Heat and cold production for winemaking using pruning residues: environmental impact assessment

Jacopo Bacenetti

Department of Environmental and Policy Science, Università degli Studi di Milano, Milan, 20133, Italy.

E-mail: jacopo.bacenetti@unimi.it

Abstract

In grape production, managing the pruning residues is an issue due to economic (low value and poor market demand) and phytosanitary reasons. Energetic valorisation is an option but up to now, no attention has been paid on the possibility of valorising this biomass for the contextual generation of heat and cold to supply the requirement of winemaking. In this study, three scenarios are compared using the Life Cycle Assessment approach. In the Baseline Scenario, the pruning residues are left on the soil, in the Alternative Scenario 1 they are collected and used to produced heat and cold, while in the Alternative Scenario 2 only pruning residues needed to supply heat to the winery are collected. The environmental results are not univocal and the identification of the best scenario depends on the considered impact category. Alternative Scenario 1 involves environmental benefits for impact categories such as climate change, ozone depletion, acidification and freshwater eutrophication due to the avoided heat production from natural gas and to the avoided electricity consumption for cooling. The energetic valorisation of residues reduces (from 1.6 to 9.5 times) the environmental impact for the impact categories not affected by the emissions from wood combustion; for these impact categories, the impact increases from 4% to 38 times. Pollutants control devices should be considered in new installations while specific subsidies for this kind of investment should be foreseen by policymakers.

Keywords

Life Cycle Assessment, agricultural by-products, biomass, renewable energy.

1. Introduction

Over the years, the concerns about the environmental impact related to human activities (Kampa and Castanas, 2008; Parolini et al., 2018) and food production systems (Van der Werf and Petit, 2002) have grown dramatically (Tilman, 1999). At the same time, the attention to possible environmental mitigation strategies is rising. Among the strategies to be implemented in the agro-food and agro-energy sectors, key roles are played by increasing crop productivity (Edgerton, 2009; Foley et al., 2011), reducing losses during storage, post-harvest and processing, increasing the shelf-life of food products (Sala et al., 2017), substituting fossil energy sources with renewable ones (Ferreira et al., 2014) and, finally, properly exploiting the agricultural (De Menna et al., 2018) and agro-food (Bacenetti et al., 2015) by-products and wastes (Mirabella et al., 2014;). This study focuses on this last point, which is the energetic valorisation of pruning residues from grapevine cultivation.

Concerning renewable energy sources, the EU set in 2014 a target to increase the European share of renewable energy to at least 27% by 2030 (Knopf et al., 2015). Thanks to this legislative framework, of the global total installed capacity of renewable energy in 2012 (1440 GW), about 22% was located in the European Union (Cucchiella et al., 2018). In this context, generating renewable energy from the valorisation of agricultural and agro-food by-products could be an effective solution. In the last years, several studies have investigated the possible recovery of energy and nutrient of organic by-products and wastes through anaerobic digestion and biogas production (Poschl et al., 2014; Bacenetti et al., 2016). Strong attention has been paid also on the renewable energy production from woody biomass, but with focus on the exploitation of biomass from forestry (Schmidt et al., 2010; Kanematsu et al., 2017) or from dedicated plantations (Dias et al., 2017; Gonzalez Garcia and Bacenetti, 2019). However, agricultural woody residues are available in massive quantities and provide a considerable potential for energy production (Yang and Chen, 2014; Boschiero et al., 2015). The valorisation of agricultural biomass for renewable energy production can also be considered as an extra income source (Hendricks et al., 2016). Nevertheless, in grape production, the management of pruning residues is often problematic due to economic and phytosanitary reasons. Although considerable amounts of pruning residues are available in the different wine districts and this biomass is spread on a large area, its harvesting has a high cost due to orographic characteristics of the vineyards and to the low economic value and poor market demand. Consequently, pruning residues are usually collected outside the vineyards to be burnt or chopped and left in the inter-rows using a shredder or a mulcher coupled with a tractor. However, this second solution is not optimal, because it involves phytosanitary concerns related to the possible overwintering of pests and pathogens from pruning residues left on field. Therefore, valorising pruning residues of grapevine can have also an additional benefit. However, it is feasible only if the produced energy is fully exploited and locally utilised (if possible, directly from the wine producers) (Picchi et al., 2013).

In the last years, several studies focused on the energetic valorisation of pruning residues for energy purposes. Carone et al. (2011) and Zanetti et al. (2017) evaluated the quality of pellet from pruning residues of olive and vineyard, respectively. Boschiero et al. (2016) assessed the environmental performance related to electricity production in a Combine Heat and Power (CHP) plant in Northern Italy, while Amirante et al. (2017) studied a tri-generation plant fed with pruning residues from olive. García-Maraver et al. (2012) quantified the heat and electricity potential from olive residues in Andalusia. Specifically about vineyard, Spinelli et al. (2010 and 2014) studied different harvesting systems for pruning residues to be used for energy purposes and considered the energetic valorisation as a feasible alternative solution to field burning. Finally, Picchi et al. (2013) evaluated pollution emissions of the combustion of vineyard pruning residues in domestic boilers. Although focused on pruning residues deriving from different cultivations (e.g., grapevine, olive, orchards) and different geographical contexts, the reviewed studies highlight how the best solutions for energetic valorisation depend on site-specific characteristics such as demand and price of heat and electricity, logistics issues (e.g., road availability and conditions, distance from cities) and technological aspects (e.g., availability of devices with up-scalable size, presence of technical competences for the management and monitoring of the different devices). To select the best strategies for bioenergy production, the analytic evaluation of their environmental performances is needed.

Furthermore, up to now, no studies have been carried out on the possibility of valorising the pruning residues for the contextual generation of heat and cold for the supply of the energy requirements of the agro-food industry. In this context, this study aims to evaluate the environmental performances related to the valorisation of pruning residues to produce heat or heat and cold to be used during winemaking, by means of a biomass boiler and an absorption chiller. To this purpose, the Life Cycle Assessment approach is applied, and three different management scenarios of pruning residues are evaluated. The main novelty of this study is the quantification of the environmental benefits and drawbacks related to the valorisation of pruning residues for heat production using a biomass boiler and for cold generation using an absorption chiller. The achieved results could be useful to identify the best management solutions for this biomass.

2. Material and Methods

2.1 Description of the management systems

Three different management systems of pruning residues were considered. In the first one, (Baseline Scenario - BS), the residues are managed traditionally, thus chopped using a multi-purpose mulcher with interchangeable knives and left in the inter-rows to be incorporated into the soil using a disc plough. In BS, no energetic valorisation of pruning residues occurs and, consequently, the heat and cold requirements of the winery are fully supplied with fossil fuels. More in details, a boiler fed with natural gas and an electric chiller, are used to satisfy the heat and cold demand, respectively.

In the Alternative Scenario 1 (AS1), the field operations include chipping and collection of the pruning residues using a picker up-shredder as well as the transport of the produced wood chip to the winery. The transport is performed (distance 3 km) using a farm trailer coupled with a tractor. The wood chip is burnt in a biomass boiler to produce heat that is used in part to supply the thermal energy requirement of the winery and in part to feed an adsorption chiller. Both heat and cold are used at the winery during the winemaking process. Among the different solutions for the energetic valorisation of pruning residues, a biomass boiler together with an adsorption chiller result the only option that couples producing cold and heat and, consequently, results particularly suitable for the winemaking process (Dutilh and Kramer, 2000; Christ and Burritt, 2013).

More in details, in AS1:

- the heat that in BS is produced by natural gas is substituted by the one produced with the biomass boiler. This boiler has a nominal thermal power of 150 kW, is fed by an automatic feeding system constituted by an auger and can operate at partial load. The combustion process is monitored and optimised by a lambda probe. Ashes are automatically removed by an agitator and discharged in an ash container integrated in the boiler base;
- the "cold demand" is satisfied by the adsorption chiller instead of an electric refrigeration unit. The adsorption chiller is a refrigerator that uses the heat produced by the boiler (fed with the wood chips got from the chipping of pruning residues) to provide the energy needed to drive the cooling process. In a low-pressure system, an absorption fluid is evaporated, removing the heat. The heat source is needed to regenerate the absorption solution.

In the Alternative Scenario 2 (AS2), the pruning residues are collected as in AS1 but the energetic valorisation differs, since only the heat produced from the combustion of chips wood in a biomass boiler is considered. As in AS1, the produced heat substitutes the thermal energy that is generated using natural gas in BS but, differently from AS1, the "cold demand" is satisfied using a traditional refrigeration unit that consumes electricity of the national grid.

Among the thermochemical solutions to valorise energetically the pruning residues, combustion has been selected because, respect to gasification and pyrolysis, it is cheaper and requires devices with low needs of maintenance and technical competences (Fiala, 2012; Fournel et al, 2015). The solutions evaluated in this study should be implemented in wineries where the main aim remains the winemaking and not the energy production. For this reason, the solutions that require specific technical competences and/or dedicate to electricity production were not considered. A scenario producing only electricity was not considered because it is not technically feasible considering that the devices for electric energy generation from woody biomass have usually medium-large size (e.g., Organic Rankin Cycle turbine) and require technical competences that are not usually present among workers of wineries.

