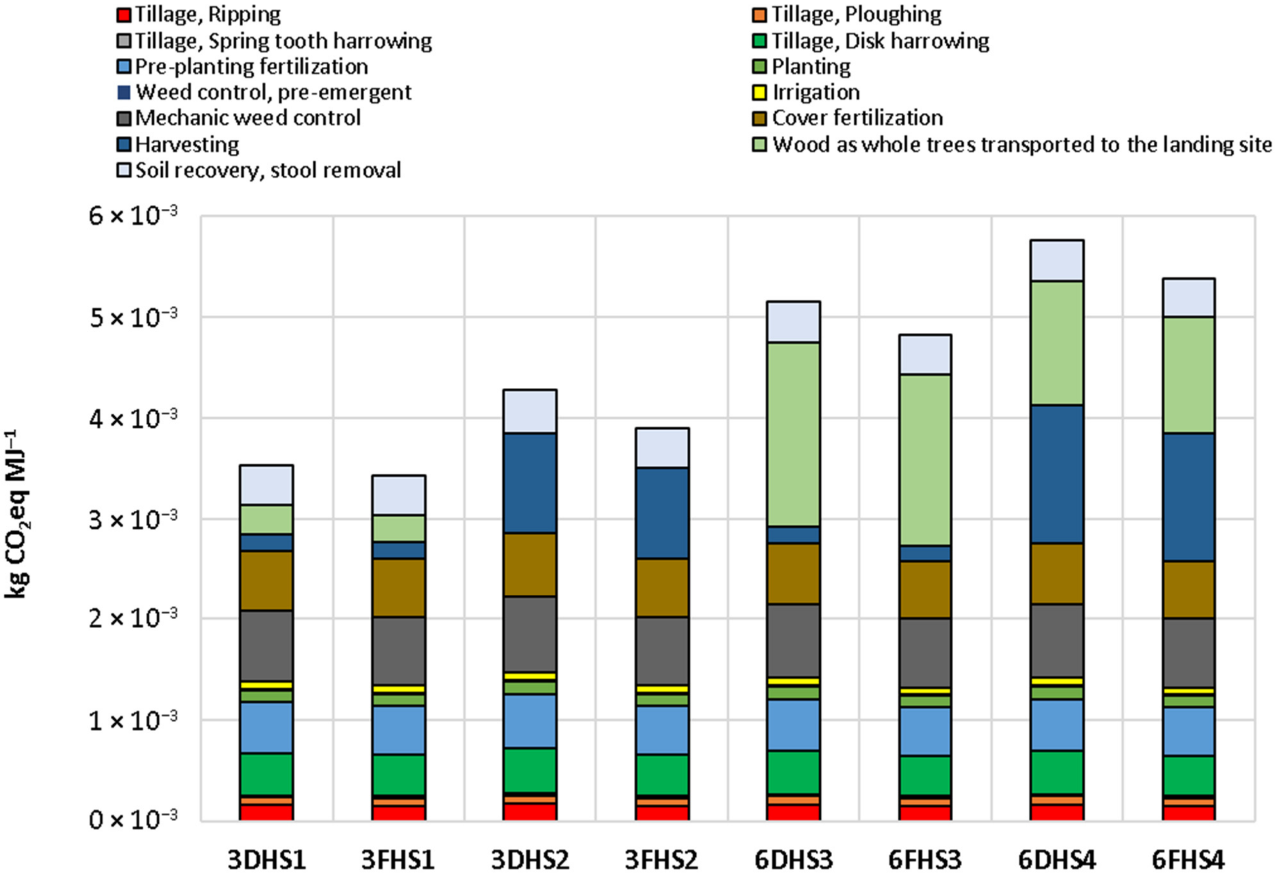

Figure 3. CF of the cultivation stage of poplar rotation coppice of 3-year and 6-year cutting cycles.

In six-year-old poplar plantations, the extraction of woody biomass (Figure 3, "Wood as whole trees transported to the landing site") represents significant energy consumption and CO_2 emissions compared to the extraction of wood from three-year-old plantations. In fact, wood extraction from the field to the land site for systems S3 and S4 generated an average emission of 1.77×10^{-3} kg CO_2-eq MJ^{-1} and 1.19×10^{-3} kg CO_2-eq MJ^{-1}, respectively. The harvesting system (Figure 3, "harvesting") used in the S4 scenarios emits an average of 1.33×10^{-3} kg CO_2-eq per MJ of thermal energy produced, making it the most unsustainable option in terms of CO_2 emissions.

The chipping stage generated a slightly higher impact when fresh biomass was chipped compared to drier biomass. However, all scenarios showed a reversal of trends in the impacts associated with the transport of fresh and dry wood chips, as well as the pellet production stage. As expected, the environmental cost associated with transporting biomass with a high moisture content is more relevant.

In scenarios 3DHS2 and 3FHS2, the three-year-old trees were collected using a forage harvester with a specific header for short rotation forestry. This harvester unloads fresh wood chips directly into wagons pulled by tractors (two) during a no-stop harvest. When biomass is placed in piles for drying (3DHS2), the formation of these piles with tractors equipped with shovels involves a certain amount of work and fuel consumption. The storage of wood chips in piles at farms involves some drying (from 52% to 34.4%) and some loss of dry matter (11.9%), which generally results in less harm to the environment than the direct transport of fresh wood chips with tractors and trailers that take them directly from the field to the pelleting plant (3FHS2).

The transportation of fresh biomass to the pelletising plant and the subsequent conversion of biomass into pellets require a greater input of energy, particularly during the drying phase. This is particularly evident in the 3DHS1 scenario, where the natural drying of whole trees in the field reduces the wood moisture content from 52% to 13.6% without the need for artificial drying in the pelletising plant. Consequently, the 3DHS1 scenario is more sustainable in terms of its impact on climate change.

The pellet production stage showed significant differences in GWP across scenarios, particularly between those involving different levels of drying. However, these differences were somewhat offset by variations in the total heat output.

Overall, the results highlight the trade-offs involved in the different wood pellet production scenarios. While certain harvesting methods and drying treatments can reduce greenhouse gas emissions, they may also result in variations in the total heat output. These findings provide valuable insights into the development of sustainable and efficient wood pellet production systems.

3.2. Economic Assessment

The overall results relating to the costs per Mg of pellet produced divided by the individual phases of the entire pellet production chain are shown in Figure 4. This total cost varies from a minimum of 175 € Mg^{-1} for the 3DHS1 scenario to a maximum value of 263 € Mg^{-1} for the 6FHS3 scenario, with an average cost of 226 € Mg^{-1}. The difference is attributable to the significant variation in costs found for biomass harvesting between the 3-year cutting cycles (lower costs) compared to the 6-year ones and the humidity conditions of the biomass before the pelletisation process. The above-described process of transforming raw biomass into pellets in the dedicated plant was the most expensive, representing an average of 46.5% of the total costs, corresponding to 104.89 € Mg^{-1}. The second most expensive process was the harvesting of biomass from poplar plantations, which on average required a cost of 45.81 € Mg^{-1}, corresponding to 20.3% of the total. With reference to each scenario and the type of biomass treatment, the high technology used in the harvesting of poplar biomass generally resulted in lower costs compared to harvesting conducted with a lower level of mechanisation. The cost of biomass harvesting in the 3FHS2 scenario (19.80 € Mg^{-1}) was 45.5% lower than the cost of harvesting in the 3FHS1 scenario (36.31 € Mg^{-1}), as well as the 3DHS2 scenario (21.42 € Mg^{-1}) was 30.8% lower than the 3DHS1 scenario (30.98 € Mg^{-1}). Over 6-year cycles, the cost of harvesting in the 6FHS4 mechanised scenario (59.39 € Mg^{-1}) was 16.4% lower than 6FHS3 (71.02 € Mg^{-1}), while 6DHS4 (57.33 € Mg^{-1}) was 18.4% lower than 6DHS3 (70.25 € Mg^{-1}). The third cost item was represented by the transport of wood chips from the plantations to the pellet plant and pellets from the plant to the end-user. On average, this cost amounted to 29.89 € Mg^{-1}, which is 13.3% of the total. The other cost items were represented by the investment (9.6%) and management (9.3%) of poplar plantations, which together reached 42.63 € Mg^{-1} (18.9%). Finally, the initial investment costs of the pellet plant were equal to 2.33 € Mg^{-1} (1.0%). However, if we consider the impact of the aggregate costs relating to the production of raw biomass, these represent, on average, 88.44 € Mg^{-1}, approximately 39.2% of the total cost.

