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An environmental and economic analysis of the wood-pellet chain: two case studies in Southern Italy

Maria Pergola[1] **· Amalia Gialdini**[2] **· Giuseppe Celano**[3] **· Marina Basile**[2] **· Donatella Caniani**[4] **· Mario Cozzi**[2] **· Tiziana Gentilesca**[2] **· Ignazio M. Mancini**[4] **· Vittoria Pastore**[1] **· Severino Romano**[2] **· Gennaro Ventura**[2] **· Francesco Ripullone**[2]

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Abstract
Purpose Wood pellet heating systems are considered as an essential component of European plans to reduce greenhouse gas (GHG) emissions. The goal of this analysis was to estimate and compare the environmental impacts and the costs of the production of packed wood pellets. Two pellet production systems, using roundwood logs (case 1) and mainly sawdust (case 2), have been analysed in 2015 in Basilicata region (Southern Italy).
Methods A life cycle assessment (LCA) analysis was applied to calculate the environmental impact indicators of each system, whilst a life cycle cost (LCC) analysis was implemented to evaluate the pellets' cost production. Hence, the functional unit chosen was 1 t of produced pellets. The system boundaries considered for the purpose of the current investigation were from the tree felling to the pellet packaging. In particular, the following activities were considered: motor-manual felling and delimbing with a chainsaw, timber yarding with a tractor along the forest track, loading and transportation of the logs to the collection point, transportation of timber to the factories for a distance of 35 km, pellet production and pellet packaging in low-density polyethylene bags with a total weight of 15 kg bag^{-1}.
Results and discussion The production of 1 t of pellets emitted about 83 kg of CO_2eq in case 1 and 38 kg in case 2. In addition, 2.7 kg of SO_2eq and 0.005 kg of $PO^3{}_4$-eq were produced in case 1 and 1.4 kg of SO_2eq and 0.002 kg of $PO^3{}_4$-eq in case 2. Mineral extraction was equal to 0.9 MJ surplus energy in both cases. Case 1 led to higher environmental impacts (about 50% more), essentially for the operation of pelletisation, and in particular for the higher consumption of electricity that characterised it, whereas the production costs were 172 and 113 € t^{-1} in case 1 and case 2, respectively. In both study cases, consumption costs (costs for raw material, electricity consumption, fuel usage) were the most important cost items.
Conclusions Our studies highlight how, in both cases, the operations carried out in the forest produced the minor part of the environmental impact but, at the same time, were the most expensive operations. Further, our studies show how mixing lumbering by-products (sawdust) and forest management products (lumbers) can be an efficient solution to reduce both manufacturing costs and environmental impacts to produce wood pellets.

Keywords Bio-economy · Climate change · LCA · LCC · Sustainable forestry · Woody biomass residues

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✉ Francesco Ripullone
francesco.ripullone@unibas.it

1 Ages s.r.l.s-Spin-off Accademico, Università degli Studi della Basilicata, Viale dell'Ateneo Lucano, 10, 85100 Potenza, Italy

2 Scuola di Scienze Agrarie, Forestali, Alimentari ed Ambientali, Università degli Studi della Basilicata, viale dell'Ateneo Lucano, 10, 85100 Potenza, Italy

3 Dipartimento di Farmacia (DIFARMA), Università degli Studi di Salerno, Via Giovanni Paolo II, 132, 84084 Fisciano, Italy

4 Scuola di Ingegneria, Università degli Studi della Basilicata, viale dell'Ateneo Lucano, 10, 85100 Potenza, Italy

1 Introduction

Climate change is an environmental issue widely recognised by the international scientific community. The European Union has set itself two important and ambitious targets in the environmental and energy policy, to be achieved by

2020 (COM 2008): a 20% reduction of greenhouse gas (GHG) emissions and 20% of Europe's energy produced by renewable sources. In addition, 42% of total renewable energy is expected to be obtained from biomass, including electricity, heating and cooling (EU 2009). A contribution to the Europe 2020 strategy goals may come from a modern bio-economy based on the sustainability in the extraction of biomass raw material, the efficiency in biomass use and the economies of scales in biomass mobilisation (Scarlat et al. 2015). The use of wood biomass for energy production and the use of renewable products (e.g. pellets) are probably the most important contributions of forest ecosystems to the reduction of GHG concentration in the atmosphere, as required by the Kyoto Protocol (Magelli et al. 2009; Murphy et al. 2015; Alivernini et al. 2016).