2.2 Life cycle assessment

Different methods have been proposed over the years to assess the environmental performances of agricultural activities. Among these, the Life Cycle Assessment (LCA) approach is the most used. LCA is a standardised methodology (ISO, 2006a; ISO, 2006b) designed for the holistic assessment of the environmental impacts and resources use associated to a product or a service throughout its entire life cycle production process. Using LCA, the potential environmental impacts of products (processes or services) throughout their whole life cycle can be evaluated.

LCA is a methodological framework useful to determine the environmental impacts of a system, product or activity (ISO 14040 and ISO 14044). LCA features a highly developed methodology, which includes the emissions of pollutants and material and energy consumptions from raw material acquisition, through the production and use phases to waste management. In this study, an attributional Life Cycle Assessment (aLCA) was applied. According to ISO standard 14040 (ISO, 2006), aLCA is a modelling approach in which inputs and outputs are attributed to the functional unit of a system by linking and/or partitioning the unit processes of the system according to a normative rule.

2.2.1 Goal and scope

The goal of this study is to compare three different management systems for vineyard pruning residues in the context of Northern Italy wine production system. In Italy, overall, the vineyard area amounts to almost 2 million hectares (ISTAT, 2002). Annual pruning, generates at least 1 oven dry ton of residual biomass per hectare (Laraia et al., 2001). The Baseline

Scenario was selected because it is the most widespread in the South Europe context (Morlat and Chaussod, 2008) and in the Italian grapevine production systems (Spinelli et al., 2014).

This LCA study aims to:

- quantify the environmental impact related to the management of the pruning residues with the different systems;
- identify the processes mainly responsible for this impact;
- identify, between the two evaluated management systems, the one presenting the best environmental performances.

The outcomes of this study could be useful for the stakeholders involved in the grape and wine production processes to identify the best solution to manage the pruning residues as well as for policymakers as a starting point for the development of policies able to stimulate the most environmentally friendly solutions for the management of pruning residues.

2.2.2 Functional unit

According to ISO standards, the functional unit (FU) is defined as the main function of the system expressed in quantitative terms (ISO, 2006a). In this study, the selected functional unit is the management of the pruning residues produced on 1 hectare (1 ha) of vineyard.

2.2.3 System boundary

Concerning the system boundary, a "from cradle to gate" approach was considered in this study. Hence, all activities from pruning residues management into the vineyards to the winery's utilities system were included. More in details, the system boundary:

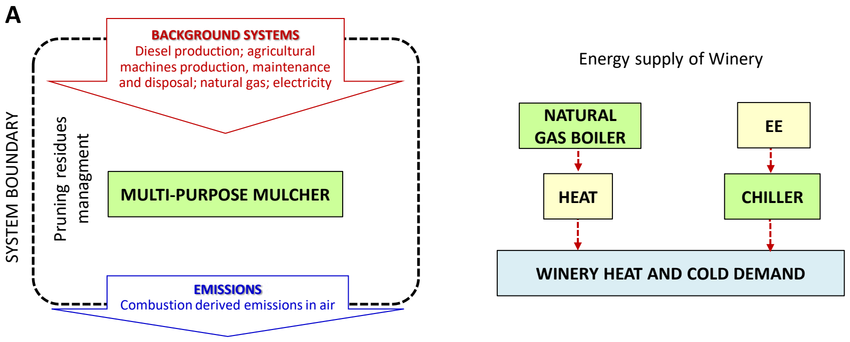
- includes: 1) extraction of raw materials (e.g., fossil fuels, metals and minerals), 2) manufacture of the different production factors use for pruning residues management (e.g., tractors and agricultural machines, electricity, diesel, etc.,) and for heat and cold production (boiler, absorption chiller), 3) use of inputs (e.g., diesel fuel emissions related to the different field operations as well as to the energy production) and maintenance and final disposal of machines (e.g., tractors and operative machines) and devices (e.g., boiler, absorption chiller);

- excludes: 1) grapevine cultivation, 2) wine-making (except for the energy supply system) 3) wine distribution, 4) use and 5) end of life.

In the three scenarios, a “zero burden” approach was applied with regard to the production of pruning residues. More in details, no environmental impact was considered for their production. Although in a LCA study alternative solutions can be used to solve the multifunctionality of the evaluated process (e.g., system expansion, allocation) (Olofsson and Börjesson, 2018), in this study the “zero burden” approach was taken into account because the pruning residues are a waste of another production system (the grape production). In fact, vineyards are grown with the only purpose to produce grape and the pruning residues are a waste product of the grape production system, they have no economic value and, as stated above, their management is an economic cost and a phytosanitary issue. The same approach is usually applied to biogas production from animal slurry: no environmental burden is associated to the slurry since it is a waste of another production system (the production of meat or milk) (Lijò et al., 2017, Ingrao et al., 2019).

In accordance with previous studies (Cherubini, 2010; Bosco et al., 2012; Boschiero et al., 2016), no changes in the soil organic carbon content were considered. However, concerning this aspect a sensitivity analysis was performed (see. Section 3.1.2).

Figure 1 shows the system boundary for the three evaluated scenarios.



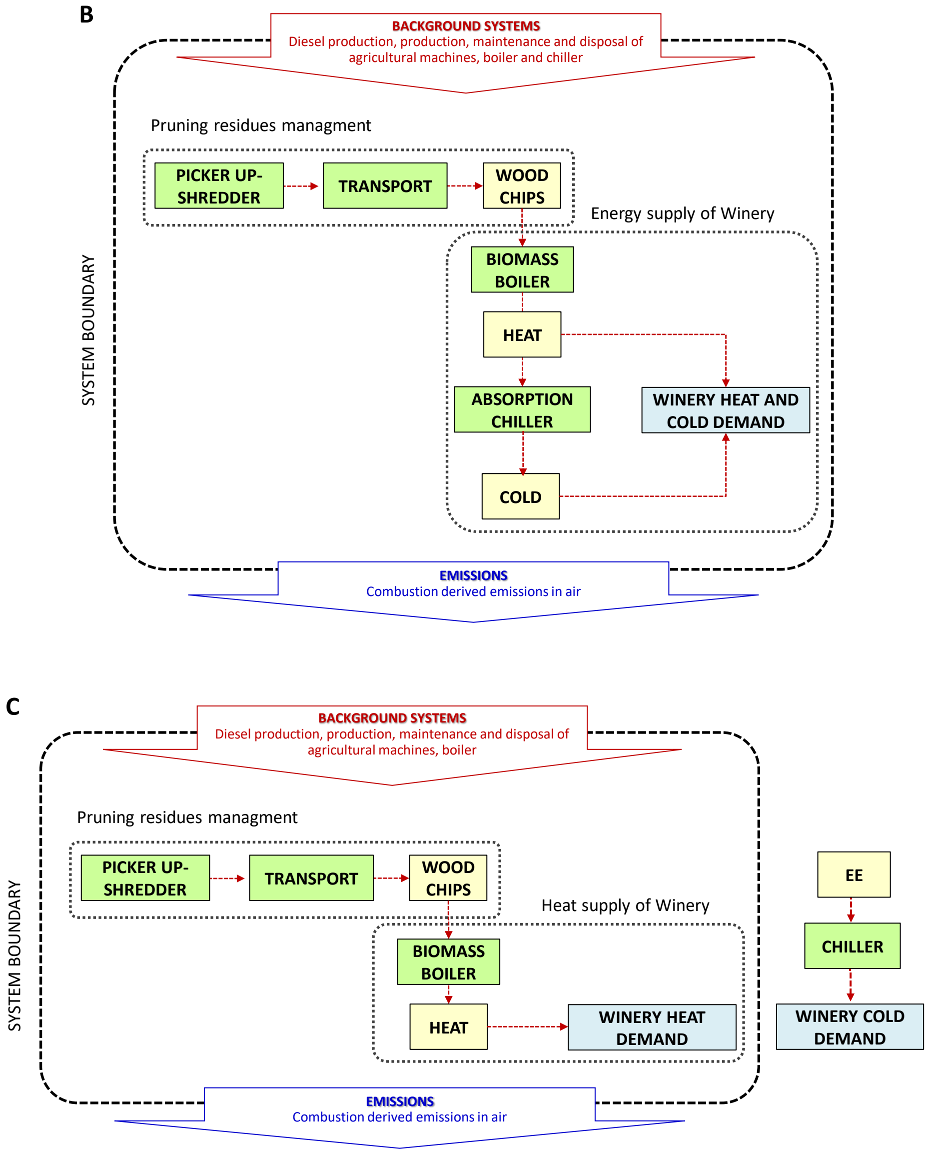


Fig 1 System boundary for the three scenarios; Baseline Scenario -BS (A), -BS (A), where the energy supply of the winery is fully produced using fossil fuel, Alternative Scenario 1 – AS1 (B), where the heat and cold are produced valorising the pruning residues (by a biomass boiler and an absorption chiller) and Alternative Scenario 2 – AS2 (C) in which heat is produced from pruning residues using a biomass boiler while the cold derives from an electric chiller.

