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Wood pellet as biofuel: a comparative life cycle analysis of a domestic and industrial production chain

Tesi di laurea in: Sistemi di gestione ambientale, di politica ed economia ambientale

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Summary

Abstract

This study focuses on the environmental impact assessment through Life Cycle Assessment (LCA). In particular, the aims are to compare the environmental impacts of ‘‘A1 premium’’ wood pellet manufacturing in a large industrial plant with “domestic” wood pellet manufacturing in a small pelletiser, and to identify the environmental hotspots of these two pellet productive chains. The raw material, for both systems is maritime pine wood, a cradle-to grave life-cycle inventory is used and, thus, the system boundary began with the forest stage and ends with ashes disposal after pellet burning. For the forest stage, two scenarios were simulated (intensive and extensive). Moreover, in a sensitivity analysis, alternative scenarios were tested for pellet burning (higher and lower emissions) and for transports (higher distances). The results underline the fact that electricity consumption due to machinery used for the compressing phases of pelletising process has a key role in the environmental profile, together with pellet burning. The production of the wood has a low impact if compared with the other main stages of the pellet production chain. The sensitivity analysis revealed that transport distances have a great impact in the ozone depletion category and climate change, especially when a high transport distance is assumed. Moreover the sensitivity analysis demonstrated that the pellet burning stage has a large impact, even when low emissions are adopted. The industrial model, with high emissions assumed for pellet burning is the worst scenario in terms of environmental performance. The model with less overall environmental impacts is the domestic model, with low emissions for pellet burning and extensive forest management. The comparison between the domestic and industrial model shows that, the domestic model performs better, having better performances on 6 impact categories out of 8 (the exceptions are freshwater eutrophication and metal depletion category, due to higher electricity consumption in pellet manufacturing than the industrial model). Great differences can be seen in particulate matter formation, the industrial model shows an impact 67%

higher than the domestic model, mainly due to forest residues burning process (for the thermal energy production for wood drying in the industrial pellet plant), this process is avoided in case of domestic production. The pellet burning stage and the electricity consumption have to be considered as key phases in the production chain, to achieve good environmental performances, the best available emission saving technologies should be used for the pellet stove, together with a renewable source of the electricity for the pelletizing process.

1 Introduction

With the increasing concerns in the advanced countries over energy needs, fossil fuels, and the environmental dangers connected with climate changes, energy policies started to move in the direction of renewable energy sources. *Cleary et al. (2015)*

The environmental issue to which big attention is paid today, is the global warming generated by some chemical compounds named GHG, greenhouse gases (CH_4, CO_2, N_2O, O_3, and halocarbons): if they are released into the atmosphere, they can absorb a portion of electromagnetic spectrum in the range of infrared, that allows to transmissions of heat. Those gases absorb infrared radiations emitted from earth and contribute to a rise in temperature.
This is not a direct trouble for mankind, but it changes the ecosystem equilibrium in an irreversible way.
The production and usage of biofuels or generally green energy is a must, because already in the year 2004 the use of fossil fuels was responsible for the 57% of CO_2 emissions on a world scale.
These emissions are responsible of various processes which are related to climate changes, as:

- Oceans temperature rising
- Oceans level rising
- Oceans chemistry changes
- Ecosystem depletion
- Biodiversity reduction

Considering these issues, politics over the worlds moved to the concepts of sustainability development that wants to achieve a better environmental performance to guarantee a future to the new generations
Currently, with the European directive 2009/29/CE (20+20+20), Europe wants to reduce GHG emissions by 20% respect to 2005 (reference year), reduce consumption by 20% and to produce the 20% of consumed energy by renewable sources. *European commission (2007)*

1.1 Biomass and energy resources

Since long times, biomass has been a convenient and renewable energy source for humanity. Thanks to its easy supply and relatively high heating value, biomass was used for a long time in many applications, from cooking to spatial heating, lighting, and steam production. *Cespi et al. (2014).*

Biomass was afterwards substituted by fossil fuels that have a higher energy efficiency, but with some disadvantage: pollution, depletion, and management difficulties that increase with the consecutive extraction, in attrition to the fact that nonrenewable resources are located only in certain places of the world.

With those concerns, the trend expected for the next years is to expand the use of biomass for energy and heat requirements, reductions in fossil fuels will happen especially in power plants were coal is used. Biomass combustion emits less GHGs (greenhouse gases) than other fuels, so a replacement with biomass will be an international recognized means of reducing climate change impact.

As detailed in the study of *Calderón et al. (2016)* “generally, more than two thirds of biomass used in Europe consist of solid biomass (69%), biogas and biofuels represent 12% and 13% of gross inland energy consumption of biomass and biowaste.“

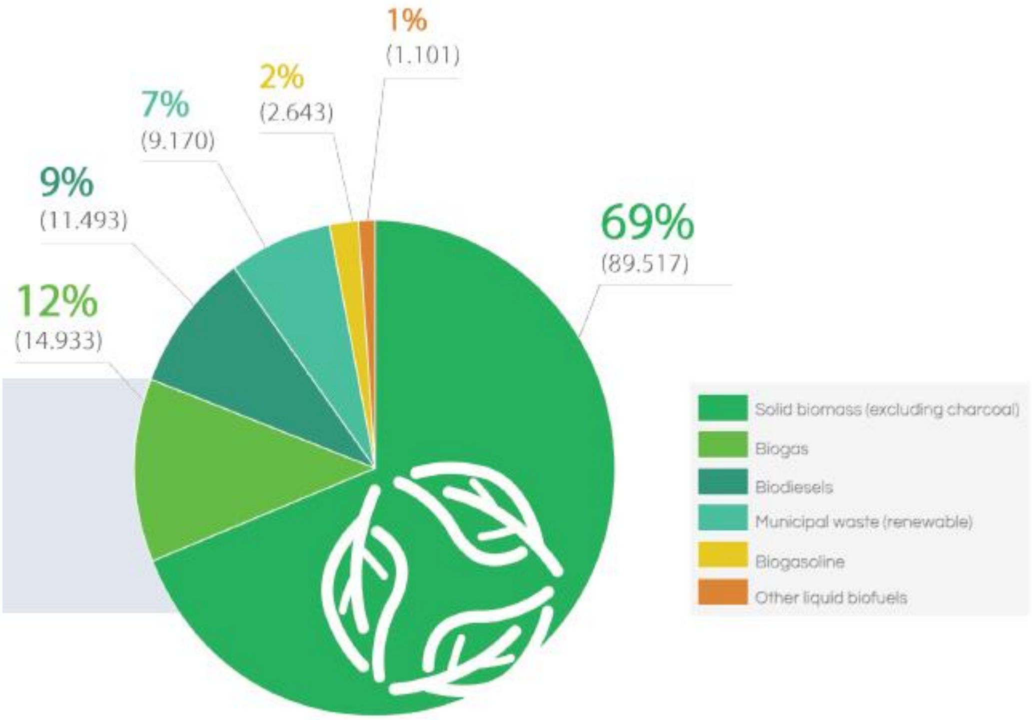


Figure 1: Gross inland energy consumption of biomass and biowaste Calderón et al. (2016)

This type of biomass (solid) is the market driver for biomass (fig 1), and is generally represented by compressed wood, although woody biofuel includes logs, chips and pellets.

In Europe, the Directive 2009/28/EC incentivizes the use of woody biomass as fuel in combustion plants to generate heat or power and aims to reduce fossil resource consumption. *Cleary and Caspersen (2015).*

For heating systems of residential users, woody biomass provides an attractive option for domestic needs, where fossil fuels account for about 15 % of the total energy consumed in domestic sector throughout Europe. *Verma et al. (2009).*

Biomass resources can be easily collected respect to fossil fuels, and they are commonly recognized as having better environmental performance thanks to a lower contribution to global warming, supporting the goal of achieving a Low Carbon Society. However, the carbon balance should be carefully evaluated and different implications on the environment (e.g., land use occupation and depletion) may result whether or not energy related implications from dedicated crop cultures are considered. *Cespi et al. (2014)*

According to *Sikkema et al. (2011)* the energy consumption of wood and wood waste has grown from 125 million tonnes in 2000 to 175 million tonnes in 2009, however woody biomass use in the transport sector (as biofuel) is still limited.

The forest sector in EU has a key role in the development of woody biomass use, in the year 2000 the consumption of wood logs was 366 million m^3, for the year 2020 the consumption prevision is about 481-576 million m^3, with an increase of 80-125 million (in tonnes). *Sikkema et al. (2011)*

Statistical studies on bioenergy, (Figure 2, *Calderón et al. (2016))* highlight that the domestic usage of wood as energy source, is the main consumption (27%), followed by the industrial use (22%) and domestic small scale use of wood chips (14%), pellet consumption is constantly growing, and it currently represents 6% of the total EU wood energy consumption.

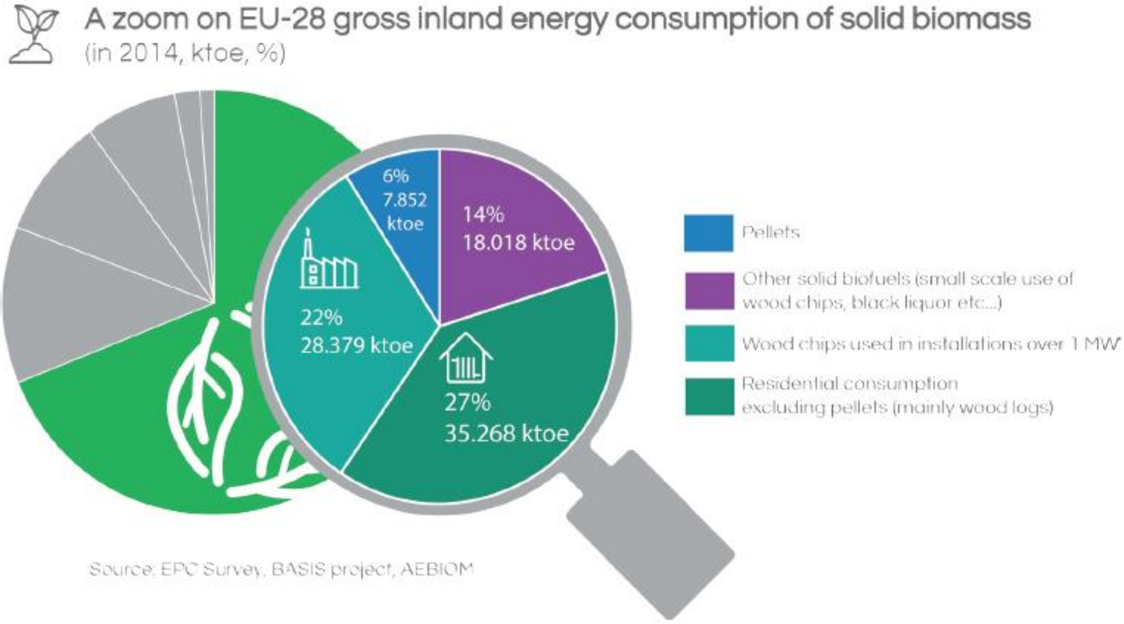


Figure 2: Energy consumption of solid biomass Calderón et al (2016)

Despite common belief, the forests of Europe are growing (fig 3), and as detailed by *Calderón et al. (2016*) the forest of EU increased their area by 34% in the last twenty-five years, with a gaining of 322.800 hectares every year, the carbon stock is increasing as well.

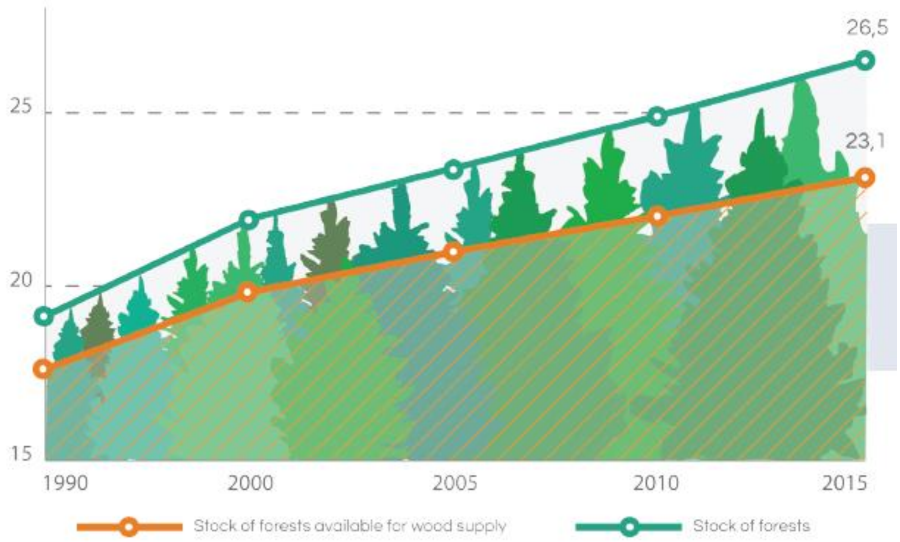


Figure 3: Evolution of forest stock of EU, from 1990 to 2015, million m3

As shown by figure 4, a 38% percent of forest is left untouched, with great increments over the years; this growth is mainly due to the European protection and afforestation programmes, which include a forest management that performs operation as cleaning and thinning that allows to increase forest productivity and carbon stock capacity. This expansion allows great possibilities for woody biofuels exploitation.

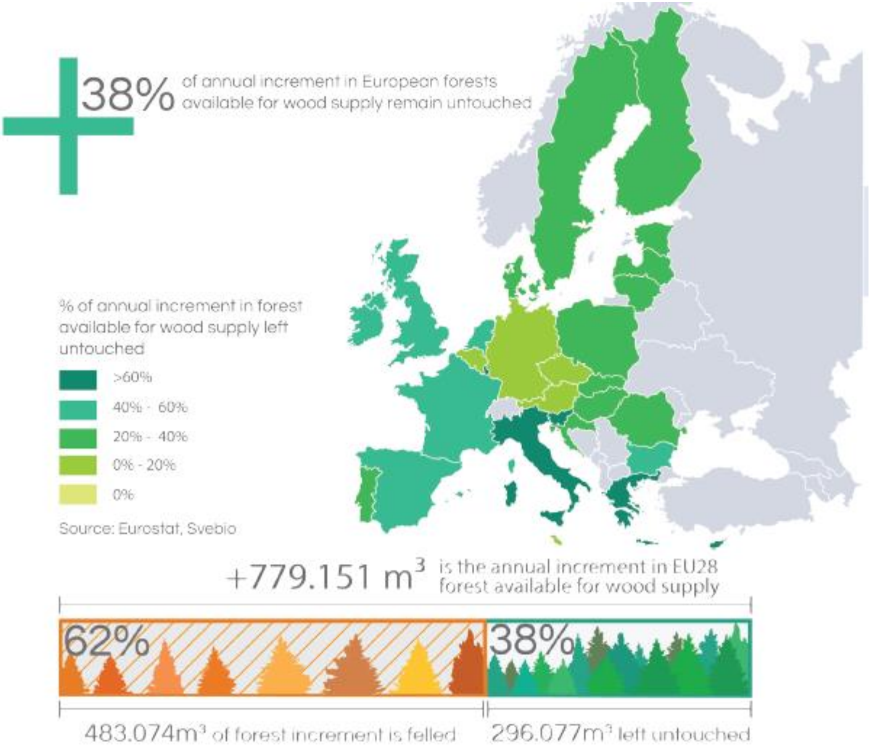


Figure 4: Increment in forest available for wood supply Calderón et al. (2016).

The biofuel analyzed in this study is wood pine pellet that can be produced from large plants to local small plants. However, as Cleary *and Casperse* (2015) explained: “Large plants are usually more efficient at converting biomass to electricity, the feedstock is usually transported to large distances.”

In the present thesis, life cycle assessment (LCA) methodology is applied to create a model that compares the environmental impacts of two types of pellets, a class A1 plus pellet produced by a large pellet industry, and a pellet produced in laboratory, to simulate a local production plant. The comparison between pellets was carried out in terms of tons of pellet produced. Such a functional unit of 1 ton of pellet was chosen in order to make the model suitable for the comparison.

A sensitivity analysis was performed to check the robustness of results and their sensitivity to uncertainty factors of the model. The environmental impacts resulting from the two investigated systems were assessed using the ReCiPe 2008 v.1.12 method for the following midpoint categories: climate change, ozone depletion, terrestrial acidification, freshwater eutrophication, marine eutrophication, photochemical oxidation, particulate e matter formation, metal depletion, fossil depletion.

1.2 Wood Pellet as Biofuel

Wood pellet is a solid biomass fuel with good quality, low moisture content, high energy density and homogeneous size and shape.

Figure 5: Pellet from pine wood

The problems of conventional biomass fuels as an alternative to coal, oil or gas, are attributed mainly to their low energy density, high moisture content and heterogeneity. Those problems are prevented by the use of pellet. Consistent fuel quality makes pellets a suitable fuel type for all areas of application, from stoves and central heating systems to large-scale plants, and with practically complete automation in all these capacity ranges. *Thek et al. (2012).*

The raw material for pellet production used in this study is virgin wood from *Maritime Pine* that is the most abundant forest species in Portugal, being dominant in 25% of the total forest area.

Pellets are made by compressing wood residues into sawdust, and subsequently compressing the sawdust through the holes of a pelletizing machine.

The high pressure applied generates a high quantity of heat that leads to a reducing in pellet moisture (5-10%), after this process the pellet needs to be cooled.

The dimension of a standard pellet is generally 2-3 cm with a packing density is around 650 kg m^3. *Laschi et al. (2016).*

Top quality pellets are used in domestic appliance, and contain high level specs, as low ashes content, low chlorine content and good mechanical proprieties, that allow the transportation of packed pellet in trucks without breaking down*. Laschi et al. (2016).*

As found by the research of *Laschi et al. (2016)* who studied environmental performance of wood pellets through life cycle analysis "Wood pellet production started in the United States as an alternative to fossil fuels during the energy crisis of the '70s. In the last 10 years, the demand has increased together with a demand for higher quality, which derived from a potential conflict between biomass used for energy and its conventional uses (e.g. wood panels)".

Economic incentives and credits have pushed the grown of biomass usage for the production of heat and electricity, with an exponential growth in Europe during the last years despite the fact that densification of wood has been practiced in Europe since 1970s. *Magelli et al. (2009).*

As explained in the study of *Magelli et al. (2009)* "Pelletization creates a clean burning, convenient and energy concentrated fuel from bulky fibrous waste such as sawdust and wood shavings. Wood pellet heating systems are considered as an essential component of European plans to reduce GHG emissions and are targeted by incentive programs in countries such as Germany, Norway and Sweden "

More accurate data can be found in the study of *Sikkema et al. (2011)* that estimates a reduction in 12.6 million tonnes of CO2 eq. in 2008 in Europe plus Norway and Switzerland, based on the substitution of coal and heating oil with 8.2 million tonnes of wood pellet.

Considering the increasing interest in environmental concerns and the development of woody biomass as well as pellet market, and their role in renewable energy and environmental politics, there is an increasing interest in understanding the environmental performances and impacts of this kind of woody biomass, that is living a period of expansion for industrial and domestic usage. Various scientific studies have been made on products from wood, such as paper, bioethanol, or some studies were applied to wood pellets boilers. *Laschi et al (2016).* By the way, there is a lack of studies about the environmental impacts of the pellet production chain especially for the domestic appliance.

In literature there are some studies applied to torrefaction of pellet: *Laschi et al. (2016)* studied the impacts of the domestic productive chain of a high quality pellet, starting from wood production, but in his study the usage process (burning of the pellet) is not taken into account. Pellets are burned (in residential appliance) mainly in pellet stoves that are individual domestic stoves that are primarily used for space heating. Some models are equipped with heat exchangers for a communication with a central heating system and/or sanitary water. Pellet stoves are fulfilled manually. This leads to a stable burning process compared to manually filled stoves and also increases the efficiency of the process. With an automatic fill it is also possible to control the heating output from a range to 30 -100% of the maximum heating process. The normal heating range of the pellet stoves is from 2.5 kW to 25 kW. *Kruse (2016)*

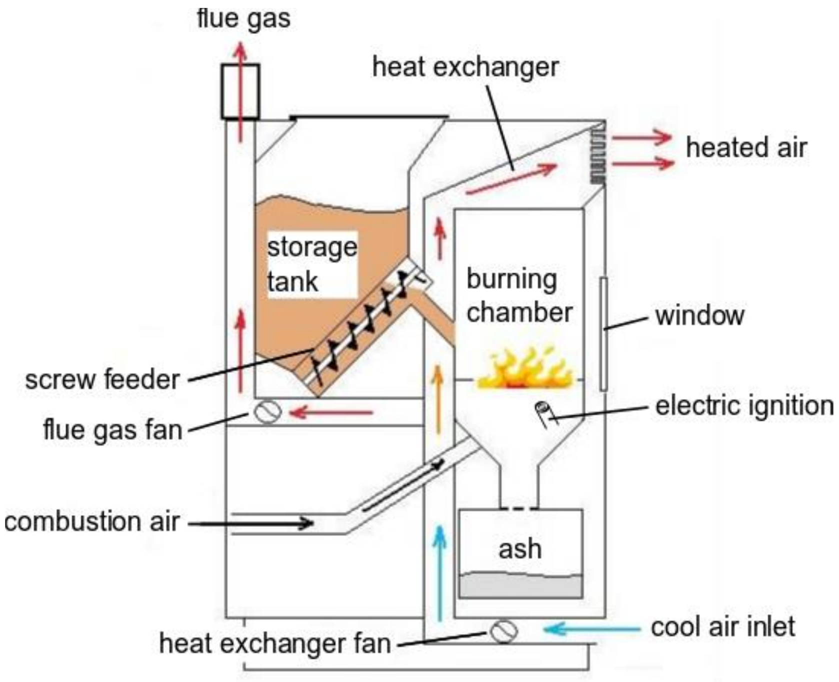


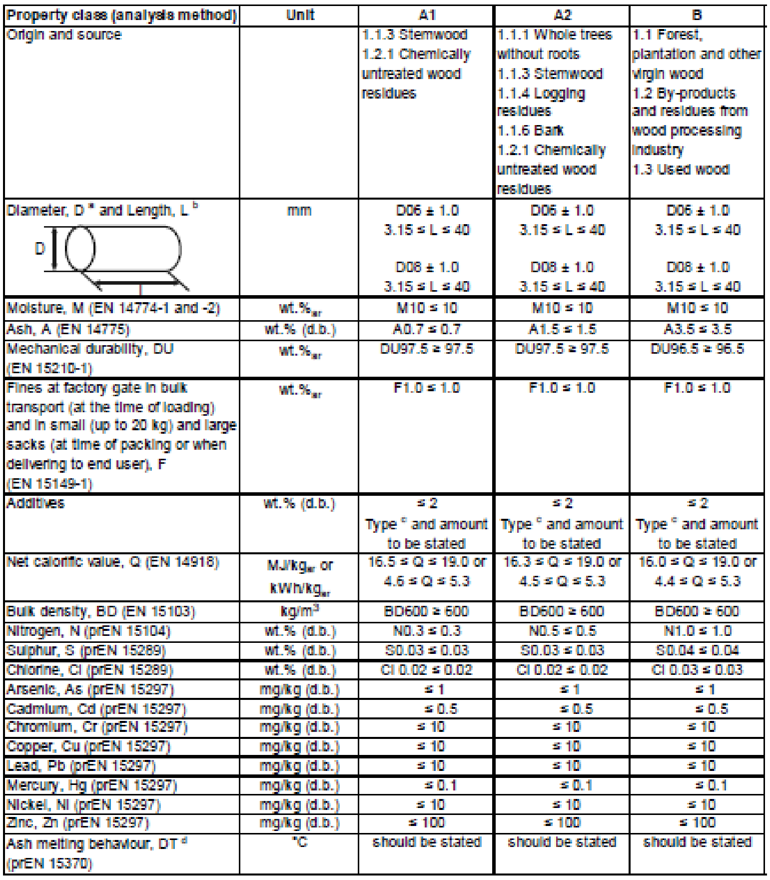
Figure 6: Operating principle of a pellet stove. Kruse (2016)

1.3 Pellet quality standard

In order to be classified as certified pellets they have to respect some quality standards regarding their size, minimal heating value, water content and origin of raw material. This standard is detailed in the EU-norm EN14961-2.

This standard differentiates three different levels of quality, A1, A2 and B.

A1 pellets are the maximum in terms of quality and are the type of pellet analyzed in this study. Pellets that are conform to A1 and A2 quality are usually used for small and medium sized heating system, up to 300 kW. Pellet with an A2 certification are usually burned in industrial scale systems, or generally large power plants. Kruse (2016). The most significant properties for all solid biofuels are moisture content, particle size and ash content. For avoiding dangers to local consumers, some heavy metals are regulated in terms of maximum quantity for wood pellets. A1 wood pellet class represent virgin woods and chemically untreated wood residues low in ashes and chlorine content. Pellets with higher quantities of chlorine or ashes are classified as A2. Class B represent chemically treated industrial wood by-products or used wood. *Obernberger and Thek (2010)*



Property class (analysis method)	Unit	A1	A2	B
Origin and source		1.1.3 Stemwood 1.2.1 Chemically untreated wood residues	1.1.1 Whole trees without roots 1.1.3 Stemwood 1.1.4 Logging residues 1.1.6 Bark 1.2.1 Chemically untreated wood residues	1.1 Forest, plantation and other virgin wood 1.2 By-products and residues from wood processing industry 1.3 Used wood
Diameter, D ^{a} and Length, L ^{b}	mm	D06 ± 1.0 3.15 ≤ L ≤ 40 D08 ± 1.0 3.15 ≤ L ≤ 40	D06 ± 1.0 3.15 ≤ L ≤ 40 D08 ± 1.0 3.15 ≤ L ≤ 40	D06 ± 1.0 3.15 ≤ L ≤ 40 D08 ± 1.0 3.15 ≤ L ≤ 40
Moisture, M (EN 14774-1 and -2)	wt.%$_{ar}$	M10 ≤ 10	M10 ≤ 10	M10 ≤ 10
Ash, A (EN 14775)	wt.% (d.b.)	A0.7 ≤ 0.7	A1.5 ≤ 1.5	A3.5 ≤ 3.5
Mechanical durability, DU (EN 15210-1)	wt.%$_{ar}$	DU97.5 ≥ 97.5	DU97.5 ≥ 97.5	DU96.5 ≥ 96.5
Fines at factory gate in bulk transport (at the time of loading) and in small (up to 20 kg) and large sacks (at time of packing or when delivering to end user), F (EN 15149-1)	wt.%$_{ar}$	F1.0 ≤ 1.0	F1.0 ≤ 1.0	F1.0 ≤ 1.0
Additives	wt.% (d.b.)	≤ 2 Type ^{c} and amount to be stated	≤ 2 Type ^{c} and amount to be stated	≤ 2 Type ^{c} and amount to be stated
Net calorific value, Q (EN 14918)	MJ/kg$_{ar}$ or kWh/kg$_{ar}$	16.5 ≤ Q ≤ 19.0 or 4.6 ≤ Q ≤ 5.3	16.3 ≤ Q ≤ 19.0 or 4.5 ≤ Q ≤ 5.3	16.0 ≤ Q ≤ 19.0 or 4.4 ≤ Q ≤ 5.3
Bulk density, BD (EN 15103)	kg/m^{3}	BD600 ≥ 600	BD600 ≥ 600	BD600 ≥ 600
Nitrogen, N (prEN 15104)	wt.% (d.b.)	N0.3 ≤ 0.3	N0.5 ≤ 0.5	N1.0 ≤ 1.0
Sulphur, S (prEN 15289)	wt.% (d.b.)	S0.03 ≤ 0.03	S0.03 ≤ 0.03	S0.04 ≤ 0.04
Chlorine, Cl (prEN 15289)	wt.% (d.b.)	Cl 0.02 ≤ 0.02	Cl 0.02 ≤ 0.02	Cl 0.03 ≤ 0.03
Arsenic, As (prEN 15297)	mg/kg (d.b.)	≤ 1	≤ 1	≤ 1
Cadmium, Cd (prEN 15297)	mg/kg (d.b.)	≤ 0.5	≤ 0.5	≤ 0.5
Chromium, Cr (prEN 15297)	mg/kg (d.b.)	≤ 10	≤ 10	≤ 10
Copper, Cu (prEN 15297)	mg/kg (d.b.)	≤ 10	≤ 10	≤ 10
Lead, Pb (prEN 15297)	mg/kg (d.b.)	≤ 10	≤ 10	≤ 10
Mercury, Hg (prEN 15297)	mg/kg (d.b.)	≤ 0.1	≤ 0.1	≤ 0.1
Nickel, Ni (prEN 15297)	mg/kg (d.b.)	≤ 10	≤ 10	≤ 10
Zinc, Zn (prEN 15297)	mg/kg (d.b.)	≤ 100	≤ 100	≤ 100
Ash melting behaviour, DT ^{d} (prEN 15370)	°C	should be stated	should be stated	should be stated

Figure 7: Specification of wood pellets for non- industrial use Obernberger and Thek (2010)

1.4 Wood Pellet in Portugal

Nunes et al. (2016) investigated the pellet production state of art of Portugal, and found that “although there are plants throughout the country, most of them are concentrated north of Lisbon. The majority of the 38% of the Portuguese territory that consists of forestland is located there. This forestland is divided mainly into 600,000 ha of Atlantic pine *(Pinuspinaster)* and 380,000 ha of eucalyptus *(Eucalyptus globulus)*.”

The commonly used wood for pellet production is maritime pine *(P. pinaster)* that is the raw material analyzed in this study, but also eucalyptus *(E. globulus)* is used by pellet production plants, if we move to south of Portugal, *Pinuspinea* is used, as it is the most abundant pine locally.

Figure 8: Wood Pine forest in Portugal (available at http://www.leiria.theperfecttourist.com/?p=3611)

As highlighted by the researches of *Nunes et al. (2016)* regarding wood transportation until pellet plants “The critical distance beyond which no one wants to obtain raw material is in the range of 50 e 70 km. Longer distances cause high transportation costs as materials are always carried by truck, disabling the interest in the process.”

New technologies have been developed in the last year regarding pellet combustion, pellet stoves are now fully automated and require just a little maintenance, which is helping to develop and expand the local market, also progresses have been made in the large industrial boiler, that provides more combustion efficiency and an attractive option to companies attracted to woody biomass energy solutions.