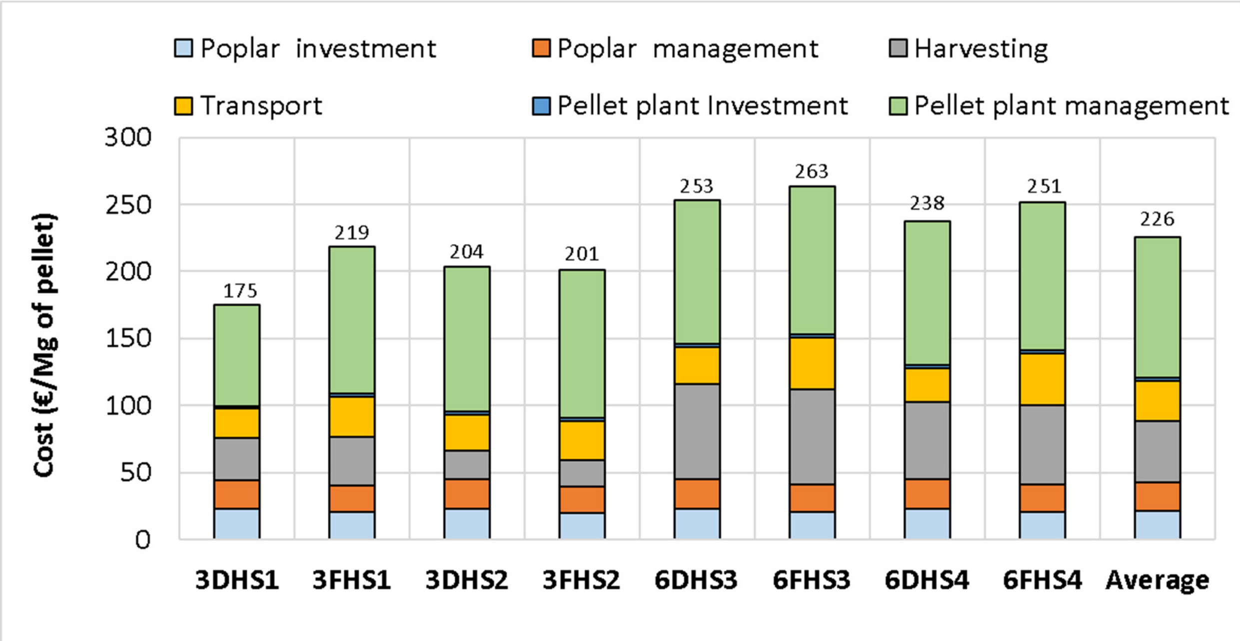

Figure 4. Costs per Mg of pellet produced divided by the individual phases of the entire pellet production chain in relation to the scenarios considered.

With regard to the costs associated exclusively with the production of pellets in the dedicated plant, Figure 5 highlights the costs of each work phase for each scenario under consideration. A notable discrepancy was observed in the 3DHS1 scenario in comparison with all other scenarios, as it exhibited a reduction in overall costs of approximately 30.2%. (76 € Mg^{-1} compared to approximately 109 € Mg^{-1} for the other scenarios). This was determined by the fact that, in the first case, the incoming biomass, already having a low moisture content, did not need to be dried but was directly refined. Considering the average costs of all scenarios, the greatest impact was due to the specific pelletising phase, which covered on average 33.4% of the costs, followed by the drying process (27.8%), refining (20.6%) and cooling and packaging processes (18.2%).

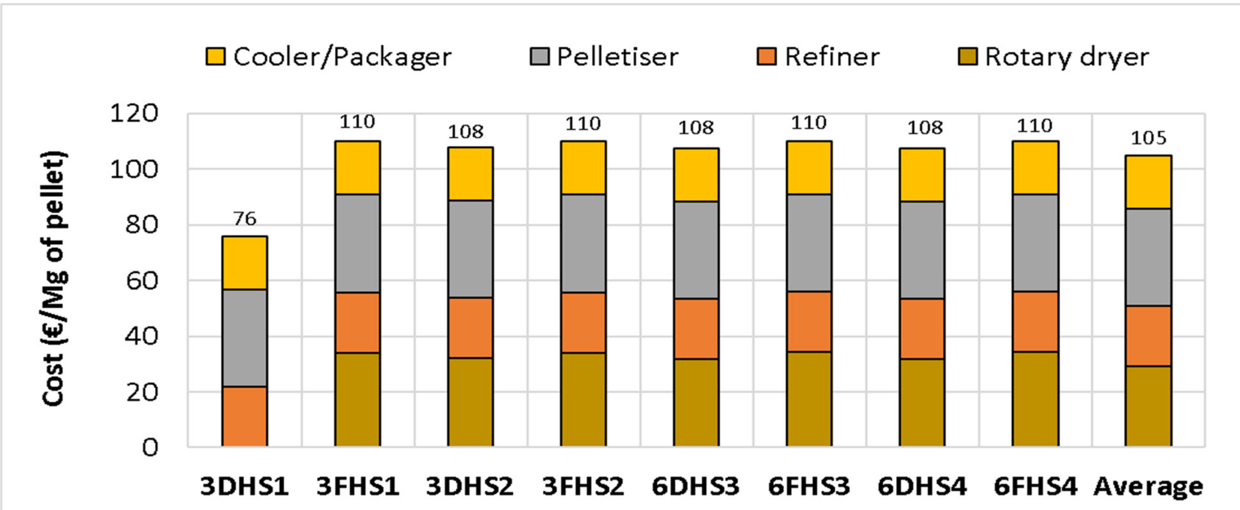

Figure 5. Costs per Mg of pellet divided into individual phases of the pellet production plant in relation to the scenarios considered.

Our results are similar or higher than those confirmed in works published by other authors. Pergola et al. [36], for example, report costs from 172 € Mg^{-1} to 113 € Mg^{-1} in relation respectively to two scenarios examined, the first of which with conditions more like those reported in this work. In other Italian conditions, Monarca et al. [87] report pellet production costs of 191 € Mg^{-1}, while Sikkema et al. [88] compare costs in Sweden, Italy, and the Netherlands, which vary between 110 and 170 € Mg^{-1}. In both previous cases, however, the lower costs compared to those presented in this work are largely justified by the different conditions examined and the market prices of materials, machinery, and labour in the considered historical period, which are significantly lower than the current ones.

