SUPPLEMENTARY MATERIAL

Woodchips from Forest Residues as a Sustainable and Circular Biofuel for Electricity Production: Evidence from an Environmental Life Cycle Assessment

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Additional information on modelling, assumptions, and calculation

UPSTREAM PHASE

Primary data regarding the forest operations were collected within the ARCADIA project activities, referring to a specific forest worksite dedicated to the production of class A woodchips as the main product of the process and class B woodchips as a by-product. Primary data regarding fossil fuels consumption in the machinery and related emissions were therefore directly collected as referred to the total volume of wood processed in this specific forest worksite. These data (Table 1) were then allocated on a volume basis to estimate the quantity of inputs (and related environmental loads) associated with the production of 1 ton class B woodchips. This allocation was based on primary data (available from the ARCADIA project) showing that branches, tops and residual parts represent the 8% in volume of the total wood intended for felling, a sawlogs-to-woodchips conversion factor equal to 2.75 m^3/m^3 and a bulk density equal to 300 kg/m^3. Then, the inputs to the system were calculated considering the woodchips required to generate 1 kWh electricity (0.8415 kg).

Table S1. Primary data collected within the ARCADIA project (referred to 1 m^3 wood processed).

	UPSTREAM		
Forest machinery transportation	Diesel	1.66E-03	kg
Felling	Petrol	2.20E-02	kg
	Lubricating oil	7.52E-03	kg
Extraction	Diesel	1.04E-01	kg
Delimbing and cutting	Petrol	6.89E-02	kg
	Lubricating oil	3.17E-03	kg
Loading	Diesel	1.30E+00	kg
Chipping	Diesel	1.02E+00	kg
CO_2 emissions from forest worksite *	-	7.42E+00	$kgCO_2eq$

* calculated based on the IPCC methodology [1] and the fuels consumption data

CORE PHASE

Energy conversion process, including the other auxiliary operational inputs, fuel preparation processes at plant, maintenance activities and core waste management, was modelled through background data of the ecoinvent 3.9 database [2]. In particular, the ecoinvent dataset *"Electricity,*

high voltage {IT}| heat and power co-generation, wood chips, 6667 kW", was used as the basis for the modelling.

According to this assumption, the CHP plant is considered as equipped with:

- A "heat and power co-generation unit, organic Rankine cycle, 1000 kW electrical", dimensioned to be connected to a biomass burning boiler with a capacity of 5000 kWth producing circa 1000 kWel. It has lifetime of 20 years and a lifetime capacity of 175,200,000 kWh;
- A "furnace, wood chips, with silo, 5000 kW", i.e. a wood chips furnace including a silo used for district heating networks, with a capacity of 5000 kW, a lifetime capacity of 876,000,000 kWh and a lifetime of 20 years;
- an electrostatic precipitator for particulate matter (PM) emission reduction, i.e. a dust collector, for industrial use with an air flow capacity of 1100 litres per second and a lifetime of 20 years.

All these processes include the materials used for the fabrication of the unit, energy required for the construction and the decommission of the unit. The amount associated to 1 kWh of net electricity generated are, therefore, the secondary data from the used ecoinvent dataset.

The Lower Heating Value (LHV) of the used woodchips was considered equal to 18.9 MJ/kg (dry mass). The literature report quite a big scattering of values for this parameter, since it depends on different factors, such as the wood species, the moisture content of woodchips, etc. Anyway, the assumed value is in line with specific studies that determined that the moisture a calorific value from 18.4 to 19.6 MJ/kg [3] and also with previous similar LCA [LCA4], that adopted exactly the same value (lower heating value on dry mass is 18.9 MJ/kg)

INPUT AND OUTPUT FLOWS OF THE SYSTEM

The fuel input to the system was 0.8415 kg woodchips with a Lower Heating Value (LHV) equal to 18.9 MJ/kg (dry mass). Consequently, the energy input was equal to 15.9 MJ. Moreover, an output of 0.144 kWh electricity per MJ heat produced was assumed, according to the ecoinvent dataset and based on expert judgement and on the share of heat from wood on the market for heat, district or industrial, other than natural gas. The overall electrical efficiency, calculated as the ratio of electric power output to the thermal power input to the system, was equal to 22.6%. This data is quite in line with market data for biomass-fired ORC cogeneration units declared by ORC manufacturers [4,5] and values presented in previous literature [6].

Mass and energy flows for the studied system are summarized in Figure S1.