According to Laschi et al. (2016), Italy is the third most important country in Europe in terms of pellet production and has the largest European market in bagged high-quality pellets for domestic use (González-García et al. 2009; Hiegl and Janssen 2009; Sikkema et al. 2011). Within the Italian territory, Basilicata (Southern Italy) is one of the regions with the highest coefficient of forest cover at the national level with almost one third of its land area covered by forests (360,000 ha). Despite their potential, these forests are really far from their optimal use. Consequentially, the forestry sector, if well managed, could be one of the sectors with higher territorial enhancement capabilities both in terms of employment and activation of new enterprises. One of the aims of the current regional forest management is the realisation of a woodland-lumber chain, in which the primary and secondary wood products are processed in order to obtain firewood. In this context, the activities of the sector companies would be more and more oriented towards the realisation of very short supply chain products (at 0 km), in order to have lower costs and impacts on the environment (less pollution from products transport) and to use resources and local manpower (Bidini et al. 2006).

Hence, there is a need to enhance the communications of the environmental performances of these products to the final consumer through, e.g. the carbon footprint. This labelling communicates one important aspect of the sustainability of a product through the indication of the amount of carbon dioxide emitted during its realisation (Andrić et al. 2015). This system, on the one hand, helps the consumers to guide their purchasing decisions towards high environmental quality products and services and, on the other hand, encourages the producers to act in the production processes with more eco-efficient technical and organisational solutions. An internationally recognised methodology that evaluates the entire life cycle of a product is the life cycle assessment (LCA), which allows to identify, quantify and environmentally analyse all inputs and outputs involved in production, use and disposal of a product (Baumann and Tillman 2004). In the last few years, LCA together with life cycle costing (LCC) has been increasingly used in order to evaluate the environmental and economic performances of products, processes and systems.

In this context, the aim of the present study is to evaluate the environmental and economic profile of the wood-pellet chain in Basilicata region following a life cycle approach and considering the forest management for raw material supply. Considering the scarcity of studies on wood pellets and on the contribution of logging operations to the global environmental problem, this study would give a contribution to these failings.

2 A brief review of the specialised scientific literature

In literature, several studies have analysed the environmental impact of the manufacturing of pellets (Magelli et al. 2009; Fantozzi and Buratti 2010; Adams et al. 2015; Monteleone et al. 2015; Röder et al. 2015; Kylili et al. 2016; Laschi et al. 2016). In some cases, this was compared to other types of biomass (Upham and Smith 2014; Dinca et al. 2014; Benetto et al. 2015; Murphy et al. 2015) or to traditional fuels (Pa et al. 2011; Sjolie and Solberg 2011; McNamee et al. 2016).

Other studies have evaluated the economic sustainability of pellet production, by analysing the manufacturing process in individual case studies (Uasuf and Becker 2011; Kebede et al. 2013; Monarca et al. 2011; Kang et al. 2013; Hoefnagels et al. 2014; Shahrukh et al. 2016) or by comparing manufacturing systems in different countries (Thek and Obernberger 2004; Trømborg et al. 2013).

Only few studies (Sikkema et al. 2011; Sultana and Kumar 2012; Tabata and Okuda 2012; Pa et al. 2013; Nishiguchi and Tabata 2016) have faced up to the economic and environmental sustainability of pellet processing, and few others (Magelli et al. 2009; Pa et al. 2012; Paolotti et al. 2015) have made an economic and environmental analysis of their transport from the production areas to the consumer areas.

3 The Italian wood pellet sector

Italy, with its 80 producers, is Europe's third largest pellet producer (0.77 million t) (Sikkema et al. 2011), and 70% of the national supply is located in Northern Italy (ETA Florence 2016). In Italy, pellets are used almost exclusively for domestic, commercial enterprise and institution heating (Sikkema et al. 2011). In 2012, Italian wood pellet consumption reached 1.9 million t and continues to increase at a rate of 400,000 t per year, with only a small fraction domestically produced. From a peak of 750,000 t in 2007, Italy now produces 550,000 t annually, 29% of its 2011 consumption. Consequently, Italy depends to a very large extent on the import of wood pellets: mainly from Austria (32%) and Eastern Europe (26%) (Ligabue 2015).

In Basilicata region, in relation to the availability of raw materials (360,000 ha of forests), the use of wood as a heating source is widely spreading and the wood supply chains have a large potential development. In the last 5 years, numerous projects have been implemented in the region to promote the development and diversification of forest products, particularly in relation to energy use. At the same time, however, the expectations to enhance the forestry sector have been disappointed for unfavourable conjunctures related to the local forest-wood market. These latter can be summarised in: (1) the scarcity of companies with an operational capability such as to continuously support the wood-pellet chain; (2) the absence of cooperativism initiatives from small companies (units with less than 5 workers and with an average operational capability of 30 ha/year of logged forest areas); and (3) the limited mechanisation and efficiency of forest logging, due to the irregular regional morphology, with the addition of the strong prevalence of public ownership, with the resulting administrative and management burdens (Lam et al. 2011).

