

Carbon Footprint of Thermal Energy Production from Poplar Short-Rotation Coppice Plantations [†]

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Abstract: The use of agroforestry biomass represents a relevant aspect in the world debate on the issue of reducing climate-altering gases in the atmosphere. One of the possible sources of wood biomass production is represented by poplar SRC plantations. In the present work, the Global Warming Potential (GWP) of the entire supply chain of four different cutting shifts (2, 3, 4, and 5 years) have been evaluated according to the IPCC method. In relation to the rotation cycle, four biomass harvesting systems were considered with a different level of mechanization. It was considered that the biomass produced by the plantations was used in a biomass plant for heating a public building. The environmental impact of 1 GJ of heat energy produced by the various forest rotation plants was assessed considering the entire life cycle, from the field stage to the thermal energy production. The results were compared with the production of the same quantity of thermal energy using a diesel boiler. The comparison between the two systems has shown that the production and use of biomass to generate thermal energy can reduce the Global Warming Potential by more than 70% compared to the use of fossil fuels.

Keywords: biomass; poplar; SRC; thermal energy; LCA; GWP

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1. Introduction

The use of woody biomass as a source of thermal and electrical energy production represents a much-debated aspect in terms of energy supply obtainable from renewable sources, with a view to progressive replacement of fossil sources and reduction of CO₂ emissions and atmospheric pollution. Globally, bioenergy covers about 9.5% of the total primary energy supply, corresponding to 70% of renewable energy used [1]. Bioenergy consumption is expected to grow to 30% of renewables, due to its significant use in heat generation and the transport sector [2].

Many studies have shown that the use of bioenergy can lead to a significant environmental improvement over fossil fuels [3,4] and that the wider use of biofuels will lead to a substantial reduction of greenhouse gas emissions, eutrophication, air pollution, acidification, damage to human health and depletion of the ozone layer [5].

There are different types of biomass that can be used to produce various final forms of bioenergy (thermal, electrical, liquid fuels and biogas). Among them, poplar short-rotation coppice plantations can play an interesting role in small-scale energy chains in rural energy districts for thermal energy production. In this context, it is very important to evaluate the sustainability not only in economic but also environmental terms of the use of bioenergy.

This study evaluates the carbon footprint generated in a small-scale wood-energy supply chain based on poplar short-rotation coppice plantations using the LCA

method [6,7]. Various logistic scenarios for harvesting operation and cutting cycles are analyzed. The biomass obtained is used to produce thermal energy in a biomass plant. The carbon footprint is compared with that of a conventional diesel-based boiler to produce the same thermal energy.

2. Material and Methods

2.1. Study Area, Poplar SRC Plantations and Harvesting Systems

The experimental field is located to North-East of Rome, within the farm of CREA-Research Centre for Engineering and Agro-Food Processing of Monterotondo, Italy (42°6'2.63" N; 12°37'37.36" E). The SRC poplar plantation of reference was planted in 2005 on 4.5 ha, with a planting density of 7140 trees ha⁻¹. Three poplar clones were used: AF2 (*Populus × canadensis* Moench), AF6 (*Populus nigra* L. × *Populus × generosa* A. Henry) and Monviso (*Populus × generosa* A. Henry × *Populus nigra* L.) [8]. For the purposes of this work, two periods of productive cycle of the plantation were considered: 16 and 15 years. In the first one, 2- and 4-year cutting shifts were considered; in the second one, instead, 3- and 5-year cutting shifts. For productive cycles of 2 and 3 years, two biomass harvesting systems were considered: A two-steps tractor-based harvesting system (TBHS) and forage-based harvesting system (FBHS). The TBHS uses different equipment to perform the tree felling, then the extraction of whole trees and subsequently, the chipping at the landing site. The FBHS is a single step-harvesting system that produce the fresh woodchip directly in the field where the biomass is discharged in trailer side-by-side the harvester and transported to the landing site for storage [9].

Two options were also considered for shifts of 4 and 5 years: the first one involves manual felling of the trees with a chainsaw, extraction of whole trees with a tractor equipped with a winch and subsequent chipping with a forest chipper at the landing site; the second one involves the use of a feller-buncher for felling, a skidder with grapple for trees extraction and a chipper to produce woodchip to be used in the biomass plant. From the combination of the cutting cycles and the types of mechanization adopted for the collection of the biomass, eight case studies were considered: 2y_TBHS; 2y_FBHS; 3y_TBHS; 3y_FBHS; 4y_CSHS; 4y_SBHS; 5y_CSHS; 5y_SBHS.