2.2.4 Inventory data collection

Primary inventory data concerning the amount of pruning residues available and their management as well as the energy consumption (heat and electricity) during winemaking were collected by means of surveys and interviews in a social winery. The winery "Cantine di

Codevilla e Torrazza Coste" is located in the District of Pavia (Lombardy Region, Northern Italy - Lat: 44.9635300°, Long: 9.0577300°) and yearly processes about 5000 tonnes of grape produced over about 600 ha.

For the different field operations (chopping, soil incorporation in BS and harvesting by the pruning picker up-shredder and transport in the AS1 & AS2), data about working times (h/ha) and fuel consumption (kg/ha) were collected by means of field trials. For Alternative Scenarios 1&2, the trials were carried out in the vineyards of a second winery located in the same district. An average yield of pruning residues of 3.0 t/ha and a moisture content of 45% was considered; similar values were reported also by Picchi et al. (2013) and Boschiero et al. (2016).

Secondary data were taken from the literature, in particular:

- the energy efficiency of the boiler and the coefficient of performance (cop) of the adsorption chiller (Fiala, 2012);
- the physic-chemical characteristics of pruning residues (Duca et al., 2016);
- the emissions from pruning residues combustion (Gonzalez-Garcia et al., 2014; Prando et al., 2016).
- for pruning residues, a harvest loss of 15% (Spinelli et al., 2010; Spinelli et al. 2012).

With regard to the field operations, **Table 1** shows the main inventory data.

Table 1 – Inventory data for pruning residues management in the two evaluated scenarios

Parameter	Unit	BS	AS1 & AS2
Operative machine (OM)	-	Mulcher	Picker-up shredder
Mass of OM	kg	1050	1600
Effective field capacity	ha/h	0.7	0.9
Annual working time of OM	h/y	250	200
Lifespan of OM[a]	Y	8	8
Tractor power	kW	54	60
Mass of tractor	kg	3300	3550
Annual working time of tractor[a]	h/y	600	600
Lifespan of tractors[b]	Y	12	12
Require power by OM	kW	35	40
Fuel consumption	kg/ha	23.6	10.6
Amount of OM consumed	kg/ha	0.750	1.11

Amount of TR consumed	kg/ha	0.392	0.548

[a] Lazzari and Mazzetto, 2016; [b]Lovarelli and Bacenetti, 2017.[c]

The amount of operative machine and tractor consumed is the machinery mass that is "virtually consumed" during the field operation, which allows taking into account the overall amount of materials that is consumed during the machinery lifespan; it was calculated according the method proposed by Bacenetti et al. (2018) as:

$$AM = \frac{m \cdot \left(\frac{T}{L}\right)}{A},$$

where AM is the consumed amount of the machinery (kg/ha), m is the machinery mass (kg), T is the working time of the operation (h), L is the machinery lifespan (h) and A is the field area (ha).

Table 2 reports the main data related to the energy consumption in the winery (thermal energy for heating and for bottle and plant sterilisation, and electricity for cooling) and the conversion of pruning residues into heat and "cooling energy". The electricity consumption for the other uses was considered out of the system boundary in the three evaluated scenarios.

The nutrients content (mainly nitrogen N and phosphorous P) of pruning residues was considered negligible respect to the nutrients applied with fertilisation (Tagliavini et al., 2007). In fact, even if the pruning residues are harvested, the amount of applied NPK fertiliser does not usually increase (Tonon et al., 2007). Therefore, in BS no N and P compounds emissions were considered due to the soil incorporation of chopped pruning residues, while in AS1 and AS2 no additional fertilisations were taken into account due to the collection of the residues. A sensitivity analysis was carried out with regard to this aspect in section 3.1.

Background data for the production of diesel fuel, electricity and heat, tractors and agricultural machines, boiler and chiller were obtained from the Ecoinvent database® v.3.5

(Weidema et al., 2013; Moreno Ruiz et al., 2018). The list of the processes retrieved from the Ecoinvent database is detailed in **Table 3**.

Table 2 – Main parameters and assumptions about the energetic valorisation of pruning residues

Parameter	**Symbol**	**Unit**	**Value**	**Note**
Yield of pruning residues	Y	tonne/ha	2.6	Primary data
Lower Heating Value	LHV	MJ/kg	18	Fiala, 2012
Moisture content at harvest	$M\%_{HARV}$	%	45%	Primary data
Moisture content at the utilisation	$M\%_{USE}$	%	25%	Primary data
Useful mass of pruning residues after storage	Y_{USE}	tonne /ha	1.91	$Y_{USE} = [Y \cdot (1- M\%_{HARV}]/(1- M\%_{USE})$
Lower Heating Value at $M\%_{USE}$	LHV_{USE}	kWh/kg	3.58	$LHV_{USE} = (LHV \cdot (1 - M\%_{USE}) - 2.44 \cdot M\%_{USE})/ 3.6$
Thermal Efficiency of the biomass boiler	η_{TE}	%	80%	Fiala, 2012
Thermal energy output	TE_ha	kWh/ha	5453	$TE\_ha = LHV_{USE} \cdot Y_{USE}$
Electrical power chiller	P_{EE_CHI}	kW	50	Primary data
Coefficient of performance	COP	-	3	Primary data
Required cooling power chiller	P_{COLD}	kW	150	$P_{COLD} = P_{EE\_CHI} \cdot cop$
Annual working time chiller	WT	h/y	1100	Primary data
Electricity consumption for cooling	EE_{COLD}	MWh	55.0	$EE_{COLD} = P_{EE\_CHI} \cdot WT$
Index of Cooling efficiency of absorption chiller	CEI	-	0.7	Fiala, 2012
Thermal power of absorption chiller	P_{TE_CHI}	kW	214.3	$P_{TE\_CHI} = P_{COLD} /CEI$
Thermal power of biomass boiler	P_{TE_BOI}	kW	214.3	$P_{TE\_BOI} = P_{TE\_CHI}$
Wood chip hourly consumption “for cooling”	H_{CONS}	kg/h	94	$H_{CONS} = (P_{TE\_BOI}/\eta_{TE})/ LHV_{USE}$
Wood chip yearly consumption “for cooling”	Y_{CONS}	tonne /y	82.42	$Y_{CONS} = H_{CONS} \cdot WT$
Vineyard area “for cooling”	A_{COLD}	ha	43.25	$A_{COLD} = Y_{CONS} / Y_{USE}$
Heat requirement	TE	MWh	56.4	Primary data
Vineyard area “for heating”	A_{HEAT}	Ha	10.35	$A_{HEAT} = TE/ TE\_ha$
Total vineyard required in AS1	A_{AS1}	Ha	53.6	$A_{AS1} = A_{COLD} + A_{HEAT}$
Total vineyard required in AS2	A_{AS2}	Ha	10.35	$A_{AS2}= A_{HEAT}$

Table 3 – List of processes retrieved from the Ecoinvent database v. 3.5

Ecoinvent® 3.5 Process	**Used for**	**Modifications**
Diesel {RER}| market group for | APOS, U	Diesel fuel consumed during field operations	n/a
Tractor, 4-wheel, agricultural {GLO}| market for | APOS, U	Tractors used during field operations	A life span of 12 years was considered
Agricultural machinery, unspecified {GLO}| market for | APOS, U	For mulcher used in BS and for Picker-up shredder used in AS1&2	A life span of 8 years was considered
Transport, tractor and trailer, agricultural {GLO}| processing | APOS, U	Transport of wood chip from the field to to the winery	n/a
Electricity, medium voltage {IT}| market for | APOS, U	Electricity for traditional chiller in BS and avoided electricity consumption in AS1	n/a
Heat, central or small-scale, natural gas {Europe without Switzerland}| heat production, natural gas, at boiler condensing modulating <100kW | APOS, U	Avoided heat from natural gas in AS1 and AS2	n/a
Furnace, wood chips, average storage area, 300kW {GLO}| market for | APOS, U	For wood chip combustion in AS1 and AS2	Scaled down[1] to the sizes of biomass boiler considered in this study.
Heat, central or small-scale, other than natural gas {CH}| heat production, softwood chips from forest, at furnace 50kW | APOS, U	For modelling the emissions related of the biomass combustion in AS1 and AS2	Production factors removed and emissions proportionally scaled to the produced thermal energy
Absorption chiller, 100kW {GLO}| market for | APOS, U	For cold production in AS2	Scaled up[1] to the sizes of biomass boiler considered in this study.

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[1] This has been carried out following the approach used for scaling up the costs of process plants (Coulson et al., 1993) adapted for estimation of environmental impacts from their construction (Fusi et al., 2016):

$$E_2 = E_1 \cdot (C_2/C_1)^{0.6}$$

where:

E_2	environmental impacts of the larger plant
E_1	environmental impacts of the smaller plant
C_2	capacity of the larger plant
C_1	capacity of the smaller plant
0.6	scaling factor.