Examining the proposed economic efficiency indicators (Figure 6), the best results were still obtained with reference to the 3DHS1 scenario, with indicator values equal to 0.159 and 0.0090 for *VAP* and *VAE*, respectively. The worst results are instead attributable to the 6DHS3 scenario with values *VAP* and *VAE* of 0.099 and 0.0055, respectively.

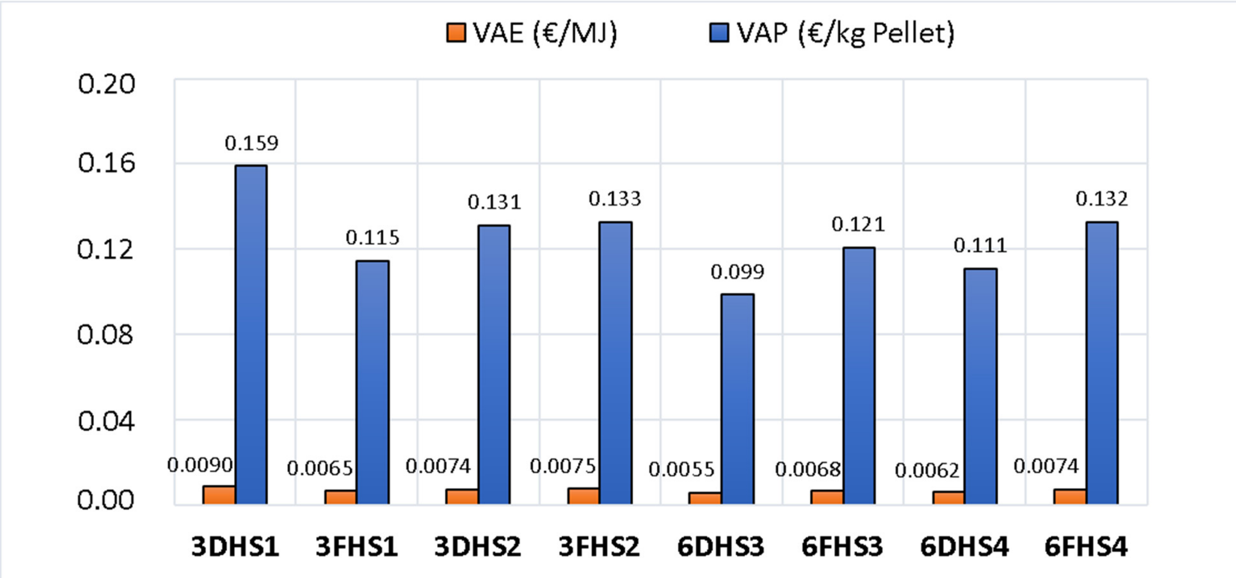

Figure 6. *VAE* and *VAP* relating to the entire pellet production chain, starting from poplar plantations as the primary source of raw biomass.

In general, the values of the indicators confirm that the scenarios referring to three-year cycles are more competitive than those referring to six-year cycles of poplar groves. The biomass harvesting phases, together with transport, are the two factors that most negatively influence the results, with costs being, on average, increasingly higher for the 6-year scenarios compared to the 3-year ones. The higher values of the economic indicators detected for the scenarios referring to the production of non-dehydrated biomass, contrary to what one might expect, are mainly due to the greater incidence of costs per kg of pellet produced. The 3DHS1 and 3FHS1 scenarios are an exception, where the highest values of the indices are found for the first scenario due to the lower costs recorded. In this particular case, in fact, the higher value of the indicators is mainly due to the high dehydration of the biomass at the entrance of the pellet plant, which allowed the drying phase to be skipped.

3.3. Eco-Efficiency of Thermal Energy from Pellet Supply Chain

The *EEIb* of thermal energy production from poplar SRC pellets in the baseline scenario was calculated by considering only the negative externality emissions of the process. Figure 7 shows that the *EEIb* of the three-year cutting scenario is less impactful when compared to that obtained from plantations with cuts made every six years. Within the same cutting system, it can be seen that natural pre-drying in the field increases the economic-environmental performance of the supply chain, although this trend and the difference between "dry" and "fresh" scenarios seem to decrease in the case of plantations with cuts every six years. In fact, although the thermal energy production costs and GHG emissions are lower in the six-year "Dry" scenarios (6DHS3 and 6DHS4) than in the six-year "Fresh" scenarios (6FHS3 and 6FHS4), the *EEIb* results between 6DH and 6FH are not that different. This can be explained by the fact that even if the natural drying of whole trees in the field results in lower drying costs for the pelleting plant, it implies higher dry matter losses and, consequently, lower yields and revenues. It is important to emphasise that these results may change over time as weather conditions and drying times vary. Thus, the eco-efficiency values obtained should obviously be contextualised on a case-by-case basis, as different production realities and climates may yield different results.

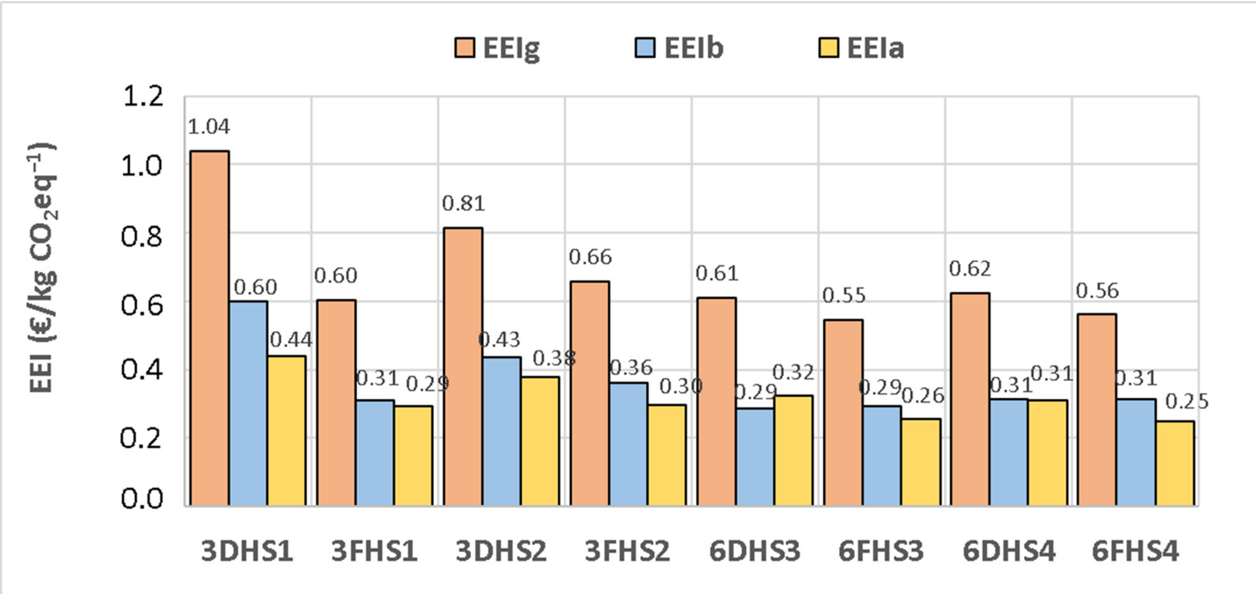

Figure 7. Values of *EEI* referring to the global (*EEIg*), baseline (*EEIb*), and added (*EEIa*) for the scenarios considered.