2.2. Biomass and Diesel Boilers

The proposed environmental assessment model referred to the entire life cycle of the poplar plantation and the biomass power plant installed within the CREA farm. The biomass production energy system in the farm and its use to produce thermal energy, was compared with a heating system of equivalent energy production, however, powered by fossil fuels (diesel).

The biomass plant, with a nominal power of 350 thermal kW, was used to heat the research Centre buildings, having a volume to be heated of about 10,000 m³. The heating period was 130 days per year, calculating an average annual biomass supply of around 290 Mg (water content of 35%). Carbon footprint assessment generated by the thermal energy production of the biomass boiler was compared with that of the diesel boiler. In Table 1, the main parameters considered for two boilers in comparison are shown.

Table 1. Main parameters considered to evaluate the annual biomass or diesel consumption in the two boilers compared.

	Boilers	
	Biomass	Diesel
Building volume (m ³)	9450	9450
Operating period (days year ⁻¹)	130	130
Heating period (h year ⁻¹)	3120	1560
Rated thermal power (kWt)	350	315
Thermal efficiency of the boiler (%)	81%	90%
Lower heating value (LHV) (kWh kg ⁻¹)	3.11	11.86
Water content (%)	35.00%	
Average biomass/diesel consumption (Mg year ⁻¹)	290.1	41.4

2.3. Environmental Analysis

The study assessed the amount of greenhouse gasses emitted by Poplar short and medium rotation forestry to produce thermal energy according to the LCA methodology. LCA is an in-depth “cradle-to-grave” analysis of the environmental impact of products or processes, and for this study the impact category considered was the 100 year time horizon global warming potential (GWP) based on the IPCC 2007 [10]. For the eight different scenarios considered in the study, the technical elements and the inputs used in the life cycle of the poplar plantations was considered. For each production cycle, all the cultivation operations were considered: (1) preparation of the field and planting in the first year (deep scarification, light plowing, fertilization, chemical weeding, irrigation, hoeing and harrowing; (2) annual management (hoeing, harrowing); (3) harvesting, distinguishing the different options considered in the years; (4) restoration of the soil by stumps grinding at the end of the productive cycle.

The CO₂ equivalent emitted per unit of thermal energy produced (1 GJ) downstream of each scenario were compared. The system considered the impact generated to produce 1 GJ of equivalent thermal energy from the agricultural, transport and transformation processes along the life cycle of the poplar plantations, with reference to the cutting cycle considered. The functional unit was chosen to guarantee the comparison of the results obtained with other energy production system such as that from fossil sources. In the case of small-scale chain, the impact deriving from the production of 1 GJ of thermal energy produced by poplar woodchip in the biomass boiler was compared with 1 GJ produced by a diesel boiler. The boundaries of the system, that is the process units included in the LCA study, involved all the agricultural phases, the subsequent transformation processes, and transport.

During the Inventory analysis, all inputs and outputs, in the form of primary and secondary data, were collected and analyzed. Primary data obtained directly from years of experimental tests on the cultivation of SRC poplar were used for the preparation of the inventory. The secondary data was obtained by Ecoinvent 3 dataset of SimaPro v.8.0.1 code (PRé Sustainability, The Netherlands). For each mechanical operation, the type of machine and equipment used, the engine power, the hours of work performed, the consumption of fuel and lubricant were considered to assess direct emissions of exhausted gases generated by the tractors, and the indirect emissions generated by the materials used for the constructions of the agricultural machine used, according to the data obtained directly in the field [11]. Emissions generated by fertilizers and herbicides use were calculated based on data from the literature and scientific software. EFE-So software (v. 2.0.0.6; Fusi and Fusi) was used to calculate the emissions due to the application of fertilizers according to [12] model. The CO₂ emissions from urea fertilization were calculated according to [13]. Herbicide emissions to air, surface water, and groundwater were assessed by PestLCI 2.0 model [14]. A dry matter (D.M.) loss of 7% [15] has been considered for wood harvesting systems that provide for the extraction of the whole plant,

drying at the landing site and chipping with a forest chipper once a biomass moisture content of 35% has been reached. The biomass storage was considered in the form of stacked and branchless trees. For these harvesting systems, 14.3 Mg per hectare per year of woodchip was produced. On the other hand, FBHS provides the storage of fresh woodchip in piles (53% of moisture content) with a D.M. loss of 22% [15]. For the latter harvesting system, the amount of woodchip obtainable from one hectare of poplar was 12 Mg⁻¹ ha⁻¹ year⁻¹ (35% M.C.) after storage. The biomass production at farm gate was assumed for all the cases examined to be equal to 10 Mg of D.M. per hectare, per year.