2.2.5 Impact assessment

Using the characterisation factors reported by the midpoint ILCD method (ILCD, 2011), the following impact categories were considered: Climate change (CC), Ozone depletion (OD), Human toxicity, cancer effects (HTc), Human toxicity, non-cancer effects (HTnoc), Particulate matter (PM), Photochemical oxidant formation (POF), Terrestrial acidification (TA), Freshwater eutrophication (FE), Terrestrial eutrophication (TE), Marine eutrophication (ME), Freshwater ecotoxicity (FEx), Mineral fossil and renewable resource depletion (MFRD).

The ILCD 2011 Midpoint method was released by the European Commission, Joint Research Centre in 2012. It supports the correct use of the characterisation factors for impact assessment as recommended in the ILCD guidance document "Recommendations for Life Cycle Impact Assessment in the European context - based on existing environmental impact assessment models and factors? (EC-JRC, 2011).

3. Results and Discussions

Figure 2 reports the relative comparison between BS, AS1 and AS2, while the absolute impacts are reported in **Table 4**. The comparison between the two scenarios shows that the environmental results are not univocal. More in details, the identification of the best scenario depends on the considered impact category. As regard to the energetic valorisation of wood chips produced by pruning residues in AS1, the production of thermal and electric energy involves environmental benefits for some impact categories such as climate change - CC, ozone depletion- OD, human toxicity – cancer effects – HT-c, terrestrial acidification – TA and freshwater eutrophication - FE. These benefits are related to the avoided production of heat from natural gas and to the avoided consumption of electricity for cooling at the winery. For both the AS, wood chips combustion worsens the results for all the impact categories (e.g., HT-noc, PM, POF, TE, ME and FEx) affected by the pollutants emitted (e.g., particulate matters, NMVOC, NOx and ammonia) in the exhaust gases of biomass boiler or by the manufacturing, maintenance and disposal of biomass boiler and chiller (e.g., MFRD). This worsening is remarkable and is due to the combustion of wood in a small size biomass boiler not equipped with specific devices for the treatment and cleaning of exhaust gas. When the pruning residues are collected to produce only heat (AS2), the impact related to the manufacturing of the adsorption chiller is not accounted for and, consequently, the impact for the toxicity related impact categories (HT-C, HT-noc and FEx) is reduced.

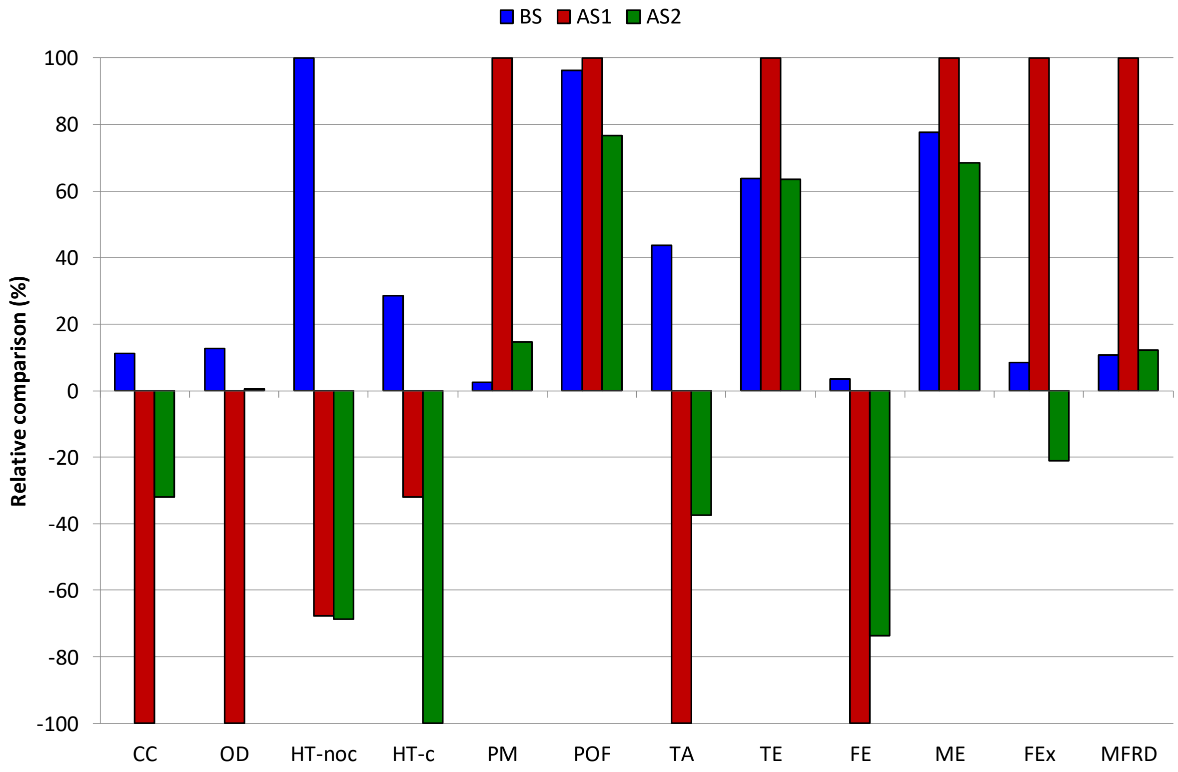

Figure 2 - Relative comparison among the environmental impact of the three evaluated scenarios (BS – Baseline; AS1 – Alternative Scenario 1; AS2 – Alternative Scenario 2).

Table 4 – Absolute environmental impact for the three scenarios.

Impact category	**Unit**	**BS**	**AS1**	**AS2**
CC	kg CO_2 eq	89.45	-807.39	-258.21
OD	mg CFC-11 eq	5.46	-42.893	0.234
HT-noc	CTUh	3.71×10^{-5}	-4.29×10^{-5}	-2.55×10^{-5}
HT-c	CTUh	9.57×10^{-7}	-1.08×10^{-6}	-3.66×10^{-6}
PM	kg PM2.5 eq	0.063	2.437	0.359
POF	kg NMVOC eq	1.112	1.157	0.888
TA	molc H+ eq	0.842	-1.931	-0.722
TE	molc N eq	4.280	6.705	4.255
FE	g P eq	3.667	-105.27	-0.078
ME	kg N eq	0.391	0.503	0.345

FEx	CTUe	136.90	1611.56	-338.32
MFRD	g Sb eq	2.645	25.017	3.052

For BS, the environmental impact could be reduced especially for CC, as a consequence of the increased soil carbon content related to the soil incorporation of chopped residues. However, this aspect is hardly quantifiable (Cowie et al. 2006; Repullo et al., 2012) and, consequently, it was not considered in the analysis. Concerning the nutrients content of pruning residues, the inclusion of the emissions of N and P compounds related to their mineralisation into the soil would result in a worsening of the environmental impact of BS (in particular for TA, TE, FE and ME). On the other hand, an impact increase would occur in alternative scenarios if an additional fertilisation was considered to compensate the higher nutrients removal. A sensitivity analysis concerning these two aspects has been carried out (see. Section 3.1).

Figure 3 shows the environmental hotspots for BS where the residues are left into the soil after chopping. In this scenario:

- the consumption of diesel represents a share of the impact ranging from 3% in HT-noc to 97% in OD;
- the emissions related to diesel combustion in the tractor engine are responsible for a share of the impact ranging from 0.3% in HT-c to 96% in TE and they are the main hotspots for CC (84%, mainly due to the emission of CO_2), HT-noc (87%, mainly due to the emission of heavy metal), PM (80%, mainly due to the emission of particulates < 2.5 µm and nitrogen oxides), POF (92%, mainly due to the emission of nitrogen oxides and NMVOC), TA (84%, mainly due to the emission of nitrogen oxides, sulfur dioxide and ammonia), TE (95%, mainly due to the emission of nitrogen oxides) and ME (95%, mainly due to the emission of nitrogen oxides and nitrate);
- tractor consumption is an hotspot for HT-c, FE and FEx (37%, 42% and 50%, mainly due to spoils produced during mining) and MFRD (89%, mainly due to mine operations for the extraction of metals);

- agricultural machinery consumption shows a low impact: <20% except for HT-c (23%), FE (15%) and FEx (11%).