This is a great opportunity to countries that have a great quantity of forestall biomass, like Portugal or Italy, and this opportunity should be used as it can be an option for climate change fighting and for new jobs creation. *Nunes et al. (2016)*

1.5 Portuguese and European wood pellets market

Nowadays, wood pellets are one of most traded solid biofuel in the world. In commercial terms pellet can be compared to biodiesel or bioethanol. The advantage of pellet is that it can be easily handled and stored, if compared to other liquid biofuels. The increasing of pellet consumption increased in 2005, with a consumption of 20.3 million tonnes in 2015 (fig 9), this trend is probably related to the good qualities of pellet, such as good environmental performances, high heating value and increasing in prices of fossil fuels, together with economics incentives. *Sikkema et al. (2011).*

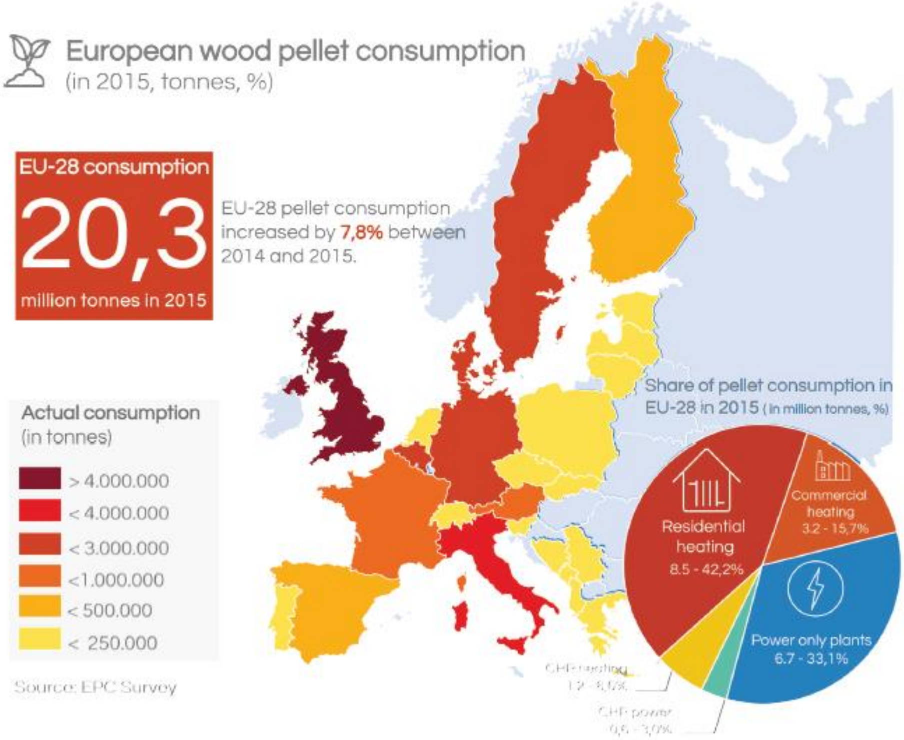


Figure 9: European wood pellet consumption, Calderón et al. (2016)

The request of pellets for domestic usage is constantly growing and, especially in Italy the consumption is one of the highest in the world, as *Laschi et al. (2016)* found “with more than 1.4 Mt of pellet used in 2013.” Only Sweden, Denmark, the

United States and the Netherlands have a higher pellet consumption ratios including industrial use, while Italy is the most important market for both domestic pellet stoves and bagged pellets. Besides that, the production ratio in Italy is low respect to its big demand, with an internal production capacity of about 0.8 Mt in 2010. *Laschi et al. (2016).*

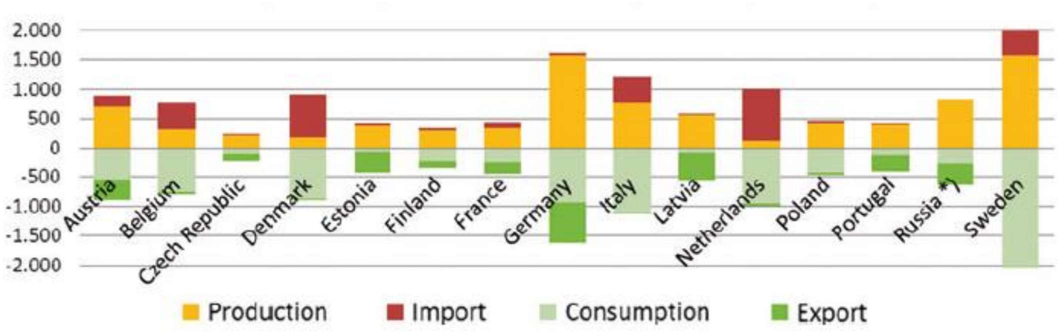


Figure 10: Major wood pellet markets, Sikkema et al. (2011).

The Portuguese pellet market consists of small direct consumers with small and medium peaks in the winter period from October to April. The main consuming sectors for pellets in Portugal are the domestic sector and public services and industries with thermal energy needs. This includes large building heating systems, i.e. bakeries and other similar facilities. In this sector, the largest consumers are mainly elderly care centers, schools and sports facilities. *Nunes et al. (2016).*

Figure 11 A pellet plant in Portugal (available at http://www.biomasspelletplant.com/news/pellet-market-portugal.html)

In the last years, a new kind of consumers has emerged. Due to their big energy needs and due to new European normative regarding incentives, climate changes and environmental protection, they are exploring new forms of cheaper and more sustainable fuels.

This group includes textile dyeing plants, which are very important for the Portuguese economy.

The substitution of fossil fuels, with a biomass as a renewable-oriented energy source, also explores the interesting opportunity of exploiting endogenous natural resources, that are locally available without international commerce and long travel transport distances that result in high emissions for the transport phases. Also, the prices of a locally extracted biomass are more stable, due to the fact that are not related to external geopolitical factors, but only to laws of the internal nation market. *Nunes et al. (2016)*

The pellet market in Portugal has been growing from 2005 till now, from small local plants to a multitude of large plants in just a few years.

The production increasing has been fast, especially in the production capacity, however the domestic sector is still small if compared to the industrial, although sales of domestic pellet burning equipment like pellet stoves and boilers are increasing.

If we have a look on specific data, in Portugal there is now a production capacity of more than a million tons per year. Pellet production in Portugal is mainly led by large factories with over 100,000 tons of annual production that mainly export industrial pellets to European costumers. Those industries are generally owned by large manufactures with just a little connection to wood and forest production chain. The other actors are medium and small pellet plants that generally produce about 40,000 /50,000 tons/year, those kinds of factories are generally connected to biomass productive chain or generally woody production chain, and generally sell pellet to residential users or in the small industries market. A great amount of pellet companies, big and small, that are producing in Portugal, started their activity in the last four years. This happened mainly due to the increase of fossil fuel prices and economic helps, that European countries give for the production and usage of renewable energies. Biofuels are an increasing and interesting business that is growing exponentially in Europe nowadays. *Nunes et al. (2016)*

1.6 Woody biomass and air quality

Besides the advantages of biomass in terms of climate change fighting, there are some issues over their usage in residential heating, due to the emissions of various pollutants such as, NOx, CO, SOx, and particulate matter. Both of the gas emission regulations contained in EU legislation, for protecting the population and the environment and technological progress, have led to more efficient combustion processes and emission control, thus helping to counter the negative effects connected with residential heating systems.

Following the study of *Cespi et al. (2014)* “A high use of biomass combustion system in residential areas together with obsolete appliances, bad stoves maintenance and bad microclimatic conditions, may lead to a worsening of air quality and dangers for human health.”

In details, the contribution of $PM_{2.5}$ is estimated to increase in the future. $PM_{2.5}$ is not only a climate changing substance, but it can also lead to health damages. WHO estimated that in 2012 482.000 premature deaths in Europe were related to indoor and outdoor produced particulate, which is related to lung cancer and respiratory effect in children (as asthma). Furthermore, it was established that particulate leads to the same health problems, whether it is emitted by a biomass or a fossil source. It’s clear that in the future, the problem of containing environmental pollution will have to face up to problems not only related to emissions from fossil fuels, but also problems related to the increase of biomass consumption. *Ranzi and Lauriola (2015)*

1.7 LCA

The rising concerns related to the importance of environmental protection, and the possible impacts associated with products - both manufactured and consumed - have focused the interest on the developing methods to better understand and reduce the environmental issues related to the production chain of products. One of the techniques being developed for this purpose is Life Cycle Assessment (LCA). This International Standard describes the principles and framework for conducting and reporting LCA studies, and includes certain minimal requirements. Industry has used LCA since the late 1980s. The usage by other stakeholders (e.g. green NGOs, consumer rights NGOs) is more recent, but has greatly increased over the past few years. LCA is helping companies and other stakeholders to make

better-informed decisions and public communications. LCA applications can be used in ecolabelling, ecodesign, environmental and carbon footprinting, and waste management. *Wolf et al. (2012)*
As Wolf et al. (2012) explains: “LCA can help to solve strategic problems related to the impact and discover the best way to improve the use of natural resources. It’s useful to guide the development of new energy forms (fuel cells) and to quantify the environmental performance of factories and companies.
LCA is also used to estimate the impacts of different environmental-related political choices and to guide the political world through the best option.”

1.7.1 About LCA

LCA is a scientific, structured and comprehensive method that is internationally standardized in ISO 14040 and 14044. It quantifies consumed resources and emissions as well as the environmental and health impacts and resource depletion issues that are associated with any specific goods or services (‘products’).
LCA is also a technique for assessing the environmental aspects and potential impacts associated with a product, by:

- compiling an inventory of relevant inputs and outputs of a product system

- evaluating the potential environmental impacts associated with those inputs and outputs

- interpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of the study. *ISO (2006)*

A clear definition of LCA studies is presented by *Wolf et al. 2012*: “LCA studies the environmental aspects and potential impacts throughout a product’s life (i.e. cradle to grave) from raw material acquisition through production, use and disposal. The general categories of environmental impacts needing consideration include resource use, human health, and ecological consequences.”

LCA is a helpful tool for:

- Clarifying which are the environmental hotspots of a production chain, contributing to understanding and quantifying which the most environmental impacting phases during the production phases are.

- Helping governments, politicians and companies to make environmental-friendly decisions.

- Create an environmental standard for declarations or certifications for marketing, as EPD, Ecolabel, Made green in Italy that are clear and proved environmental certification that can help the consumer to choose the product with the best environmental performances.

LCA studies the full life cycle of the system being analyzed, from the processing or extraction of raw material, through production phases, use, and disposal of the waste.

LCA helps to reduce the critical points of a production chain, such as waste issues, or critical emissions, or extremely impacting processes and can help the decision maker to choose among technologies, for achieving a most efficient and sustainable production chain. It also can help for making a resource-efficient society and a society in line with the objectives of sustainable development.

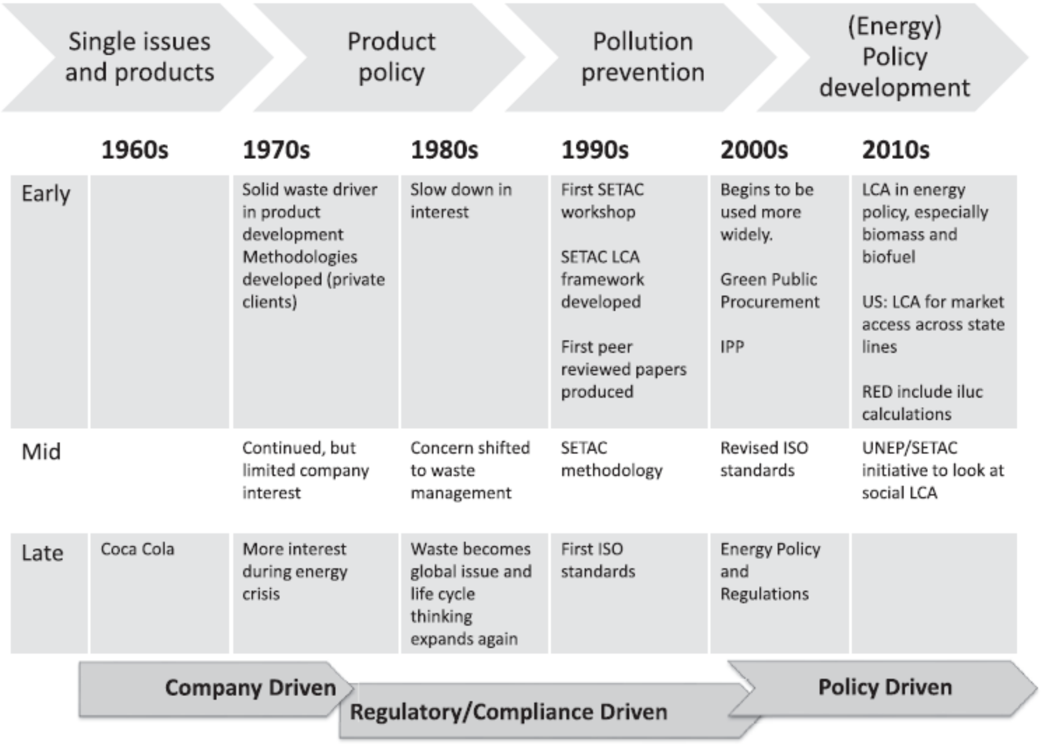
1.7.2 Industry and other stakeholders

Companies have used LCA since the late 1980s, initially it was mostly used by big companies that used it in isolated projects.

The situation changed in the last years, due to increasing communication in the supply chain and the increase of consumer demands, together with the increasing attention in the environmental concerns, LCA has been applied in a large number of sector and Nations.

Nowadays, a great number of large industries have an in-house LCA- expert team that applies a LCA approach to the production chain.

A substantial or even dominant part of LCA activities are carried out in or on behalf of industry for internal decision support and the studies are never published. Such activities help to better inform decision-making in these companies. This includes increasing awareness of activities and their impacts on supply chains, use and end-of-life phases. LCA is also being increasingly used at association level, especially in the form of database development and sector/product-specific European Retail Forum, the European Food Sustainable Consumption and Production (SCP) Round Table, and industry declarations and publications expressing a preference for life cycle-based decision support.



	1960s	1970s	1980s	1990s	2000s	2010s
Early		Solid waste driver in product development Methodologies developed (private clients)	Slow down in interest	First SETAC workshop SETAC LCA framework developed First peer reviewed papers produced	Begins to be used more widely. Green Public Procurement IPP	LCA in energy policy, especially biomass and biofuel US: LCA for market access across state lines RED include iluc calculations
Mid		Continued, but limited company interest	Concern shifted to waste management	SETAC methodology	Revised ISO standards	UNEP/SETAC initiative to look at social LCA
Late	Coca Cola	More interest during energy crisis	Waste becomes global issue and life cycle thinking expands again	First ISO standards	Energy Policy and Regulations	

Figure 12: Expansion of LCA, McManus and Taylor (2015)

The range of application of LCA has also been extended. When LCA started to be used, the main objective was a better compression of the quantitative input and output resources in the productive chain.

Nowadays, LCA has become a tool capable of influencing political decisions and is being used for choosing the best scenario or productive chain, including the best alternative as *Wolf et al. 2012* explains: LCA is "being applied to assess and compare strategic alternatives with respect to, for example, raw materials (e.g. bio-based society) and technologies (such as diesel vs. petrol engines vs. fuel cells). LCA is also employed to capture and monitor corporate environmental performance (e.g. to capture indirect effects in the Eco-Management and Audit Scheme). "

Resuming, with an LCA study it is possible to evaluate the best options within the productive chain, and to choose the processes with less impacts and best efficiency.

1.7.3 Phases of an LCA

An LCA includes five main phases: goal definition, scope definition, inventory analysis, impact assessment and interpretation. Furthermore, it usually concludes with some recommendations.

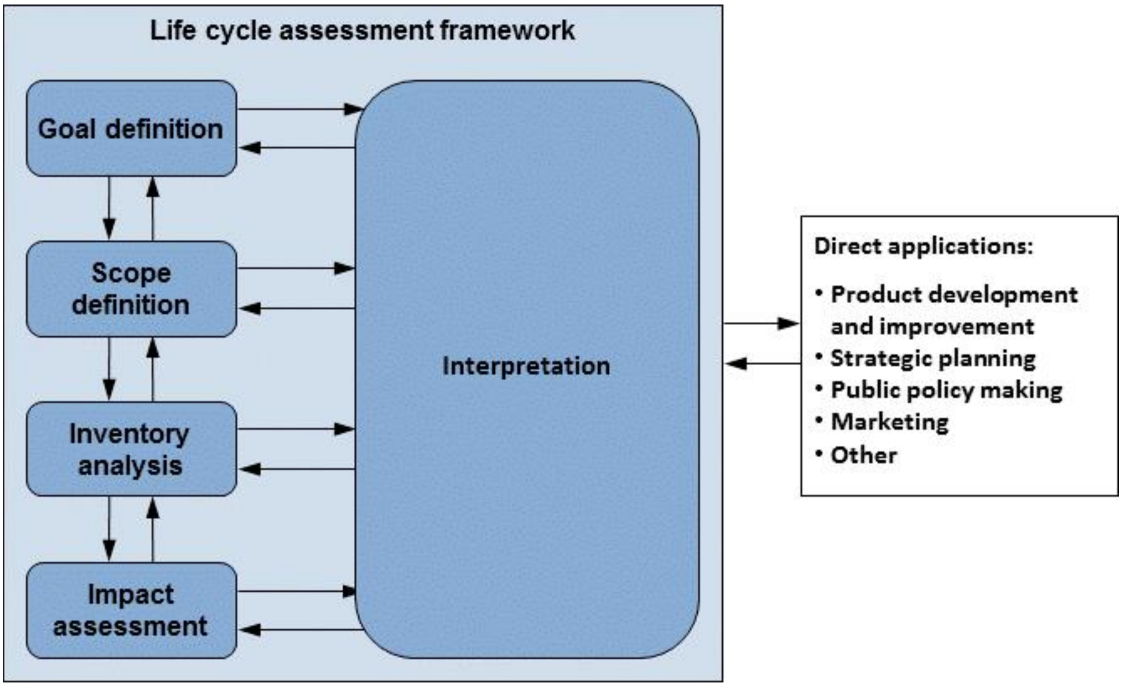


Figure 13: Phases of an LCA Wolf et al. (2012)

- The goal definition is the first step, and includes the context of LCA application and for who the study is performed: companies, decision making, politicians, scientific scope etc. It also specifies whether it will be a comparative analysis or not.

- The scope definition describes the studied system, including the system boundaries, the functional unit, and the stages that are covered by the study, together with the impact assessment method used in the study.

- The Life Cycle Inventory phase collects and uses background and foreground data analyzing in detail all the input and output energy and material flows that are in input or output from the model, including waste flows or downstream processes such as recycling.

- The life cycle impact assessment (LCIA) phase includes the use of the impact assessment method chosen for quantifying the impacts of the model. This process can be done in midpoint terms, such as climate change or ozone depletion, or to endpoint objectives, as human or ecosystem health.

- The interpretation phase identifies the most significant issues or impacts in the production chain discovered in the LCIA stage. It’s based on numerical results, and can contain sensitivity and an uncertainty analysis to increase the accuracy of the model.

LCA is an iterative analysis, due to the fact that after the interpretation phase, it is possible to follow the analysis concentrating on the most impacting and contributing processes in order to increase the performance of the model at every review, and to answer with the best precision to the objectives of the study. *Wolf et al. 2012*

As detailed in ISO (2006) “it is important that the results of LCA be interpreted and applied appropriately. If LCA is to be successful in supporting environmental understanding of products, it is essential that LCA maintains its technical credibility while providing flexibility, practicality and cost effectiveness of application. This is particularly true if LCA is to be applied within small- and medium-sized enterprises.”

1.7.4 Functional unit and reference flow

The functional unit represents the quantified performance of a product system to be used as reference unit for the LCA study. It is the unit of scale or reference on which the LCA results are based, and relates to the given function of the product. The reference flow is the measure of the outputs from processes in a given product system required to fulfil the function expressed by the functional unit.

1.7.5 LCA standards

The main standards are included in the ISO 14040 and 14044, based on those standards were created:

- ISO 14020: (Environmental labels and declarations – General principles)
- ISO 14021: (Environmental labels and declarations)
- Self-declared environmental claims (Type II environmental labelling), ISO 14024 (Environmental labels and declarations)
- Type I environmental labelling Principles and procedures), ISO 14025: (Environmental labels and declarations)
- Type III environmental declarations – Principles and procedures)
- ISO 14067 (draft) on carbon footprint.

Based on the ISO standards, ILCD handbooks were created; those handbooks are a useful guide that explains how to perform an LCA study. *Wolf et al. 2012*

‘

1.7.6 Limitations of LCA

Firstly, some impact categories are by now still not well developed, as the toxical impact characterization which still has problems in the robustness of the model; land use is also not perfectly developed and needs specific kind of data and impact assessment method.

Furthermore LCA does not consider the quality of products. Especially in the food industry a product that has a good quality can be considered having a worse environmental performance of a poor quality product, and this kind of results would be unfair. As *Wolf et al. 2012* describes “It does not include the direct effect of products on humans, such as the potential health effects of the application of beauty and personal hygiene products, of medicine, and of food itself (LCA only covers the intake of environmental pollutants via food). Such health effects are addressed by risk assessment methods that currently complement LCA”

Other limitations are due to not covering accidents or chemical risks, economics or mostly social implication of the production chain are also excluded. Other instruments should be used together with LCA for the best results and a complete approach in terms of environmental and human health performance.

1.7.7 The future of LCA

One of the problem with LCA analysis is that there is a flexibility in the way it can be performed, such as the choosing of the impact method, or the dataset, that are arbitrarily chosen by the performer of the analysis.

This arbitrariness in the analysis will soon be removed by the using of the product environmental footprint (PEF), which is a methodology for the quantification of the environmental footprint of products, the PEF:

- It is based on existing methods and standards
- It covers a broad range of environmental impact indicators
- Based on PEFCR - Product Environmental Footprint Category Rules: “Product category specific, life-cycle-based rules that complement general methodological guidance for PEF studies by providing further specification at the level of a specific product category.”

Purposes of PEFCR:

- To provide specific guidance for calculating and reporting products’ life cycle environmental impacts;
- To focus on the most important parameters in determining the environmental performance of a given product;
- To allow the comparability between PEF calculations within the same product category. *European Commission (2017)*

The specific guidance of PEF will oblige the use of settled dataset or impact methods depending on the studied product. With more restrictive guidelines, the PEF - that is currently at a final development stage - will soon replace or integrate LCA.

LCA is also expanding in more sectors, such as Life Cycle Costing (LCC), and social LCA, which not only include the product produced by the company, but also other qualitative parameters related to the company itself, such as the quality of work, equality of salaries etc.

2. Methods

2.1 Goal of the study

The main goal of this study is to perform a comparative life cycle assessment of the domestic and industrial production chain of wood pellet, for a better knowledge of the feasibility and the environmental impacts of both the production systems, following the European directives (such as 20-20-20 package) that aim to reduce the consumption of non-renewable energy resources.

This thesis was also developed following the targets of two Portuguese National Projects: **SustainFor - Sustainability assessment of forest sector management strategies in the context of a bioeconomy** and **SABIOS - Sustainability assessment of bioenergy systems.**

SustainFor

The SustainFor project aims to assess the effects of the transition to a bioeconomy on the eucalypt and maritime pine forest sectors in Portugal, providing insights for improved policy and decision-making concerning the choice of more sustainable solutions taking into account the three pillars of sustainability (environmental, economic and social). The project will provide answers to the following questions:

1. What are the current environmental, economic and social impacts of the eucalypt and maritime pine forest sectors in Portugal?

2. How can these current impacts be decreased?

3. What are possible alternative management strategies for these forest sectors in the future?

4. What are the environmental, economic and social impacts of those possible future scenarios?

5. What are the most sustainable scenarios that should be adopted in the future?

SABIOS

This project addresses the challenge of developing a methodology to establish a framework for the Life Cycle Assessment (LCA) of bioenergy systems sustainability, able to inform industry actors, policy makers and stakeholders, and to support bioenergy systems management. The chain modelling of the production of biomass and its use as an energy carrier will encompass cultivation and harvesting, transport, conversion to bioenergy products and co-products, not neglecting disposal/treatment of residues and the production and use of subsidiary inputs (e.g., agrochemicals and transport fuels).

2.2 Scope definition

2.2.1 Functional unit

The functional unit selected as reference flow to report the environmental results is ‘1 ton of wood pellets’ (with a moisture level of 7% and a LHV of 17 MJ). This choice is consistent with others studies of LCA applied to wood pellets. *(Pa et al. (2012), Reed et al. (2012))*

2.2.2 System boundaries and system description

There are two different systems analyzed in this study:

1) Industrial pellet production chain
2) Domestic pellet production chain

The system boundaries of both production chain include:

- **Forest operations**
- **Pellet production** (and sawdust production in the domestic model)
- **Pellet use** (with ashes disposal)

For both of them the initial stage is the production of wood logs performed at a national scale in Portugal. The main differences between the systems are:

- The processes related to wood transformation into pellet, moreover the processes related to the burning of forest residues for heat production used in wood drying are included only in the industrial system, because in the domestic pellet production chain the drying of raw material is done with natural drying.
- The raw material in the domestic model consists in wastes from sawmills and thus there is the presence of a sawmill in the domestic model, in the industrial model the raw material is wood logs and the factory performs alone all the operations to transform wood logs to pellet.
- The transport distances, that are lower in the domestic production chain.