The expansion of the pellet market since 2000, accentuated between 2008 and 2010 due to the massive replacement of traditional boilers in favour of those powered by pellets, and the growth of the importers and retailers of pellets on the regional territory, has allowed the local entrepreneurs to move towards innovative and cooperative actions. A form of diversification undertaken by the forest companies to try to adapt to market changes includes the provision of raw material for the production of wood chips to processing companies.

An additional strategy implemented by some forest companies in Basilicata region is represented by attempts to produce pellets from the local forest, delegating, however, some processing steps outside the region with a high incidence of transport costs of raw materials and expenses due to the commercialisation of the processed products (Sacchelli et al. 2013). Ultimately, however, company initiatives have arisen with the specific purpose to produce pellets. Hence, there were no real diversification processes or conversions of local logging companies. Therefore, the decline of traditional companies, characterised mainly by scarce generational turnover, is still in progress.

The four official pellet plants currently present in Basilicata region are characterised by low yields and small catchment areas. At the same time, the inadequate financial envelope does not allow them to sustain the realisation costs of medium-large structures. In addition, this would also require an upstream supply system capable of supporting the long-term demands of the plants. In this framework, the current state of the supply is not guaranteed by the forest governance system, especially for public ones.

4 Materials and methods

4.1 Description of the study area and the analysed systems

The analysis was performed in 2015, and two case studies were investigated. The two analysed factories are located in Tito (Potenza province, Basilicata region, Italy). The first enterprise (case 1) produced pellets from roundwood beech logs (*Fagus sylvatica* L.) from regional forests. In this case, after the motor-manual felling and delimbing with a chainsaw, timber was yarded with a tractor along the forest track and transported to the factories for chipping and pelletisation.

The second enterprise (case 2) was a sawmill producing semi-finished, wooden packing cases and railway sleepers in oak (*Quercus cerris* L. and *Quercus pubescens* Willd.). Ecological pellets were mainly produced from the sawdust as co-products. The transformation process was the same as in case 1, but in this case, there was no chipping operation but the manufacture of semi-finished, the mixing of the sawdust produced with bought wood chips and pelletisation to produce pellets.

The wood utilised by the analysed factories belongs mainly to a regional mixed high forest stand (Abriola, Basilicata Region 40° 29′ 42″ N, 15° 54′ 28″ E). Here, the distribution of beech consists of pure and mixed stands with oak, at the lowest altitude, and occasionally silver fir (*Abies alba* Mill.) and douglas fir (*Pseudotsuga menziesii* Mirb.) (stands artificially planted during the 1960s).

4.2 Environmental analysis

The environmental analysis was carried out according to LCA methodology from ISO 14040 and 14044 standards (ISO 14040: 2006; ISO 14044: 2006). The SimaPro v. 8.04 software (PRé, various authors 2015) was used to determine the environmental impacts of the examined systems.

4.2.1 Goal definition, functional unit and system boundaries

The goal of this analysis was to estimate and compare the environmental impacts of the production of packed wood pellets by two different systems (logs and sawdust). The results of this analysis can be useful, on the one hand, for forest harvesting enterprises, sawmills, technicians and local politicians to build the chain of custody for forest products and, on the other hand, for consumers to trace the chain of these products to a definite territory of origin. Therefore, the functional unit chosen, namely the reference unit that expresses the function of the system in quantitative terms and provides the reference to which all data in the assessment are normalised, was 1 t of produced pellets.

The system boundaries considered for the purpose of the current investigation were from the tree felling to the pellet packaging (Fig. 1). In particular, the following activities were