Figure 4 shows the environmental hotspots for the Alternative Scenario 1 (AS1); the label "Electricity and Water cons" reported in the figure includes the electricity consumed by the biomass boiler - e.g., for biomass loading - and by the adsorption chiller and the related consumed water. For 5 of the 12 evaluated impact categories (CC, OD, HT-c, TA and FE), the environmental benefits due to the avoided consumption of heat produced from natural gas and of electricity from the Italian electric grid are higher than the environmental impact of the different operations characterising the scenario evaluated. Energy generation from biomass completely offsets the environmental impact of the collection and transformation of pruning residues. For the other impact categories, the avoided production of heat and electricity from fossil fuel brings to a reduction (but not the offset) of the environmental impact. This is mainly due to the emissions related to wood chips combustion,

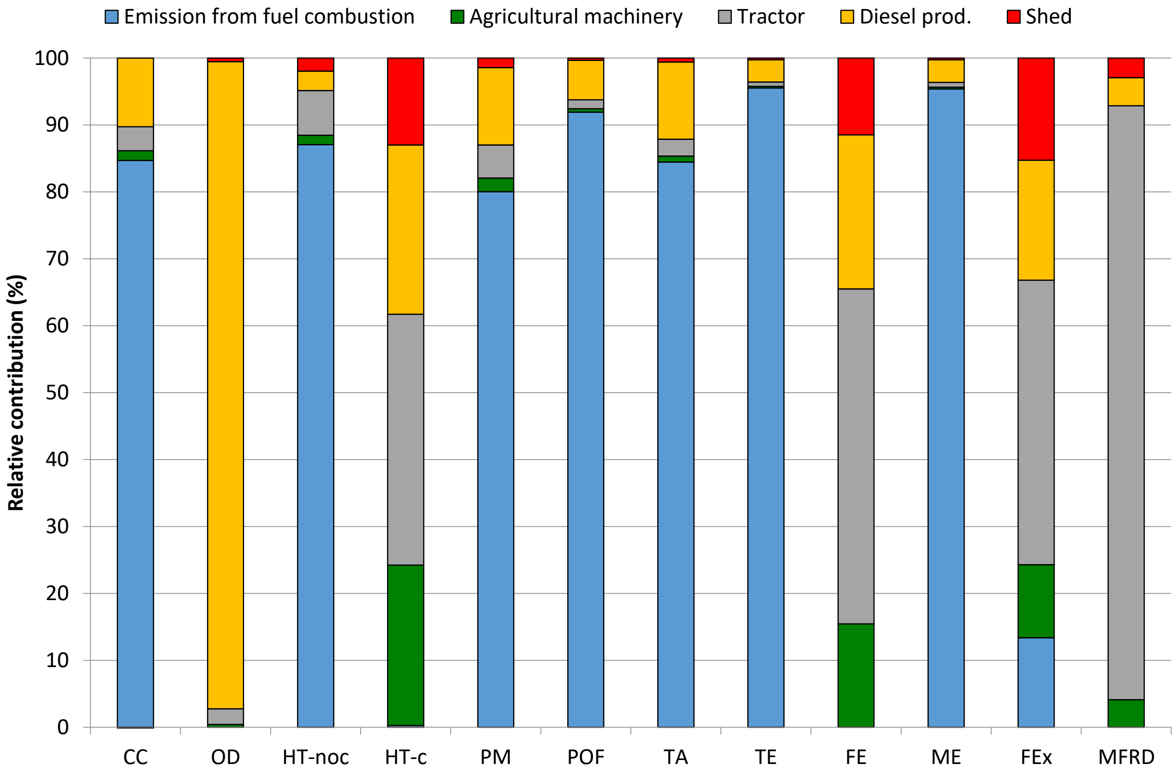

Figure 3 - Contribution analysis of the different inputs and outputs for the Baseline Scenario (traditional management of pruning residues)

The main hotspots for AS 1 are:

- The emissions related to the combustion of pruning residues in the biomass boiler and to the ash disposal. In particular, HT-noc is mainly due to emissions of heavy metals into the soil such as zinc during ash disposal, while PM, POF, TE and ME are mainly related to the emissions from wood combustion (particulates and nitrogen oxides for PM, benzaldehyde for POF and nitrogen oxides and ammonia for TE and ME),
- The manufacturing, maintenance and disposal of both the biomass boiler and the adsorption chiller for HT-c and FEx (54% and 50% of the total impact, respectively, and mainly due to the consumption of steel and to the waste treatment of mine activities) and for MFRD (62%, mainly due to the consumption of zinc, copper and ferronickel).

The role of SS1 (chipping and loading of pruning residues and transport of wood chips) is small: it results lower than 10% of the impact in all the evaluated impact categories except for POF (17%), TE (16%), ME (17%) and MFRD (21%). In particular, the share of the impact related to the transport of wood chips is always lower than 2%.

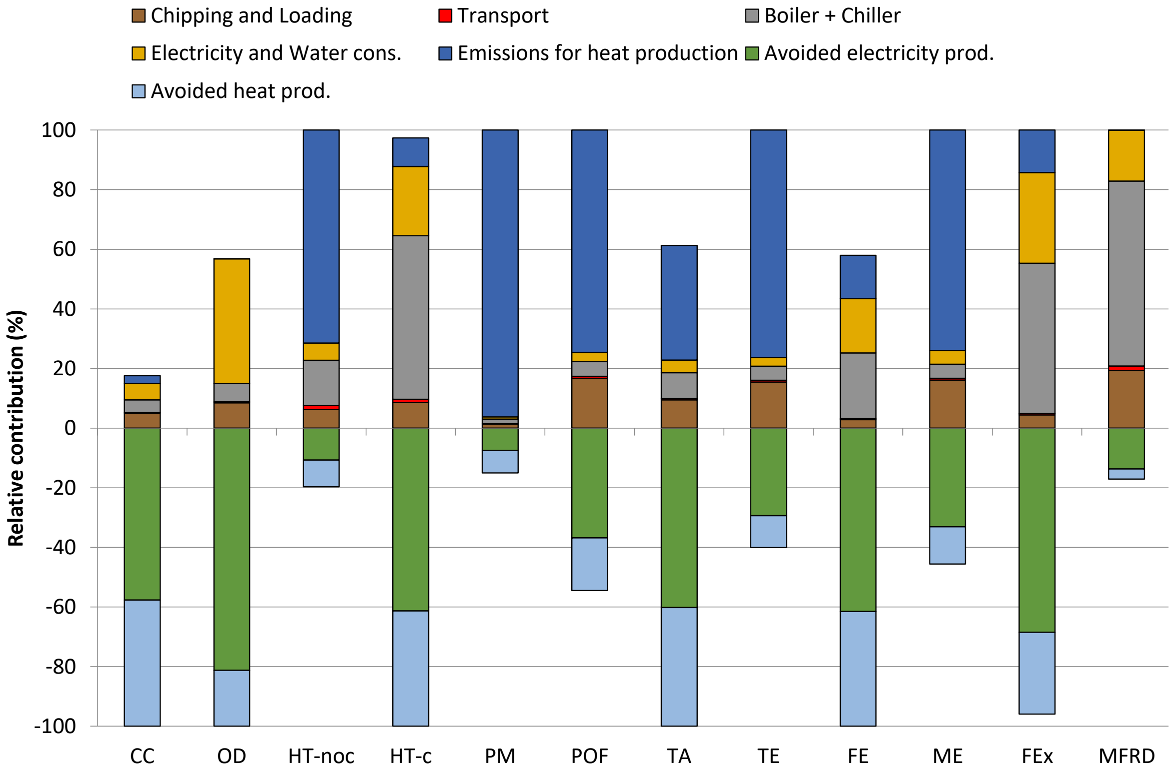

Figure 4 - Contribution analysis of the different inputs and outputs for the Alternative scenario 1.

Finally, **Figure 5** shows the main contributors to the environmental performances of AS2. Respect to AS1, the differences are due to two main issues: first, the chopping of pruning residues on the area that is not harvested because of the lower amount of wood chip needed and secondly, to the reduction of the credits because only heat is produced.

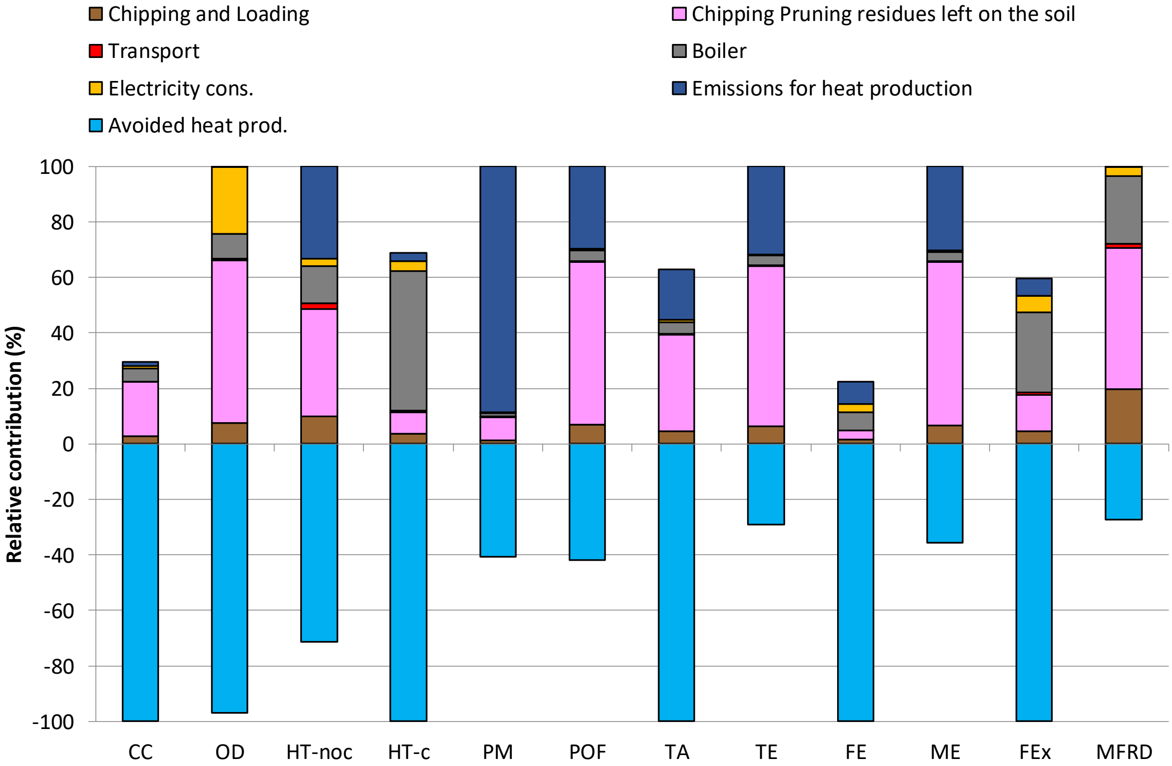

Figure 5 - Contribution analysis of the different inputs and outputs for Alternative scenario 2.