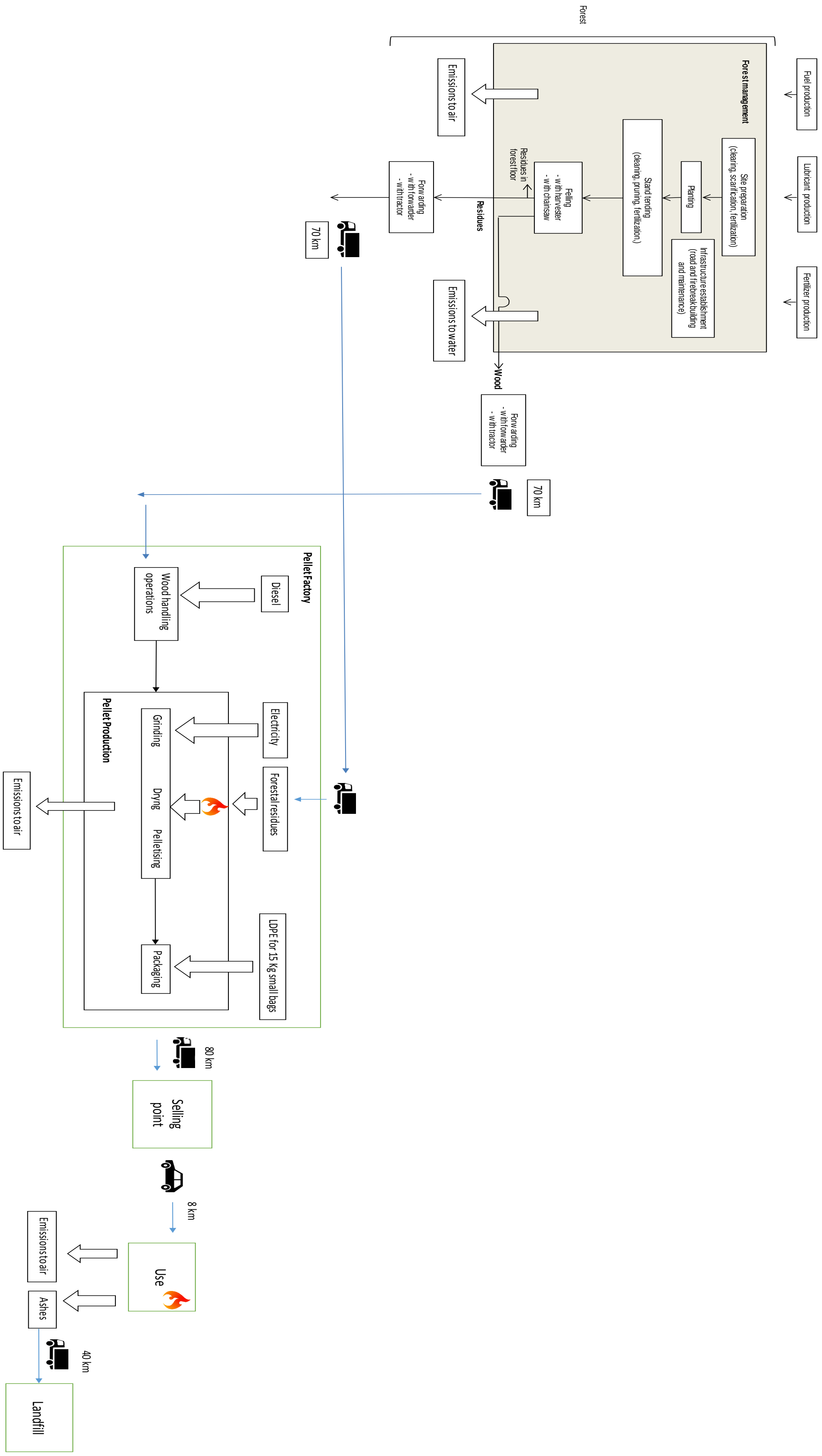


Figure 14: System boundaries of the Industrial pellet productive chain

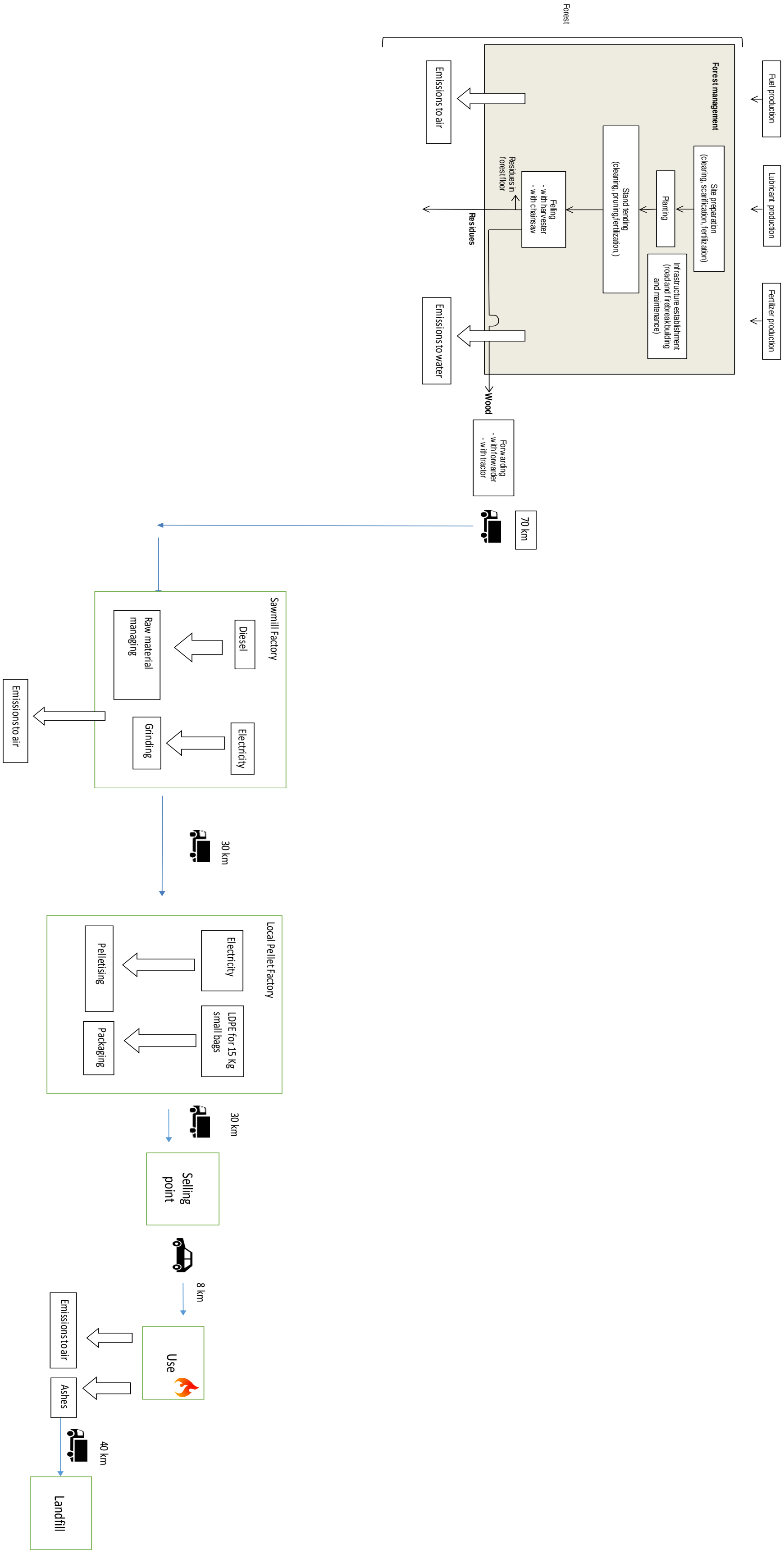


Figure 15: System boundaries of the domestic pellet productive chain

2.2.2.1 Forest stage

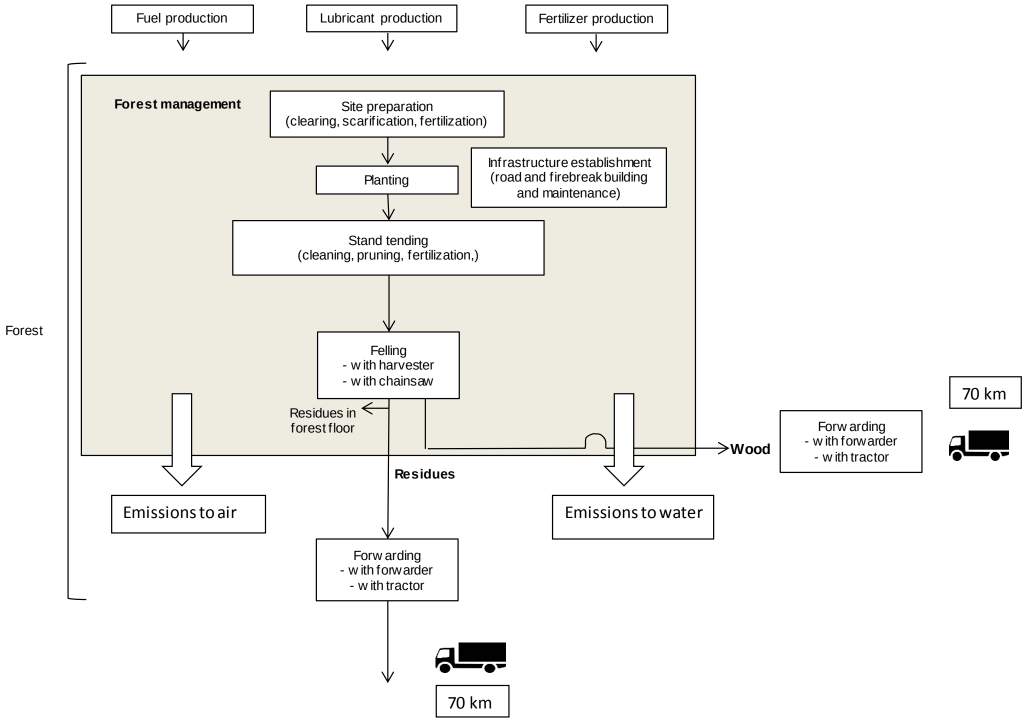


Figure 16: Flow chart and system boundaries for the forest stage

For forest stage, all the operations carried out during infrastructure establishment, site preparation, planting, stand tending, and tree felling were considered. In the default scenario pine stands were assumed to be managed according to the high intensity model described by *Dias et al. (2007)* and *Dias and Arroja (2012)*, which relies on best management practices.

Figure 17: Forest site preparation (available at http://www.farmforestline.com.au/pages/5.3_site.html)

Site preparation comprises undesirable vegetation clearing (by disking), soil scarification (ripping followed by subsoiling), and fertilization (triple superphosphate (42% P_2O_5) applied together with subsoiling). Planting is a manual

Figure 18: Disking operation: available at http://extension.msstate.edu/publications/publications/mechanical-site-preparation-for-forestry-mississippi

operation. During stand tending, several interventions are necessary to ensure forest viability and to improve wood quality, namely cleaning and pruning (manual), Planting is a manual operation. The infrastructure establishment comprises road and firebreak building (once per rotation) and road and firebreak maintenance (nine times for rotation).

Figure 19: Chainsaw cutting available at https://dengarden.com/landscaping/tree-saw

Maritime pine is exploited as a high forest stand with final cutting usually occurring when the trees are more than 35 years old. In this study, the most representative age for final cutting is assumed to be 45 years. In Portugal, tree felling is usually performed with harvester or chainsaw, and extraction could be accomplished with a forwarder or a farm tractor adapted to forest work.

Harvesters and forwarders are mainly used when stands are managed by forest product industries or when large areas are harvested. It was assumed that harvesters are used in combination with forwarders (default scenario), whereas chainsaws are used together with modified farm tractors.

Figure 20: Forwarder (available at https://en.wikipedia.org/wiki/Forwarder)

The forestal residues are collected in the forest and transported to the pellet factory, after the transport phases the residues are burned to produce the heat to rapidly dry the raw material that has too high level of moisture to be pelletized.

Figure 21: Forest residues (available at http://www.biopad.eu/content/logging-residues-5/)

Table 1: Forest operations performed in maritime pine stands, Dias and Arroja (2007)

Age (years)	Operation
0	Clearing (disking)
	Soil scarification (ripping and subsoiling)
	Fertilizing (together with subsoiling)
1	Planting (manual)
1-5	Cleaning (disking twice)
5-10	Pruning (manual)
	Cleaning and soil loosening (disking)
10-20	Thinning. limbing. bucking and debarking (chainsaw)
	Extraction (modified farm tractor)
	Loading of the logs onto trucks (crane of the truck or extraction equipment)
	Pruning (manual)
	Cleaning and soil loosening for incorporation of woody material (disking)
20-30	Thinning. limbing. bucking and debarking (chainsaw)
	Extraction (modified farm tractor)
	Log loading onto trucks (crane of the truck or extraction equipment)
	Soil loosening (disking)
30-40	Thinning. limbing. bucking and debarking (chainsaw)
	Extraction (modified farm tractor)
	Log loading onto trucks (crane of the truck or extraction equipment)
	Soil loosening (disking)
45	Final cutting. limbing. bucking and debarking (chainsaw)
	Extraction (modified farm tractor)
	Log loading onto trucks (crane of the truck or extraction equipment)

2.2.2.2 Industrial pellet factory

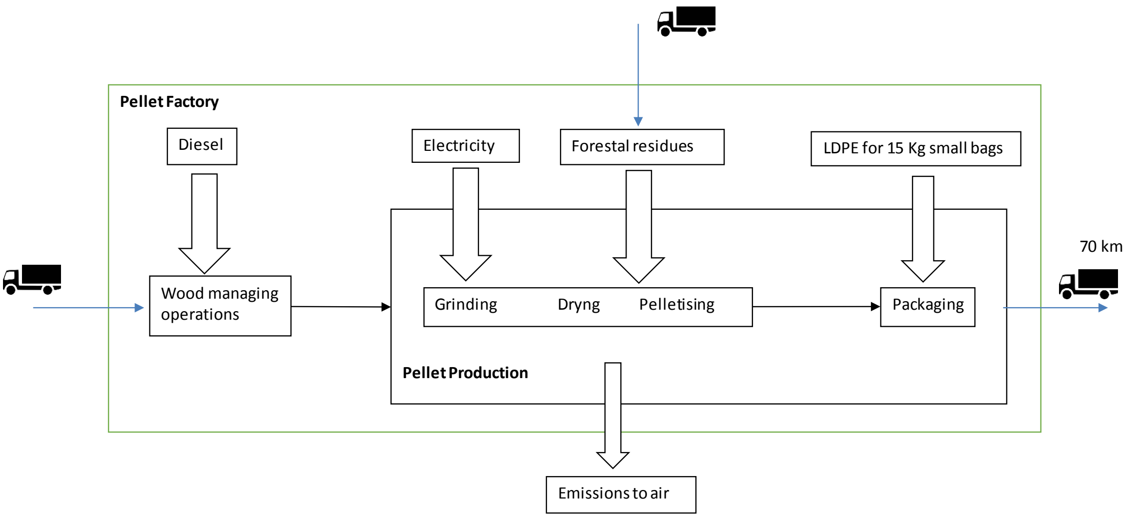


Figure 22 : Flow chart for the industrial pellet production

The operations considered in the industrial pellet production chain are: the discharging operation of the raw material, the pelletization process, the packaging and the transport to the endpoint (point of sale).

The wood logs are unloaded by a hydraulic excavator and chipped. After this process they are ready for the pelletizing process which consists of three unit operations:

Size reduction (grinding), drying and densification (pelletizing).

Figure 23: Sawdust (available at http://spec-yar.ru/opilki.html)

Green woodchips arriving at the mill typically contain about 50–65% of moisture.

Figure 24: rotary dryier (available at https://www.youtube.com/watch?v=bYLcoiXhY3w)

This high moisture is reduced to about 10% by drying. After drying, a hammer mill is used to reduce the biomass to a particle size suitable for pelleting.

A hammer mill screen size of 6.4 or 3.2 mm is normally used for size reduction of biomass.

The hammer mill is powered by an electric motor.

Part of the energy from the hammer mill is converted into heat, which is helpful for further extracting moisture from the raw material. The dry ground biomass is finally compacted in the press mill to form pellets.

Figure 25: Hammer mill (available at http://www.biomass-pelletizer.com/blog/what-should-we-do-if-the-machine-is-jammed.html)

Wood pellets coming out of the pelleting machine usually have a temperature of about 70–90 C°, due to the frictional heat generated during extrusion and material pre-heating. It is necessary to cool the pellet down to a temperature of about 25 C°, to harden and stabilize the wood pellet and to maintain the quality of the product during storage and handling. The cooled pellets are conveyed from the cooler to storage areas using mechanical or pneumatic conveying systems. *Magelli et al. (2009)*

2.2.2.3 Domestic pellet production chain

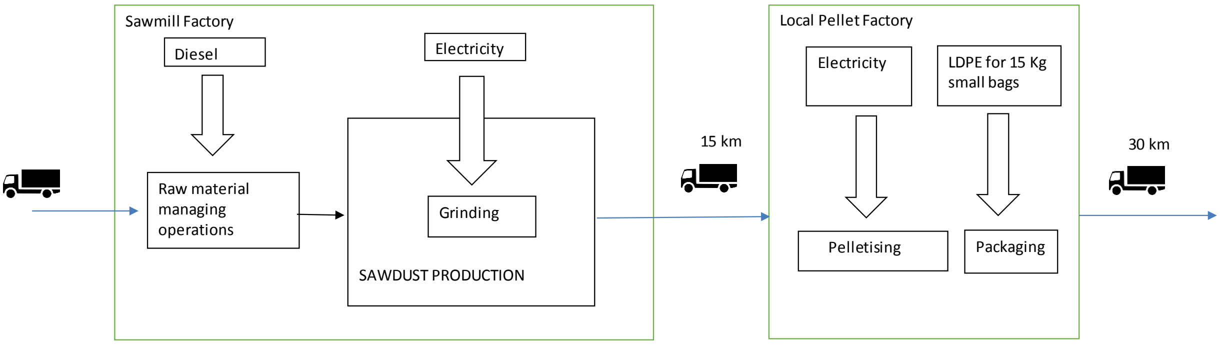


Figure 26: Flow chart for domestic pellet production, the transport distances are intended as roundtrip

In the domestic pellet production chain it is assumed that the local producer has to buy the sawdust from a local sawmill (in this study the local producer is the University of Aveiro), where the wood is grinded to sawdust and the material is transported to the pellet production site.

The raw material (sawdust) is only atmosphere-dried, and, thus, in this production chain the burning of forest residues is not needed.

The transport phases considered are: from the sawmill to the pellet production site and from the pellet production site until the selling point.

Figure 27: Pelletizing Machine for a local production (University of Aveiro)

2.2.2.4 Storage and transportation processes

Figure 28: A typical European pellet truck (available at https://www.bachmann-group.it/commerce/pellets/)

The transport phases are broken down in multiple segments *(for more details check: 2.3.6 transport processes).*

The first phase is the transportation between harvesting field and roadside and it's already included in the harvesting data.

The second phase is represented by the transportation of wood logs to the pelleting plant by truck, in the domestic model the wood logs are transported firstly to the sawmill and after the sawdust production the material goes to the pellet plant.

For the discharging of wood, which comes from the forest, following *Silva (2009)* it was assumed that the movement inside the storage area is carried out by a hydraulic excavator.

Figure 29: 15 Kg pellet bags (available at http://www.pelleten.it/en/index.php/pellet-di-abete-6mm-in-sacchi-da-15kg)

Pellets, packed in 15 kg polyethylene bags are distributed by trucks, which deliver the pellet bags into the shopping center, a car is assumed to be used by the final user for buying the pellet, for the disposal of the ashes a municipal waste collector truck is used.

2.2.2.5 Pellet use stage

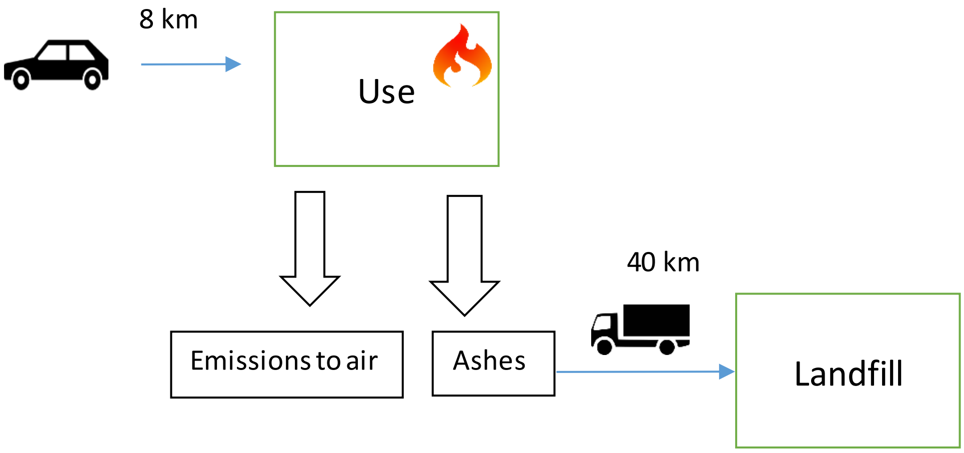


Figure 30: Flow chart for pellet use stage

Figure 31: A modern pellet stove (available at http://www.cursos-de-moda.com/4018/modern-pellet-stove-04-09-2017/terrific-modern-pellet-stove-17-for-your-exterior-house-design-with-modern-pellet-stove/)

For the pellet combustion process, a modern pellet stove was assumed to be used by the final user, as this is a common stove used for domestic needs.

This is a type of advanced stove using an automatic feed for pelletized fuels such as wood pellets, which are distributed to the combustion chamber by a fuel feeder from a small fuel storage. Modern pellets stoves are often equipped with active control system to supply combustion air. They reach high combustion efficiencies by providing the proper air/fuel mixture ratio in the combustion chamber at all times.

For this reason they are characterized by high efficiency (between 80 % and 90 %) and low emissions. *EMEP/EEA (2016).*

The transport phases considered is the transport from selling point to final user house.

In this model it is assumed that the ashes are trashed by the user and collected by a municipal waste truck.

Wood ashes of pine wood could be used as a potassium fertilizer, but the ashes composition is very variable, depending on the combustion system and the material: different combustion systems can produce very different types of ashes, making a specific analysis necessary to determine it. Ashes are thus considered as an inert residue disposed at landfilling facilities.

Figure 32: wood ashes (available at https://www.growveg.com/guides/using-wood-ash-in-the-vegetable-garden/)

2.2.3 Allocation

Wood production is a multifunctional process that generates both wood and slash (residual material produced during harvesting such as bark, branches, tops and foliage). Part of this slash is currently left in the forest soil to decay, playing an important role in restoring the nutrients that have been removed from the soil during tree growth. Another part is used as fuel to produce energy in power plants or is processed into pellets used for heating purposes.

In this study a mass allocation is applied to allocate the environmental burdens to wood and residues that leave the forest (percentages in table 2), in agreement with other forest-related LCA studies*. Dias and Arroja. (2012)*

Table 2: Allocation percentages

Multipe output to technosphere:	Quantity	Measure Unit	% Allocation
1 Wood After Final cut	1	t	52 %
2 Wood after thinning, intensive model, mass allocation	0.483	t	25,1 %
3 Bark after cut,intensive model, mass allocation	0.165	t	8,6 %
4 Forestal residues after cut, intensive model, mass allocation	0.275	t	14,3 %

In the domestic pellet production model, the sawmill process (sawdust production) is taken from ecoinvent database *ecoinvent (2015)* and an economic allocation is done between the wood logs and the resulting sawdust (sawmill process), This allocation is settled by default by the creators of the database.

2.2.4 Scenario Analysis

As explained in the “system boundaries” section there are two different systems analyzed:

- Industrial pellet production chain
- Domestic pellet production chain

For both of them two different scenarios regarding the forest management are considered: intensive model and extensive model.

Intensive model

The intensive model it’s the default model. It requires high intensity management of maritime pine forest, and is characterized by the adoption of the best management practices recommended for the stands under study (table 1); logging is accomplished by harvesters and forwarders for felling and extraction, commonly adopted mainly when the forest is managed by forest product industries or when large areas are harvested.

Extensive model

The extensive model represents low intensity management, management with maritime pine stands established by natural regeneration, and only logging is undertaken with chainsaws for felling and modified farm tractors for extraction, *Dias and Arroja (2012)*.

Thus basically there are four possible scenarios:

1) Industrial pellet production chain intensive model
2) Industrial pellet production chain extensive model
3) Domestic pellet production chain intensive model
4) Domestic pellet production chain extensive model

2.2.5 Exclusions

Transport of workers, machinery and materials (fuels, lubricants and fertilizers) are excluded, as associated distances and means of transportation greatly vary within the country under study. The production of capital goods (buildings, machinery and equipment) is also excluded from the system boundary.

Anyhow *Fantozzi and Buratti (2010)* included in their analysis regarding the combustion of Short Rotation Coppice wood pellets for domestic heating purposes, the environmental impact of machinery and infrastructure. They concluded that these contributed only to 2% of the overall impacts.

Lubricants are excluded from pellet factories, because there is a lack of data in the need of lubricants in the pelletization process, although the need of lubricant in the pelletization process is very small and shouldn't have a relevant influence in the overall impacts, this is confirmed by another study of a pellet production chain *Reed et al. (2012).*

Toxicity impact categories were excluded from this study, as the robustness of the impact model for those substances is still not well developed. Water depletion was excluded due to the fact that there aren't significant waste of water in the pellet productive chain. Land use was excluded as ReCiPe methodology only assesses the area of land occupied and transformed, some author as *Dias and Arroja (2012*) consider that the fact that a forest occupies land is not necessarily bad, however there are other methodologies for land use impact assessment, but they require other kind of data, as for example soil carbon stocks, that are not easily available.

2.3 Inventory Analysis

2.3.1 The SimaPro software

SimaPro is a professional software tool to collect, analyze and monitor the sustainability performance of products and services. In this thesis, the SimaPro 8.3 Analyst with Ecoinvent v. 3.2 database was used, which is based directly on data from the industry, evaluated by professionals, and is well known as a reliable database. With SimaPro it is possible to:

- Easily model and analyze complex life cycles in a systematic and transparent way.
- Measure the environmental impact of products and services across all life cycle stages.
- Identify the hotspots in all aspects of a supply chain, from extraction of raw materials to manufacturing, distribution, use, and disposal.

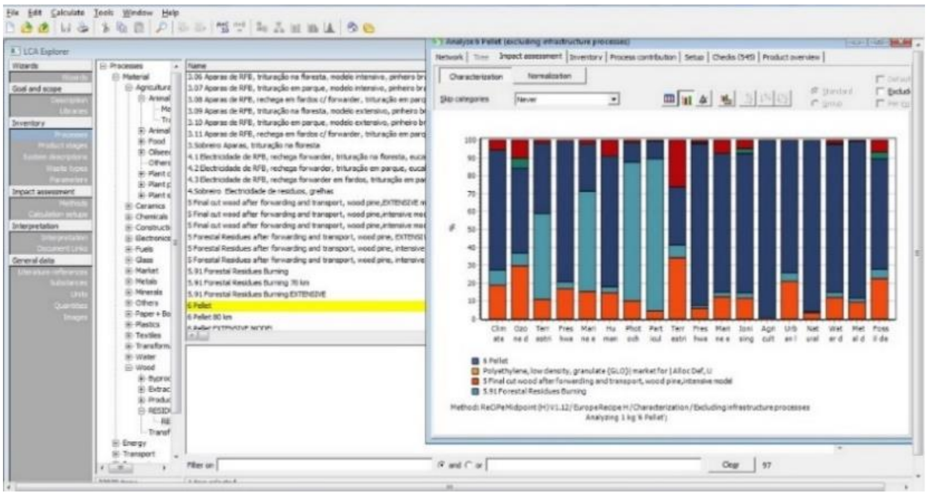


Figure 33: The SimaPro program, on the right part of the figure there is an example of an impact assessment analysis.

2.3.2 Forest stage

Inventory data for forest stage are taken from the study of *Dias and Arroja (2012)* which studied in details the maritime mine wood production in Portugal.

The inputs from the technosphere for forest stage operations include fuels, lubricants and fertilizers, which were quantified for each operation. The stand establishment stage has no inputs as planting is performed manually. For logging operations, the inputs were directly obtained per unit of wood volume produced, whereas for the operations carried out during site preparation, stand tending and infrastructure establishment were obtained firstly per unit of forest area. In order to express these inputs per wood volume, they were accounted for over one revolution and were divided by the total volume of wood produced in the same period.

The amounts of fuels consumed in motor-manual and mechanized operations were calculated based on the effective work time needed to perform each operation and the respective fuel consumption per hour of machine work as published by *Dias et al. (2007).*

Inputs from nature, such as CO_2 assimilated due to forest growth and land occupation, were not taken into account.

The amount of CO_2 assimilated during forest growth was assumed to be equal to the amount of CO_2 that will be released back to the atmosphere due to wood oxidation along the downstream life cycle stages of wood.

Land occupation was excluded as, currently, there is no agreement on how to assess land use impacts in LCA. *Dias and Arroja (2012).*

	Volumetric Weight (Kg m-3)	Carbon Emission factor (Kg GJ-1)	Net calorific value (Mj kg-1)
Fuel			
Diesel oil	850a	20.2	43.33
Gasoline	725b	18.9	44.80

Table 3: Technical specifications of the fuels used in the forestry management

The data adopted for the effective work time and fuel consumption of the operations performed during site preparation, stand tending and infrastructure establishment were taken from relevant literature and are representative of Portuguese averages. *Dias et al. (2007)* is the source of the data used for the effective work times and fuel consumptions of the operations covered by logging. These data are also typical of maritime pine stands in Portugal.

Table 4 Effective work time and fuel consumption of the operations carried out during site preparation, stand tending and infrastructure establishment. Dias et al. (2007)

Operation	Effective work time (h ha^{-1})	Fuel consumption (l h^{-1})	Fuel type
Stump removal (with digger)	8	15	Diesel oil
Clearing/cleaning			
Mowing	4.5	8	Diesel oil
Disking	3.5	13.5	Diesel oil
Soil scarification			
Excavating planting pits	3.25	8	Diesel oil
Ripping	4.25	20.5	Diesel oil
Subsoiling	3	14.5	Diesel oil
Ploughing	3.75	8.5	Diesel oil
Furrowing and ridging	2.65	9.5	Diesel oil
Terrace construction	17	15	Diesel oil
Soil loosening (disking)	1.25	11.5	Diesel oil
Precommercial thinning (with chainsaw)	12	1	Gasoline
Road building	1.65	15	Diesel oil
Road maintenance	0.6	14	Diesel oil
Firebreak building	0.225	15	Diesel oil
Firebreak maintenance	0.06	14	Diesel oil

Table 5: Effective work time and fuel consumption of the operations carried out during logging. Dias et al. (2007)

Operation	Effective work time (h m-3)	Fuel consumption (l h^{-1})	Fuel type
Felling. limbing. bucking and debarking			
Chainsaw	0.24	1	Gasoline
Harvester	0.07	12	Diesel oil
Extraction			
Modified farm tractor	0.12	10	Diesel oil
Forwarder	0.08	12	Diesel oil
Log loading onto trucks			
Crane (of the truck or extraction equipment)	0.01	10	Diesel oil

Two types of lubricants were considered: lubricants blended with petrol used in two stroke motors (in chainsaws) in a volumetric ratio of one part lubricant to 25 parts petrol, and lubricants used in machinery. The consumed amount of the second type of lubricant was assumed to be 5% of the amount of fuel consumed by the machine.

According to *Dias and Arroja. (2012*), P-containing fertilizer should be applied before stand establishment in moist sites (180 kg/ha of triple superphosphate (42% P_2O_5)). In the absence of real data about current fertilization practices over all the area of maritime pine in Portugal, this recommendation was adopted for all the area.

The outputs considered for forest management operations include air emissions from fuel combustion and air and water emissions from fertilizer applications. Air emissions from fuel combustion (Carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), sulhpur dioxide (SO_2), carbon monoxide (CO),ammonia (NH_3) and nitrogen oxides (NOx)) were calculated based on emission factors taken from *EEA (2009).*

Application of P-containing fertilizers in maritime pine stands was considered to release P to water. Following *Dias and Arroja* (2012), who studied the processes related to the forestal management in Portugal, an emission factor of 0.024 kg P per kg of P in fertilizer was considered.

Data concerning the production of fuels (diesel and petrol), lubricants and fertilizers were taken from the Ecoinvent database *Ecoinvent (2010).*

Maritime Pine Scenarios	**Intensive Model**	**Extensive model**
Inputs:		
Diesel (g)	3211	1133
Petrol (g)	0	176
Lubricants (g)	161	63.4
Triple superphosphate (g)	667	0
Air emissions:		
CO_2 (g)	10,148	4144
CH_4 (g)	0.106	0.425
N_2O (g)	0.443	0.159
SO_2 (g)	6.42	2.27
CO (g)	25.2	118
NH_3 (g)	0.0257	0.00959
No_x	93.4	33.5
Water emissions:		
P (g)	2.94	0

Table 6: Inventory data for forest managment, under different forest managment scenarios. Dias and Arroja (2012)

2.3.3 Industrial pellet factory

The data for the pellet industry were provided by a Portuguese wood pellet production factory.

Input	For t of Pellets	Unit
Maritime Pine wood	1.335	t
Electricity, medium voltage (PT mix)	129.77	kWh
Polyethylene. low density. granulate	0.00035	kg
Forestal residues burning (drying process)	3.09	GJ
Transport. freight. lorry >32 metric ton. EURO4	80	t/km
Diesel. low-sulfur	0.79	kg

Table 7: Inputs for industrial pellet factory

The first process in the pellet factory is the storage of raw material. Following *Silva (2009)* it was assumed that the movement of raw materials, inside the storage area, is carried out by a hydraulic excavator. The fuel consumption was calculated using data from the same author and considering a fuel consumption of 0.794 kg (diesel) for 1.335 ton of wood that is the quantity required for producing 1 ton of pellet.

Inventory data collection for the pellet production was based on the production ratios in the factory under assessment. It was not possible to consider separately as independent processes the grinding, drying, pelletising and packaging because the information given by the factory was aggregated for all of the operations.

Wood pelletization primarily has energy and wood residues inputs and two outputs, wood pellets and emissions to air. Electricity is used to operate in all of the pelletising phases. The electicity mix used is medium voltage (Portuguese mix) taken from *ecoinvent (2015)*. Wood pelletization does not create a solid waste stream.

All wood residues are recycled in the pelletization process, and airborne particulate emissions from the wood compression (dust) are assumed to be insignificant. Air emissions are mostly from on-site forest residues burning, water, and solid waste emissions are minimal, the majority of emissions are those associated with pre-gate actions.