After considering all the agricultural phases, impacts, and resources used (initially referred to a hectare of land) was compared to 1 GJ of energy produced. This was possible by transforming the total production (Mg ha⁻¹) into energy (GJ ha⁻¹) considering a low calorific value (LHV) of poplar wood equal to 11.2 MJ per kg of woodchip, according to the Hartmann formula. The total inputs and emissions referring to one hectare then were divided by the production per hectare expressed in equivalent energy. In this way it was possible to obtain the share of each agricultural phase to be attributed to 1 GJ of biomass produced. Average annual emissions and inputs were increased by the number of inputs used and emissions generated in the years of planting, cutting, and explanting, divided by the presumed life years of the crop (15 and 16 years). Reference was also made to an average annual production, calculated considering the yields obtained by poplar plantation during the year of the life cycle.

3. Results and Discussion

The various scenarios examined did not reveal significant differences. From the first observations it can be said that more frequent harvests contribute to increasing the number of agricultural practices adopted. This aspect is evident above all in the case of the SRC with a two-year cutting cycle (Figure 1a), where the fertilization represented 49% of the overall emissions of the woodchip production. In particular, the nitrogen-based fertilization (over 1 Mg of N in 16 years) contributed for the 33% of the total emissions of the woodchip production phase (34.6 kg CO₂eq per Mg of woodchip at 35% of M.C.). In the five-year cut, the lower contribution of nitrogen inputs (about 0.4 Mg of N in 15 years), distributed only in the cutting years, led to a reduction of emissions attributed to the fertilizers compared to the two-year one of almost 60%. Generally, by analyzing the four different production cycles, slightly higher emissions occur in relation to the application of a higher level of mechanization.

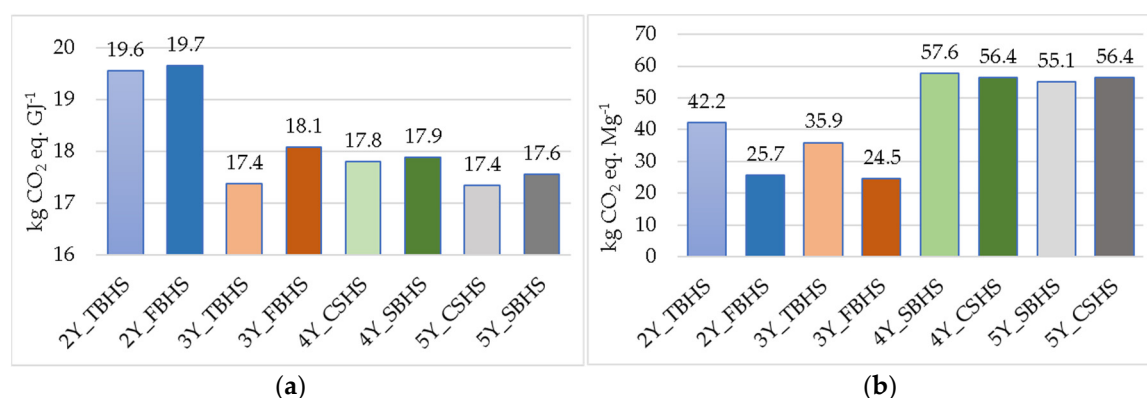


Figure 1. kg CO₂ eq emitted per GJ of thermal energy produced (a), and kg CO₂ eq emitted per MgD.M. of woodchip produced by the various harvesting logistics considering the storage losses, and excluding the emissions of all the other agricultural practices (b). TBHS—Tractor-based harvesting system; FBHS—Forage-based harvesting system; CSHS—Chainsaw-based harvesting system; SBHS—Shear head-based harvesting system (IPCC GWP 100a).

A more marked difference is found between the two-year production cycles (19.6–19.7 kg CO₂ GJ⁻¹), which is more impactful than all the others (17.4–18.1 kg CO₂ GJ⁻¹).

According to our study, the highest CO₂ emissions were due to the biennial poplar chain. In fact, for each GJ of thermal energy produced by the combustion of the biennial poplar woodchip a maximum of 19.7 kg CO₂eq was generated (Figure 1a). A comparison of the emissions generated by the two two-year poplar supply chains studied showed no substantial differences. In fact, the difference in emissions was less than 1%. This minimal difference that can be seen in Figure 1a is essentially due to two aspects which, in the biennial poplar supply chains, are compensated: on the one hand, the greater storage losses of fresh woodchips which lead to greater emissions from the 2Y_FBHS supply chain, and on the other hand the higher emissions of the 2Y_TBHS system harvest due to the higher number of agricultural phases that a two-stage harvest requires.