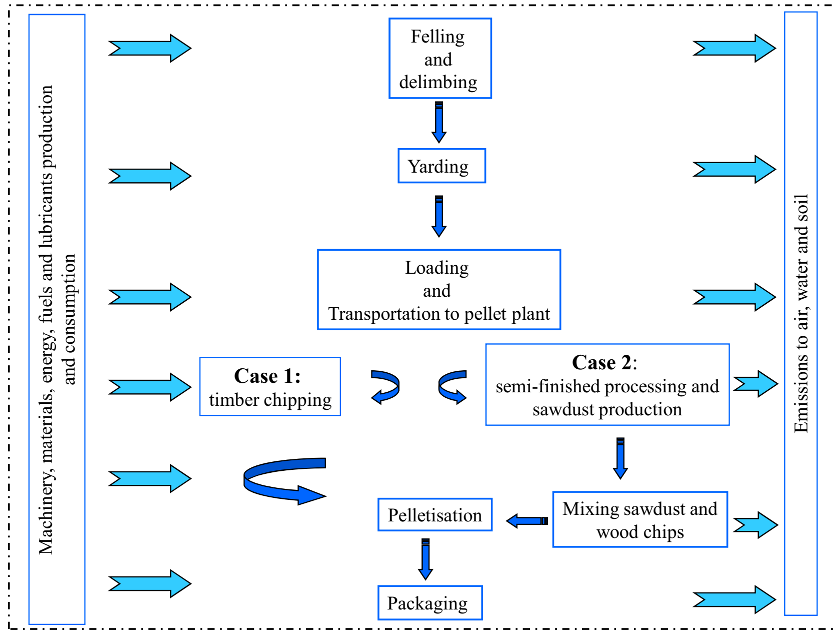

Fig. 1 System boundaries for the case studies analysed

considered: motor-manual felling and delimbing with a chainsaw; timber yarding with a tractor along the forest track; loading and transportation of the logs to the collection point, transportation of timber to the factories for a distance of 35 km, pellet production (chipping and pelletisation for case 1, sawdust production from semi-finished products processing and pelletisation of the sawdust for case 2) and pellet packaging in LDPE (low-density polyethylene) bags with a total weight of 15 kg bag^{-1}. Therefore, the system boundaries encompassed impacts associated with fuel usage and electricity consumed in the various operations. Referring to machines, only those used in forestry were considered; in particular, manufacturing, maintenance and final disposal were taken into account.

In case 2, the production of the pellets was a co-product of the enterprise. Indeed, it was a sawmill producing mainly semi-finished, wooden packing cases and railway sleepers in oak. Allocation, or the division, of the environmental impacts between the products and co-products has been performed on the quantity produced. In particular, pellet production represented 40% of the total production of case 2, so pellets give 40% of the environmental impacts.

4.2.2 Data collection and life cycle inventory analysis

The inventory of the data associated to the studied systems was collected in situ, using a data collection sheet. Information on the quantities of machinery, fuel, electricity and other items used was gathered. All items and all machinery used in the examined systems are reported in Tables 1 and 2.

In the present study, the quantity of materials and the amount of electricity, fuel and lubricants consumed for each operation (felling, yarding, loading and transportation, pellet production and packaging) have been measured and used in the analysis. Emissions from input production (diesel, lubricants, electricity, LDPE) and those from the construction of the vehicles were derived from the ECOINVENT 3 database (Moreno Ruiz et al. 2013).

Referring to the electricity, the dataset describes the transformation from medium to low voltage as well as the distribution of electricity at low voltage. In particular, it encompasses the electricity production in Italy and from imports and the transmission network. Also, electricity losses during low-voltage transmission and transformation from medium voltage were accounted by Moreno Ruiz et al. (2013). The fuel and lubricant consumption model considered the transportation of products from the refinery to the end user. The inventory of vehicles and machines used in the forest took into account the use of resources and the amount of emissions during their production, use, maintenance, repair and final disposal. The machines used for the pellet production (chipper and pelletiser machines) were not considered in the present analyses for the lack of appropriate and specific information (constructive features and weights).

4.2.3 Life cycle impact assessment

The impact assessment was performed following the IMPACT 2002+ (acronym of IMPact Assessment of Chemical Toxics) method, a combination of four methods: IMPACT 2002 (Pennington et al. 2005), Eco-indicator 99 (Goedkoop and Spriensma 2000), CML (Guinée et al. 2002) and IPCC (Jolliet et al. 2003). The following six impact categories were evaluated according to the selected method: ozone layer depletion (OLD), photochemical oxidation (PO), acidification (A), eutrophication (E), global warming (GW) and mineral extraction (ME). As suggested by the authors of IMPACT 2002+

Table 1 Items used in the examined case studies. Values per ton of the pellet. In case 1, pellets are produced from roundwood logs; in case 2, pellets are produced mainly from sawdust