Data for pellet packaging materials and respective amounts are taken following the study of *Laschi et al. (2016)*

Forest residues are burned in the pellet factory for thermal energy. This energy will be used for drying the sawdust, this process has emissions taken from *(IPCC 2006, EMEP/EEA 2016).*

For the burning of forest residues a lower heating value of 17 (MJ/kg) (dry basis) is assumed, following the study of *Tarelho et al. (2015)* who studied biomass thermal power plant,the moisture content assumed is 65%.

CO_2 is not considered as emissions because the amount of CO_2 released to the environment after wood oxidation is considered equal to the uptake of CO_2 by biomass grown. *Dias and Arroja (2012).*

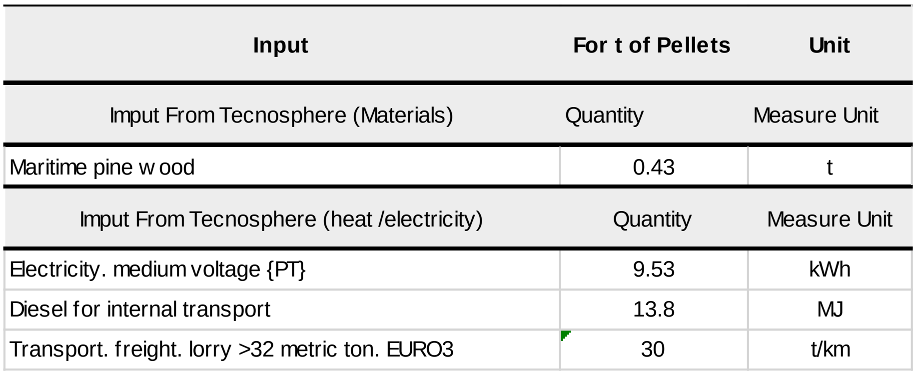
Substance	*Quantity*	***Unit***
Carbon monoxide. biogenic	1761	g
Particulates. < 10 um	442	g
Particulates. < 2.5 um	433	g
NMVOC	927	g
Nitrogen oxides	281	g
Ammonia	114	g
Sulfur oxides	34	g
Methane. biogenic	9	g
Dinitrogen monoxide	12	g

Table 8: Emission factors used for forestal residues combustion, for t of pellets (IPCC 2006, EMEP/EEA 2016)

2.3.4 Domestic pellet production chain

2.3.4.1 Sawmill

In the local production chain, the raw material is maritime pine sawdust, that comes from the forest goes to a local sawmill (15 km from Aveiro). The energy consumption of the sawmill comes from ecoinvent database *(ecoinvent 2015)*, the electricity mix used (medium voltage, Portuguese mix) and the diesel for internal transport are taken from *ecoinvent (2015)*.



Input	**For t of Pellets**	**Unit**
Imput From Tecnosphere (Materials)	Quantity	Measure Unit
Maritime pine wood	0.43	t
Imput From Tecnosphere (heat /electricity)	Quantity	Measure Unit
Electricity. medium voltage {PT}	9.53	kWh
Diesel for internal transport	13.8	MJ
Transport. freight. lorry >32 metric ton. EURO3	30	t/km

Table 9: Inputs for the sawmill stage

2.3.4.2 Energy consumption of domestic pellet production measure experiment

The data for the local pellet production were developed in the laboratory of the University of Aveiro in a Pellet Machine (MOKIL 225 2015 model) with a power of 7.5 kW.

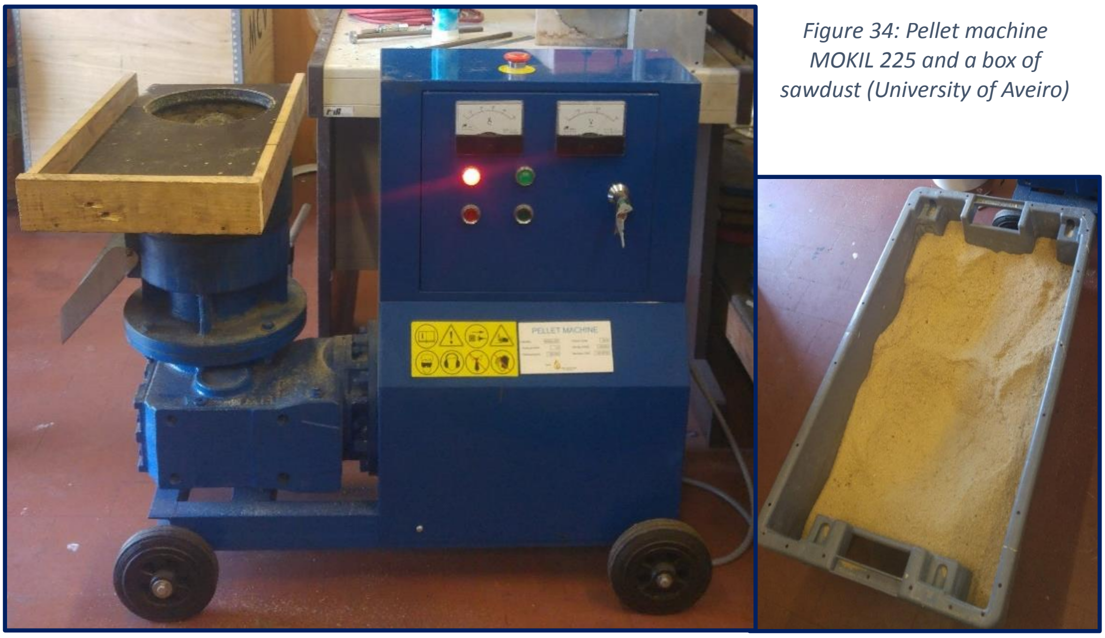


Figure 34: Pellet machine MOKIL 225 and a box of sawdust (University of Aveiro)

The pine wood sawdust, used as raw material for the pelletizing process, has normally a high content of moisture and to be pelletized it needs a drying process. For a domestic production the best option due to cost reductions is the natural drying that is performed by leaving the raw material at atmospheric condition.

After the drying process, the sawdust was manually inserted in the pellet machine, and a voltage and current analyzer HT Vega 76 was used to analyze the consumption of the pellet machine during the pelletization process.
The experiment was repeated twice.

Figure 35: Measurement of energy consumption of the pelletization process,

13-07-2017 University of Aveiro,

The HT Vega 76 was measuring the instantaneous power consumption in kW of the machine, with the rhythm of 1 measure every 5 seconds.

Experiment 1: date 13/07/2017, start time: 11:51:25, end time 12:35:25.

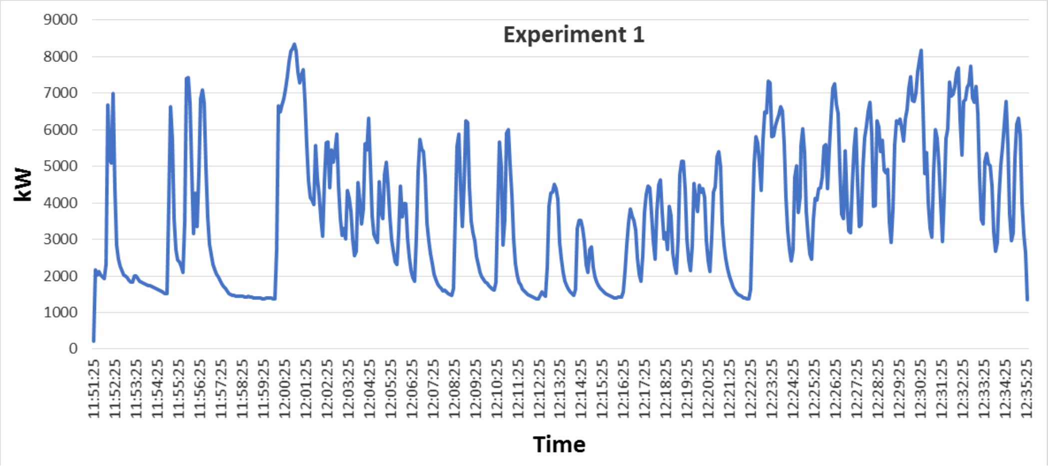


Figure 36: HT Vega 76 instantaneous power measurement, experiment 1.

Experiment 1, date: 13/07/2017, start time: 12:54:55, end time 13:21:45.

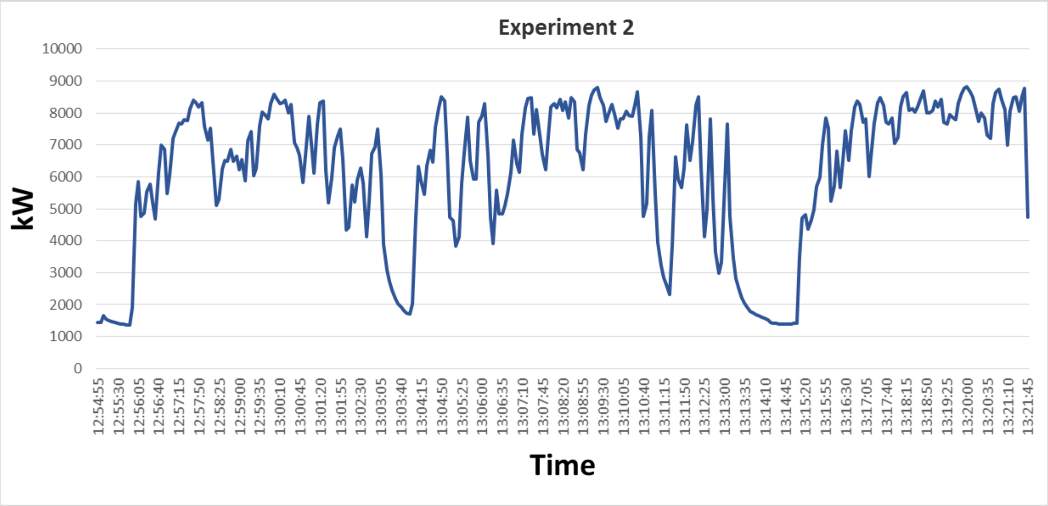


Figure 37: HT Vega 76 instantaneous power measurement, experiment 2.

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The sawdust was stored in different plastic boxes, each box was exposed to different levels of drying. The main differences in the pelletization process from a domestic to an industrial production is the lack of quality control in the raw material that is poor compared to an industrial pellet factory. The moisture quantity in the raw material is very important in the pelletization process because it affects the easiness and the velocity of the compression process, Different levels of moisture were tried and with an optimal moisture level (around 15-20 %) it was possible to obtain no more than 25 kg/hour of pellet with the pellet machine.

The formulas below were applied to convert instantaneous power in kW, that were measured from the instrument, in kWh consumed in 1 hour, An average value from the two experiment was taken and the final result was adjusted with an equivalence for the production of 1 ton of pellet that is the functional unit.

The formula below was applied to convert instantaneous power in kW, that was measured from the instrument, in energy consumed expressed in kWh.

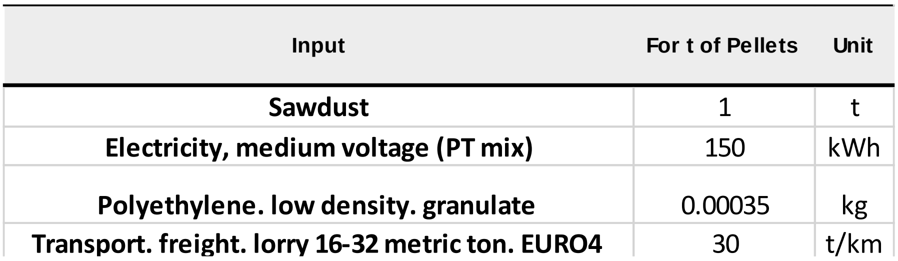
$$\boldsymbol{E} = \boldsymbol{P} \times \Delta \boldsymbol{t} \,/\, \mathbf{3600}$$

Equation 1: Conversion from instantaneous power to kWh, where E = energy consumed (kWh), P = average power measured (kW), and Δt = time interval (s)

The value obtained for producing 1 ton of pine wood pellet with MOKIL 225 pellet machine, that is representative for a domestic pellet production chain, is 150 kWh.

Figure 38: Domestic pellet production, University of Aveiro.

2.3.4.3 Domestic pellet production



Input	For t of Pellets	Unit
Sawdust	1	t
Electricity, medium voltage (PT mix)	150	kWh
Polyethylene. low density. granulate	0.00035	kg
Transport. freight. lorry 16-32 metric ton. EURO4	30	t/km

Table 10: Inputs for domestic pellet production

The process of pelletizing wood waste only changes the density of the wood residue raw material. Therefore, it takes 1 ton of sawdust (dried) to produce 1 ton of wood pellets *Reed et al. (2012*). Data for pellet packaging are taken from *Laschi et al. (2016)*

2.3.5 Pellet use stage (pellet burning)

This stage is the same for both industrial and domestic model. The pellet is bought from a local market and is burned in a pellet stove. From the market to the house, a car is assumed to be used for the transport. This stage includes also the ashes disposal and its transport in a municipal waste collector truck.

For an estimation of the emissions to air, emissions factors are used *(IPCC (2006), EMEP/EEA (2016))*

For the pellet burning, a lower heating value (dry basis) of 17 $MJ \cdot kg^{-1}$ and a moisture content of 7% is assumed following *Vicente et al (2015),* who studied the particulate and gaseous emissions from the combustion of pellet in a pellet stove. Since the raw material is the same (virgin pine wood) there are no differences between industrial and domestic production in the LHV. CO_2 is not considered as emissions because the amount of CO_2 released to the environment after wood oxidation is considered equal to the uptake of CO_2 by biomass grown. *Dias and Arroja (2012).*

Substance	Quantity	***Unit***
Carbon monoxide. biogenic	4890	g
Particulates. < 10 um	472,7	g
Particulates. < 2.5 um	472,7	g
NMVOC	163	g
Nitrogen oxides	1304	g
Ammonia	195,6	g
Sulfur oxides	179,3	g
Methane. biogenic	57,05	g
Dinitrogen monoxide	179,3	g

Table 11: Emission factors used for pellets combustion, for t of pellets (IPCC 2006, EMEP/EEA 2016)

2.3.6 Transport processes

Transport distances are taken mostly from other LCA applied to pellet studies *(Magelli et al. (2009), Fantozzi and Buratti (2010), Laschi et al. (2016).*

Following *Nunes (2016)* it is known that in Portugal the maximum distance when no one wants the raw material due to high transport costs is 70 km, and this is taken as maximum distance for wood transports, for the domestic model, travel distances are based on the distance from the sawmill (Aveiro) to the university of Aveiro.

Domestic pellet productive chain	Transport (roundtrip)	Distance (km)
Inside the forest	wood forwarder / modified farm tractor	15
From the forest to the saw mill	Transport, freight, lorry >32 metric ton, EURO3 {RER}	70
From the saw mill to the domestic pellet factory	Transport, freight, lorry >32 metric ton, EURO3	30
From the domestic pellet factory to the market	Transport, freight, lorry 16-32 metric ton, EURO4	30
From the market to final user	Transport, passenger car, EURO 4	8
From the final user to disposal site	Municipal waste collection service (21 metric ton lorry)	40

Table 12: Transport types and distances assumed in the domestic pellet production chain

Industrial pellet productive chain	Transport (roundtrip)	Distance (km)
Inside the forest	wood forwarder / modified farm tractor	15
From the forest to the industrial pellet factory	Transport, freight, lorry >32 metric ton, EURO3	70
From the industrial pellet factory to the market	Transport, freight, lorry >32 metric ton, EURO4	80
From the market to final user	Transport, passenger car, EURO 4	8
From the final user to disposal site	Municipal waste collection service (21 metric ton lorry)	40

Table 13: Transport types and distances assumed in the industrial pellet production chain

2.3.7 Sensitivity Analysis

The aim of the sensitivity analysis was to evaluate the effects on environmental impacts induced by changes in some assumptions adopted in the models. Three scenarios were studied as an alternative to the default scenarios:

- **Higher transport distances**
- **Lower emissions in the combustion process**
- **Higher emissions in the combustion process**

Those parameters were allowed to vary to simulate the variability of the transport distances that could exist between the forest and the final user, that are strongly variable in relation to the dimension of the factory, the zone, the country. Of course, if the distances are higher the emissions related to the transport phases will be higher too. The transport distances were allowed to vary only in the industrial model, because in a local production the transport distances are short, and modification of those distances wouldn't produce relevant changes in the model.

Industrial pellet productive chain	Transport (roundtrip)	Distance (km)
Inside the forest	w ood forw arder / modified farm tractor	15
From the forest to the industrial pellet factory	Transport. freight. lorry >32 metric ton. EURO3	140
From the industrial pellet factory to the market	Transport. freight. lorry >32 metric ton. EURO4	160
From the market to final user	Transport. passenger car. EURO 4	16
From the final user to disposal site	Municipal w aste collection service (21 metric ton lorry)	40

Table 14: Variations in transport distances applied for the sensitivity analysis

The sensitivity analysis was applied also to pellet burning, due to the fact that the emissions of pellet burning can vary in a certain range, due to several reasons, such as a different model of domestic pellet stove used by the final user, or a wood pine pellet produced by a different company, or different parameters settled in the stove, like the heating output etc.

Substance	Quantity (Maximum)	Quantity (Minimum)	Measure Unit
Carbon monoxide. biogenic	12062	1075,8	g
Particulates. < 10 um	2298,3	472,7	g
Particulates. < 2.5 um	472,7	472,7	g
NMVOC	163	163	g
Nitrogen oxides	1695,2	342,3	g
Ammonia	195,6	195,6	g
Sulfur oxides	179,3	179,3	g
Methane. biogenic	114,1	3,749	g
Dinitrogen monoxide	293,4	65,2	g

Table 15: Emission factors used in the sensitivity analysis, for t of pellet (IPCC 2006, EMEP/EEA 2016)

3 Results

With the LCA software SimaPro Analyst 8.2.3.0, using the Recipe 2008 v1.12 method and Ecoinvent database v 3.2, for a detailed explanation of the impact categories used in this study, please check "5 Annex" section.

The value obtained are expressed in:

- Table containing the impact score of each process of the stage, as analysed in the model, and the total, that is the sum of the processes of that production stage.
- 100% stacked column figure showing the percentage by which each process contributes to the total impacts: with this type of representation, it's easier to understand which the most environmental impacting processes are for each impact category.

All of this environmental impacts are referred to the functional unit: "1 ton of pellet".

As explained in the previous sections, the stages analysed for the pellet production chain are:

- Forest stage, which is further divided in forest management, final cut of wood, and wood forwarding and transport

- Sawdust production (Domestic model only)
- Pellet production
- Pellet use (including ashes disposal)

Moreover, the following scenarios are also analysed (for a detailed explanation check '2 Methods' part):

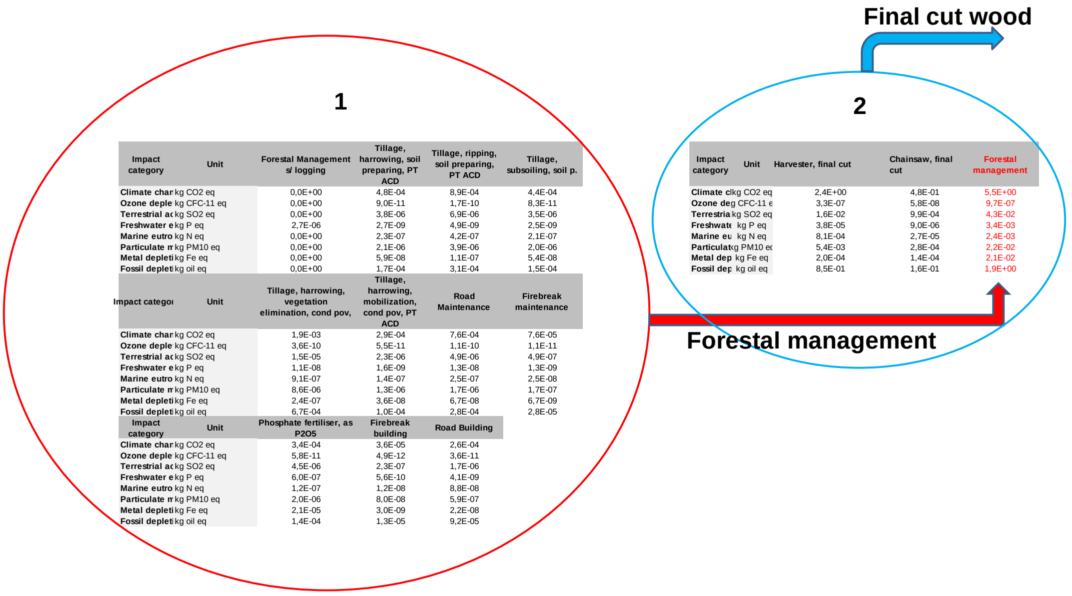
- Intensive and extensive scenario for the forest stage
- Highest and lowest emissions for pellet use (pellet burning phase)
- Highest distances (Industrial production chain only)

Every showed result is matched with this type of figure, that shows the point of the productive chain being analysed with respect to the entire productive chain. This is useful to guide the reading of the results without mistakes.

3.1 About Simapro

SimaPro analyses every phase in a step by step analysis. The form of modelling used in this study implies that every point of the production chain is the result of the previous phase, plus the processes included in the new phase. Therefore, the total value of the last process (the pellet burning phase in this study) is the total impact of the entire model.

For example, as showed in Fig 39, the first process is forestal management while the second step is named final cut wood and includes the total of the previous phase (i.e. forestal management) plus harvester and chainsaw, that are processes included in this phase.



Impact category	Unit	Forestal Management s/ logging	Tillage, harrowing, soil preparing, PT ACD	Tillage, ripping, soil preparing, PT ACD	Tillage, subsoiling, soil p.
Climate char	kg CO2 eq	0,0E+00	4,8E-04	8,9E-04	4,4E-04
Ozone deple	kg CFC-11 eq	0,0E+00	9,0E-11	1,7E-10	8,3E-11
Terrestrial ac	kg SO2 eq	0,0E+00	3,8E-06	6,9E-06	3,5E-06
Freshwater e	kg P eq	2,7E-06	2,7E-09	4,9E-09	2,5E-09
Marine eutro	kg N eq	0,0E+00	2,3E-07	4,2E-07	2,1E-07
Particulate m	kg PM10 eq	0,0E+00	2,1E-06	3,9E-06	2,0E-06
Metal depleti	kg Fe eq	0,0E+00	5,9E-08	1,1E-07	5,4E-08
Fossil depleti	kg oil eq	0,0E+00	1,7E-04	3,1E-04	1,5E-04

Impact categor	Unit	Tillage, harrowing, vegetation elimination, cond pov,	Tillage, harrowing, mobilization, cond pov, PT ACD	Road Maintenance	Firebreak maintenance
Climate char	kg CO2 eq	1,9E-03	2,9E-04	7,6E-04	7,6E-05
Ozone deple	kg CFC-11 eq	3,6E-10	5,5E-11	1,1E-10	1,1E-11
Terrestrial ac	kg SO2 eq	1,5E-05	2,3E-06	4,9E-06	4,9E-07
Freshwater e	kg P eq	1,1E-08	1,6E-09	1,3E-08	1,3E-09
Marine eutro	kg N eq	9,1E-07	1,4E-07	2,5E-07	2,5E-08
Particulate m	kg PM10 eq	8,6E-06	1,3E-06	1,7E-06	1,7E-07
Metal depleti	kg Fe eq	2,4E-07	3,6E-08	6,7E-08	6,7E-09
Fossil depleti	kg oil eq	6,7E-04	1,0E-04	2,8E-04	2,8E-05

Impact category	Unit	Phosphate fertiliser, as P2O5	Firebreak building	Road Building
Climate char	kg CO2 eq	3,4E-04	3,6E-05	2,6E-04
Ozone deple	kg CFC-11 eq	5,8E-11	4,9E-12	3,6E-11
Terrestrial ac	kg SO2 eq	4,5E-06	2,3E-07	1,7E-06
Freshwater e	kg P eq	6,0E-07	5,6E-10	4,1E-09
Marine eutro	kg N eq	1,2E-07	1,2E-08	8,8E-08
Particulate m	kg PM10 eq	2,0E-06	8,0E-08	5,9E-07
Metal depleti	kg Fe eq	2,1E-05	3,0E-09	2,2E-08
Fossil depleti	kg oil eq	1,4E-04	1,3E-05	9,2E-05

Impact category	Unit	Harvester, final cut	Chainsaw, final cut	Forestal management
Climate c	kg CO2 eq	2,4E+00	4,8E-01	5,5E+00
Ozone de	g CFC-11 e	3,3E-07	5,8E-08	9,7E-07
Terrestria	kg SO2 eq	1,6E-02	9,9E-04	4,3E-02
Freshwate	kg P eq	3,8E-05	9,0E-06	3,4E-03
Marine eu	kg N eq	8,1E-04	2,7E-05	2,4E-03
Particulat	kg PM10 ec	5,4E-03	2,8E-04	2,2E-02
Metal dep	kg Fe eq	2,0E-04	1,4E-04	2,1E-02
Fossil dep	kg oil eq	8,5E-01	1,6E-01	1,9E+00

Figure 39: Step by step process chain as analyzed in the LCA SimaPro software.

3.2 Forest stage (Intensive model)

3.2.1 Forest management

Figure 40 shows the processes performed in the forest management and their impacts.

Impact category	Unit	Forestal Management,logging	Tillage, harrowing, soil preparing	Tillage, ripping, soil preparing	Tillage, subsoiling, soil preparing
Climate change	kg CO2 eq	0,0E+00	4,8E-01	8,9E-01	4,4E-01
Ozone depletion	kg CFC-11 eq	0,0E+00	9,0E-08	1,7E-07	8,3E-08
Terrestrial acidification	kg SO2 eq	0,0E+00	3,8E-03	6,9E-03	3,5E-03
Freshwater eutrophication	kg P eq	2,7E-03	2,7E-06	4,9E-06	2,5E-06
Marine eutrophication	kg N eq	0,0E+00	2,3E-04	4,2E-04	2,1E-04
Particulate matter formation	kg PM10 eq	0,0E+00	2,1E-03	3,9E-03	2,0E-03
Metal depletion	kg Fe eq	0,0E+00	5,9E-05	1,1E-04	5,4E-05
Fossil depletion	kg oil eq	0,0E+00	1,7E-01	3,1E-01	1,5E-01

Impact category	Unit	Tillage, harrowing, vegetation elimination	Tillage, harrowing, mobilization	Road Maintenance	Firebreak maintenance
Climate change	kg CO2 eq	1,9E+00	2,9E-01	7,6E-01	7,6E-02
Ozone depletion	kg CFC-11 eq	3,6E-07	5,5E-08	1,1E-07	1,1E-08
Terrestrial acidification	kg SO2 eq	1,5E-02	2,3E-03	4,9E-03	4,9E-04
Freshwater eutrophication	kg P eq	1,1E-05	1,6E-06	1,3E-05	1,3E-06
Marine eutrophication	kg N eq	9,1E-04	1,4E-04	2,5E-04	2,5E-05
Particulate matter formation	kg PM10 eq	8,6E-03	1,3E-03	1,7E-03	1,7E-04
Metal depletion	kg Fe eq	2,4E-04	3,6E-05	6,7E-05	6,7E-06
Fossil depletion	kg oil eq	6,7E-01	1,0E-01	2,8E-01	2,8E-02

Impact category	Unit	Phosphate fertiliser, as P2O5	Firebreak building	Road Building	Total
Climate change	kg CO2 eq	3,4E-01	3,6E-02	2,6E-01	5,5E+00
Ozone depletion	kg CFC-11 eq	5,8E-08	4,9E-09	3,6E-08	9,7E-07
Terrestrial acidification	kg SO2 eq	4,5E-03	2,3E-04	1,7E-03	4,3E-02
Freshwater eutrophication	kg P eq	6,0E-04	5,6E-07	4,1E-06	3,4E-03
Marine eutrophication	kg N eq	1,2E-04	1,2E-05	8,8E-05	2,4E-03
Particulate matter formation	kg PM10 eq	2,0E-03	8,0E-05	5,9E-04	2,2E-02
Metal depletion	kg Fe eq	2,1E-02	3,0E-06	2,2E-05	2,1E-02
Fossil depletion	kg oil eq	1,4E-01	1,3E-02	9,2E-02	1,9E+00

Table 16: Impact assessment results obtained for the Process forest management

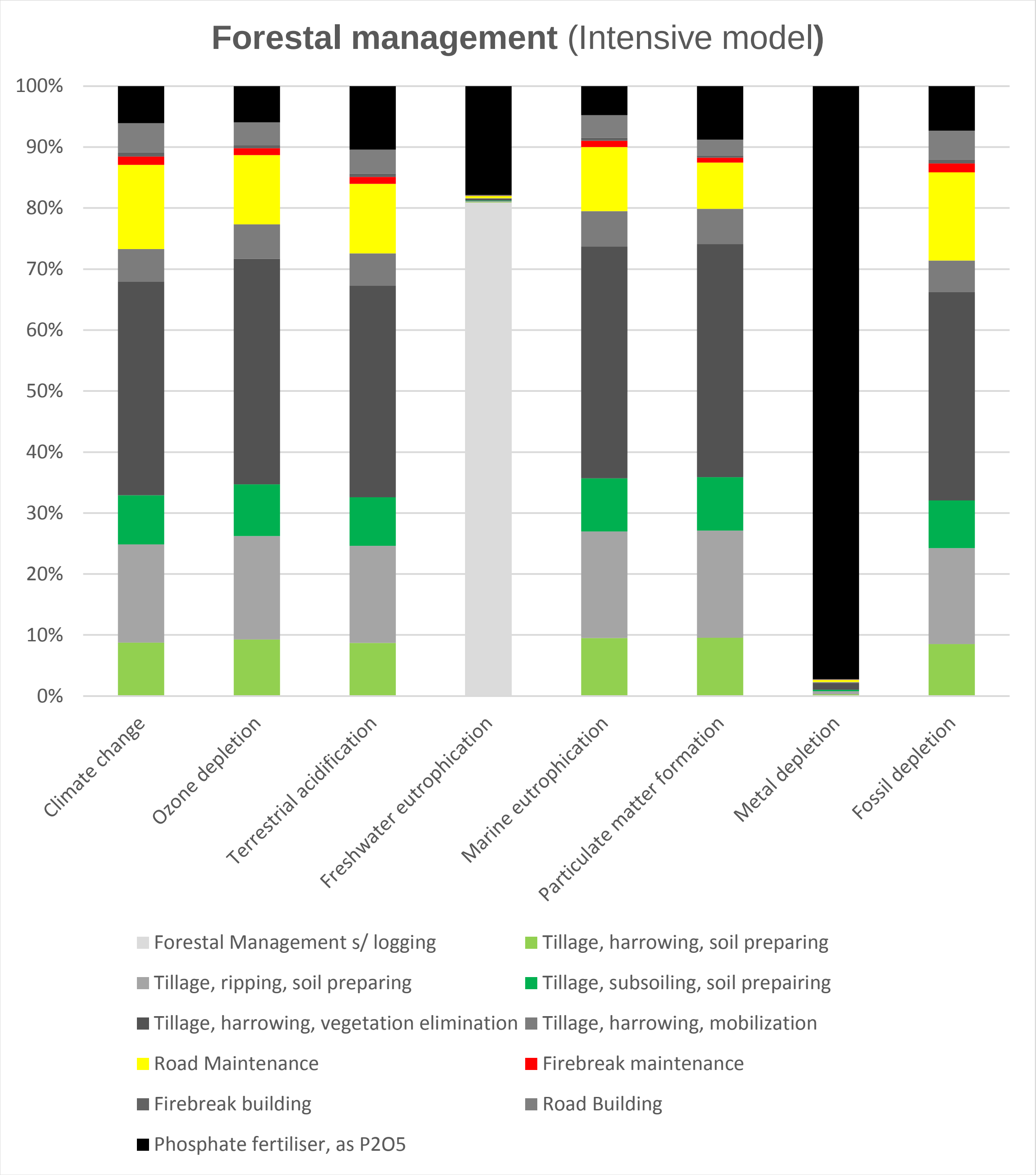


Figure 40: Impact assessment results for the process Forestal Management showed in 100% stacked column chart

In general the main contributor to the environmental impacts of the forest management process is the cleaning, (vegetation elimination process during stand tending). However for the freshwater eutrophication category, the main contributor is the fertilizing process.