In fact, the CO₂ emissions generated by the FBHS harvesting system reported in Figure 1b are due for 73% from the field harvesting phase of the forage harvester (18.8 kg CO₂eq MgD.M.⁻¹) and for 27% from the movement of woodchip for the formation of piles (6.9 kg CO₂eq MgD.M.⁻¹). In the TBHS system, on the other hand, 78.2% of emissions are due to chipping carried out with a forest chipper performed at the landing site (33 kg CO₂eq MgD.M.⁻¹), 14.4% from the transport of plants from the field to the landing site by tractor with winch (6.1 kg CO₂eq MgD.M.⁻¹) and the remaining 7.4% of emissions are due to the cutting of plants with TBHS (3.1 kg CO₂eq MgD.M.⁻¹). Considering that in the FBHS scenario much higher D.M. losses were considered than in the TBHS scenario, and this is due to the different storage system used, it is plausible to believe that by optimizing the storage phase of fresh woodchip, with the aim of reducing losses, the FBHS system could show even lower emissions than the TBHS system. This aspect can also be observed in the case of the triennial poplar which shares the same logistic harvesting with the biennial, although here the differences were slightly more marked (4%). In general, the cycles above the second showed lower emissions than the biennial. The emissions measured for the four- and five-year cycles share the same collection method based on the shear head-based harvesting system (SBHS) and chainsaw-based harvesting system (CSHS). Figure 1a shows very similar amounts of CO₂ emissions per GJ produced by the two supply chains (an average of 17.6 kg CO₂eq GJ⁻¹). The harvesting in the four-year and five-year cycles resulted in an average of 43% and 124% more CO₂ emissions when compared with the TBHS and FBHS systems, respectively, both used in the two-year and three-year cycles (Figure 1b). The results of the study showed that from an environmental point of view the emissions of greenhouse gases produced by the wood energy supply chains analyzed ranged from a maximum of 19.7 (biennial supply chain) to a minimum of 17.4 kg CO₂eq per GJ of thermal energy produced by the biomass boiler considered. In Figure 2, it can be seen how the transition from a diesel boiler to a biomass fueled biennial poplar woodchip (which was the least efficient compared to the other scenarios analyzed) allows a 77% reduction in greenhouse gas emissions.

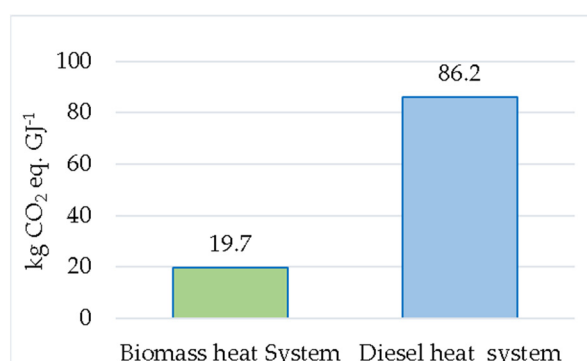


Figure 2. Comparison of the emissions generated by a biomass boiler fueled with woodchip produced by the biennial poplar supply chain which was less efficient and a diesel fueled boiler, for the production of 1 GJ of thermal energy.

4. Conclusions

The dependence on fossil fuels for energy production results in significant greenhouse gas (GHG) emissions and the progressive depletion of non-renewable resources. The interest in poplar as an energy crop is due to its potential to produce energy, heat and/or electricity, reducing the consumption of fossil fuels and the production of GHG. In this context a study on the carbon footprint was carried out by analyzing different logistical scenarios regarding different harvesting and cutting cycles in order to evaluate the environmental sustainability of a small wood-energy supply chain based on poplar SRC.

Among all the scenarios analyzed, the production of thermal energy generated by three-year and five-year poplar woodchip, which used the TBHS and CSHS harvesting system, were more sustainable than the other production chains, even if the most marked difference can only be observed between the biennial supply chains and those of the other cutting cycles.

The most sustainable harvesting method is the one that involves fewer production steps. For this reason, the direct chipping of the plants in the field (FBHS) was more sustainable than the two-phase harvesting (TBHS, CSHS and SBHS), although involved greater losses of D.M. during the storage phase. The production of thermal energy generated by a biomass boiler compared to a fossil fuel one can allow a reduction of greenhouse gas emissions by 77%. This result in reality can be further improved if we consider the CO₂ stored in the soil in the form of SOC at the end of SRF life cycle and that is the key point that should be analyzed in more depth and included in future study.

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