This analysed biomass-to-energy production chain was designed based on the energy requirement of the cooperative winery. For this reason, the pruning residues were collected only on part of the total available vineyard area. If a higher amount of pruning residues was harvested, the energy produced would be higher than the one needed to supply the winery and the surplus would be wasted or it should be sold. Even if a specific subsidy framework exists for renewable energy production, it focuses on electricity.

Hence, selling surplus energy produced by the pruning residues would be complex: from one side, the heat transfer over a long distance is economically expensive, and from the other side, the remuneration for this energy would be low and its selling would involve bureaucratic complications. Nevertheless, if a full energetic exploitation of the pruning residues in small-medium size plants at the wineries is unrealistic due to the above-mentioned issues, the evaluated solution based on energy production for self-consumption could be applied to the whole Oltrepò wine district. In the district, the area dedicated to vineyard is 12,857 ha. Considering the outcomes of this study, to supply the heat and cold requirements of wineries, 10% of the pruning residues should be collected, which corresponds to 1,300 ha. This figure would bring to an increase of the benefits highlighted for:

- CC, -1050 and -336 t CO_2 eq in AS1 and AS2, respectively,
- human toxicity impact categories, -3.7×10^{-2} and 3.3×10^{-5} CTUh in AS1 and AS2, respectively in HT-noc and -1.4×10^{-3} and 4.4×10^{-7} CTUh in AS1 and AS2, respectively in HT-c,
- TA, -2511 and -939 molc H+ eq in AS1 and AS2, respectively,
- FE, -137 and 101 molc N eq in AS1 and AS2, respectively,
- OD, in -5.58 kg CFC-11 eq in AS1
- FEx, 4.40 CTUe $\times 10^5$ in AS2.

3.1 Sensitivity analysis

The results of every LCA study depend on the assumptions made concerning the inclusion (or exclusion) of specific aspects in the assessment. In this subsection, in order to investigate how the environmental results are affected by these choices, a sensitivity analysis was carried out regarding the following aspects:

- The inclusion in the system boundary of an additional amount of fertilisers to balance the nutrient removal related to the collection of pruning residues;

- An increase of soil organic carbon content in baseline scenario where the pruning residues are incorporated into the soil (currently no changes in the soil organic carbon content was assumed in the three scenarios)
- The possibility to equip the biomass boiler with control pollutants devices.

3.1.1 Considering nutrient removal and additional fertilisation in AS1

In accordance with Tagliavini et al. (2007) and Tonon et al. (2007), the nutrients content in the pruning residues is negligible. Consequently, in BS the soil incorporation of pruning residues does not involve the supply of nutrients, while in AS the pruning residues collection does not require additional fertilisations. To test the robustness of the achieved results with respect to this assumption, a sensitivity analysis was carried out considering, for the AS1, a supplementary mineral fertilisation. More in detail, taking into account the composition of the pruning residues and, in particular, their content in N, P and K (**Table 5**) the application of an additional amount of 18.7 kg/ha of urea, 17.2 kg/ha of superphosphate and 28.7 kg/ha of potassium sulphate was considered. No additional fertilisations were considered because the extra-amount of fertilisers was supposed to be spread during the fertilisations already foreseen in the grapevine production process. For the three fertilisers, an efficiency equal to 100% (i.e. 1 kg of nutrient applied with the fertiliser substitutes 1 kg of nutrient removed by the plant) was considered according to Hanserud et al. (2018) and Bacenetti et al. (2016).

Table 5 – Nutrient composition of pruning residues

Nutrient	**Composition**
N	0.6 %
P	0.1 %
K	0.4 %

Table 6 reports the impact variation related to the additional application of NPK fertilisers. This variation is lower than 10% only for 3 of the 12 evaluated impact categories, while is higher than 50% for the toxicity-related impact categories and for MFRD. For HTc and HT-noc, the additional amount of NPK consumed involves large relative variations (>100%).

For these impacts, even if the absolute variations are small, the additional consumption of fertilisers is able to offset completely the benefits related to avoided energy production from fossil fuel and to make higher than 0 the absolute values. For MFRD, the impact increase is related mainly to the energy consumption for nitrogen fertiliser production.

Figure 6 highlights the environmental hotspots for AS1 considering the additional fertilisation; in the figure, the label "Electricity and Water cons" includes the electricity consumed by the biomass boiler - e.g., for biomass loading - and by the adsorption chiller as well as the water consumed by this latter. Excluding the credits for the avoided consumption of heat and electricity from fossil fuel, the relative contribution of NPK fertilisers consumption is higher than the 20% of the impact for:

- CC (26.4%), corresponding to an absolute impact of 65.8 kg CO_2 eq, mainly due to the consumption of energy (heat and electricity) as well as of liquid ammonia for urea production,
- HT-noc (28.9%), corresponding to an absolute impact of 3.48 x10^{-6} CTUh, mainly due to the treatment of sulfidic tailing (produced during fertiliser manufacturing) as well as to the emissions of heavy metals into water;
- TA (20.3%), corresponding to an absolute impact of 0.771 molc H+ eq, mainly due to ammonia losses occurring during urea production;
- FE (28.1%), corresponding to an absolute impact of 32.64 g P eq, mainly due to the emissions of phosphate into water during the production process of superphosphate;
- MFRD (38.3%) corresponding to an absolute impact of 176.4 g Sb eq, mainly due to the energetic consumption required for urea production.

Table 6 – Impact for AS1 scenario considering the additional application of fertilisers.

Impact Category	Impact	Variation respect to AS1
CC	-741.6 kg CO_2 eq	-8.15%
OD	-39.7 mg CFC-11 eq	-7.43%
HT-noc	9.63 x10^{-6} CTUh	-138.33%
HT-c	2.83 x10^{-6} CTUh	-363.04%
PM	2.456 kg PM2.5 eq	4.49%
POF	1.392 kg NMVOC eq	20.42%

TA	-1.159 molc H+ eq	-39.96%
TE	7.942 molc N eq	18.46%
FE	-72.62 g P eq	-31.01%
ME	591.47 kg N eq	17.61%
FEx	2455.9 CTUe	52.40%
MFRD	42.65 g Sb eq	70.50%

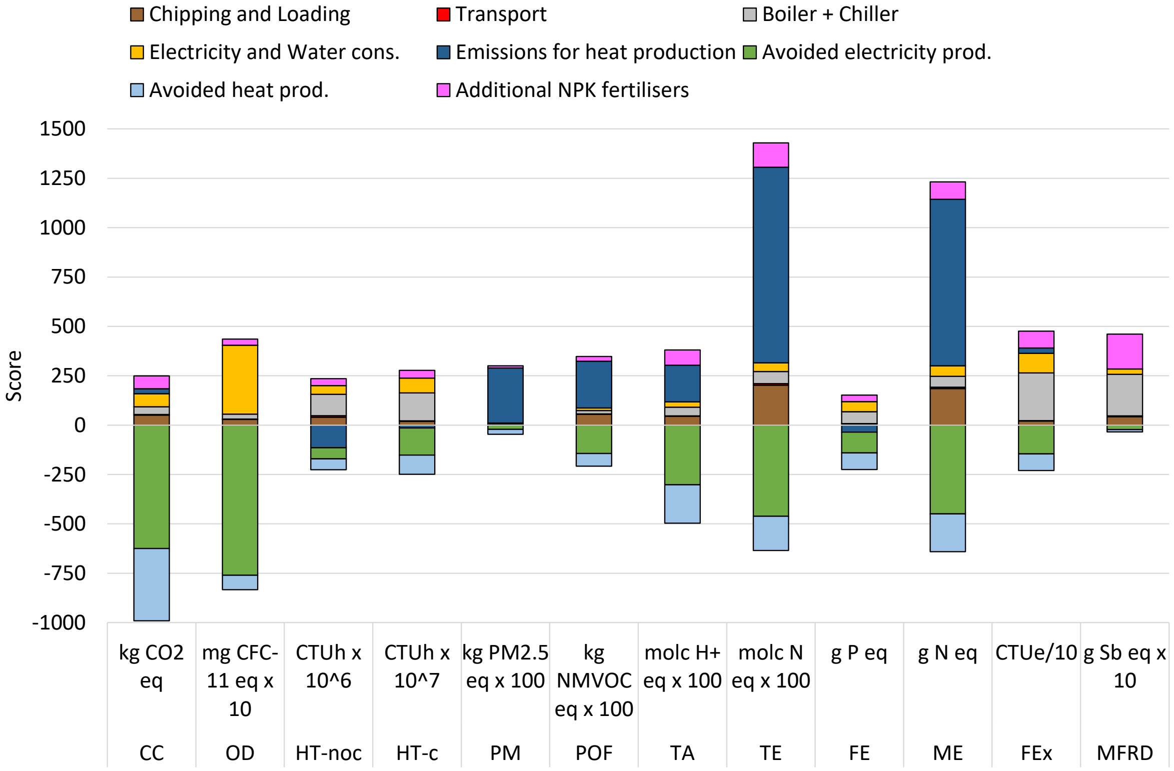

Figure 6 – Contribution analysis for Alternative Scenario 1 considering the application of an additional amount of NPK fertilisers.