The phosphate fertilizer accounts for almost the 100% of the metal depletion impact category, this is explained by the waste of metals that are created during the production stages of the fertilizer. *Ecoinvent (2015).*

Firebreak building and maintenance don’t have a relevant environmental impact, contributing only to 1 /2 % of all impact categories.

3.2.2 **Wood After final cut** (Intensive model)

Impact category	Unit	Harvester, final cut	Chainsaw, final cut	Forestal management	Total
Climate change	kg CO2 eq	2,4E+00	4,8E-01	5,5E+00	8,4E+00
Ozone depletion	kg CFC-11 eq	3,3E-07	5,8E-08	9,7E-07	1,4E-06
Terrestrial acidification	kg SO2 eq	1,6E-02	9,9E-04	4,3E-02	6,0E-02
Freshwater eutrophication	kg P eq	3,8E-05	9,0E-06	3,4E-03	3,4E-03
Marine eutrophication	kg N eq	8,1E-04	2,7E-05	2,4E-03	3,2E-03
Particulate matter formation	kg PM10 eq	5,4E-03	2,8E-04	2,2E-02	2,8E-02
Metal depletion	kg Fe eq	2,0E-04	1,4E-04	2,1E-02	2,2E-02
Fossil depletion	kg oil eq	8,5E-01	1,6E-01	1,9E+00	3,0E+00

Table 17: Impact assessment results obtained for the Process wood after final cut (Intensive model)

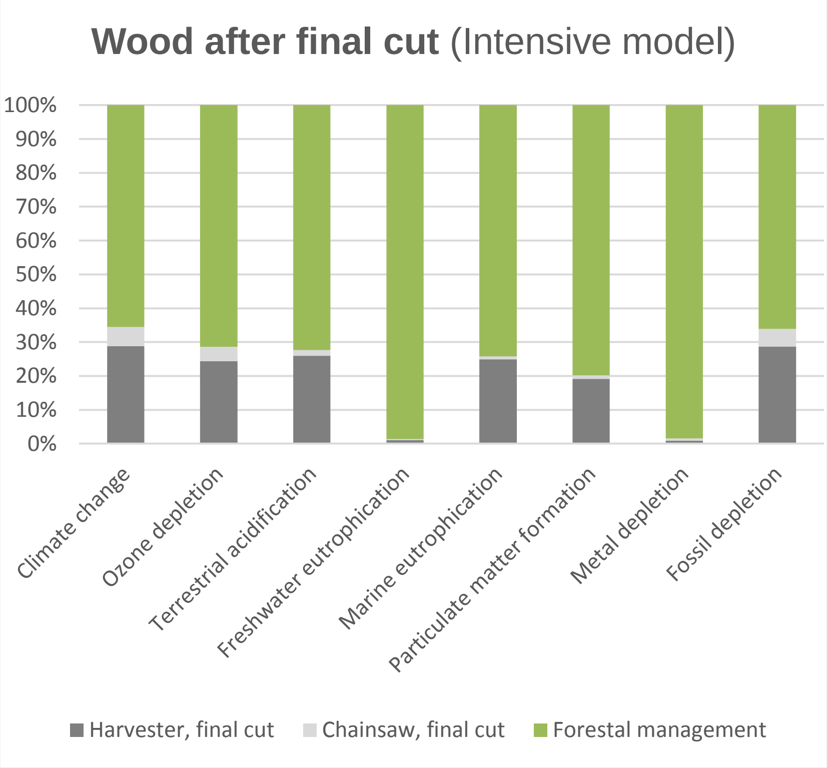
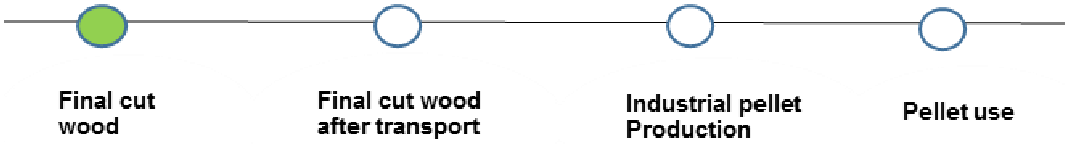


Figure 41: Impact assessment results for the process Wood after final cut showed in 100% stacked column chart

For the wood after final cut process, the biggest environmental impact comes from the forest management (the previous stage of the production chain), the harvesting process also has a relevant impact on the total amount. The cutting of the wood with chainsaw is the less impacting process (from 1 to 4%).

3.2.2.1 **Wood after final cut** (Extensive model)



Impact categories	Chainsaw, final cut
Climate change	7,2E-01
Ozone depletion	8,7E-08
Terrestrial acidification	1,5E-03
Freshwater eutrophication	1,3E-05
Marine eutrophication	4,0E-05
Particulate matter formation	4,2E-04
Metal depletion	2,1E-04
Fossil depletion	2,3E-01

Table 18: Impact assessment results obtained for the Process wood after final cut (Extensive model)

In the extensive model, the first process to be analysed is the cutting of the wood, as when extensive management is performed for forest stage, natural regeneration is assumed and the forest site preparation processes are not needed. Chainsaw cutting is the only input process, and since the engine works with fossil fuel, fossil depletion and climate change are affected by chainsaw CO^2 emissions and fuel depletion of the motor.

3.2.3 Wood after final cut and transport to the roadside (Intensive model)

This process includes the transportation of the cut wood logs (wood after final cut) to the roadside (with the forwarder) and until the pellet factory with the truck.

Impact category	Unit	Wood after final cut	Wood Forwarding	Transport, freight, lorry >32 metric ton, EURO3	total
Climate change	kg CO2 eq	8,4E+00	3,3E+00	6,8E+00	1,8E+01
Ozone depletion	kg CFC-11 eq	1,4E-06	4,1E-07	1,3E-06	3,0E-06
Terrestrial acidification	kg SO2 eq	6,0E-02	1,9E-02	3,5E-02	1,1E-01
Freshwater eutrophication	kg P eq	3,4E-03	4,6E-05	7,8E-05	3,5E-03
Marine eutrophication	kg N eq	3,2E-03	9,9E-04	2,0E-03	6,3E-03
Particulate matter formation	kg PM10 eq	2,8E-02	6,6E-03	1,7E-02	5,1E-02
Metal depletion	kg Fe eq	2,2E-02	2,5E-04	1,8E-03	2,4E-02
Fossil depletion	kg oil eq	3,0E+00	1,0E+00	2,3E+00	6,3E+00

Table 19: Impact assessment results obtained for the Process wood after final cut and transport

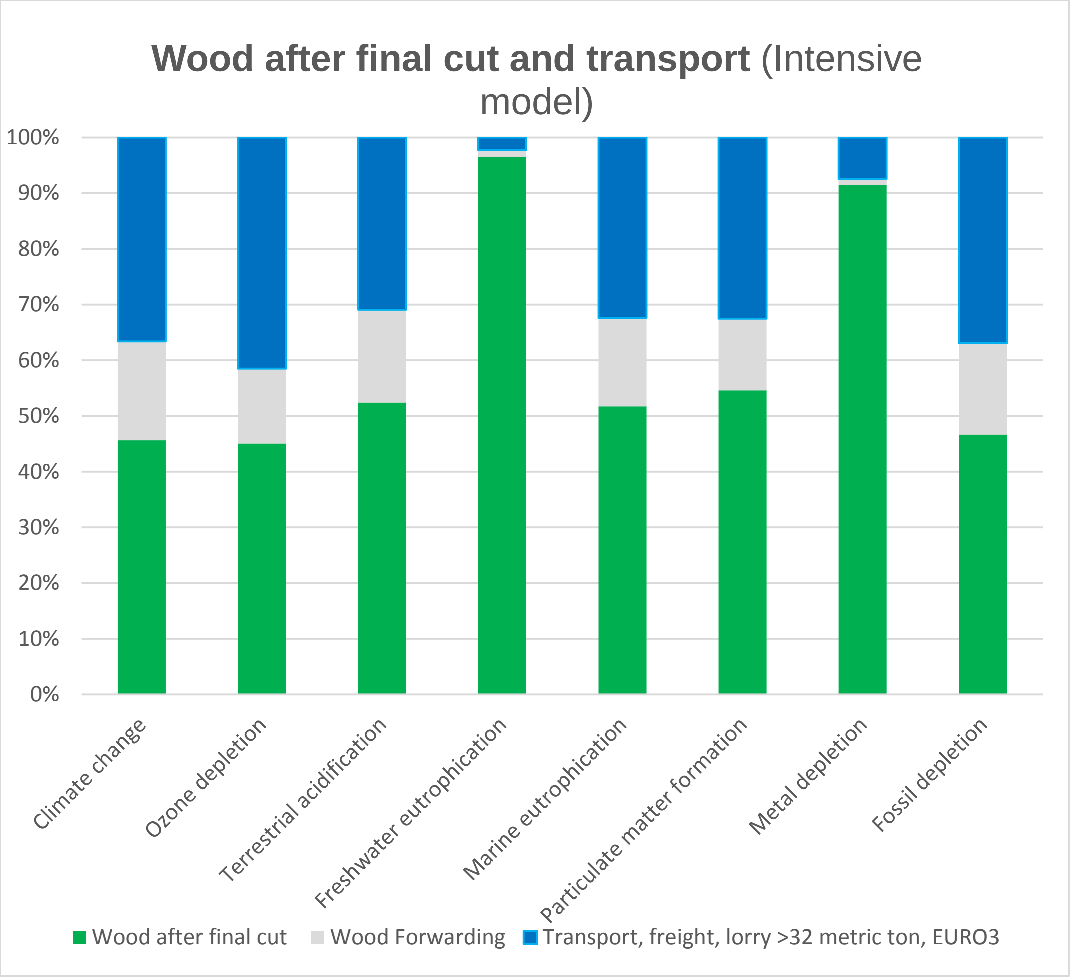


Figure 42: Impact assessment results for the process Wood after final cut and transport showed in 100% stacked column chart

As we can observe the forest stage until this point and the transport of the wood until the factory have the largest overall impact (wood after final cut generally range around 45/50%, and transport phase to 30/35%) with the exception of freshwater eutrophication and fossil depletion (more than 90%), where impacts comes from previous stages, due to forest management operations (fig 40), the forwarding process is the smallest contributor (not more than 10/15%).

3.2.3.2 Wood after final cut and transport to the roadside (Extensive model)

This process includes the transportation of the cut wood logs (wood after final cut) to the roadside (with the forwarder) and until the pellet factory with the truck.

Impact category	Wood After final cut *(Extensive)*	Wood Forwarding	Transport, freight, lorry >32 metric ton, EURO3	Total
Climate change	9,3E-01	3,3E+00	6,8E+00	1,1E+01
Ozone depletion	1,1E-07	4,1E-07	1,3E-06	1,8E-06
Terrestrial acidification	1,9E-03	1,9E-02	3,5E-02	5,6E-02
Freshwater eutrophication	1,7E-05	4,6E-05	7,8E-05	1,4E-04
Marine eutrophication	5,2E-05	9,9E-04	2,0E-03	3,1E-03
Particulate matter formation	5,4E-04	6,6E-03	1,7E-02	2,4E-02
Metal depletion	2,7E-04	2,5E-04	1,8E-03	2,3E-03
Fossil depletion	3,0E-01	1,0E+00	2,3E+00	3,7E+00

Table 20: Impact assessment results obtained for the Process wood after final cut and transport (Extensive model)

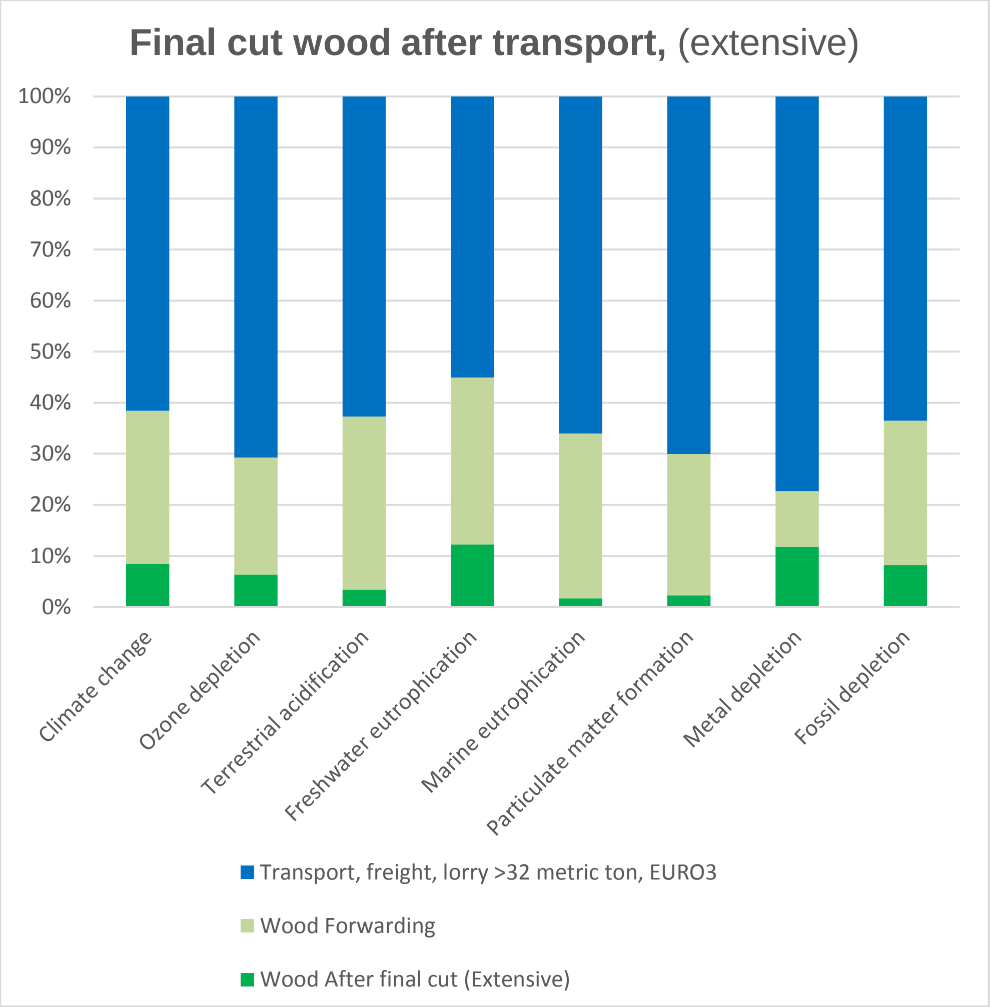


Figure 43: Impact assessment results for the process Wood after final cut and transport showed in 100% stacked column chart (Extensive model)

Since in the extensive model the forest stage operations are reduced to the minimum, the transport phase (60-70%) and the forwarding process (30%) are the main contributors to environmental impacts.

The low intensity scenario has less impacts (climate change is 18.5 kg of CO_2 eq. vs only 11.1 in the extensive one) since only a few operations are performed, no fertilizers are used, stand tending, and infrastructure establishment aren't performed and the fuel consumed is smaller.

3.3 Industrial pellet production chain

3.3.1 Pellet Production

Figure 44 represents the processes that take place inside the factory that produces the pellet, considering the wood that comes from the forest and adding the transport until the selling polling (market or etc.)

Impact category	Unit	Polyethylene, low density, granulate	Final cut wood after forw. and transport	Forestal Residues Burning	Electricity, medium voltage {PT}	Diesel, low-sulfur	Transport, freight, lorry 16-32 ton EURO 4
Climate change	kg CO2 eq	7,7E-04	1,8E+01	8,3E+00	6,5E+01	3,9E-01	1,1E+01
Ozone depletion	kg CFC-11 eq	4,2E-12	3,0E-06	7,2E-07	4,9E-06	5,5E-07	2,1E-06
Terrestrial acidification	kg SO2 eq	2,7E-06	1,1E-01	5,0E-01	4,0E-01	3,8E-03	3,9E-02
Freshwater eutrophication	kg P eq	1,4E-08	3,5E-03	8,1E-04	1,6E-02	3,4E-05	1,3E-04
Marine eutrophication	kg N eq	6,2E-08	6,3E-03	2,3E-02	1,1E-02	7,6E-05	2,0E-03
Particulate matter formation	kg PM10 eq	8,9E-07	5,1E-02	9,9E-01	1,1E-01	1,0E-03	2,1E-02
Metal depletion	kg Fe eq	9,7E-07	2,4E-02	5,4E-03	2,2E-01	7,5E-04	2,9E-03
Fossil depletion	kg oil eq	5,7E-04	6,3E+00	1,5E+00	1,7E+01	1,0E+00	3,8E+00

Impact category	Unit	Total
Climate change	kg CO2 eq	1,0E+02
Ozone depletion	kg CFC-11 eq	1,1E-05
Terrestrial acidification	kg SO2 eq	1,1E+00
Freshwater eutrophication	kg P eq	2,1E-02
Marine eutrophication	kg N eq	4,2E-02
Particulate matter formation	kg PM10 eq	1,2E+00
Metal depletion	kg Fe eq	2,5E-01
Fossil depletion	kg oil eq	3,0E+01

Table 21: Impact assessment results obtained for the Process Pellet Production

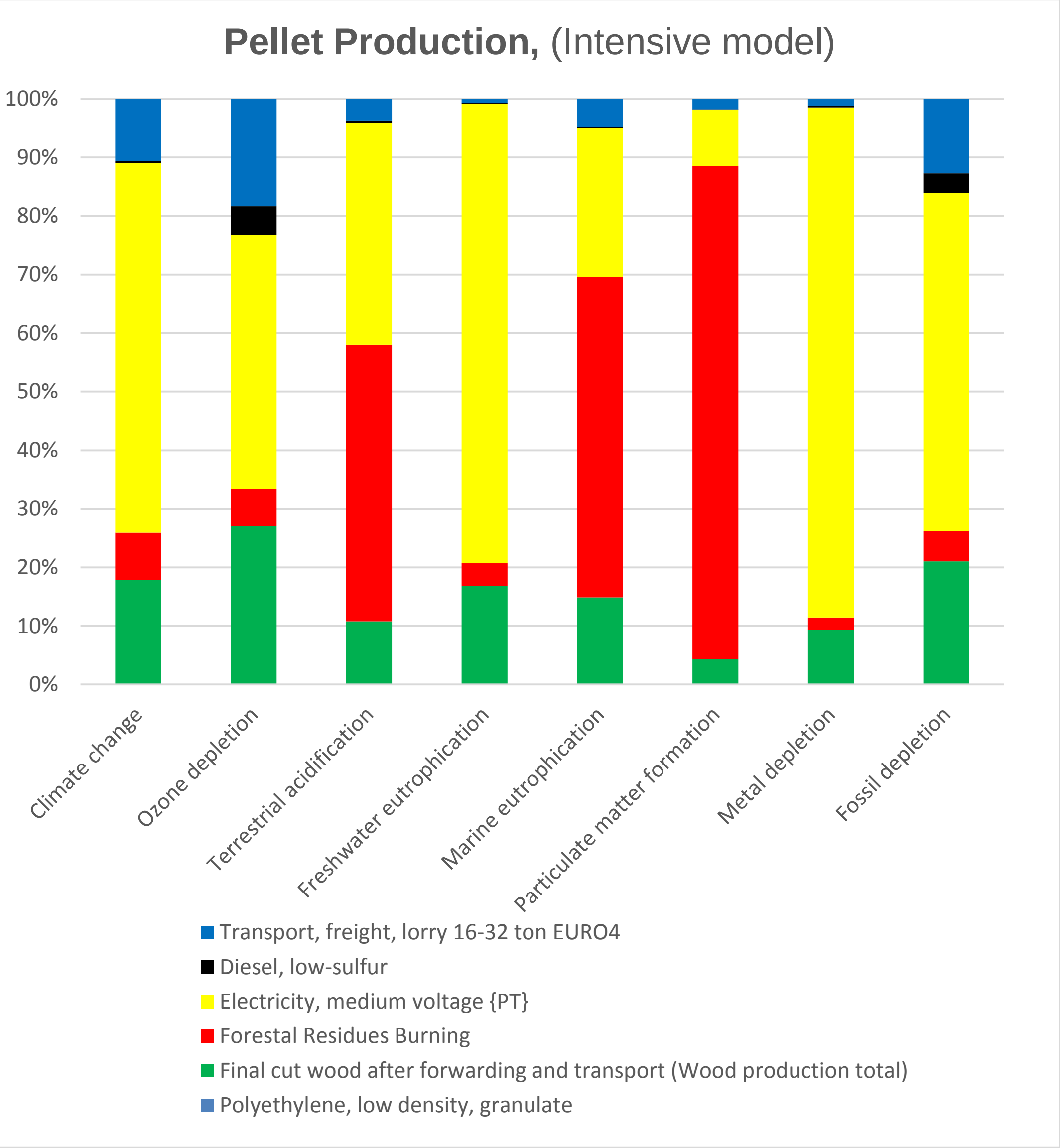


Figure 44: Impact assessment results for the process pellet production showed in 100% stacked column chart

The production stage consumes a large amount of energy, and as showed in figure 44, the biggest environmental impacting process in the industrial pellet production factory, is the electricity consumption, used for the pelletizing machineries, also the burning of forestal residues, needed for a more intensive drying procedure (compared to the domestic model) for the pelletization process, has a relevant environmental impact, but both of those stages are fundamental steps for an industrial wood densification process.

The total of the previous phases of the forest stage (final cut wood after forwarding and transport) have less environmental impacts (from 5% to 25% of the total) compared to the processes of burning and electricity consumption that happens inside the pellet factory; these results agree with others LCA applied to pellet studies *(Laschi et. Al 2016)*

The plastic for packaging has an insignificant environmental impact together with the diesel used for moving the loading and unloading of wood inside de pellet factory.

3.3.1.2 Pellet Production (Extensive model)

Figure 45 represents the processes that take place inside the pellet factory, considering the wood that comes from the forest (with low intensity management) and adding the transport until the selling polling (market or etc.)

Impact category	**Polyethylene, low density, granulate**	**Final cut wood after forwarding and transport** (Extensive model)	**Forestal Residues Burning** (Extensive model)	**Electricity, medium voltage {PT}**	**Diesel, low-sulfur**	**Transport, freight, lorry 16-32 metric ton, EURO4**	**Total**
Climate change	7,7E-04	1,1E+01	6,6E+00	6,5E+01	3,9E-01	1,1E+01	9,4E+01
Ozone depletion	4,2E-12	1,8E-06	4,4E-07	4,9E-06	5,5E-07	2,1E-06	9,7E-06
Terrestrial acidification	2,7E-06	5,6E-02	4,9E-01	4,0E-01	3,8E-03	3,9E-02	9,9E-01
Freshwater eutrophication	1,4E-08	1,4E-04	3,7E-05	1,6E-02	3,4E-05	1,3E-04	1,7E-02
Marine eutrophication	6,2E-08	3,1E-03	2,2E-02	1,1E-02	7,6E-05	2,0E-03	3,8E-02
Particulate matter formation	8,9E-07	2,4E-02	9,9E-01	1,1E-01	1,0E-03	2,1E-02	1,1E+00
Metal depletion	9,7E-07	2,3E-03	5,2E-04	2,2E-01	7,5E-04	2,9E-03	2,3E-01
Fossil depletion	5,7E-04	3,7E+00	9,4E-01	1,7E+01	1,0E+00	3,8E+00	2,7E+01

Table 22: Impact assessment results obtained for the Process Pellet Production (Extensive model)

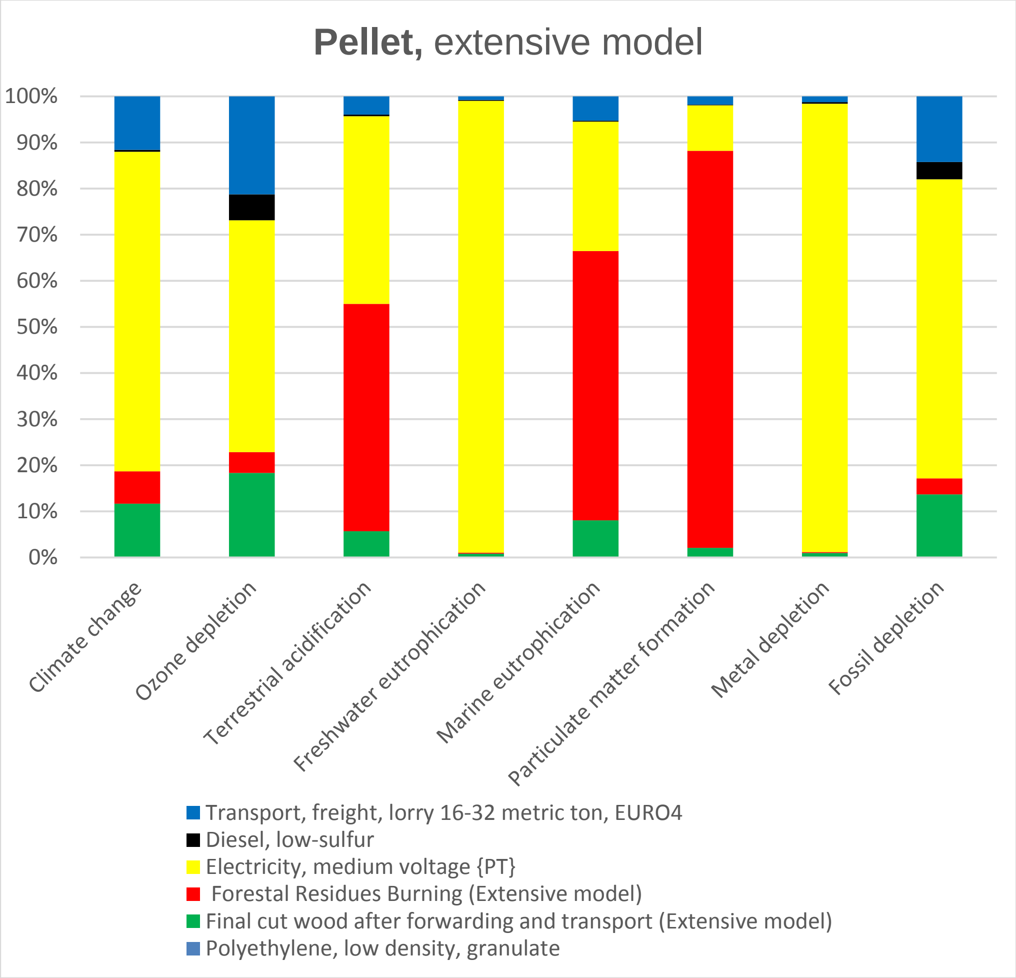


Figure 45: Impact assessment results for the process pellet production showed in 100% stacked column chart (Extensive model)

The results are similar to the intensive model (fig 44), but the impacts related to forest operations have less environmental impacts, from 10%-20% less for most of the impact categories *(Climate change Ozone depletion, Terrestrial acidification, Marine eutrophication, Particulate matter formation, Metal depletion, Fossil depletion)* to 90% less (*Freshwater eutrophication, Metal depletion*).

Energy consumption and forestal residues burning are the most impacting processes.

3.3.2 Pellet Use

Figure 46 represents the final point of the industrial pellet production chain, the pellet burning for heat generation in a final user house, it contains also the truck used for ashes disposal.