Taking into account the positive externalities generated by the CO_2 avoided by not using fossil fuels to produce 1 MJ of thermal energy and the potential carbon stored in the soil over the 18 years that the poplar plant has been in operation, the results of the climate change impacts and the *EEI* of the thermal energy from the pellet supply chain change significantly. Bidini et al. (2006) found that the environmental impact of heat from SRF pellet combustion is significantly lower than that of methane combustion [89]. This suggests that the use of SRF pellets for thermal energy in household stoves could lead to a reduction in GHG emissions, as highlighted in some studies [90,91]. Sperandio et al. (2021) found out that the transition from a diesel boiler to a biomass-fuelled biennial poplar wood chip allows a 77% reduction in greenhouse gas emissions [61]. However, as far as we know, there are no readily available studies that provide specific information on the eco-efficiency of thermal energy from poplar SRF wood pellets in domestic stoves instead of fossil fuels. In Table 3 are shown the values of the variables that contribute to the determination of the *EEIg*, while in Figure 7 the values of Eco-Efficiencies ("baseline", "added" and "global") are graphically represented. The *EEIg* of the thermal energy generated from poplar pellets burned in the end-users' stoves, including avoided fossil fuels and agroforestry carbon sequestration, is significantly higher than the *EEIb* obtained in the baseline scenario.

Table 3. Monetary value of CO_2-eq saved or sequestered through fossil fuel avoidance (AFV) and agroforestry carbon sequestration (SCV) for the thermal energy from the pellet supply chain in relation to the scenarios considered.

Scenario	Cutting Cycle	GWP (Baseline Scenarios) (kg CO_2-eq MJ^{-1})	SOCs (kg CO_2-eq MJ^{-1})	GWD (kg CO_2-eq MJ^{-1})	SCV (€ MJ^{-1})	AFV (€ MJ^{-1})
3DHS1	3	1.50×10^{-2}	-4.77×10^{-3}	-8.86×10^{-2}	4.2×10^{-4}	6.20×10^{-3}
3FHS1	3	2.09×10^{-2}	-4.77×10^{-3}	-8.86×10^{-2}	4.2×10^{-4}	5.70×10^{-3}
3DHS2	3	1.70×10^{-2}	-4.77×10^{-3}	-8.86×10^{-2}	4.2×10^{-4}	6.3×10^{-3}
3FHS2	3	2.07×10^{-2}	-4.77×10^{-3}	-8.86×10^{-2}	4.2×10^{-4}	5.72×10^{-3}
6DHS3	6	1.93×10^{-2}	-4.77×10^{-3}	-8.86×10^{-2}	4.2×10^{-4}	5.83×10^{-3}
6FHS3	6	2.32×10^{-2}	-4.77×10^{-3}	-8.86×10^{-2}	4.2×10^{-4}	5.51×10^{-3}
6DHS4	6	1.99×10^{-2}	-4.77×10^{-3}	-8.86×10^{-2}	4.2×10^{-4}	5.78×10^{-3}
6FHS4	6	2.37×10^{-2}	-4.77×10^{-3}	-8.86×10^{-2}	4.2×10^{-4}	5.46×10^{-3}

The positive impact of avoiding fossil fuels for heating and of the carbon stored in the soil by trees in the 18 hypothesised years led to an improvement in the Eco-Efficiency of the entire production process, compared to the baseline scenarios, varying from a minimum of 73% for the 3DHS1 scenario (1.04 vs. 0.60) up to a maximum of 113% for the 6DHS3 scenario (0.61 vs. 0.29).

3.4. Sensitivity Analysis

A sensitivity analysis of the global Eco-Efficiency Indicator (*EEIg*) was conducted, assuming a change in the price of pellets and a change in the length of the wood chip transport route to the processing plant. Figure 8 shows the analysis results in the form of a matrix graph.

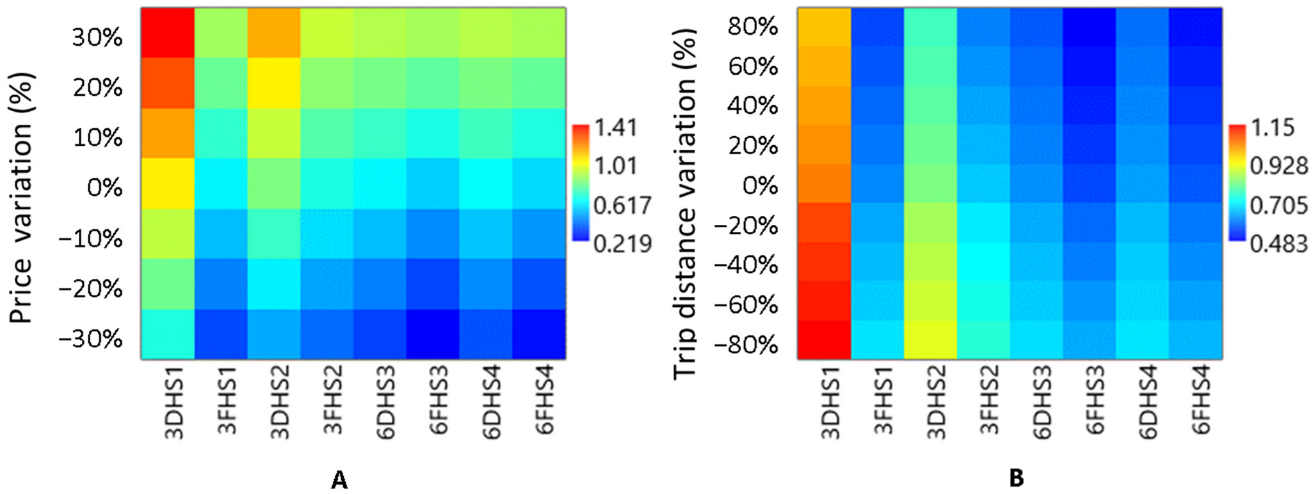

Figure 8. Sensitivity analysis of the *EEIg* value (€ kg CO_2-eq^{-1}) to percentage variations in the Pellet Price (**A**) and Trip distance (**B**).

The colour gradient from deep blue to bright red indicates an increase in indicator value. The lowest values are concentrated in the scenarios referring to 6-year cycles. Even for the variation in the transport path, a result similar to the previous one is confirmed, even if the colour gradient is arranged in the opposite way since the increase in the path acts in a worsening way. The minimum values are concentrated in the scenarios referring to 6-year cycles, with the lowest value (0.22) recorded for the 6FHS3 scenario when the price of pellets drops by 30% compared to the reference price. The maximum positive value of 1.41 was obtained from the 3DHS1 scenario when the price of pellets increased by 30%.

If the length of the route increases by 80% (90 km) compared to the one considered (50 km), the *EEIg* value is reduced by 6–10% for the three-year scenarios, while it is reduced by 8–12% for the six-year scenarios. If, however, the transport route is reduced by 80% (only 10 km), the indicator increases by 11–13% for the three-year scenarios and by 10–16% for the six-year scenarios, respectively.

3.5. Future Technological Advancements in Wood Pellet Production for Improved Economic and Environmental Sustainability

Potential technological advances in wood pellet production are expected to focus on improving efficiency, sustainability, and product quality in the future. Therefore, it can be reasonably assumed that the role of artificial intelligence (AI) will also play an important role in this sector through the implementation of fully automated production lines, with real-time monitoring and adjustment of the production process to achieve optimal efficiency, ensuring consistent quality, and identifying inefficiencies. The use of artificial intelligence-based systems will also be able to predict equipment failures before they occur, thereby reducing downtime and maintenance costs. Other aspects may involve the implementation of dynamic pricing models driven by AI to better respond to fluctuations in market supply and demand. These models use big data and machine learning to analyse historical prices, production costs, and market trends to optimise prices for maximum profit. Furthermore, these systems facilitate the efficient management of inventory, preventing the accumulation of excesses or deficiencies. Additionally, they enable the implementation of tailored pricing strategies for distinct customer segments. By promptly responding to market fluctuations and competitive pricing, these models enhance competitiveness and operational efficiency. The integration of predictive analytics could potentially enhance resource utilisation, ultimately leading to increased profitability and overall sustainability.