3.1.2 Inclusion of Soil Organic Carbon Change

In the two alternative scenarios the pruning residues are collected, therefore their biomass is not incorporated into the soil. On the contrary, in BS the chopped pruning residues are left on the soil and, after degradation, could increase the soil organic content resulting in an absorption of CO_2. To test the impact on the environmental results for this aspect, changes in carbon fluxes were taken into account and the approach outlined by Petersen et al.

(2013) was used. It was assumed that from the annual addition of carbon, approximately 10% of the C added to the soil organic matter will be sequestered in a 100-year perspective and this factor was implemented, as in previous studies (Knudsen et al., 2014; Mogensen et al., 2014). According to Toscano et al., (2018), a carbon content equal to 47% of the dry matter was taken into account for the pruning residues. Consequently, 245 kg of CO_2 were considered annually stored into the soil thanks to the soil incorporation of residues.

Figure 7 reports the results for Climate Change in the different scenarios. CC is the only impact category affected by changes in the soil carbon content. If changes in soil organic carbon content, due to soil incorporation of pruning residues, are considered, the CC impact category is deeply affected and a negative value (-155.6 kg CO_2 eq/FU) is achieved also in the BS. Nevertheless, the two scenarios where pruning residues are valorised energetically show better results for Climate Change.

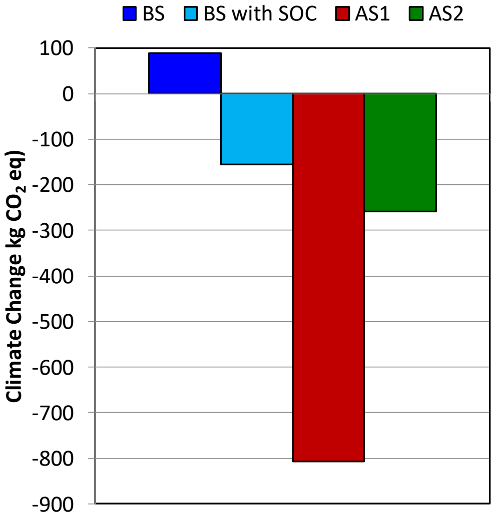

Figure 7 – Climate change impact for the different scenarios (BS with SOC = Baseline Scenario considering soil organic carbon change)

3.1.3 Pollutant reduction with Flue Gas Recirculation systems (FGR)

In both the alternative scenarios, the emissions of pollutants related to the biomass combustion are an environmental hotspot for HT-noc, PM, POF, TE and ME. To improve the boiler efficiency and to reduce the exhausts emissions, besides monitoring temperature, oxygen and carbon monoxide levels, some control devices and technologies have been developed and can be installed. However, the most effective devices are usually too expensive to be installed on small-medium size biomass boilers (Hinckley and Doshi, 2010).

Among the devices for the reduction of pollutants from wood combustion, the Flue Gas Recirculation (FGR) can be used also on small-medium size biomass boilers to reduce the emission of NOx. FGR is a promising primary control technique to reduce effectively the NOx level by re-circulating part of the flue gas to the furnace. The flue gas is diverted from a location downstream of the boiler and is mixed with the combustion air from the forced draft fan. Chen et al. (2015) highlighted that on a biomass boiler of 500 kW with FGR, the temperature inside the furnace is lowered and, consequently, a 10% reduction of NOx is achieved. However, NOx reduction is associated with an increase up to 4.5 times of CO. A sensitivity analysis was performed considering the variation of NOx and CO emissions highlighted by Chen et al. (2015) and the results are reported **Table 7**.

Table 7 – Impact variation for the two alternative scenarios (AS1 and AS2) due to the installation of FGR on the biomass boiler

Impact category	**Impact variation**	
	AS1	**AS2**
CC	0.00%	0.00%
OD	0.00%	0.00%
HT-noc	0.00%	0.00%
HT-c	0.00%	0.00%
PM	0.22%	0.28%
POF	-18.62%	-4.66%
TA	8.25%	4.24%
TE	-13.68%	-4.14%
FE	0.00%	0.00%
ME	-16.66%	-4.67%
FEx	0.00%	0.00%
MFRD	0.00%	0.00%

The installation of FGR positively affects the impact categories related to the emissions of nitrogen oxides and, in particular, POF, TA, TE and ME; instead, a small benefit is achieved for PM, where the role of NOx is less relevant. The impact reduction achieved with this solution is higher in AS1, where a higher amount of pruning residues is used. In fact, besides the heat requirement, in AS1 also the cooling requirement of the winery is met with this woody biomass. The outcomes of the sensitivity analysis highlight that the energetic valorisation of pruning residues in the biomass boiler can be more environmentally friendly when a reduction of the combustion pollutants is achieved. Nevertheless, it should be considered that, in addition to the increase of CO emissions already counted in this analysis, FGR might introduce some drawbacks, such as the risk of erosion, corrosion and fouling (Yang et al., 2018).

3.2 Uncertainty analysis

An uncertainty analysis was carried out with the Monte Carlo technique (1,000 iterations and a confidence interval of 95%) to test the robustness of the achieved results concerning the comparison between the three scenarios. **Figure 8 – 9** and **10** report the results of uncertainty analysis.

In **Figure 8**, the bars on the right represent the probability that the environmental impact of AS1 is higher (or equal) than the one of BS, while those on the left represent the opposite probability (i.e., the energetic valorisation of pruning residues in AS1 shows a lower environmental impact respect to BS). For CC, PM, POF, TA and FE, there is a reduced uncertainty level (lower than 6%); for TE, ME and MFRD the uncertainty level is lower than 30%. For the remaining impact categories (OD, HT-noc, HT-c and FEx), the level of uncertainty is higher; in particular, for HT-noc and HT-c the differences between BS and AS1 are mainly related to the uncertainty of the inventory data.

Figure 9 shows the results of the uncertainty analysis between BS and AS2. Respect to the comparison between BS and AS1, the uncertainty is high for all the evaluated impact categories except for CC and PM. For BS, the probability to perform better than AS2 is 95% for CC and 87% for PM. For the other impact categories, the probability that one scenario performs better than the other is not higher than 65%.

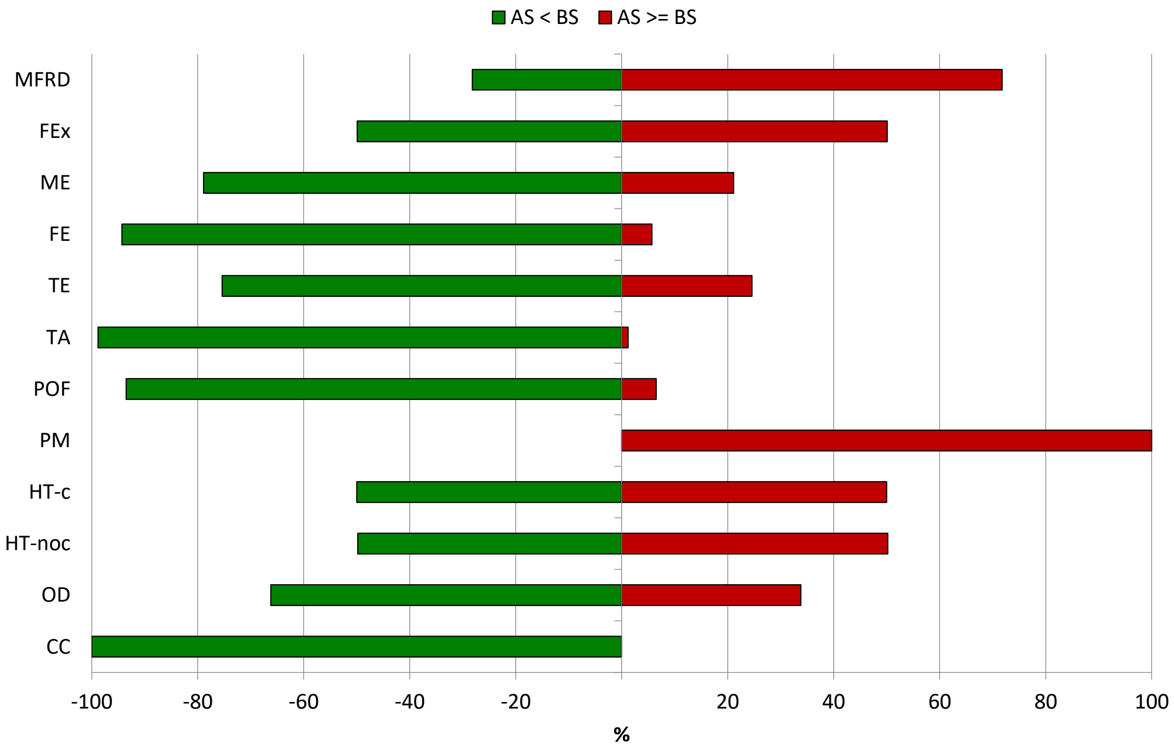

Figure 8 – Uncertainty analysis results regarding the comparison between baseline scenario and Alternative Scenario 1