Impact category	Unit	Pellet Production	Transport, passenger car, EURO 4	Pellet burning	Municipal waste collection service by 21 metric ton lorry	Total
Climate change	kg CO2 eq	1,0E+02	1,8E+00	5,5E+01	4,9E-01	1,6E+02
Ozone depletion	kg CFC-11 eq	1,1E-05	3,3E-07	0,0E+00	9,2E-08	1,2E-05
Terrestrial acidification	kg SO2 eq	1,1E+00	4,1E-03	1,4E+00	2,4E-03	2,5E+00
Freshwater eutrophication	kg P eq	2,1E-02	2,6E-05	0,0E+00	4,1E-06	2,1E-02
Marine eutrophication	kg N eq	4,2E-02	1,5E-04	6,9E-02	1,3E-04	1,1E-01
Particulate matter formatior	kg PM10 eq	1,2E+00	1,6E-03	1,3E+00	1,1E-03	2,5E+00
Metal depletion	kg Fe eq	2,5E-01	1,1E-03	0,0E+00	6,5E-05	2,5E-01
Fossil depletion	kg oil eq	3,0E+01	6,3E-01	0,0E+00	1,7E-01	3,1E+01

Table 23: Impact assessment results obtained for the Process Pellet use

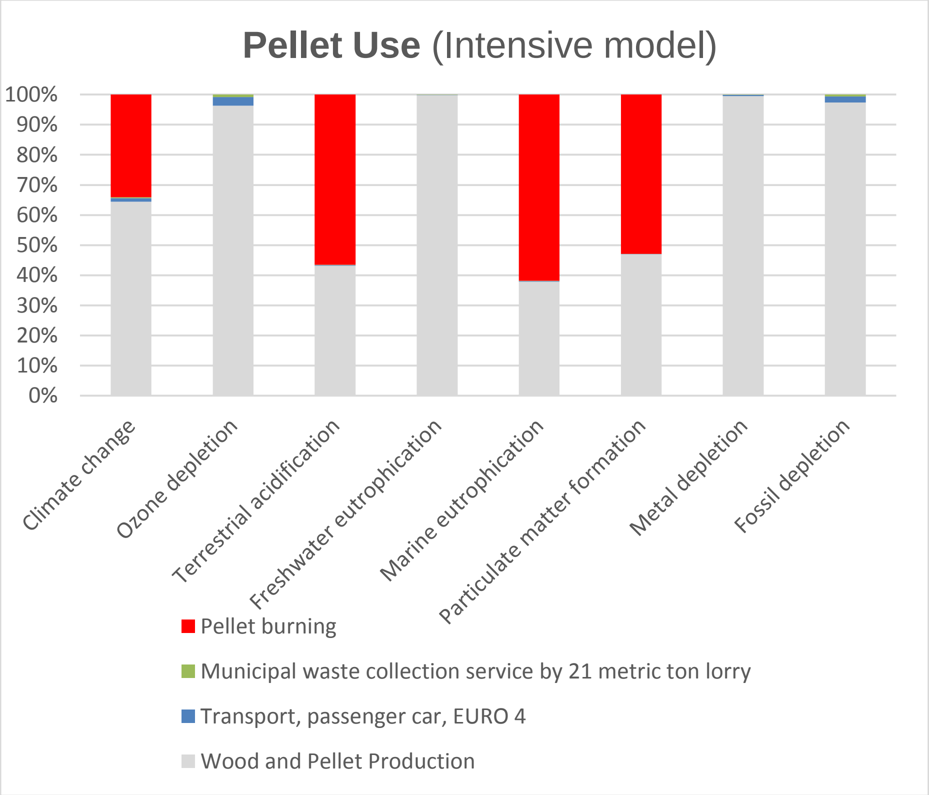


Figure 46: Impact assessment results for the process pellet use showed in 100% stacked column chart

As it is possible to see in fig 46, the pellet burning process has relevant environmental impacts in four categories *(climate change, terrestrial acidification, marine eutrophication, particulate matter formation).* In fact, the pellet is assumed to come from uncontaminated pine wood (no release of metals and etc.).

Most of the impacts, in the categories not affected by pellet burning emissions, come from the previous stages (wood and pellet production) because pellet transport by car and the waste collection service have a total impact of no more than 3-4% of the total.

3.3.2.2 Pellet Use (Extensive model)

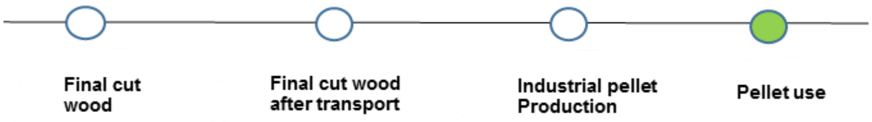


Figure 47 represents the final point of the industrial pellet production chain (extensive model), the pellet burning for heat generation in a final user house, it contains also the truck used for ashes disposal.

Impact category	**Pellet burning**	**Pellet Production** (Extensive model)	**Transport, passenger car, EURO 4**	**Municipal waste collection service by 21 metric ton lorry**	**Total**
Climate change	5,5E+01	9,4E+01	1,8E+00	4,7E-01	1,5E+02
Ozone depletion	0,0E+00	9,7E-06	3,3E-07	8,1E-08	1,0E-05
Terrestrial acidification	1,4E+00	9,9E-01	4,1E-03	2,2E-03	2,4E+00
Freshwater eutrophication	0,0E+00	1,7E-02	2,6E-05	1,4E-06	1,7E-02
Marine eutrophication	6,9E-02	3,8E-02	1,5E-04	1,3E-04	1,1E-01
Particulate matter formation	1,3E+00	1,1E+00	1,6E-03	1,1E-03	2,5E+00
Metal depletion	0,0E+00	2,3E-01	1,1E-03	3,8E-05	2,3E-01
Fossil depletion	0,0E+00	2,7E+01	6,3E-01	1,5E-01	2,8E+01

Table 24: Impact assessment results obtained for the Process Pellet use (Extensive model)

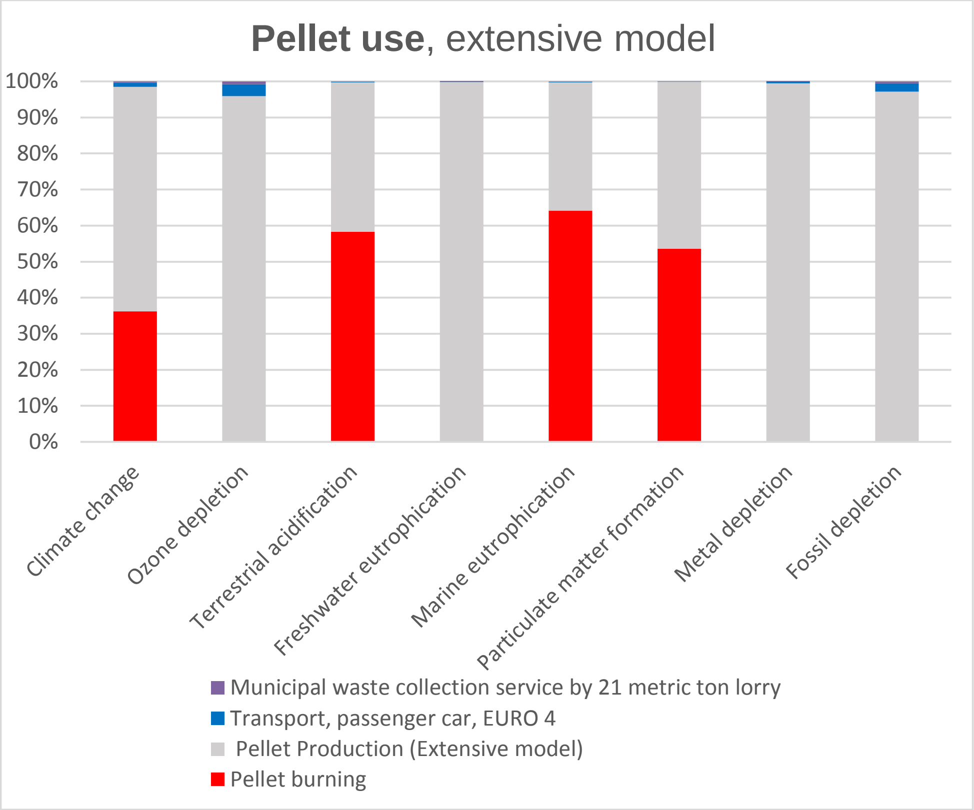


Figure 47: Impact assessment results for the process pellet use showed in 100% stacked column chart

Considering the total impacts of the whole model, the difference between the extensive and the intensive model can be overlooked because other factors have a much higher impact. When the extensive model is considered, fewer pellet production impacts can be noticed, and this is because forest stage is less impacting in the extensive model. Pellet burning has a relevant impact (from 35% to 60%) in the impact categories *Climate change, terrestrial acidification, marine eutrophication, particulate matter formation.* Transport by car and waste disposal are irrelevant.

3.3.3 Sensitivity analysis (Industrial production chain)

3.3.3.1 Pellet Use (Highest Emissions scenario)

This is the last stage analysed and it represents the final point of the pellet production chain, the pellet burning, for heat generation in a final user house, when the emissions of the pellet stoves are assumed to be maximum or minimum as explained in the Method part of this study.

Impact category	Pellet burning (higher emissions)	Pellet Production	Transport, passenger car, EURO 4	Municipal waste collection service by 21 metric ton lorry	Total
Climate change	9,0E+01	1,0E+02	1,8E+00	4,7E-01	2,0E+02
Ozone depletion	0,0E+00	1,1E-05	3,3E-07	8,1E-08	1,2E-05
Terrestrial acidification	3,4E+00	1,1E+00	4,1E-03	2,2E-03	4,5E+00
Freshwater eutrophication	0,0E+00	2,1E-02	2,6E-05	1,4E-06	2,1E-02
Marine eutrophication	1,6E-01	4,2E-02	1,5E-04	1,3E-04	2,1E-01
Particulate matter formatic	2,5E+00	1,2E+00	1,6E-03	1,1E-03	3,7E+00
Metal depletion	0,0E+00	2,5E-01	1,1E-03	3,8E-05	2,5E-01
Fossil depletion	0,0E+00	3,0E+01	6,3E-01	1,5E-01	3,1E+01

Table 25: Impact assessment results obtained for the Process Pellet use (Higher Emissions scenario)

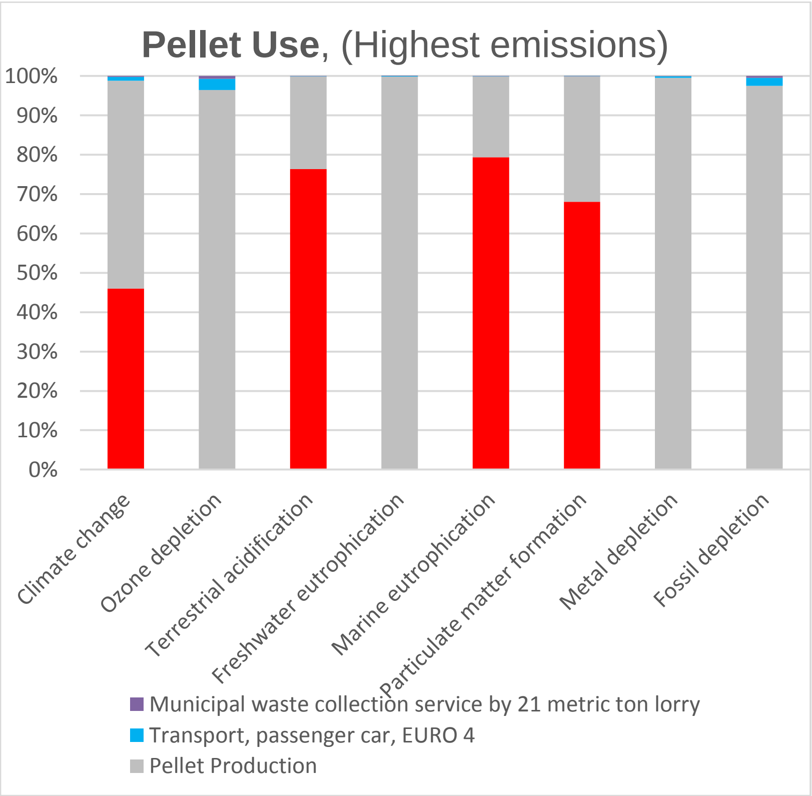


Figure 48: Impact assessment results for the process pellet use (Higher emissions scenario) showed in 100% stacked column chart

3.3.3.2 Pellet use (Lowest emissions scenario)

Impact category	Pellet burning (lower emissions)	Pellet Production	Transport, passenger car, EURO 4	Municipal waste collection service by 21 metric ton lorry	Total
Climate change	1,9E+01	1,0E+02	1,8E+00	4,7E-01	1,3E+02
Ozone depletion	0,0E+00	1,1E-05	3,3E-07	8,1E-08	1,2E-05
Terrestrial acidification	8,3E-01	1,1E+00	4,1E-03	2,2E-03	1,9E+00
Freshwater eutrophication	0,0E+00	2,1E-02	2,6E-05	1,4E-06	2,1E-02
Marine eutrophication	4,1E-02	4,2E-02	1,5E-04	1,3E-04	8,3E-02
Particulate matter formation	5,5E-01	1,2E+00	1,6E-03	1,1E-03	1,7E+00
Metal depletion	0,0E+00	2,5E-01	1,1E-03	3,8E-05	2,5E-01
Fossil depletion	0,0E+00	3,0E+01	6,3E-01	1,5E-01	3,1E+01

Table 26: Impact assessment results obtained for the Process Pellet use (Lower Emissions scenario)

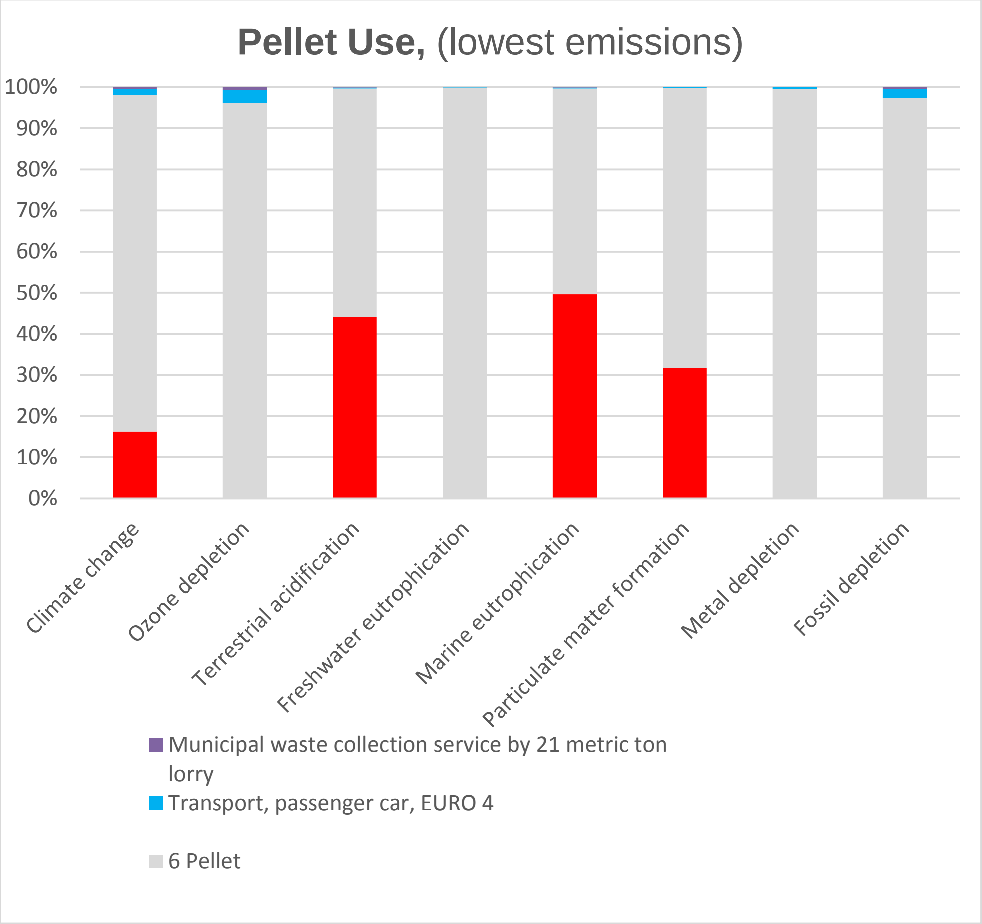


Figure 49: Impact assessment results for the process pellet use (Higher emissions scenario) showed in 100% stacked column chart

If we consider high emissions in the pellet burning, the combustion phase becomes relevant, as only this phase accounts for the 45% of the overall impacts for the climate change category, and for more than 60% in the categories where wood burning has an effect.

As it is possible to see in fig 49, although we are considering a lowest emissions scenario, the pellet burning process still has a relevant environmental impact, anyhow most of the impacts come from the previous stages (wood and pellet production).

3.3.4 Environmental hotspot in the industrial pellet production chain

The following figures (50, 51, 52, 53, 54) represent the main stages of the industrial pellet production chain, considering the forest stage, the pellet production, the transport phase, and the burning stage. They have been separated and referred to the functional unit, in order to be compared with each other, together with the extensive model and the variations considered in the sensitivity analysis.

Table 27: Impact assessment results obtained for the main stages of the industrial pellet production chain (intensive model)

Impact category	Unit	Forest stage	Pellet Production	Pellet Burning	Transport Phases
Climate change	kg CO2 eq	1,5E+01	6,9E+01	5,5E+01	2,3E+01
Ozone depletion	kg CFC-11 eq	2,2E-06	5,4E-06	0,0E+00	4,3E-06
Terrestrial acidification	kg SO2 eq	1,0E-01	8,8E-01	1,4E+00	9,8E-02
Freshwater eutrophication	kg P eq	4,2E-03	1,6E-02	0,0E+00	2,7E-04
Marine eutrophication	kg N eq	5,3E-03	3,2E-02	6,9E-02	5,3E-03
Particulate matter formation	kg PM10 eq	4,4E-02	1,1E+00	1,3E+00	4,8E-02
Metal depletion	kg Fe eq	2,7E-02	2,2E-01	0,0E+00	6,7E-03
Fossil depletion	kg oil eq	5,0E+00	1,8E+01	0,0E+00	8,0E+00

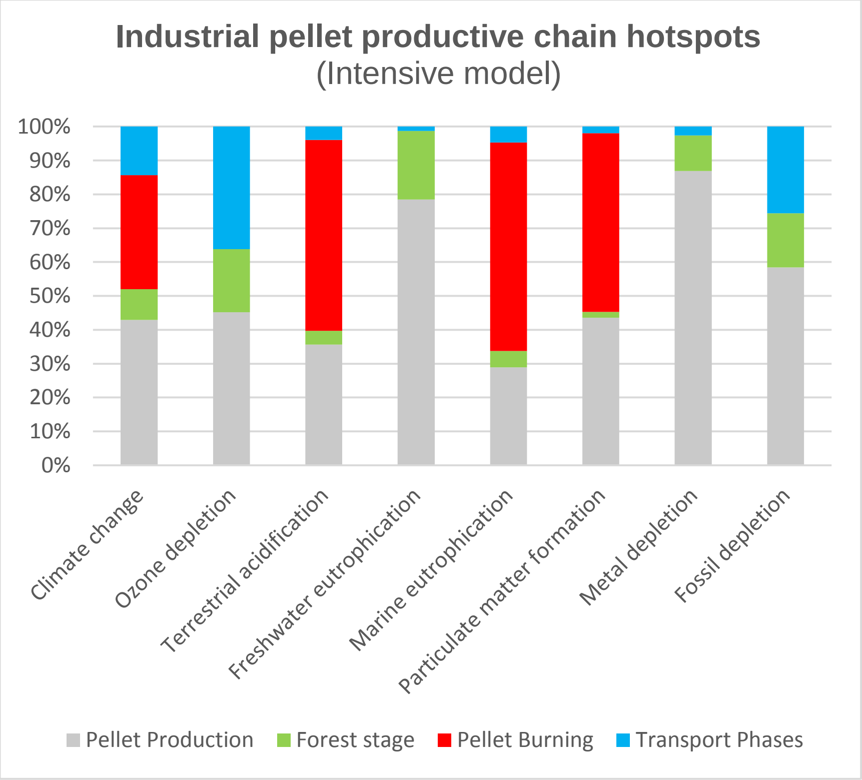


Figure 50: Impact assessment results for the pellet production chain main stages showed in 100% stacked column chart (intensive model)

Table 28: Impact assessment results obtained for the main stages of the industrial pellet production chain (extensive model)

Impact category	Unit	Forest stage	Pellet Production	Pellet Burning	Transport Phases
Climate change	kg CO2 eq	7,7E+00	6,9E+01	5,5E+01	2,3E+01
Ozone depletion	kg CFC-11 eq	9,7E-07	5,4E-06	0,0E+00	4,3E-06
Terrestrial acidification	kg SO2 eq	4,2E-02	8,8E-01	1,4E+00	9,8E-02
Freshwater eutrophication	kg P eq	1,2E-04	1,6E-02	0,0E+00	2,7E-04
Marine eutrophication	kg N eq	2,2E-03	3,2E-02	6,9E-02	5,3E-03
Particulate matter formation	kg PM10 eq	1,5E-02	1,1E+00	1,3E+00	4,8E-02
Metal depletion	kg Fe eq	7,8E-04	2,2E-01	0,0E+00	6,7E-03
Fossil depletion	kg oil eq	2,5E+00	1,8E+01	0,0E+00	8,0E+00

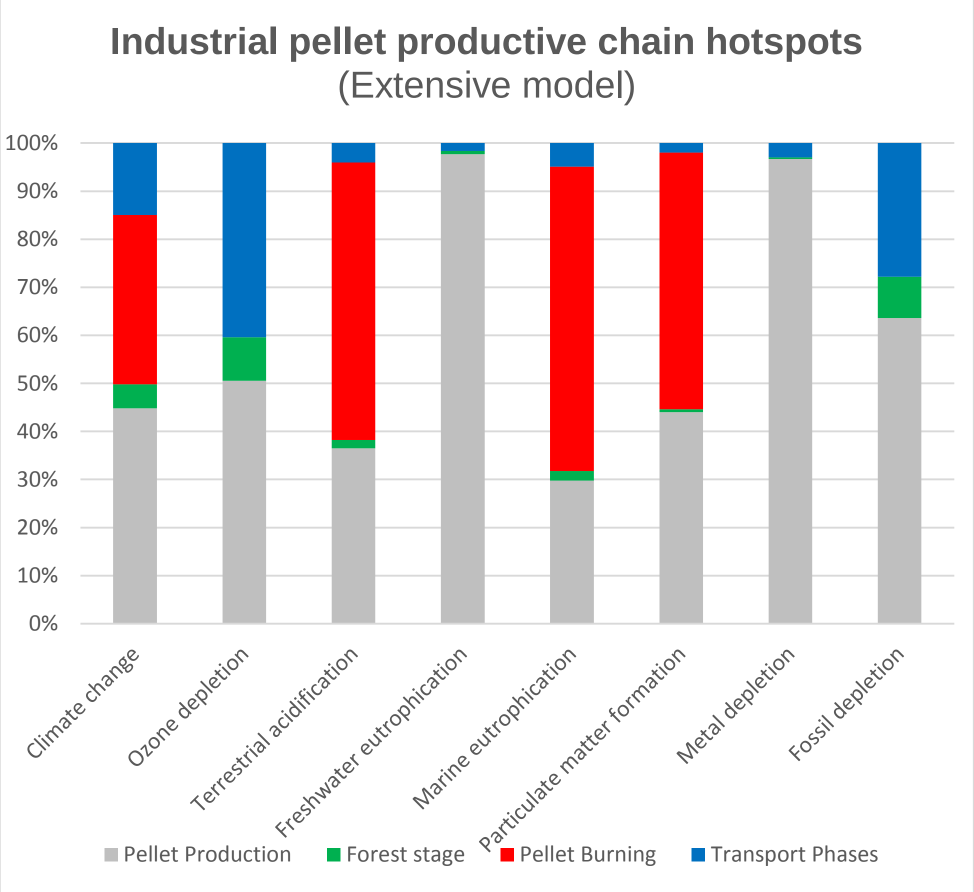


Figure 51: Impact assessment results obtained for the main stages of the industrial pellet production chain showed in 100% stacked column chart (Extensive model)

Table 29: Impact assessment results obtained for the main stages of the industrial pellet production chain (highest emissions scenario)

Impact category	Unit	Forest stage	Pellet Production	Pellet Burning	Transport Phases
Climate change	kg CO2 eq	1,5E+01	6,9E+01	9,0E+01	2,3E+01
Ozone depletion	kg CFC-11 eq	2,2E-06	5,4E-06	0,0E+00	4,3E-06
Terrestrial acidification	kg SO2 eq	1,0E-01	8,8E-01	3,4E+00	9,8E-02
Freshwater eutrophication	kg P eq	4,2E-03	1,6E-02	0,0E+00	2,7E-04
Marine eutrophication	kg N eq	5,3E-03	3,2E-02	1,6E-01	5,3E-03
Particulate matter formation	kg PM10 eq	4,4E-02	1,1E+00	2,5E+00	4,8E-02
Metal depletion	kg Fe eq	2,7E-02	2,2E-01	0,0E+00	6,7E-03
Fossil depletion	kg oil eq	5,0E+00	1,8E+01	0,0E+00	8,0E+00

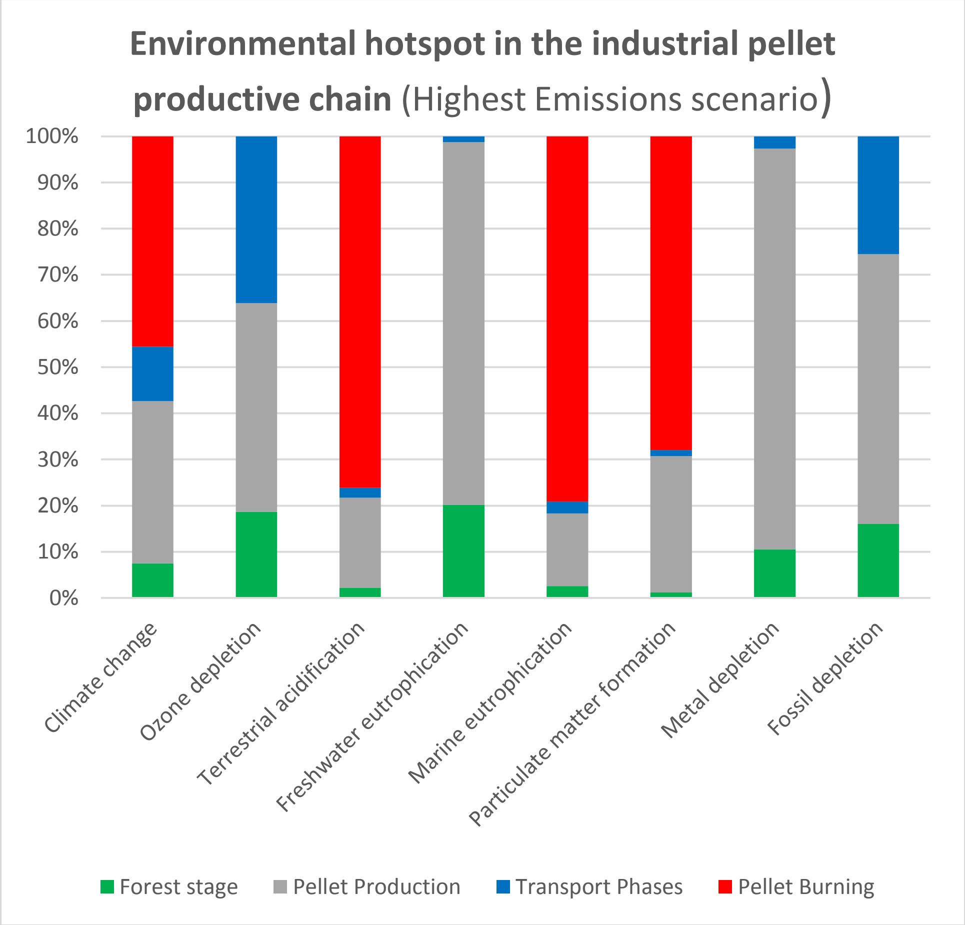


Figure 52: Impact assessment results obtained for the main stages of the industrial pellet production chain showed in 100% stacked column chart (Highest emissions scenario, intensive model)

Table 30: Impact assessment results obtained for the main stages of the industrial pellet production chain (lowest emissions scenario)

Impact category	Unit	Forest stage	Pellet Production	Pellet burning	Transport Phases
Climate change	kg CO2 eq	1,5E+01	6,9E+01	1,9E+01	2,3E+01
Ozone depletion	kg CFC-11 eq	2,2E-06	5,4E-06	0,0E+00	4,3E-06
Terrestrial acidification	kg SO2 eq	1,0E-01	8,8E-01	8,3E-01	9,8E-02
Freshwater eutrophication	kg P eq	4,2E-03	1,6E-02	0,0E+00	2,7E-04
Marine eutrophication	kg N eq	5,3E-03	3,2E-02	4,1E-02	5,3E-03
Particulate matter formation	kg PM10 eq	4,4E-02	1,1E+00	5,5E-01	4,8E-02
Metal depletion	kg Fe eq	2,7E-02	2,2E-01	0,0E+00	6,7E-03
Fossil depletion	kg oil eq	5,0E+00	1,8E+01	0,0E+00	8,0E+00

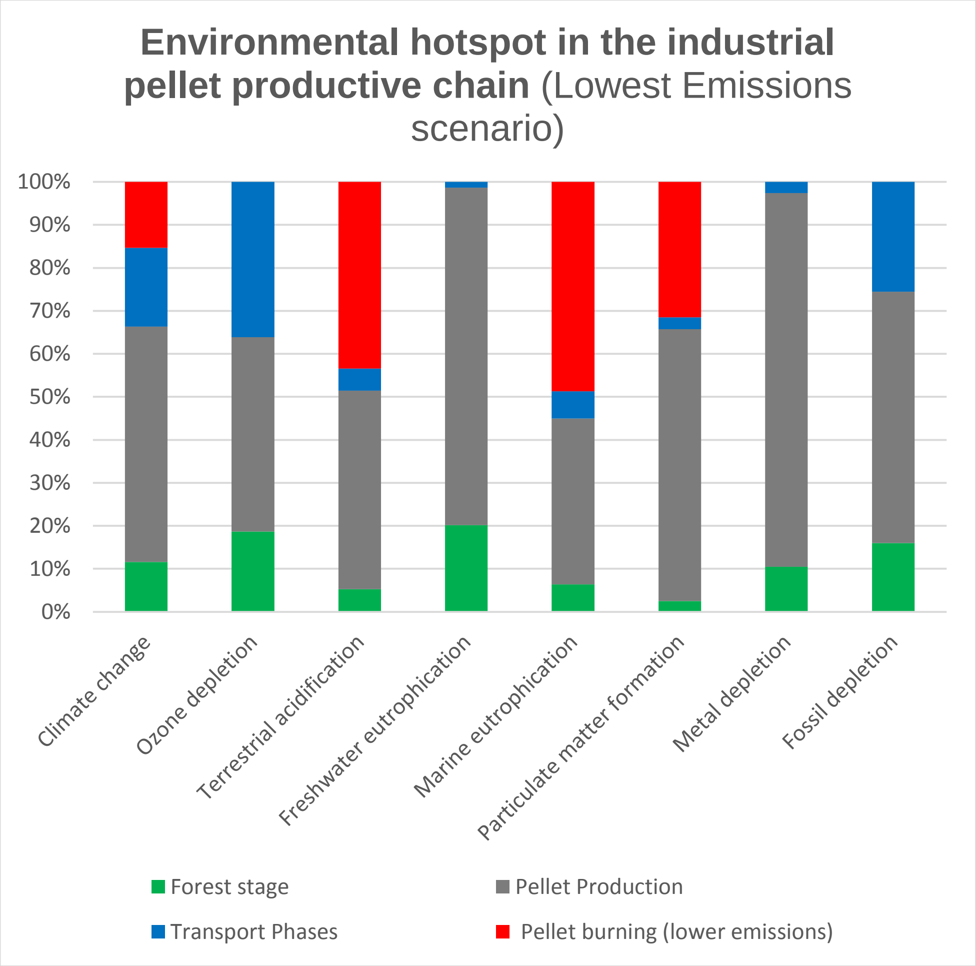


Figure 53: Impact assessment results obtained for the main stages of the industrial pellet production chain showed in 100% stacked column chart (Highest emissions scenario, industrial model)