<table>
<tr><th></th><th>Case 1</th><th>Case 2</th></tr>
<tr><td>Felling</td><td></td><td></td></tr>
<tr><td>Lumber (t)</td><td colspan="2">2.00</td></tr>
<tr><td>Machinery (h)</td><td colspan="2">0.88</td></tr>
<tr><td>Diesel and lubricants (kg)</td><td colspan="2">1.85</td></tr>
<tr><td>Human labour (h)</td><td colspan="2">0.88</td></tr>
<tr><td>Load</td><td></td><td></td></tr>
<tr><td>Machinery (h)</td><td colspan="2">0.17</td></tr>
<tr><td>Diesel and lubricants (kg)</td><td colspan="2">0.82</td></tr>
<tr><td>Human labour (h)</td><td colspan="2">0.17</td></tr>
<tr><td>Transportation</td><td></td><td></td></tr>
<tr><td>Machinery (h)</td><td colspan="2">0.13</td></tr>
<tr><td>Diesel and lubricants (kg)</td><td colspan="2">2.01</td></tr>
<tr><td>Human labour (h)</td><td colspan="2">0.11</td></tr>
<tr><td>Timber chipping</td><td></td><td></td></tr>
<tr><td>Machinery (h)</td><td>0.20</td><td>–</td></tr>
<tr><td>Diesel and lubricants (kg)</td><td>2.49</td><td>–</td></tr>
<tr><td>Human labour (h)</td><td>0.03</td><td>–</td></tr>
<tr><td>Sawdust production from semi-finished processing</td><td></td><td></td></tr>
<tr><td>Machinery (h)</td><td>–</td><td>0.08</td></tr>
<tr><td>Diesel and lubricants (kg)</td><td>–</td><td>0.03</td></tr>
<tr><td>Electricity (kWh)</td><td>–</td><td>2.00</td></tr>
<tr><td>Human labour (h)</td><td>–</td><td>0.01</td></tr>
<tr><td>Pelletisation</td><td></td><td></td></tr>
<tr><td>Machinery (h)</td><td>3.93</td><td>1.02</td></tr>
<tr><td>Diesel and lubricants (kg)</td><td>–</td><td>2.45</td></tr>
<tr><td>Electricity (kWh)</td><td>83.00</td><td>18.00</td></tr>
<tr><td>Wood chips (used as fuel) (kg)</td><td>–</td><td>321.00</td></tr>
<tr><td>Human labour (h)</td><td>0.05</td><td>0.16</td></tr>
<tr><td>Packaging</td><td></td><td></td></tr>
<tr><td>LDPE bags (no.)</td><td>67.00</td><td>67.00</td></tr>
<tr><td>Human labour (h)</td><td>0.16</td><td>0.16</td></tr>
</table>

method, normalised scores were analysed at damage level (Humbert et al. 2012). The normalisation analyses the respective share of each impact to the overall damage of the considered categories, and it is performed as the ratio between the impact (at damage categories) and the respective normalisation factors. These latter represent the total impact of the specific category divided by the total European population. The total impact of the specific category is the sum of the products among all the European emissions plus resource consumption in 2000 and the respective damage factors.

Table 2 Machinery considering in the analysis of the examined case studies

Operation	Machinery
Felling	Chainsaw 455 Rancher II AutoTune
Load	Tractor Same Explorer 80 CHD
	Crane for tractor 60 NFG
Transportation	Tractor Motransa FIAT 980 DT 12 1
	Lorry Volvo/Straller 430
Chipping	Chipper CIP2300 Motor IVECO N45 (TRIAL3)

In the present study, after classification, characterisation and normalisation, we also added the weighting phase, an optional step in life cycle impact assessment (LCIA). In particular, weighting entails multiplying the normalised results of each of the impact categories with a weighting factor that expresses the relative importance of the impact category. Thanks to weighting, results all have the same unit (mPt) and can be added up to create one single score for the environmental impact of a product or scenario.

4.3 Cost production analysis

The production cost of 1 t of pellets was analysed according to the life cycle costing (LCC) methodology, a method utilised to calculate the total cost throughout the product's life including acquisition, installation, operation, maintenance, refurbishment and disposal (Bai 2009). LCC is a complementary tool, which provides an economic analysis of the operations composing the supply chain of a product or service (Brandão et al. 2010). LCC does not have a standardisation framework to follow. However, the life cycle approach and methodologies from ISO 14040 for LCA can be applied to these other aspects (ISO 2006). In order to join LCC with LCA, in this study, the analysis was conducted with the same system boundaries described for LCA. The life cycle inventory of the LCA was an excellent basis for identifying and allocating all costs in an efficient manner.