4. Conclusions

In this study, the entire thermal energy from the poplar wood pellet supply chain was analysed, from the production of raw biomass from dedicated poplar plantations to the thermal energy produced by the end-user. The analysis jointly covered the environmental and economic aspects through the LCA and LCC methodologies, respectively. Eight different study scenarios were defined in relation to the type of mechanised harvesting applied to the plantations and the type of post-harvest partial dehydration treatment applied to the raw biomass. Three supply chain efficiency indicators were used to perform a comparative evaluation of the eight scenarios. The Eco-Efficiency Indicator (*EEI*) was used to assess the added value generated for each kg of CO_2 emitted. The results demonstrated that the thermal energy production chain benefited from the use of pellet biomass derived from poplar plants that were harvested every three years using a low-level mechanisation harvesting system, with a pre-treatment of partial natural dehydration of the plants in the field (scenario 3DHS1). This scenario allows the eco-efficiency of the baseline production system to be increased by 110% compared to the worst scenario, represented by biomass coming from cuts carried out every six years with a low mechanisation harvesting system (scenario 6DHS3). Also, considering the environmental benefits attributable to the life cycle of poplar plantations in terms of storage capacity of organic carbon in the soil and avoidance of the use of equivalent energy quantities of fossil fuels for heating, the global eco-efficiency increases by 73–113%. The outcomes are substantially influenced by the characteristics of the biomass and its moisture content. Although GWP100a is an important environmental indicator of climate change, it alone is a limitation of this study. To assess the environmental impact of supply chains, future studies should focus on evaluating other environmental indicators that highlight the damage caused by pellet thermal energy supply chains to human health, biodiversity, and resource use.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/en17133137/s1, Table S1: Main technical and economic data of the poplar cultivation stage employed in the study; Table S2: Main technical and economic elements for calculating the hourly cost of machines and equipment used in felling (chipping) and extraction operations for HS1 and HS2; Table S3. Main technical and economic elements for calculating the hourly cost of machines and equipment used in the felling and extraction operations of whole trees for HS3 and HS4; Table S4. Main technical and economic elements for calculating the hourly cost of machines and equipment used in chipping and handling operations for relevant harvesting systems; Table S5. Main technical and economic elements of the wood chip and pellet transportation; Table S6. Main technical and economic elements of the biomass pelletising process, divided into individual production phases.

Author Contributions: Conceptualization, G.S.; methodology, G.S. and A.S.; visualization, A.S.; software, A.S.; formal analysis, G.S. and A.S.; data curation, G.S. and A.S.; writing—original draft preparation, G.S., A.S. and A.A.; writing—review and editing, G.S., A.S., A.A. and V.C. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: Data is contained within the article and in the Supplementary Materials.

Conflicts of Interest: The authors declare no conflict of interest.

Glossary

3DHS1	3 = years cutting cycle; D = pre-dried biomass; HS1 = Harvesting system 1 (tractor equipped with a disc saw + tractor with front grapple)
3FHS1	3 = years cutting cycle; F = fresh biomass; HS1 = Harvesting system 1 (tractor equipped with a disc saw + tractor with front grapple)
3DHS2	3 = years cutting cycle; D = pre-dried biomass; HS2 = Harvesting system 2 (self-propelled forage harvester + two tractors with trailers)
3FHS2	3 = years cutting cycle; F = fresh biomass; HS2 = Harvesting system 2 (self-propelled forage harvester + two tractors with trailers)
6DHS3	6 = years cutting cycle; D = pre-dried biomass; HS3 = Harvesting system 3 (chainsaw + tractor with winch)
6FHS3	6 = years cutting cycle; F = fresh biomass; HS3 = Harvesting system 3 (chainsaw + tractor with winch)
6DHS4	6 = years cutting cycle; D = pre-dried biomass; HS4 = Harvesting system 4 (excavator equipped with a forest shear + skidder with rear grapple)
6FHS4	6 = years cutting cycle; F = fresh biomass; HS4 = Harvesting system 4 (excavator equipped with a forest shear + skidder with rear grapple)
AEV	Annual Equivalent Value
AFV	Avoided fossil fuel (diesel) value
EEI	Eco-Efficiency Indicator
EEIa	Additional Eco-Efficiency Indicator
EEIb	Basic Eco-Efficiency Indicator
EEIg	Global Eco-Efficiency Indicator
GWP100a	Global Warming Potential over a 100-year period
GWP	GWP100a of heat produced by wood pellet from poplar cultivation supply chain
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
MRC	Medium Rotation Coppice
NPV	Net Present Value
SCV	Soil Carbon Value
SOCs	Sequestered soil organic carbon into the soil by the rotation forestry cultivation (CO_2-eq)
VAP	Value Added per unit of Product
VAE	Value Added per unit of Energy produced