Table 31: Impact assessment results obtained for the main stages of the industrial pellet production chain (higher transport distances scenario)

Impact category	Unit	Forest stage	Pellet Production	Pellet burning	Transport Phases
Climate change	kg CO2 eq	1,6E+01	7,1E+01	5,5E+01	4,7E+01
Ozone depletion	kg CFC-11 eq	2,4E-06	5,6E-06	0,0E+00	8,6E-06
Terrestrial acidification	kg SO2 eq	1,1E-01	8,9E-01	1,4E+00	2,0E-01
Freshwater eutrophication	kg P eq	4,6E-03	1,7E-02	0,0E+00	5,5E-04
Marine eutrophication	kg N eq	5,7E-03	3,3E-02	6,9E-02	1,1E-02
Particulate matter formation	kg PM10 eq	4,6E-02	1,1E+00	1,3E+00	9,7E-02
Metal depletion	kg Fe eq	2,9E-02	2,3E-01	0,0E+00	1,3E-02
Fossil depletion	kg oil eq	5,3E+00	1,9E+01	0,0E+00	1,6E+01

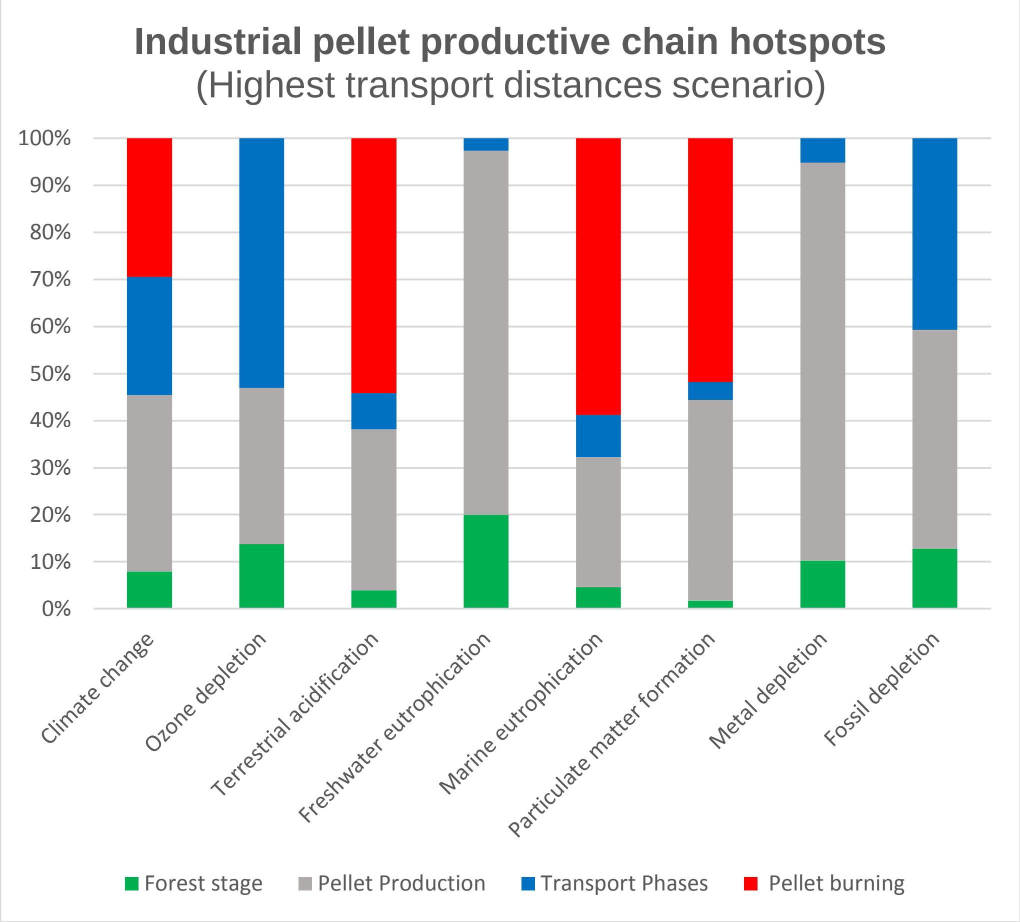


Figure 54: Impact assessment results obtained for the main stages of the industrial pellet production chain showed in 100% stacked column chart (highest transport distances scenario, intensive model)

It is possible to notice that, if compared to the other main stages of the production chain, the forest stage is the less impacting phase. (no more than 20%). If we consider a low intensity management, the impact of forest stage becomes almost negligible (1-3% of overall impacts).

The key stages in the production chain are the pellet production and the pellet burning, although pellet burning only affects some impact categories. The most impacting stage in the production chain for most impacts and scenarios is the pellet production, due to machinery high energy consumption during the pelletisation processes.

When we assume high emissions, the impact of the pellet burning becomes the hotspot on the production chain with a minimum overall impact of 65% in the affected categories, the pellet production also has a relevant impacting profile.

If the emissions are lower, the pellet production stage has the most impacting environmental profile except in the case of marine eutrophication. It’s interesting to notice that despite the lower emissions scenario, the pellet burning still accounts for 13 % of the total climate change impact and from 30% to 60% in the categories were the burning process has an impact. For this reason the pellet burning phase is a key process, no matter the analysed scenario.

In high transport distances scenario, transport phases account for 30% of overall climate change and 50% of the impacts in the ozone depletion category. Furthermore, they have a relevant impact in the fossil depletion category, due to fuel consumption.

It’s interesting to notice that the transport phases have higher impacts (except for metal depletion category) than the operation related to forest stage.

The pellet production phase and the pellet burning phase (where it contributes) are still big impactor.

3.4 Local pellet production chain

3.4.1 Sawmill

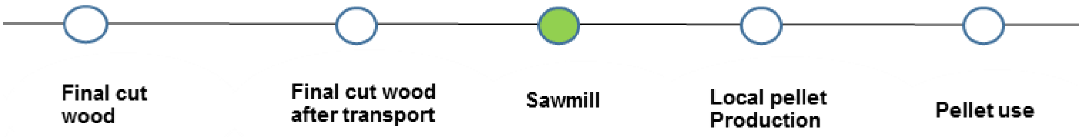


Figure 55 represents the processes that take place inside the sawmill that produces the sawdust, considering the wood that comes from the forest and adding the transport until the pellet factory.

Impact category	Unit	Final cut wood after forwarding and transport	Electricity, medium voltage {PT}	Diesel	Transport, freight, lorry >32 metric ton, EURO3	Total
Climate change	kg CO2 eq	6,0E+00	4,8E+00	1,2E+00	2,2E+00	1,4E+01
Ozone depletion	kg CFC-11 eq	9,8E-07	3,6E-07	2,3E-07	4,0E-07	2,0E-06
Terrestrial acidification	kg SO2 eq	3,7E-02	2,9E-02	9,9E-03	1,1E-02	8,8E-02
Freshwater eutrophication	kg P eq	1,1E-03	1,2E-03	1,2E-05	2,5E-05	2,4E-03
Marine eutrophication	kg N eq	2,0E-03	7,9E-04	5,9E-04	6,5E-04	4,1E-03
Particulate matter formation	kg PM10 eq	1,7E-02	8,3E-03	5,0E-03	5,4E-03	3,5E-02
Metal depletion	kg Fe eq	7,6E-03	1,6E-02	1,7E-04	5,6E-04	2,5E-02
Fossil depletion	kg oil eq	2,0E+00	1,3E+00	4,2E-01	7,5E-01	4,5E+00

Table 32: Impact assessment results obtained for the sawmill process of the domestic pellet production chain

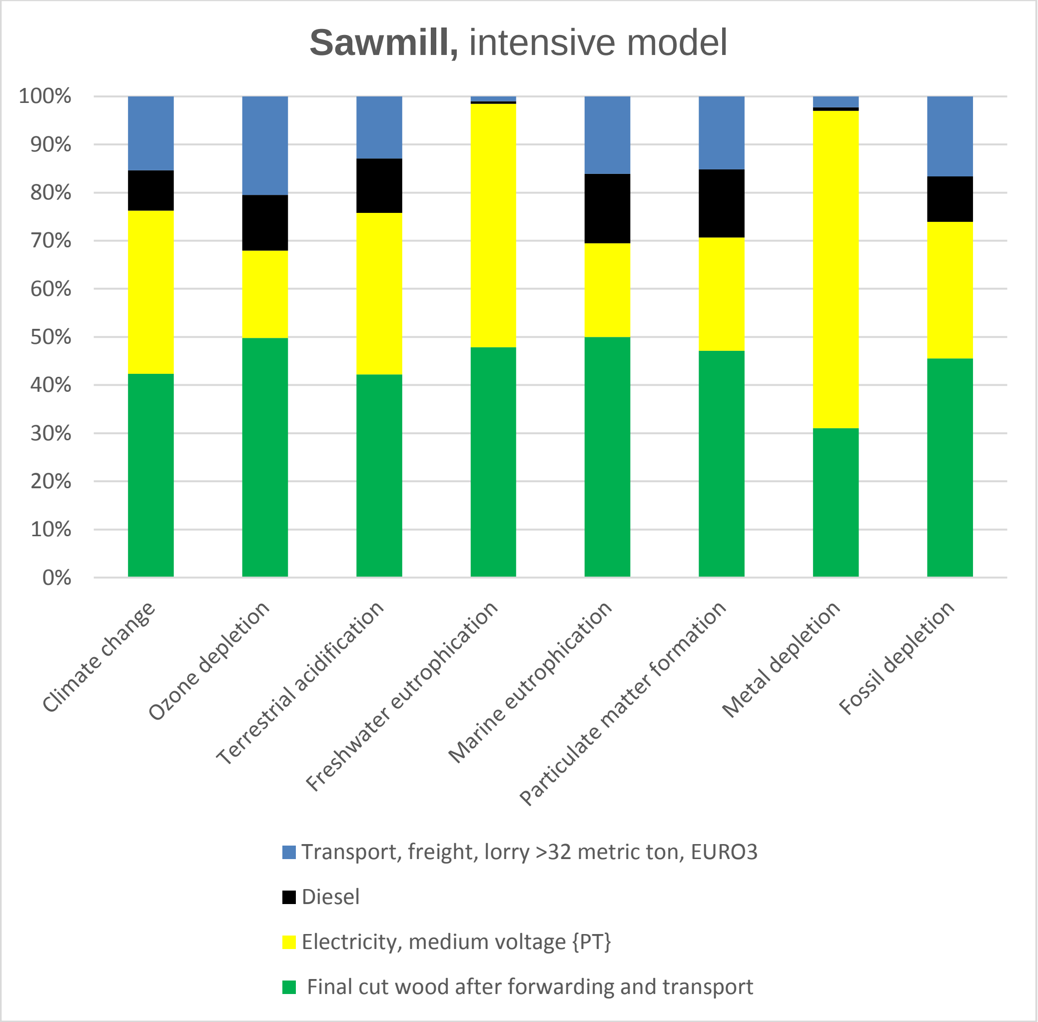


Figure 55 : Impact assessment results obtained for the sawmill process of the domestic pellet production chain showed in 100% stacked column chart

The total of the previous forest stage processes (final cut wood after forwarding and transport) have the largest amount of environmental impacts (from 40% to 50% of the total). Electricity consumption also has relevant environmental impacts.

The diesel used for moving, loading and unloading wood inside the sawmill accounts for 10/15% of the impacts.

3.4.1.2 Sawmill (Extensive model)

Figure 56 represents the processes that take place inside the sawmill that produces the sawdust, considering the wood that comes from the forest (low intensity management) and adding the transport until the pellet factory.

Impact category	Final cut wood after forwarding and transport	Electricity, medium voltage {PT}	Diesel	Transport, freight, lorry >32 metric ton, EURO3	Total
Climate change	3,6E+00	4,8E+00	1,2E+00	2,2E+00	1,2E+01
Ozone depletion	5,8E-07	3,6E-07	2,3E-07	4,0E-07	1,6E-06
Terrestrial acidification	1,8E-02	2,9E-02	9,9E-03	1,1E-02	6,9E-02
Freshwater eutrophication	4,6E-05	1,2E-03	1,2E-05	2,5E-05	1,3E-03
Marine eutrophication	1,0E-03	7,9E-04	5,9E-04	6,5E-04	3,0E-03
Particulate matter formation	7,7E-03	8,3E-03	5,0E-03	5,4E-03	2,6E-02
Metal depletion	7,4E-04	1,6E-02	1,7E-04	5,6E-04	1,8E-02
Fossil depletion	1,2E+00	1,3E+00	4,2E-01	7,5E-01	3,6E+00

Table 33: : Impact assessment results obtained for the sawmill process of the domestic pellet production chain (extensive model)

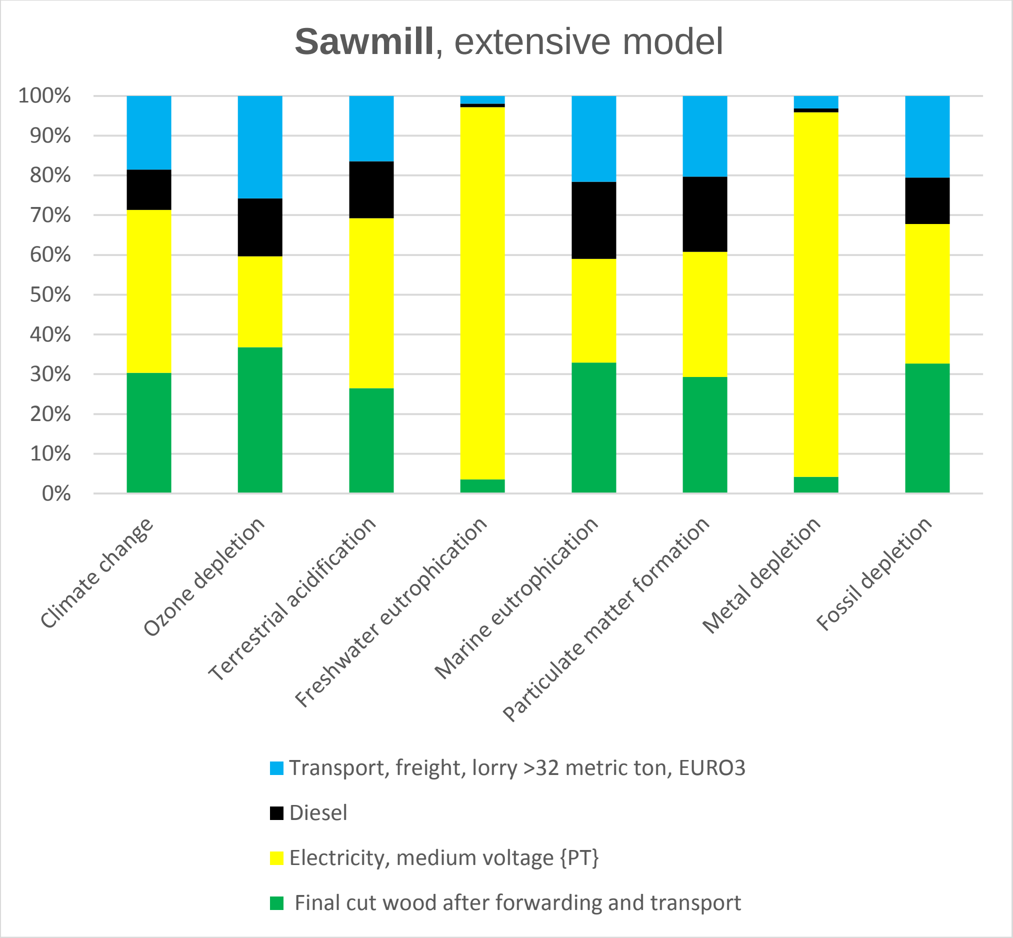


Figure 56: Impact assessment results obtained for the sawmill process of the domestic pellet production chain (extensive model) showed in 100% stacked column chart

This phase is similar to what explained in fig 55, but when low intensity management is applied the impact of forest stage is less, and varies from 5% to 35%. The electricity consumption is the environmental hotspot.

3.4.2 Local pellet production

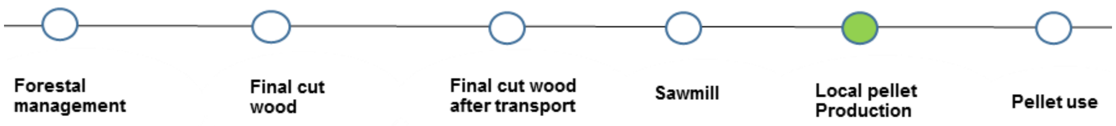
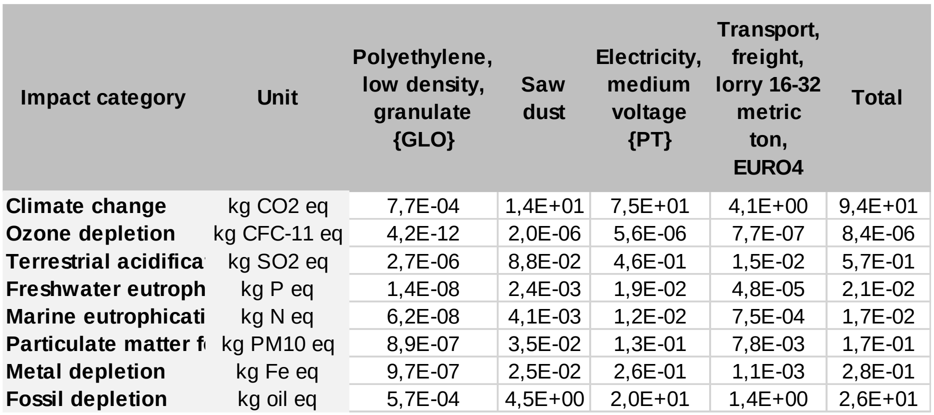


Figure 57 represents the processes that take place inside the factory that produces the pellet, considering the sawdust that comes from the sawmill and adding the transport until the selling polling (market or etc.)



Impact category	Unit	Polyethylene, low density, granulate {GLO}	Saw dust	Electricity, medium voltage {PT}	Transport, freight, lorry 16-32 metric ton, EURO4	Total
Climate change	kg CO2 eq	7,7E-04	1,4E+01	7,5E+01	4,1E+00	9,4E+01
Ozone depletion	kg CFC-11 eq	4,2E-12	2,0E-06	5,6E-06	7,7E-07	8,4E-06
Terrestrial acidifica	kg SO2 eq	2,7E-06	8,8E-02	4,6E-01	1,5E-02	5,7E-01
Freshwater eutroph	kg P eq	1,4E-08	2,4E-03	1,9E-02	4,8E-05	2,1E-02
Marine eutrophicati	kg N eq	6,2E-08	4,1E-03	1,2E-02	7,5E-04	1,7E-02
Particulate matter f	kg PM10 eq	8,9E-07	3,5E-02	1,3E-01	7,8E-03	1,7E-01
Metal depletion	kg Fe eq	9,7E-07	2,5E-02	2,6E-01	1,1E-03	2,8E-01
Fossil depletion	kg oil eq	5,7E-04	4,5E+00	2,0E+01	1,4E+00	2,6E+01

Table 34: Impact assessment results obtained for the local pellet production process of the domestic pellet production chain showed in 100% stacked column chart

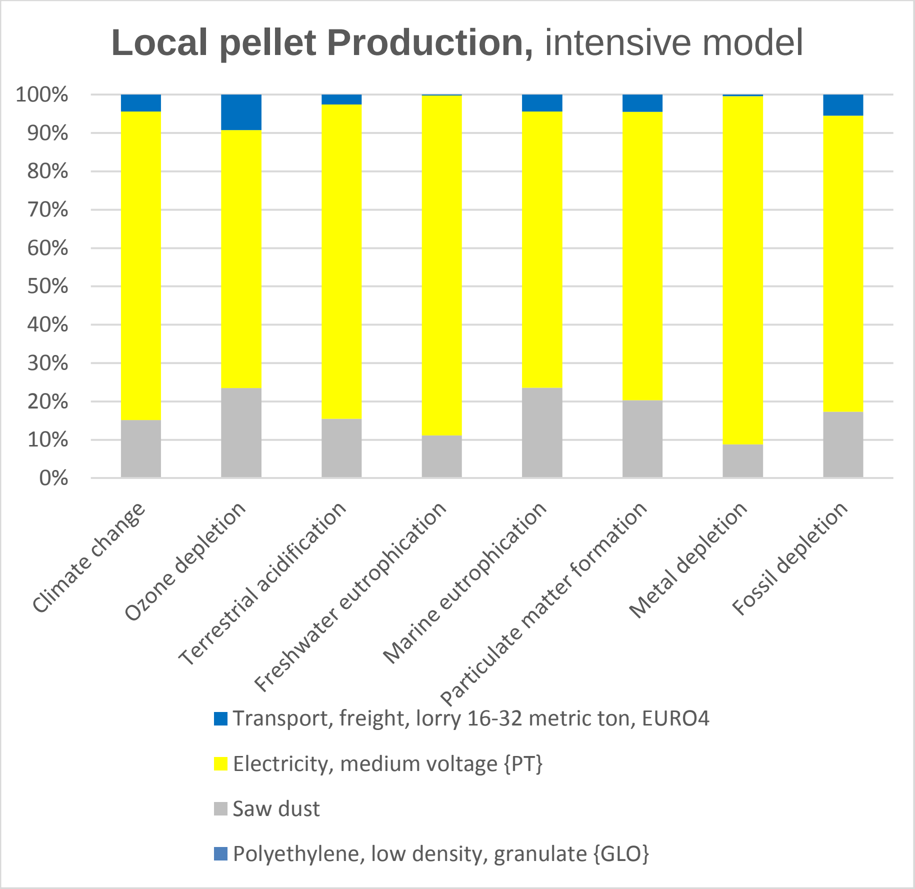


Figure 57: Impact assessment results obtained for the local pellet production process of the domestic pellet production chain 100% stacked column chart

The local pellet production stage consumes a large amount of energy, more than in the industrial model due to a lack of quality control and a lower machinery efficiency (150 kW only for pelletization process vs 129 kW for the entire densification process from wood logs) so as showed in figure 59, the biggest environmental impacting process in the local pellet production factory, is the electricity consumption, used by pelletizing machine, that accounts for 80-90% of overall impacts.

The total of the previous forest stage processes (sawdust production) has less environmental impacts (from 8% to 20% of the total).

The plastic for packaging has an insignificant environmental impact, and the transport phase accounts for a maximum of 10% due to reduced transport distances of a domestic model.

3.4.2.1 Local pellet production (Extensive model)

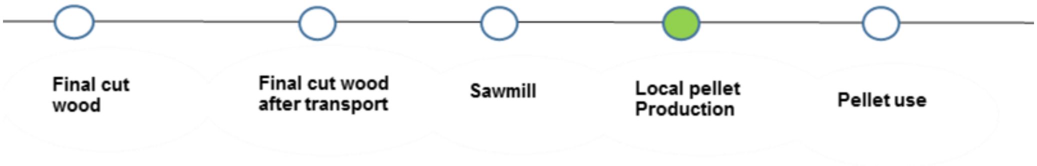


Figure 58 represents the processes that take place inside the factory that produces the pellet, considering the sawdust that comes from the sawmill and adding the transport until the selling polling (market or etc.)

Impact category	Unit	Polyethylene, low density, granulate	Saw dust, wet, {PT}	Electricity, medium voltage {PT}	Transport, freight, lorry 16-32 metric ton, EURO4	Total
Climate change	kg CO2 eq	7,7E-04	1,2E+01	7,5E+01	4,1E+00	9,1E+01
Ozone depletion	kg CFC-11 eq	4,2E-12	1,6E-06	5,6E-06	7,7E-07	8,0E-06
Terrestrial acidification	kg SO2 eq	2,7E-06	6,9E-02	4,6E-01	1,5E-02	5,5E-01
Freshwater eutrophication	kg P eq	1,4E-08	1,3E-03	1,9E-02	4,8E-05	2,0E-02
Marine eutrophication	kg N eq	6,2E-08	3,0E-03	1,2E-02	7,5E-04	1,6E-02
Particulate matter formation	kg PM10 eq	8,9E-07	2,6E-02	1,3E-01	7,8E-03	1,7E-01
Metal depletion	kg Fe eq	9,7E-07	1,8E-02	2,6E-01	1,1E-03	2,7E-01
Fossil depletion	kg oil eq	5,7E-04	3,6E+00	2,0E+01	1,4E+00	2,5E+01

Table 35: Impact assessment results obtained for the local pellet production process of the domestic pellet production chain (extensive model

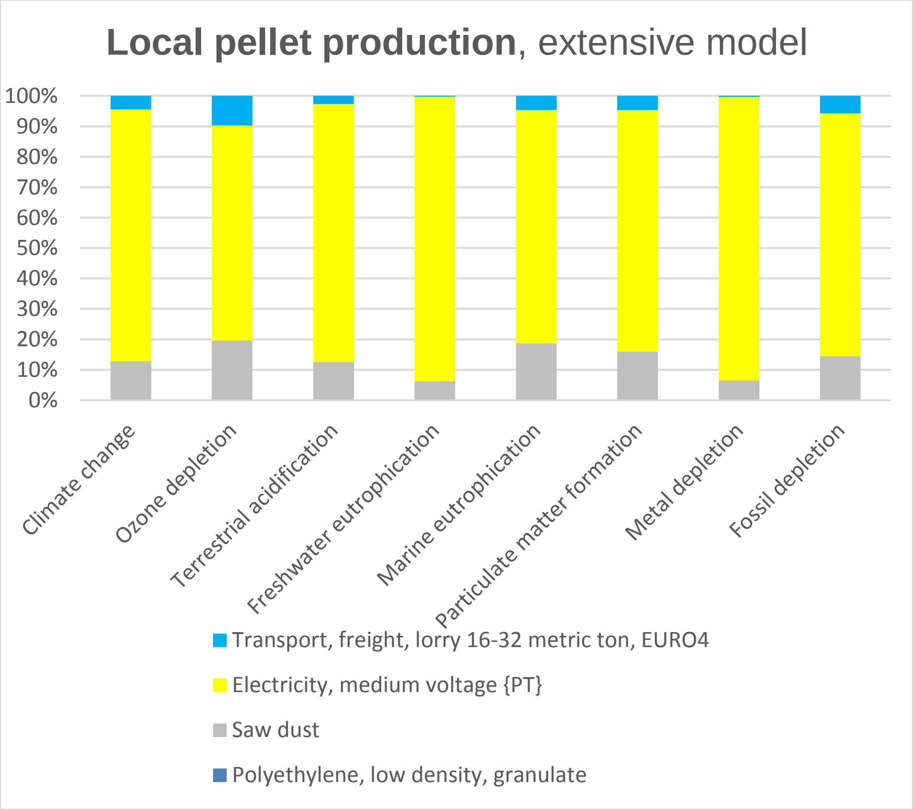


Figure 58: Impact assessment results obtained for the local pellet production process of the domestic pellet production chain (extensive model) showed in 100% stacked column chart

This phase is similar to what explained in fig 57, but when low intensity management is applied the impact sawdust production is less and varies from 5% to 20%. Electricity consumption has an impact of 90% in almost all impact categories.

3.4.3 Local pellet use

Figure 59 represents the final point of the domestic pellet production chain, the pellet burning for heat generation in a final user house together with the transport of ashes for disposal.