According to Thek and Obernberger (2004), for each case, the economic evaluation of the total pellet processing was done taking into account the following costs: capital and maintenance costs (investment costs of all units of the pellet production process as well as of construction, offices and data processing, market introduction and planning as well as the utilisation period and maintenance costs of all units and facilities), consumption costs (costs for raw material, electricity consumption, fuel usage), operating costs (personnel costs) and other costs (insurance rates, overall dues, taxes and administration costs).

In order to calculate the different costs, data on capital equipment expenditures were taken from literature (Thek and Obernberger 2004; Monarca et al. 2011) for lack of this information; consumption and operating costs were collected in situ during 2015; whilst the "other costs" were calculated as a percentage of the overall investment costs (2%) (Uasuf and Becker 2011).

Table 3 Life cycle impacts per ton of pellet from the two case studies. In case 1, pellets are produced from roundwood logs; in case 2 pellets are produced mainly from sawdust

Impact categories	Unit t^{-1}	Case 1	Case 2
Acidification	kg SO_2eq	2.712	1.359
Eutrophication	kg PO_4P-lim	0.005	0.002
Global warming	kg CO_2eq	83.237	37.567
Mineral extraction	MJ surplus	0.947	0.835
Ozone layer depletion	kg CFC_{-11}eq	0.00001	0.000002
Photochemical oxidation	kg C_2H_4eq	0.060	0.041

The raw material assumed for pellet production was beech logs for case 1 and a mix of oak and beech sawdust for case 2. The average raw material prices were recorded on the marketplace of Potenza province in 2015 (60 €/t for beech and oak timber at the collection point). The personnel costs were accounted as hourly labour, and tariffs were recorded as above (9 €/h for specialised labour; 6 €/h for generic labour net of taxes). The prices of the electricity consumption and diesel fuel usage were 0.27 €/kWh and 0.8 €/l, respectively.

5 Results and discussion

5.1 Environmental impacts

Table 3 shows the results on the life cycle impacts per ton of pellets produced according to the study cases. The production of 1 t of pellets mainly emitted:

- 83 kg of CO_2eq in case 1 and 38 kg in case 2, which is mainly responsible for global warming;
- 2.7 kg of SO_2eq in case 1 and 1.4 kg in case 2, which causes air acidification;
- 0.005 kg of $PO^3{}_4$-eq in case 1 and 0.002 kg in case 2, which is responsible of eutrophication.

In addition, we also obtained mineral extraction, expressed in megajoules surplus energy/kg extracted, equal to 0.9 both in cases 1 and 2.

Referring to global warming potential (GWP), the only impact category which can be compared with other studies, because no other results are available, was on average similar to most of the data available in literature: i.e. 40 kg CO_2eq t^{-1} for high-quality pellet production for domestic heating in the Tuscany region (Laschi et al. 2016) and 87.19 kg CO_2eq t^{-1} for the wood pellet production in British Columbia (Magelli et al. 2009), etc, whilst, in other cases, our values were slightly higher: i.e. from 16 to 35 kg CO_2eq t^{-1} for the pelleting process of olive husks using solar thermal collectors for heat production and solar photovoltaics for electricity production in Cyprus (Kylili et al. 2016). In some other cases, our values were much lower: i.e. from 167 to 240 kg CO_2eq t^{-1} for conventional pelleting process of olive husks in Cyprus (Kylili et al. 2016) and from 100 to 1102.5 kg CO_2eq t^{-1} for the wood pellet production in Ireland (Murphy et al. 2015). The differences among our results and literature data could be due to several factors: diverse system boundaries, inventory analysis, software and method used for the impact characterisation.

The differences obtained between cases 1 and 2 (Fig. 2) highlighted how case 1 led to higher environmental impacts, and this was even more evident observing weighed data. It was observed that pelletisation and packaging were operations with more impact in case 1, representing 46 and 19% of the total impact, respectively, followed by chipping (15%) and transportation (13%). On the contrary, in case 2, packaging