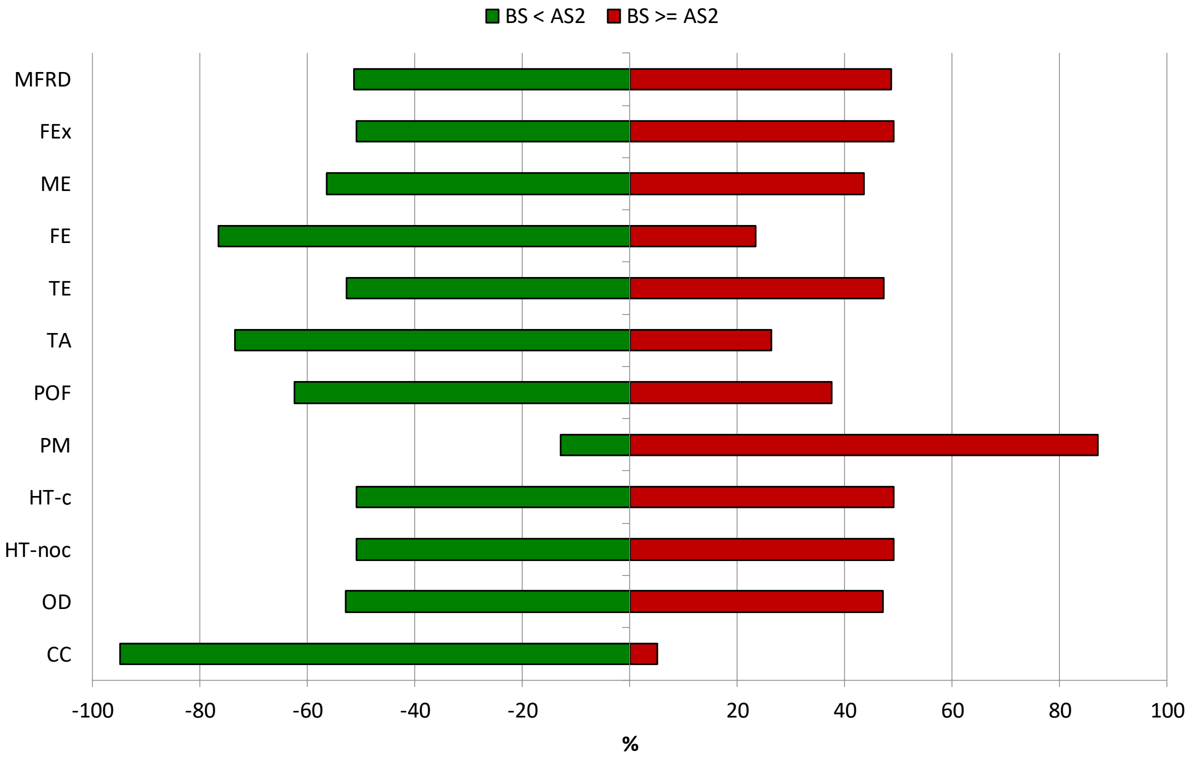

Figure 9 – Uncertainty analysis results with regard to the comparison between Baseline Scenario and Alternative Scenario 2

When the two alternative scenarios are compared (**Figure 10**), the level of uncertainty in the results is <1% for CC, OD and TA (impact categories for which AS1 shows a lower impact respect to AS2) and PM (where AS1 has a higher impact respect to AS2)

The results of the uncertainty analysis show that the uncertainty due to selection of the data from databases, model imprecision and variability of data does not significantly affect the environmental results:

- for 7 of the 12 evaluated impact categories, but plays a relevant role in the remaining 5, when BS is compared to AS1,
- for 2 of the 12 evaluated impact categories, but plays a relevant role in the remaining 10, when BS is compared to AS2,
- for 8 of the 12 evaluated impact categories, but plays a relevant role in the remaining 4, when AS1 is compared to AS2.

Among the evaluated impact categories, the toxicity related impact categories are those showing the highest uncertainty.

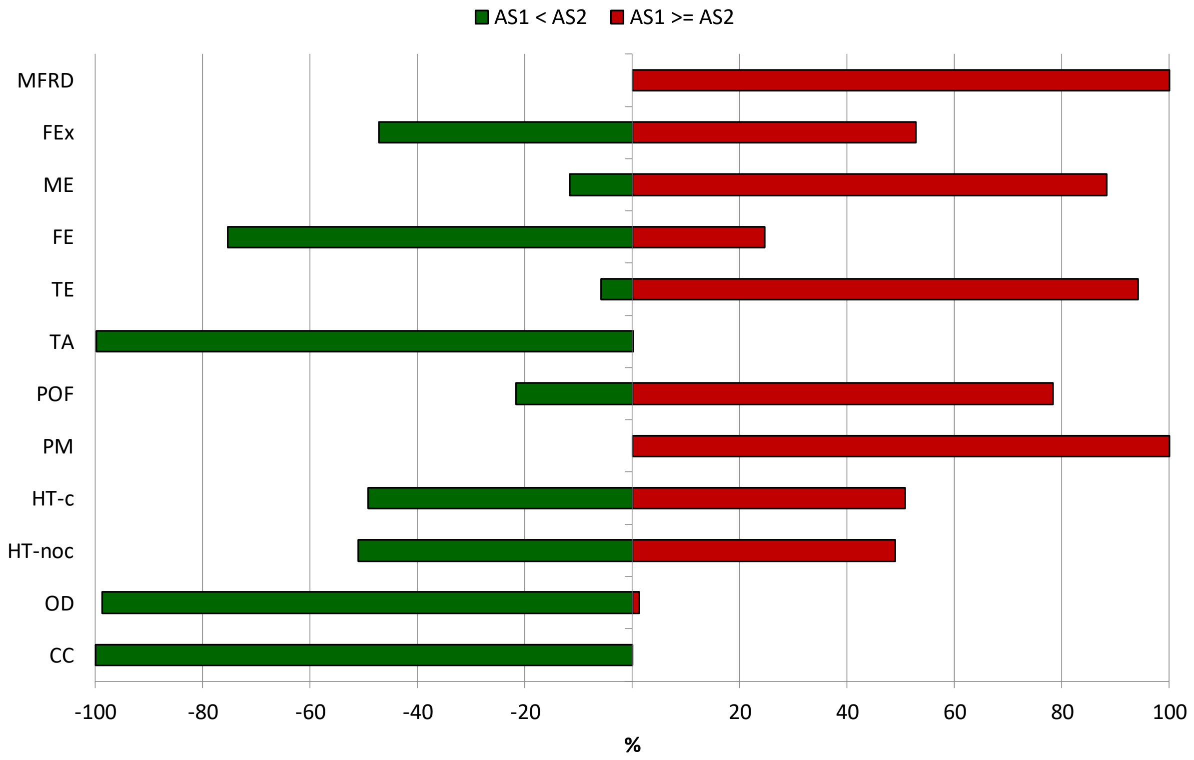

Figure 10 – Uncertainty analysis results about the comparison between Alternative Scenario1 and 2

4. Conclusions

Among the three evaluated scenarios (pruning residues chopped and left on the soil (Baseline Scenario) versus collection for energy production to produce heat and cold (Alternative Scenario 1) or only heat (Alternative Scenario 2), the results are not univocal, and the best solution depends on the evaluated environmental impact. The energetic valorisation of the residues reduces (from 1.6 to 9.5 times) the environmental impact for the impact categories not affected by the emissions related to wood combustion; for these impact categories, the impact increases from 4% to 38 times. The higher impact increase occurs for the impact categories (e.g., particulate matter formation) directly affected by the pollutants emitted due to woody biomass combustion. In this regard, attention should be paid on the identification of pollutants control devices whose investment cost should be affordable for wine-making industry and wine cooperatives interested into the energetic valorisation of pruning residues. Policymakers should foresee specific subsidies for this kind of investment in order to achieve a full exploitation of this biomass without any environmental concern.

Finally, future research activities should consider an expansion of the system boundary to consider the possible variation of the soil carbon content as well as the effect due to the higher nutrients removal related to the collection of pruning residues. Particular attention should be paid on the possibility that, in the long run, the collection of the residues involves a decrease of the soil organic matter content able to offset the benefits related to energy production.

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