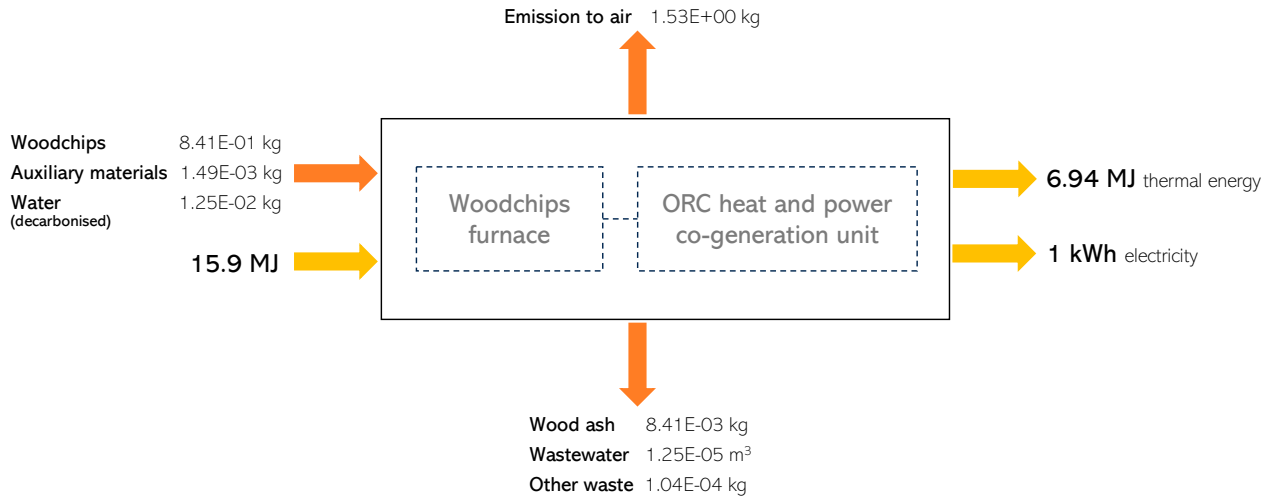


Figure S1. Mass and energy flows for the studied system.

Additional results

Table S2. Carachterization—Case study.

Impact category	Unit	Case study results
Carcinogens	kg C_2H_3Cl eq	2,82E-03
Non-carcinogens	kg C_2H_3Cl eq	3,33E-02
Respiratory inorganics	kg $PM_{2.5}$ eq	2,90E-04
Ionizing radiation	Bq C-14 eq	3,71E-02
Ozone layer depletion	kg CFC-11 eq	5,14E-10
Respiratory organics	kg C_2H_4 eq	7,45E-05
Aquatic ecotoxicity	kg TEG water	2,23E+01
Terrestrial ecotoxicity	kg TEG soil	4,36E+01
Terrestrial acid/nutri	kg SO_2 eq	1,13E-02
Land occupation	m2org.arable	9,65E-04
Aquatic acidification	kg SO_2 eq	1,50E-03
Aquatic eutrophication	kg PO_4 P-lim	1,14E-04
Global warming	kg CO_2 eq	2,94E-02
Non-renewable energy	MJ primary	4,28E-01
Mineral extraction	MJ surplus	2,35E-04

Table S3. Carachterization—Sensitivity analysis.

Impact category	Unit	Alternative scenario (efficiency 27.8 %)
Carcinogens	kg C_2H_3Cl eq	2.49E-03
Non-carcinogens	kg C_2H_3Cl eq	2.73E-02
Respiratory inorganics	kg $PM_{2.5}$ eq	2.41E-04
Ionizing radiation	Bq C-14 eq	4.59E-02
Ozone layer depletion	kg CFC-11 eq	1.01E-08
Respiratory organics	kg C_2H_4 eq	6.42E-05
Aquatic ecotoxicity	kg TEG water	1.83E+01
Terrestrial ecotoxicity	kg TEG soil	3.55E+01
Terrestrial acid/nutri	kg SO_2 eq	9.26E-03
Land occupation	m2org.arable	9.08E-04
Aquatic acidification	kg SO_2 eq	1.23E-03
Aquatic eutrophication	kg PO_4 P-lim	9.38E-05
Global warming	kg CO_2 eq	2.73E-02
Non-renewable energy	MJ primary	3.91E-01
Mineral extraction	MJ surplus	1.04E-03

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