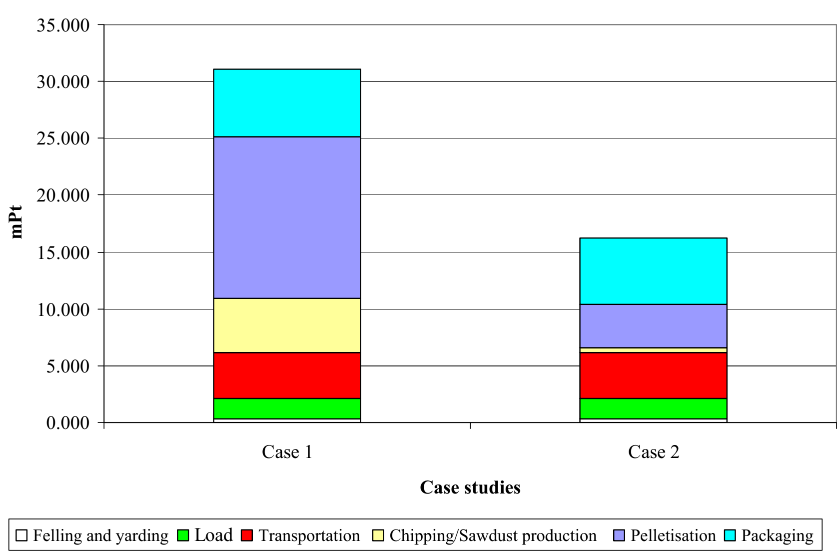

Fig. 2 Weighing of the impact categories of the examined case studies. *White*: felling and yarding, *green*: load, *red*: transportation, *yellow*: chipping/sawdust production, *blue*: pelletisation, *blue green*: packaging

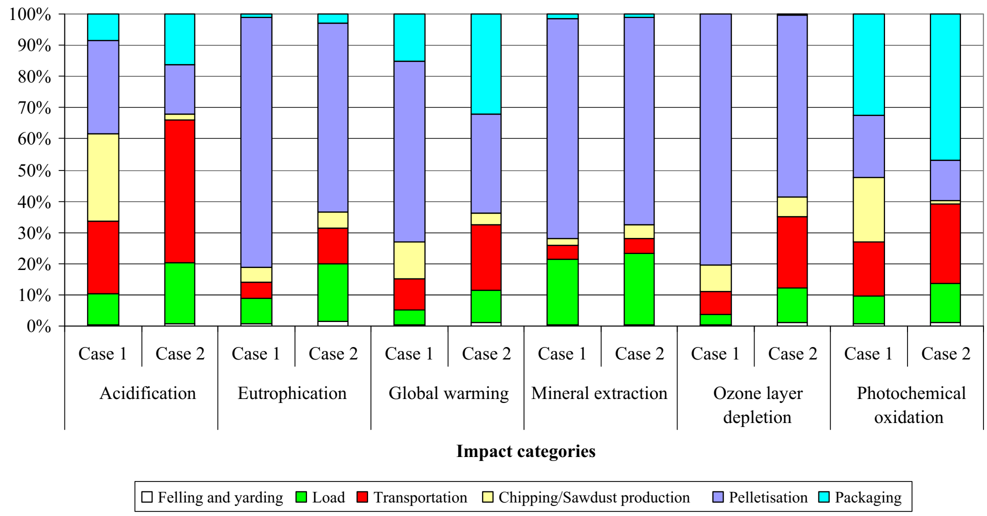

Fig. 3 Characterisation of the impact categories of the examined case studies. *White*: felling and yarding, *green*: load, *red*: transportation, *yellow*: chipping/sawdust production, *blue*: pelletisation, *blue green*: packaging

was the most impactful operation (36%), followed by transportation (25%) and pelletisation (23%). Operations carried out in the forest (felling and yarding) produced the minor part of the impact (1% in case 1 and 2% in case 2). This latter result was in line with data reported by Laschi et al. (2016), who showed that in the production of high-quality pellets for domestic heating, the forest operations produced from 1 to less than 10% of the impact depending on the category.

The highest environmental impacts of case 1 (about 50% more) were essentially due to the operation of pelletisation and in particular to the electricity consumed in this phase (83 versus 18 kWh). In case 2, the pellet plant was powered by electricity, also by wood chips and diesel fuel, making it more sustainable (Table 3).

The electricity consumed during pelletisation caused mainly ME, OLD, eutrophication and GWP in both study cases. The production of the LDPE bags for packaging operation caused mainly PO, GWP and air acidification. Production and consumption of fuel during transportation caused mainly air acidification above all in case 2 (Fig. 3). Therefore, in both study cases from the normalisation data (Fig. 4), the most damage affected resource depletion and human health.