References

1. García, R.; González-Vázquez, M.P.; Pevida, C.; Rubiera, F. Pelletization properties of raw and torrefied pine sawdust: Effect of co-pelletization, temperature, moisture content and glycerol addition. *Fuel* **2018**, *215*, 290–297. [CrossRef]
2. Kizuka, R.; Ishii, K.; Sato, M.; Fujiyama, A. Characteristics of wood pellets mixed with torrefied rice straw as a biomass fuel. *Int. J. Energy Environ. Eng.* **2019**, *10*, 357–365. [CrossRef]
3. Padilla-Rivera, A.; Barrette, J.; Blanchet, P.; Thiffault, E. Environmental Performance of Eastern Canadian Wood Pellets as Measured through Life Cycle Assessment. *Forests* **2017**, *8*, 352. [CrossRef]
4. Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021 establishing the framework for achieving climate neutrality and amending Regulations (EC) No 401/2009 and (EU) 2018/1999 (European Climate Law) 2021. Available online: https://eur-lex.europa.eu/eli/reg/2021/1119/oj (accessed on 22 May 2024).
5. Directive (EU) 2023/2413 of the European Parliament and of the Council of 18 October 2023 amending Directive (EU) 2018/2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as regards the promotion of energy from renewable sources and repealing Council 2023. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32023L2413 (accessed on 22 May 2024).
6. Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources European Commission. *Off. J. Eur. Union* **2018**, *L328*, 82–209. Available online: https://eur-lex.europa.eu/eli/dir/2018/2001/oj (accessed on 22 May 2024).
7. Civitarese, V.; Acampora, A.; Sperandio, G.; Bassotti, B.; Latterini, F.; Picchio, R. A Comparison of the Qualitative Characteristics of Pellets Made from Different Types of Raw Materials. *Forests* **2023**, *14*, 2025. [CrossRef]
8. Tumuluru, J.S. Effect of pellet die diameter on density and durability of pellets made from high moisture woody and herbaceous biomass. *Carbon Resour. Convers.* **2018**, *1*, 44–54. [CrossRef]
9. Latterini, F.; Civitarese, V.; Walkowiak, M.; Picchio, R.; Karaszewski, Z.; Venanzi, R.; Bembenek, M.; Mederski, P.S. Quality of Pellets Obtained from Whole Trees Harvested from Plantations, Coppice Forests and Regular Thinnings. *Forests* **2022**, *13*, 502. [CrossRef]
10. Mendonça, H.L.; van Aduard de Macedo-Soares, T.D.L.; Fonseca, M.V.d.A. Working towards a framework based on mission-oriented practices for assessing renewable energy innovation policies. *J. Clean. Prod.* **2018**, *193*, 709–719. [CrossRef]
11. Nunes, L.J.R.; Godina, R.; Matias, J.C.O.; Catalão, J.P.S. Evaluation of the utilization of woodchips as fuel for industrial boilers. *J. Clean. Prod.* **2019**, *223*, 270–277. [CrossRef]
12. Castellano, J.M.; Gómez, M.; Fernández, M.; Esteban, L.S.; Carrasco, J.E. Study on the effects of raw materials composition and pelletization conditions on the quality and properties of pellets obtained from different woody and non woody biomasses. *Fuel* **2015**, *139*, 629–636. [CrossRef]
13. Tumuluru, J.S. Effect of process variables on the density and durability of the pellets made from high moisture corn stover. *Biosyst. Eng.* **2014**, *119*, 44–57. [CrossRef]
14. Stachowicz, P.; Stolarski, M.J. Short rotation woody crops and forest biomass sawdust mixture pellet quality. *Ind. Crops Prod.* **2023**, *197*, 116604. [CrossRef]
15. Stolarski, M.J.; Stachowicz, P.; Dudziec, P. Wood pellet quality depending on dendromass species. *Renew. Energy* **2022**, *199*, 498–508. [CrossRef]
16. Purohit, P.; Chaturvedi, V. Biomass pellets for power generation in India: A techno-economic evaluation. *Environ. Sci. Pollut. Res.* **2018**, *25*, 29614–29632. [CrossRef] [PubMed]
17. Ruiz, D.; San Miguel, G.; Corona, B.; López, F.R.R. LCA of a multifunctional bioenergy chain based on pellet production. *Fuel* **2018**, *215*, 601–611. [CrossRef]
18. Acampora, A.; Civitarese, V.; Sperandio, G.; Rezaei, N. Qualitative Characterization of the Pellet Obtained from Hazelnut and Olive Tree Pruning. *Energies* **2021**, *14*, 4083. [CrossRef]
19. Cardozo, E.; Malmquist, A. Performance comparison between the use of wood and sugarcane bagasse pellets in a Stirling engine micro-CHP system. *Appl. Therm. Eng.* **2019**, *159*, 113945. [CrossRef]
20. Cao, L.; Yuan, X.; Li, H.; Li, C.; Xiao, Z.; Jiang, L.; Huang, B.; Xiao, Z.; Chen, X.; Wang, H.; et al. Complementary effects of torrefaction and co-pelletization: Energy consumption and characteristics of pellets. *Bioresour. Technol.* **2015**, *185*, 254–262. [CrossRef] [PubMed]
21. Hoefnagels, R.; Junginger, M.; Faaij, A. The economic potential of wood pellet production from alternative, low-value wood sources in the southeast of the U.S. *Biomass Bioenergy* **2014**, *71*, 443–454. [CrossRef]
22. Harun, N.Y.; Afzal, M.T. Effect of Particle Size on Mechanical Properties of Pellets Made from Biomass Blends. *Procedia Eng.* **2016**, *148*, 93–99. [CrossRef]
23. Bioenergy Europe Policy Brief: Pellets—A Growing Market. Available online: https://bioenergyeurope.org/wp-content/uploads/2023/12/Pellets_Policy-Brief23.pdf (accessed on 18 March 2024).
24. ENplus Manuale ENplus, Parte 3—Requisiti di qualità del pellet—V 3.0 (ENplus Manual, Part 3—Quality Requirements for Pellets); European Pellet Council (EPC) c/o, Ed. 2015. Available online: https://www.pelletsfuso.com/wp-content/uploads/2021/04/MANUALE-EN-PLUS-1.pdf (accessed on 22 May 2024).
25. Bergström, D.; Israelsson, S.; Öhman, M.; Dahlqvist, S.-A.; Gref, R.; Boman, C.; Wästerlund, I. Effects of raw material particle size distribution on the characteristics of Scots pine sawdust fuel pellets. *Fuel Process. Technol.* **2008**, *89*, 1324–1329. [CrossRef]

26. Ilari, A.; Foppa Pedretti, E.; De Francesco, C.; Duca, D. Pellet Production from Residual Biomass of Greenery Maintenance in a Small-Scale Company to Improve Sustainability. *Resources* **2021**, *10*, 122. [CrossRef]
27. Sgarbossa, A.; Boschiero, M.; Pierobon, F.; Cavalli, R.; Zanetti, M. Comparative Life Cycle Assessment of Bioenergy Production from Different Wood Pellet Supply Chains. *Forests* **2020**, *11*, 1127. [CrossRef]
28. Bacenetti, J.; Bergante, S.; Facciotto, G.; Fiala, M. Woody biofuel production from short rotation coppice in Italy: Environmental-impact assessment of different species and crop management. *Biomass Bioenergy* **2016**, *94*, 209–219. [CrossRef]
29. Rajabi Hamedani, S.; Colantoni, A.; Gallucci, F.; Salerno, M.; Silvestri, C.; Villarini, M. Comparative Energy and Environmental Analysis of Agro-Pellet Production from Orchard Woody Biomass. *Biomass Bioenergy* **2019**, *129*, 105334. [CrossRef]
30. Kylili, A.; Christoforou, E.; Fokaides, P.A. Environmental Evaluation of Biomass Pelleting Using Life Cycle Assessment. *Biomass Bioenergy* **2016**, *84*, 107–117. [CrossRef]
31. Laschi, A.; Marchi, E.; González-García, S. Environmental performance of wood pellets' production through life cycle analysis. *Energy* **2016**, *103*, 469–480. [CrossRef]
32. Monteleone, B.; Chiesa, M.; Marzuoli, R.; Verma, V.K.; Schwarz, M.; Carlon, E.; Schmidl, C.; Ballarin Denti, A. Life cycle analysis of small scale pellet boilers characterized by high efficiency and low emissions. *Appl. Energy* **2015**, *155*, 160–170. [CrossRef]
33. Röder, M.; Whittaker, C.; Thornley, P. How certain are greenhouse gas reductions from bioenergy? Life cycle assessment and uncertainty analysis of wood pellet-to-electricity supply chains from forest residues. *Biomass Bioenergy* **2014**, *79*, 50–63. [CrossRef]
34. McNamee, P.; Adams, P.W.R.; McManus, M.C.; Dooley, B.; Darvell, L.I.; Williams, A.; Jones, J.M. An assessment of the torrefaction of North American pine and life cycle greenhouse gas emissions. *Energy Convers. Manag.* **2016**, *113*, 177–188. [CrossRef]
35. Visser, L.; Hoefnagels, R.; Junginger, M. Wood pellet supply chain costs—A review and cost optimization analysis. *Renew. Sustain. Energy Rev.* **2020**, *118*, 109506. [CrossRef]
36. Pergola, M.; Gialdini, A.; Celano, G.; Basile, M.; Caniani, D.; Cozzi, M.; Gentilesca, T.; Mancini, I.M.; Pastore, V.; Romano, S.; et al. An environmental and economic analysis of the wood-pellet chain: Two case studies in Southern Italy. *Int. J. Life Cycle Assess.* **2018**, *23*, 1675–1684. [CrossRef]
37. Shahrukh, H.; Oyedun, A.O.; Kumar, A.; Ghiasi, B.; Kumar, L.; Sokhansanj, S. Techno-economic assessment of pellets produced from steam pretreated biomass feedstock. *Biomass Bioenergy* **2016**, *87*, 131–143. [CrossRef]
38. Trømborg, E.; Ranta, T.; Schweinle, J.; Solberg, B.; Skjevrak, G.; Tiffany, D.G. Economic sustainability for wood pellets production—A comparative study between Finland, Germany, Norway, Sweden and the US. *Biomass Bioenergy* **2013**, *57*, 68–77. [CrossRef]
39. Wang, Y.; Wang, J.; Zhang, X.; Grushecky, S. Environmental and Economic Assessments and Uncertainties of Multiple Lignocellulosic Biomass Utilization for Bioenergy Products: Case Studies. *Energies* **2020**, *13*, 6277. [CrossRef]
40. Nishiguchi, S.; Tabata, T. Assessment of social, economic, and environmental aspects of woody biomass energy utilization: Direct burning and wood pellets. *Renew. Sustain. Energy Rev.* **2016**, *57*, 1279–1286. [CrossRef]
41. Pa, A.; Bi, X.T.; Sokhansanj, S. Evaluation of wood pellet application for residential heating in British Columbia based on a streamlined life cycle analysis. *Biomass Bioenergy* **2013**, *49*, 109–122. [CrossRef]
42. Boukherroub, T.; LeBel, L.; Lemieux, S. An integrated wood pellet supply chain development: Selecting among feedstock sources and a range of operating scales. *Appl. Energy* **2017**, *198*, 385–400. [CrossRef]
43. Paolotti, L.; Martino, G.; Marchini, A.; Pascolini, R.; Boggia, A. Economic and environmental evaluation of transporting imported pellet: A case study. *Biomass Bioenergy* **2015**, *83*, 340–353. [CrossRef]
44. Pa, A.; Craven, J.S.; Bi, X.T.; Melin, S.; Sokhansanj, S. Environmental footprints of British Columbia wood pellets from a simplified life cycle analysis. *Int. J. Life Cycle Assess.* **2012**, *17*, 220–231. [CrossRef]
45. Civitarese, V.; Sperandio, G.; Acampora, A.; Santangelo, E.; Tomasone, R. Pioppo da SRF per produrre pellet. Caratterizzazione del materiale di 3 e 6 anni (Poplar from SRF to produce pellets. Characterisation of 3- and 6-year-old material). *Sherwood* **2018**.
46. Civitarese, V.; Acampora, A.; Sperandio, G.; Assirelli, A.; Picchio, R. Production of Wood Pellets from Poplar Trees Managed as Coppices with Different Harvesting Cycles. *Energies* **2019**, *12*, 2973. [CrossRef]
47. Civitarese, V.; Acampora, A.; Sperandio, G.; Tomasone, R.; Caracciolo, G.; Gallucci, F.; Carnevale, M.; Assirelli, A. Poplar Wood from SRF for Pellet Production. Characterization of the Raw Materials Derived from 3 and 6 Years Old Trees. In Proceedings of the 27th European Biomass Conference and Exhibition, Lisbon, Portugal, 27–30 May 2019; pp. 299–302.
48. Civitarese, V.; Sperandio, G. Raccolta meccanizzata, aspetti tecnici e produttivi. In *Manuale Tecnico: Processi di Valorizzazione del Cippato Agroforestale*; 2015.
49. Anerud, E.; Krigstin, S.; Routa, J.; Brännström, H.; Arshadi, M.; Helmeste, C.; Bergström, D.; Egnell, G. Dry matter losses during biomass storage. Measures to minimize feedstock degradation. *Renew. Bioenergy Res.* **2019**, *45*.
50. Sperandio, G.; Acampora, A.; Del Giudice, A.; Civitarese, V. Models for the Evaluation of Productivity and Costs of Mechanized Felling on Poplar Short Rotation Coppice in Italy. *Forests* **2021**, *12*, 954. [CrossRef]
51. Costa, C.; Sperandio, G.; Verani, S. Use of multivariate approaches in biomass energy plantation harvesting: Logistics advantages. *Agric. Eng. Int. CIGR J.* **2014**, 70–79.
52. Maesano, M.; Zimbalatti, G.; Scarascia Mugnozza, G.; Macrì, G.; Antonucci, F.; Costa, C.; Sperandio, G.; Proto, A.R. A Three-Step Neural Network Artificial Intelligence Modeling Approach for Time, Productivity and Costs Prediction. *Croat. J. For. Eng.* **2020**, *41*, 35–47. [CrossRef]
53. 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. [CrossRef]