5.2 Pellet production costs

LCC was employed to compare the economic results of two study cases in order to better evaluate the sustainability of the pellet production in Basilicata region. In our experimental conditions, the production costs of 1 t of pellets were equal to 172 € in case 1 and about 113 € in case 2 (Table 4). Our findings were similar compared to the ones reported in other studies. In particular, Thek and Obernberger (2004) accounted for 90.7 € t^{-1} pellets under Austrian framework conditions. Specific wood pellet production costs under Italian framework conditions (Umbria region) were 191 € t^{-1} pellets (Monarca et al. 2011). Wood pellet production costs in Finland, Germany, Sweden, Norway and the USA vary between 119 and 160 € t^{-1} including domestic transport (Trømborg et al. 2013). Sikkema et al. (2011) compared production costs for pellet production in Sweden, Italy and the Netherlands and found these costs ranging between 110 and 170 € t^{-1}. Only Uasuf and Becker (2011) showed relative lower costs, ranging from 35 to 47 € t^{-1} of wood pellets, under different framework conditions in Northeast Argentina.

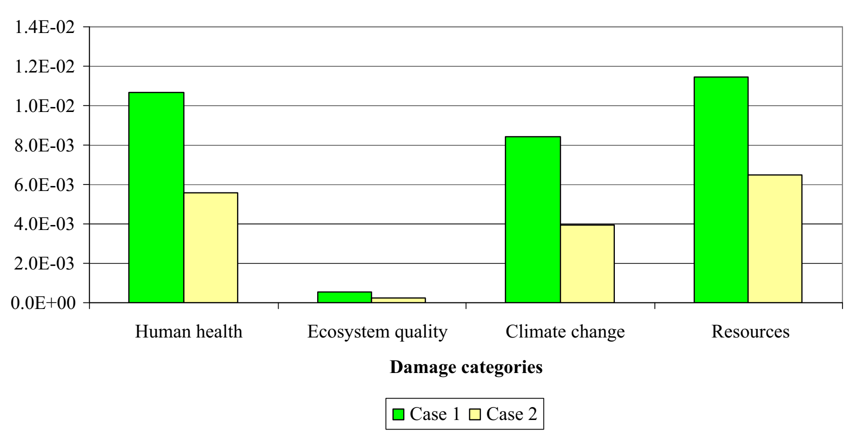

Fig. 4 Normalisation of the damage categories of the examined case studies. *Green*: case 1, *yellow:* case 2

Table 4 Cost items in the examined pellet productions (€ t^{-1} of pellets). In case 1, pellets are produced from roundwood beech logs; in case 2, pellets are produced mainly from sawdust

	Case 1	Case 2
Capital and maintenance costs	3.0	2.6
Consumption costs	161.0	101.7
Costs for raw material	120.0	72.0
Electricity consumption	22.3	4.9
Fuel usage	1.9	0.1
Wood chips	–	8.0
Bags	16.8	16.8
Operating costs	8.2	8.5
Personnel costs	8.2	8.5
Other costs	0.1	0.1
Total	172.2	112.8

In both of our study cases, consumption costs (costs for raw material, electricity consumption, fuel usage, wood chips and bags) were the most important cost items. Within these costs, the acquisition of raw material (beech and oak logs) constituted the major cost, representing 70 and 64% of the total cost in case 1 and case 2, respectively. These results were in good agreement with Uasuf and Becker (2011), which showed that raw material was the dominant cost factor in their four analysed scenarios, and with Thek and Obernberger (2004), who stated that the production costs for wood pellets are mainly influenced by the raw material costs and, in the case of using wet raw materials, by the drying costs. These two parameters can contribute up to one third of the total pellet production costs. In our findings, the lower production costs of case 2 are essentially attributable to the processing of pellet production that in this case is carried out for 40% of virgin wood and 60% by sawdust (wood processing waste). As suggested by Kang et al. (2013), mixing lumbering by-products (sawdust) and forest management products (lumber) in appropriate ratio rather than to use only sawdust or lumber can be an efficient solution for reducing the manufacturing costs of wood pellet production.

6 Conclusions and future perspectives

Under our experimental conditions, the production of 1 t of pellets mainly from sawdust (case 2) had a lower impact and lower production costs, if compared with the pellet production using beech logs in case 1. Furthermore, in both analysed cases, the operations carried out in the forest produced the minor part of the impact but, at the same time, were the most expensive operations.

We can conclude that the combined use of LCA and LCC could be useful to provide information for policy makers and producers in choosing sustainable management systems or products. Furthermore, Basilicata region, with its high rate of forested areas, if better managed, can help Italy to satisfy its domestic needs without resorting to imports and create a sustainable, low-carbon, resource-efficient and competitive economy.

Indeed, future perspectives concern, on the one hand, the precision, completeness and representativeness of the data and the consistency and reproducibility of the methods used; on the other hand, future studies should concern the expansion of the economic analysis of the production of wood pellets, also including the monetisation of the main effects, positive and negative, on the environment.

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