54. Verani, S.; Sperandio, G.; Picchio, R.; Marchi, E.; Costa, C. Sustainability assessment of a self-consumption wood-energy chain on small scale for heat generation in central Italy. *Energies* **2015**, *8*, 5182–5197. [CrossRef]
55. Di Matteo, G.; Nardi, P.; Verani, S.; Sperandio, G. Physiological adaptability of Poplar clones selected for bioenergy purposes under non-irrigated and suboptimal site conditions: A case study in Central Italy. *Biomass Bioenergy* **2015**, *81*, 183–189. [CrossRef]
56. Bascietto, M.; Santangelo, E.; Beni, C. Spatial Variations of Vegetation Index from Remote Sensing Linked to Soil Colloidal Status. *Land* **2021**, *10*, 80. [CrossRef]
57. Sperandio, G.; Pagano, M.; Acampora, A.; Civitarese, V.; Cedrola, C.; Mattei, P.; Tomasone, R. Deficit Irrigation for Efficiency and Water Saving in Poplar Plantations. *Sustainability* **2022**, *14*, 13991. [CrossRef]
58. Brentrup, F.; Kusters, J.; Lammel, J.; Kuhlmann, H. Methods to estimate on-field nitrogen emissions from crop production as an input to LCA studies in the agricultural sector. *Int. J. Life Cycle Assess.* **2000**, *5*, 349–357. [CrossRef]
59. De Klein, C.; Novoa, R.S.A.; Ogle, S.; Smith, K.A.; Rochette, P.; Wirth, T.C.; McConkey, B.; Mosier, A.; Rypdal, K. IPCC guidelines for national greenhouse gas inventories, Volume 4, Chapter 11: N_2O emissions from managed soils, and CO_2 emissions from lime and urea application. In *Technical Report. Technical Report 4-88788-032-4, Intergovernmental Panel on Climate Change*; IPCC: Geneva, Switzerland, 2006.
60. Dijkman, T.J.; Birkved, M.; Hauschild, M.Z. PestLCI 2.0: A second generation model for estimating emissions of pesticides from arable land in LCA. *Int. J. Life Cycle Assess.* **2012**, *17*, 973–986. [CrossRef]
61. Sperandio, G.; Suardi, A.; Acampora, A.; Civitarese, V. Environmental Sustainability of Heat Produced by Poplar Short-Rotation Coppice (SRC) Woody Biomass. *Forests* **2021**, *12*, 878. [CrossRef]
62. Dewar, R.C.; Cannell, M.G.R. Carbon sequestration in the trees, products and soils of forest plantations: An analysis using UK examples. *Tree Physiol.* **1992**, *11*, 49–71. [CrossRef] [PubMed]
63. Yan, M.; Wang, L.; Ren, H.; Zhang, X. Biomass production and carbon sequestration of a short-rotation forest with different poplar clones in northwest China. *Sci. Total Environ.* **2017**, *586*, 1135–1140. [CrossRef]
64. Fang, S.; Xue, J.; Tang, L. Biomass production and carbon sequestration potential in poplar plantations with different management patterns. *J. Environ. Manag.* **2007**, *85*, 672–679. [CrossRef] [PubMed]
65. Garten, C.T.; Wullschleger, S.D.; Classen, A.T. Review and model-based analysis of factors influencing soil carbon sequestration under hybrid poplar. *Biomass Bioenergy* **2011**, *35*, 214–226. [CrossRef]
66. Lerma-Arce, V.; Oliver-Villanueva, J.-V.; Segura-Orenga, G. Influence of raw material composition of Mediterranean pinewood on pellet quality. *Biomass Bioenergy* **2017**, *99*, 90–96. [CrossRef]
67. Terzopoulou, P.; Kamperidou, V.; Lykidis, C. Cypress Wood and Bark Residues Chemical Characterization and Utilization as Fuel Pellets Feedstock. *Forests* **2022**, *13*, 1303. [CrossRef]
68. Thiffault, E.; Barrette, J.; Blanchet, P.; Nguyen, Q.N.; Adjalle, K. Optimizing Quality of Wood Pellets Made of Hardwood Processing Residues. *Forests* **2019**, *10*, 607. [CrossRef]
69. Filbakk, T.; Jirjis, R.; Nurmi, J.; Høibø, O. The effect of bark content on quality parameters of Scots pine (*Pinus sylvestris* L.) pellets. *Biomass Bioenergy* **2011**, *35*, 3342–3349. [CrossRef]
70. Arshadi, M.; Gref, R.; Geladi, P.; Dahlqvist, S.-A.; Lestander, T. The influence of raw material characteristics on the industrial pelletizing process and pellet quality. *Fuel Process. Technol.* **2008**, *89*, 1442–1447. [CrossRef]
71. Monedero, E.; Portero, H.; Lapuerta, M. Pellet blends of poplar and pine sawdust: Effects of material composition, additive, moisture content and compression die on pellet quality. *Fuel Process. Technol.* **2015**, *132*, 15–23. [CrossRef]
72. Whittaker, C.; Shield, I. Factors affecting wood, energy grass and straw pellet durability—A review. *Renew. Sustain. Energy Rev.* **2017**, *71*, 1–11. [CrossRef]
73. Labbé, R.; Paczkowski, S.; Knappe, V.; Russ, M.; Wöhler, M.; Pelz, S. Effect of feedstock particle size distribution and feedstock moisture content on pellet production efficiency, pellet quality, transport and combustion emissions. *Fuel* **2020**, *263*, 116662. [CrossRef]
74. Yılmaz, H.; Çanakcı, M.; Topakcı, M.; Karayel, D. The effect of raw material moisture and particle size on agri-pellet production parameters and physical properties: A case study for greenhouse melon residues. *Biomass Bioenergy* **2021**, *150*, 106125. [CrossRef]
75. Anukam, A.; Berghel, J.; Henrikson, G.; Frodeson, S.; Ståhl, M. A review of the mechanism of bonding in densified biomass pellets. *Renew. Sustain. Energy Rev.* **2021**, *148*, 111249. [CrossRef]
76. Zhao, H.-X.; Zhou, F.-S.; Evelina, L.M.A.; Liu, J.-L.; Zhou, Y. A review on the industrial solid waste application in pelletizing additives: Composition, mechanism and process characteristics. *J. Hazard. Mater.* **2022**, *423*, 127056. [CrossRef]
77. Stelte, W.; Holm, J.K.; Sanadi, A.R.; Barsberg, S.; Ahrenfeldt, J.; Henriksen, U.B. Fuel pellets from biomass: The importance of the pelletizing pressure and its dependency on the processing conditions. *Fuel* **2011**, *90*, 3285–3290. [CrossRef]
78. Miranda, T.; Montero, I.; Sepúlveda, F.; Arranz, J.; Rojas, C.; Nogales, S. A Review of Pellets from Different Sources. *Materials* **2015**, *8*, 1413–1427. [CrossRef] [PubMed]
79. Mani, S.; Sokhansanj, S.; Bi, X.; Turhollow, A. Economics of producing fuel pellets from biomass. *Appl. Eng. Agric.* **2006**, *22*, 421–426. [CrossRef]
80. Krokida, M.K.; Maroulis, Z.B.; Kremalis, C. Process design of rotary dryers for olive cake. *Dry. Technol.* **2002**, *20*, 771–788. [CrossRef]
81. Fantozzi, F.; Buratti, C. Life cycle assessment of biomass chains: Wood pellet from short rotation coppice using data measured on a real plant. *Biomass Bioenergy* **2010**, *34*, 1796–1804. [CrossRef]

82. Miyata, E.S. *Determining Fixed and Operating Costs of Logging Equipment*; General Technical Report NC-55; Department of Agriculture, Forest Service, North Central Forest Experiment Station: St. Paul, MN, USA, 1980.
83. MISE. *Update of the Rate to Be Applied for Transactions of Discounting and Revaluation for the Purposes of Granting and Disbursement of Facilities for Enterprises*; 2022; p. 136.
84. Hartini, S.; Wicaksono, P.; Purbasari, A.; Fatliana, A.N.; Handayani, N.U.; Rashif, M.N. Eco-efficiency index of the recycling process of fuel husks into briquettes in Tofu SMEs using life cycle assessment. *IOP Conf. Ser. Earth Environ. Sci.* **2023**, *1268*, 012073. [CrossRef]
85. GSE Gestore Servizi Energetici. EU ETS Rapporto Sulle aste di Quote Europee di Emissioni—III Trimestre 2023. Available online: https://www.gse.it (accessed on 13 December 2023).
86. Kabir, M.R.; Kumar, A. Comparison of the energy and environmental performances of nine biomass/coal co-firing pathways. *Bioresour. Technol.* **2012**, *124*, 394–405. [CrossRef] [PubMed]
87. Monarca, D.; Cecchini, M.; Colantoni, A. Plant for the production of chips and pellet: Technical and economic aspects of an case study in the central Italy. In Proceedings of the Computational Science and Its Applications-ICCSA 2011: International Conference, Santander, Spain, 20–23 June 2011; Proceedings, Part IV 11. Springer: Berlin/Heidelberg, Germany, 2011; pp. 296–306.
88. Sikkema, R.; Steiner, M.; Junginger, M.; Hiegl, W.; Hansen, M.T.; Faaij, A. The European wood pellet markets: Current status and prospects for 2020. *Biofuels Bioprod. Biorefining* **2011**, *5*, 250–278. [CrossRef]
89. Bidini, G.; Cotana, F.; Buratti, C.; Fantozzi, F.; Barbanera, M. Analisi del ciclo di vita del pellet da SRF attraverso misure dirette dei consumi energetici (Life cycle analysis of pellets from SRF through direct measurements of energy consumption). In Proceedings of the Congresso Nazionale ATI–Perugia, Perugia, Italy, 12–15 September 2006; Volume 12, p. 15.
90. Magnani, F.; Cantoni, L. Biomasse forestali e produzione di energia: Un caso di studio in Emilia-Romagna. *Forest* **2005**, *2*, 7–11. [CrossRef]
91. Frau, C.; Loria, E.; Madeddu, A.; Fadda, M. *Studio Tecnico-Economico Sulla Applicabilità del Processo di Co-Gassificazione di Carbone e Biomasse con Produzione di Energia Elettrica nel Preesistente Impianto di Gassificazione Sotacarbo da 5 MWt*; Accordo di Programma Ministero dello Sviluppo Economico—ENEA: Roma, Italy, 2012.