Impact category	Unit	Pellet burning	Transport, passenger car, EURO 4	Domestic pellet	Municipal waste collection service by 21 metric ton lorry	Total
Climate change	kg CO2 eq	5,5E+01	1,8E+00	9,4E+01	4,7E-01	1,5E+02
Ozone depletion	kg CFC-11 eq	0,0E+00	3,3E-07	8,4E-06	8,1E-08	8,8E-06
Terrestrial acidification	kg SO2 eq	1,4E+00	4,1E-03	5,7E-01	2,2E-03	2,0E+00
Freshwater eutrophication	kg P eq	0,0E+00	2,6E-05	2,1E-02	1,4E-06	2,1E-02
Marine eutrophication	kg N eq	6,9E-02	1,5E-04	1,7E-02	1,3E-04	8,6E-02
Particulate matter formation	kg PM10 eq	1,3E+00	1,6E-03	1,7E-01	1,1E-03	1,5E+00
Metal depletion	kg Fe eq	0,0E+00	1,1E-03	2,8E-01	3,8E-05	2,8E-01
Fossil depletion	kg oil eq	0,0E+00	6,3E-01	2,6E+01	1,5E-01	2,7E+01

Table 36: Impact assessment results obtained for the local produced pellet use of the domestic pellet production chain

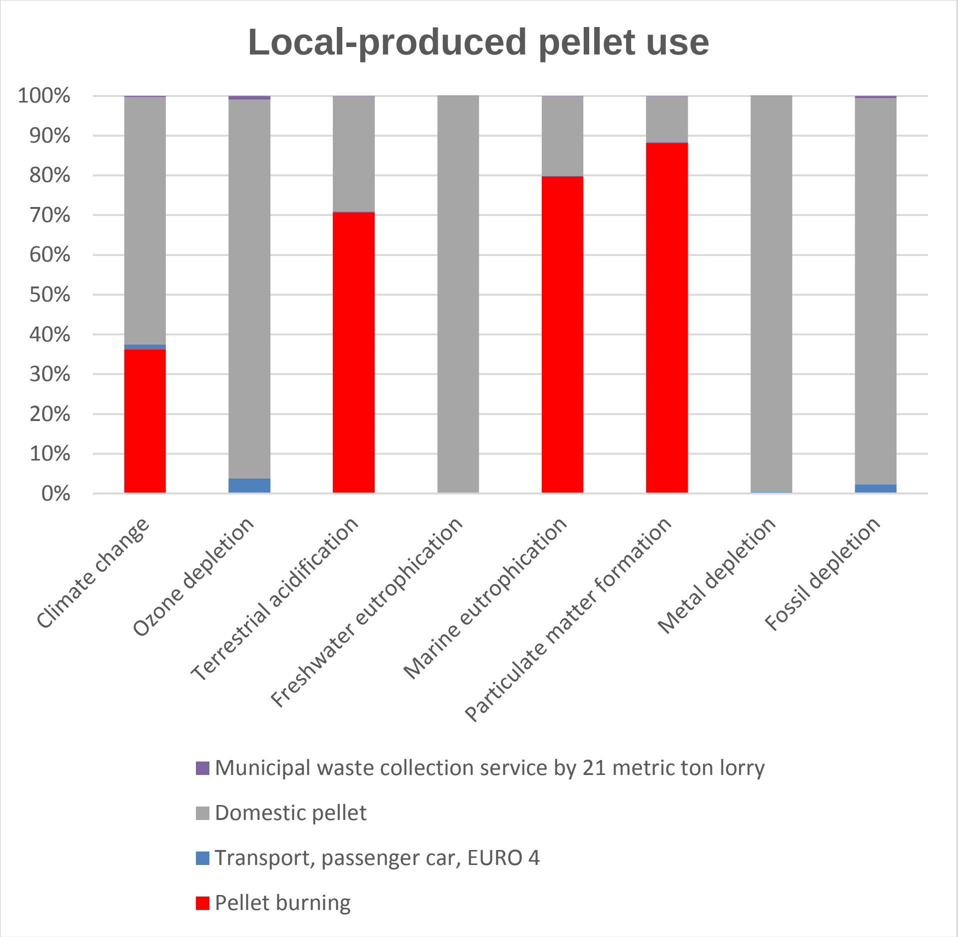


Figure 59: Impact assessment results obtained for the local produced pellet use of the domestic pellet production chain showed in 100% stacked column chart

As it is possible to see in fig 59, the pellet burning process has relevant environmental impacts (from 35% to 85%) in four categories *(Climate change, terrestrial acidification, marine eutrophication, particulate matter formation).* Most of the impacts, in the categories not affected by pellet burning emissions, come from the previous stages (wood and pellet production) because the transport of pellet by car and the waste collection service have a total impact of no more than 3-4% of the total .

3.4.3.3 Local pellet use (Extensive model)

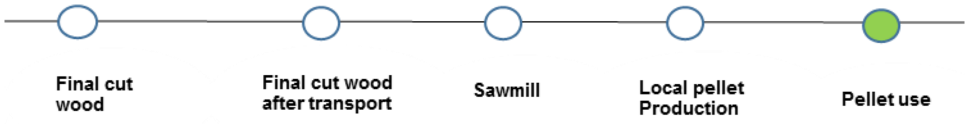


Figure 60 represents the final point of the domestic pellet production chain (extensive model), the pellet burning for heat generation in a final user house together with the transport of ashes for disposal.

Impact category	Unit	Pellet burning	Transport, passenger car, EURO 4	**Pellet** (Local production, extensive)	Municipal waste collection service by 21 metric ton lorry	Total
Climate change	kg CO2 eq	5,5E+01	1,8E+00	9,1E+01	4,7E-01	1,5E+02
Ozone depletion	kg CFC-11 eq	0,0E+00	3,3E-07	8,0E-06	8,1E-08	8,4E-06
Terrestrial acidification	kg SO2 eq	1,4E+00	4,1E-03	5,5E-01	2,2E-03	1,9E+00
Freshwater eutrophication	kg P eq	0,0E+00	2,6E-05	2,0E-02	1,4E-06	2,0E-02
Marine eutrophication	kg N eq	6,9E-02	1,5E-04	1,6E-02	1,3E-04	8,5E-02
Particulate matter formation	kg PM10 eq	1,3E+00	1,6E-03	1,7E-01	1,1E-03	1,5E+00
Metal depletion	kg Fe eq	0,0E+00	1,1E-03	2,7E-01	3,8E-05	2,7E-01
Fossil depletion	kg oil eq	0,0E+00	6,3E-01	2,5E+01	1,5E-01	2,6E+01

Table 37: Impact assessment results obtained for the local produced pellet use of the domestic pellet production chain (extensive model)

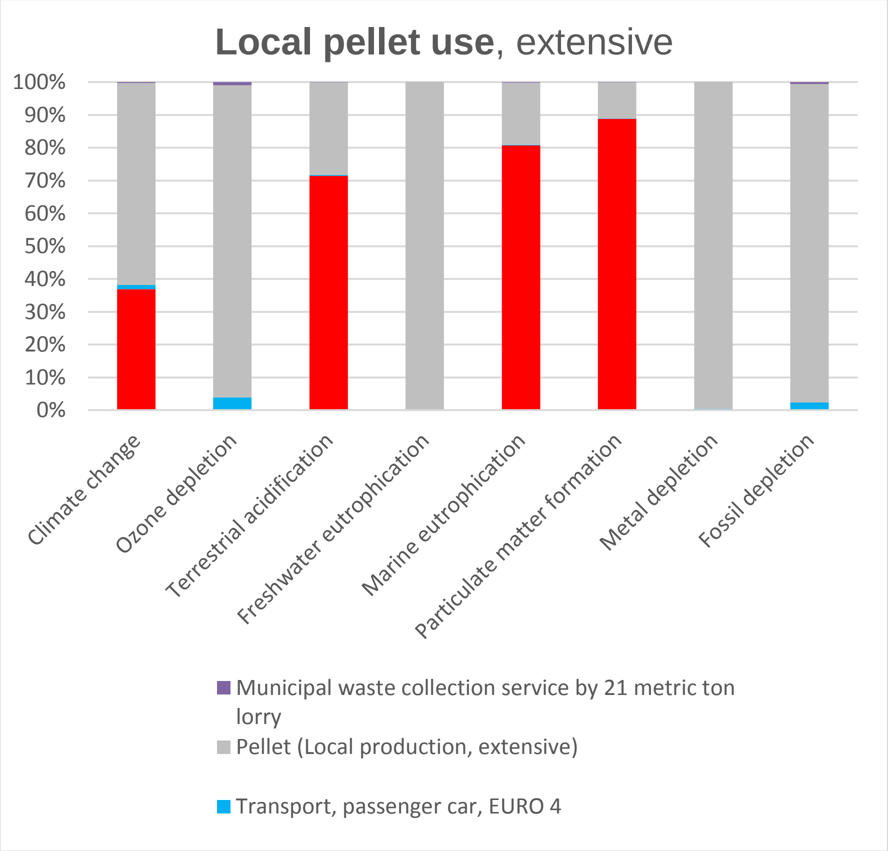


Figure 60: Impact assessment results obtained for the local produced pellet use of the domestic pellet production chain (extensive model) showed in 100% stacked column chart

Considering the total impacts of the whole model, the difference between the extensive and the intensive model can be overlooked because other factors have a much higher impact. When the extensive model is considered, fewer pellet production impacts can be noticed, and this is because wood production is less impacting in the extensive model. Pellet burning has a relevant impact (from 35% to 60%) in the impact categories *climate change, terrestrial acidification, marine eutrophication, particulate matter formation.* Transport by car and waste disposal are irrelevant.

3.4.4 Sensitivity analysis (local pellet production chain)

This is the last stage to be analysed and it represents the final point of the domestic pellet production chain, i.e the pellet burning for heat generation in a final user house when the emissions of the pellet stoves are assumed to be maximum or minimum as explained in the Method part of this study.

3.4.4.1 Local pellet use (Highest emissions scenario)

Impact category	Unit	Pellet burning (higher emissions)	Pellet (Local production)	Transport, passenger car, EURO 4	Municipal waste collection service by 21 metric ton lorry	Total
Climate change	kg CO2 eq	9,0E+01	9,4E+01	1,8E+00	4,7E-01	1,9E+02
Ozone depletion	kg CFC-11 eq	0,0E+00	8,4E-06	3,3E-07	8,1E-08	8,8E-06
Terrestrial acidification	kg SO2 eq	3,4E+00	5,7E-01	4,1E-03	2,2E-03	4,0E+00
Freshwater eutrophication	kg P eq	0,0E+00	2,1E-02	2,6E-05	1,4E-06	2,1E-02
Marine eutrophication	kg N eq	1,6E-01	1,7E-02	1,5E-04	1,3E-04	1,8E-01
Particulate matter formation	kg PM10 eq	2,5E+00	1,7E-01	1,6E-03	1,1E-03	2,7E+00
Metal depletion	kg Fe eq	0,0E+00	2,8E-01	1,1E-03	3,8E-05	2,8E-01
Fossil depletion	kg oil eq	0,0E+00	2,6E+01	6,3E-01	1,5E-01	2,7E+01

Table 38: Impact assessment results obtained for the local produced pellet use of the domestic pellet production chain (higher emissions)

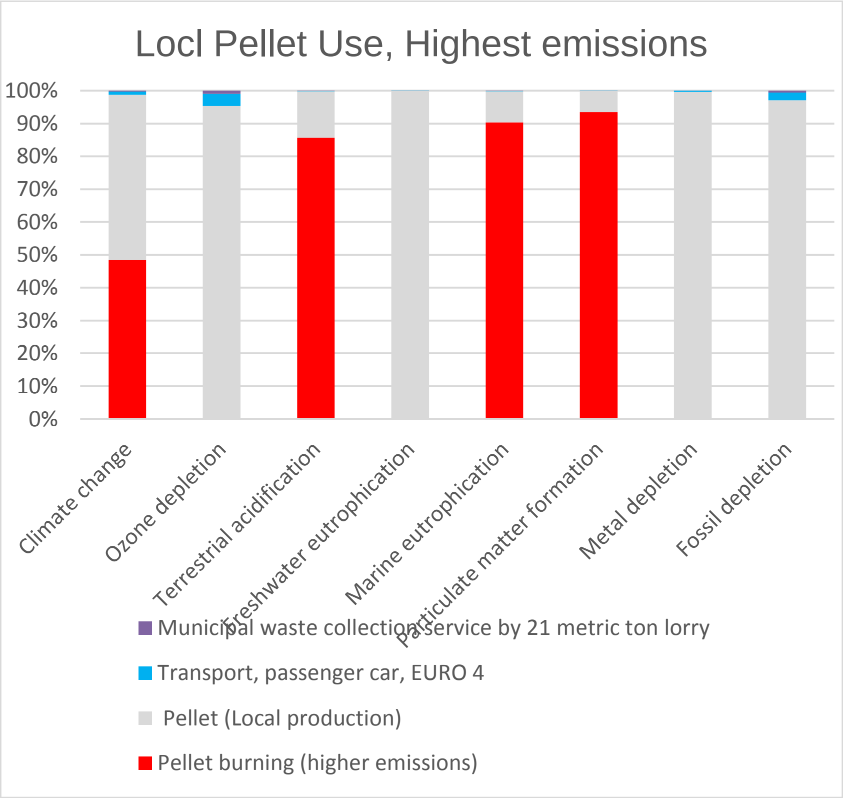


Figure 61: Impact assessment results obtained for the local produced pellet use of the domestic pellet production chain (higher emissions) showed in 100% stacked column chart

3.4.4.2 Local pellet use (Lowest emissions scenario)

Impact category	Unit	Pellet burning (lower emissions)	Transport, passenger car, EURO 4	6 Pellet (Local production)	Municipal waste collection service by 21 metric ton lorry	Total
Climate change	kg CO2 eq	1,9E+01	1,8E+00	9,4E+01	4,7E-01	1,2E+02
Ozone depletion	kg CFC-11 eq	0,0E+00	3,3E-07	8,4E-06	8,1E-08	8,8E-06
Terrestrial acidification	kg SO2 eq	8,3E-01	4,1E-03	5,7E-01	2,2E-03	1,4E+00
Freshwater eutrophication	kg P eq	0,0E+00	2,6E-05	2,1E-02	1,4E-06	2,1E-02
Marine eutrophication	kg N eq	4,1E-02	1,5E-04	1,7E-02	1,3E-04	5,8E-02
Particulate matter formati	kg PM10 eq	5,5E-01	1,6E-03	1,7E-01	1,1E-03	7,2E-01
Metal depletion	kg Fe eq	0,0E+00	1,1E-03	2,8E-01	3,8E-05	2,8E-01
Fossil depletion	kg oil eq	0,0E+00	6,3E-01	2,6E+01	1,5E-01	2,7E+01

Table 39: Impact assessment results obtained for the local produced pellet use of the domestic pellet production chain (lowest emissions)

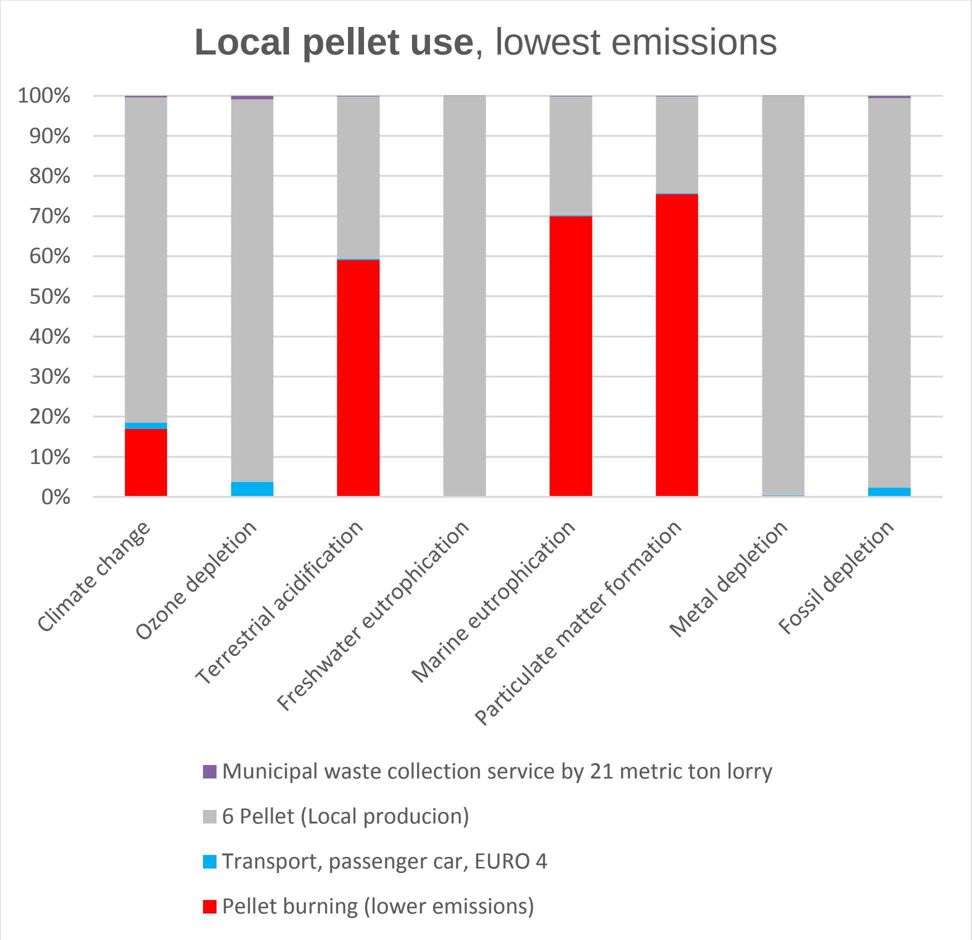


Figure 62: Impact assessment results obtained for the local produced pellet use of the domestic pellet production chain (lowest emissions) showed in 100% stacked column chart

When emissions are assumed to be as high as showed in fig 61, the combustion phase becomes very significant, as only this phase accounts for the 45% of the overall impacts for the climate change category, and for more than 90% in the other categories where wood burning has an effect.

As showed in fig 62, even in the lowest emissions scenario the pellet burning process still has a relevant environmental impact for terrestrial acidification , marine eutrophication and particulate fossil depletion (from 18.75%), for the remaining impact categories, most of the impacts come from the previous stages (wood and pellet production).

3.4.5 Environmental hotspot in the domestic production chain

The following figures (63, 64, 65, 66) represent the main phases of the domestic pellet production chain, considering the forest stage, the sawdust production, the pellet production, the transport phase, and the burning phase. They have been separated and referred to the functional unit in order to be compared with each other, together with the extensive model and the variations considered in the sensitivity analysis.

Table 40: Impact assessment results obtained for the main stages of the domestic pellet production chain

Impact category	Unit	Forest stage	Sawmill	Local pellet production	Pellet burning	Transport phases
Climate change	kg CO2 eq	3,8E+00	6,0E+00	7,5E+01	5,5E+01	1,0E+01
Ozone depletion	kg CFC-11 eq	5,7E-07	5,9E-07	5,6E-06	0,0E+00	1,9E-06
Terrestrial acidification	kg SO2 eq	2,6E-02	3,9E-02	4,6E-01	1,4E+00	4,2E-02
Freshwater eutrophication	kg P eq	1,1E-03	1,2E-03	1,9E-02	0,0E+00	1,2E-04
Marine eutrophication	kg N eq	1,4E-03	1,4E-03	1,2E-02	6,9E-02	2,2E-03
Particulate matter formation	kg PM10 eq	1,1E-02	1,3E-02	1,3E-01	1,3E+00	2,0E-02
Metal depletion	kg Fe eq	7,0E-03	1,6E-02	2,6E-01	0,0E+00	3,4E-03
Fossil depletion	kg oil eq	1,3E+00	1,7E+00	2,0E+01	0,0E+00	3,5E+00

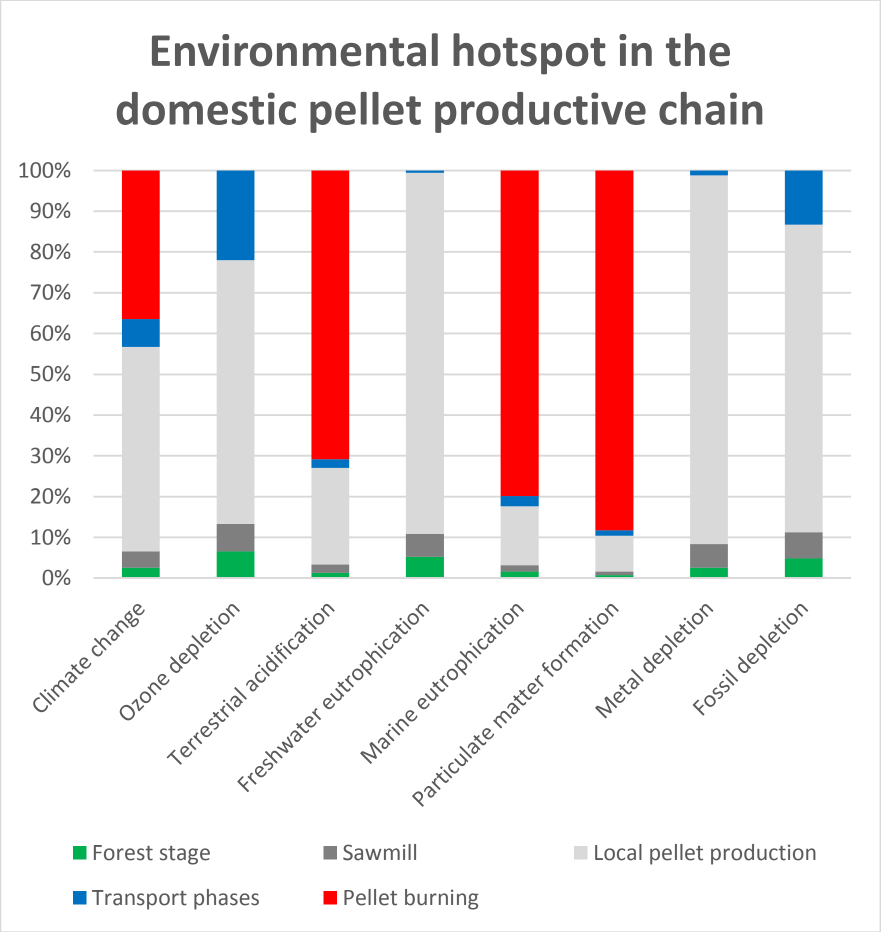


Figure 63: Impact assessment results obtained for the main stages of the local pellet production chain showed in 100% stacked column chart

Table 41: Impact assessment results obtained for the main stages of the domestic pellet production chain (Extensive model)

Impact category	Unit	Forest stage	Sawmill	Local pellet production	Transport phases	Pellet burning
Climate change	kg CO2 eq	1,42E+00	6,0E+00	7,5E+01	1,0E+01	5,5E+01
Ozone depletion	kg CFC-11 eq	1,74E-07	5,9E-07	5,6E-06	1,9E-06	0,0E+00
Terrestrial acidification	kg SO2 eq	6,59E-03	3,9E-02	4,6E-01	4,2E-02	1,4E+00
Freshwater eutrophication	kg P eq	2,07E-05	1,2E-03	1,9E-02	1,2E-04	0,0E+00
Marine eutrophication	kg N eq	3,44E-04	1,4E-03	1,2E-02	2,2E-03	6,9E-02
Particulate matter formation	kg PM10 eq	2,29E-03	1,3E-02	1,3E-01	2,0E-02	1,3E+00
Metal depletion	kg Fe eq	1,73E-04	1,6E-02	2,6E-01	3,4E-03	0,0E+00
Fossil depletion	kg oil eq	4,47E-01	1,7E+00	2,0E+01	3,5E+00	0,0E+00

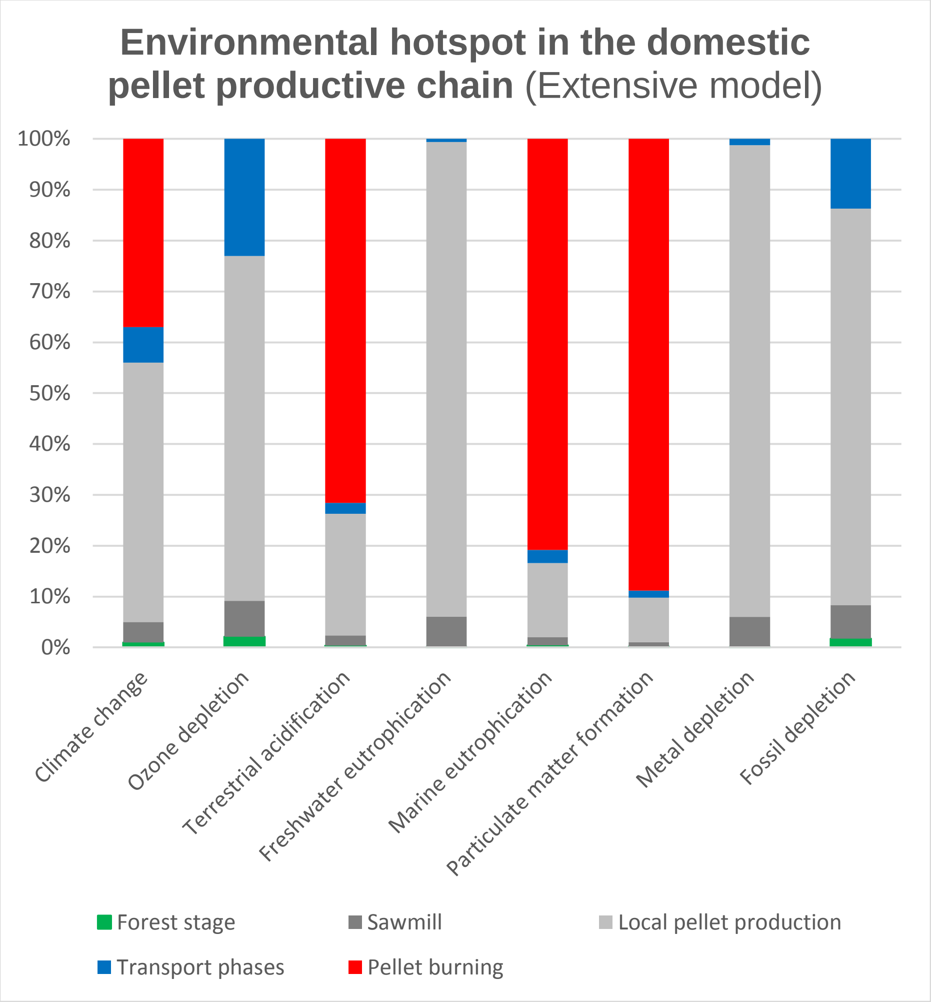


Figure 64: Impact assessment results obtained for the main stages of the domestic pellet production chain showed in 100% stacked column chart (Extensive model)

Table 42: Impact assessment results obtained for the main stages of the domestic pellet production chain (Highest emissions)

Impact category	Unit	Forest stage	Sawmill	Local pellet production	Pellet burning	Transport phases
Climate change	kg CO2 eq	3,8E+00	6,0E+00	7,5E+01	9,0E+01	1,0E+01
Ozone depletion	kg CFC-11 eq	5,7E-07	5,9E-07	5,6E-06	0,0E+00	1,9E-06
Terrestrial acidification	kg SO2 eq	2,6E-02	3,9E-02	4,6E-01	3,4E+00	4,2E-02
Freshwater eutrophication	kg P eq	1,1E-03	1,2E-03	1,9E-02	0,0E+00	1,2E-04
Marine eutrophication	kg N eq	1,4E-03	1,4E-03	1,2E-02	1,6E-01	2,2E-03
Particulate matter formation	kg PM10 eq	1,1E-02	1,3E-02	1,3E-01	2,5E+00	2,0E-02
Metal depletion	kg Fe eq	7,0E-03	1,6E-02	2,6E-01	0,0E+00	3,4E-03
Fossil depletion	kg oil eq	1,3E+00	1,7E+00	2,0E+01	0,0E+00	3,5E+00

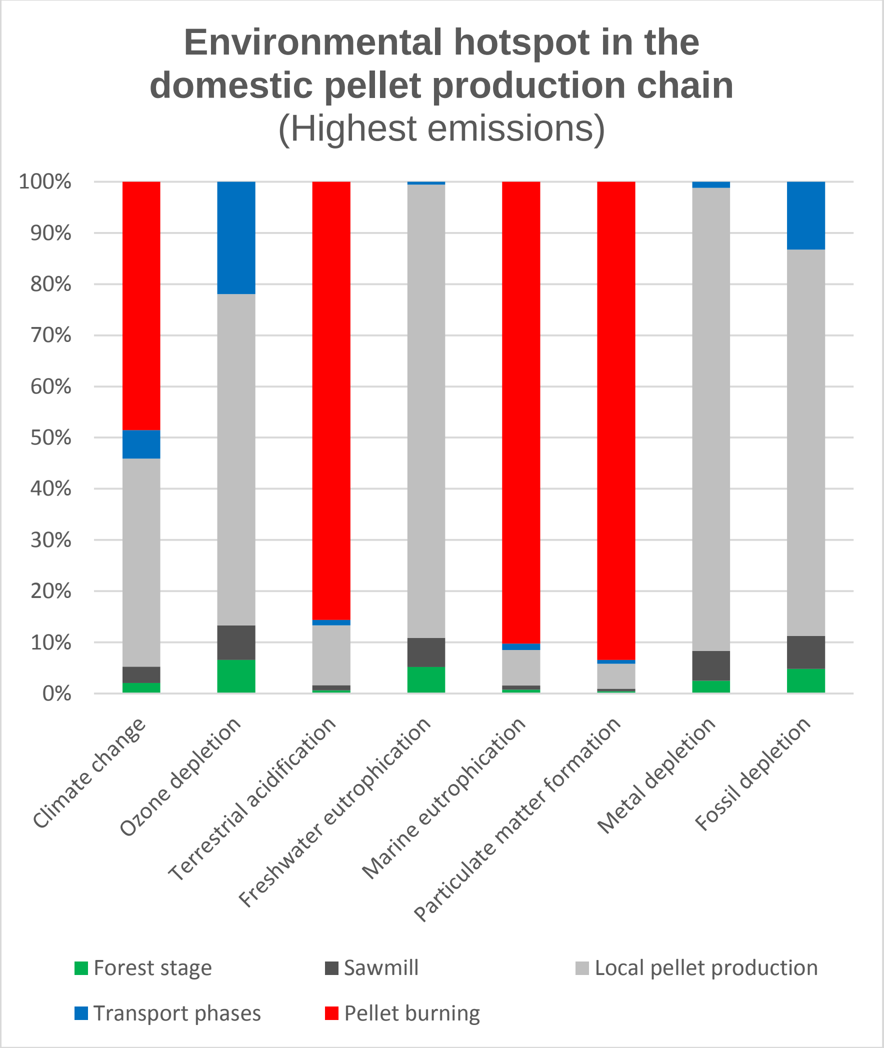


Figure 65: Impact assessment results obtained for the main stages of the domestic pellet production chain (Highest emissions, showed in 100% stacked column chart

Table 43: Impact assessment results obtained for the main stages of the domestic pellet production chain (Lowest emissions)

Impact category	Unit	Forest stage	Sawmill	local pellet production	Pellet burning	Transport phases
Climate change	kg CO2 eq	3,8E+00	6,0E+00	7,5E+01	1,9E+01	1,0E+01
Ozone depletion	kg CFC-11 eq	5,7E-07	5,9E-07	5,6E-06	0,0E+00	1,9E-06
Terrestrial acidification	kg SO2 eq	2,6E-02	3,9E-02	4,6E-01	8,3E-01	4,2E-02
Freshwater eutrophication	kg P eq	1,1E-03	1,2E-03	1,9E-02	0,0E+00	1,2E-04
Marine eutrophication	kg N eq	1,4E-03	1,4E-03	1,2E-02	4,1E-02	2,2E-03
Particulate matter formation	kg PM10 eq	1,1E-02	1,3E-02	1,3E-01	5,5E-01	2,0E-02
Metal depletion	kg Fe eq	7,0E-03	1,6E-02	2,6E-01	0,0E+00	3,4E-03
Fossil depletion	kg oil eq	1,3E+00	1,7E+00	2,0E+01	0,0E+00	3,5E+00

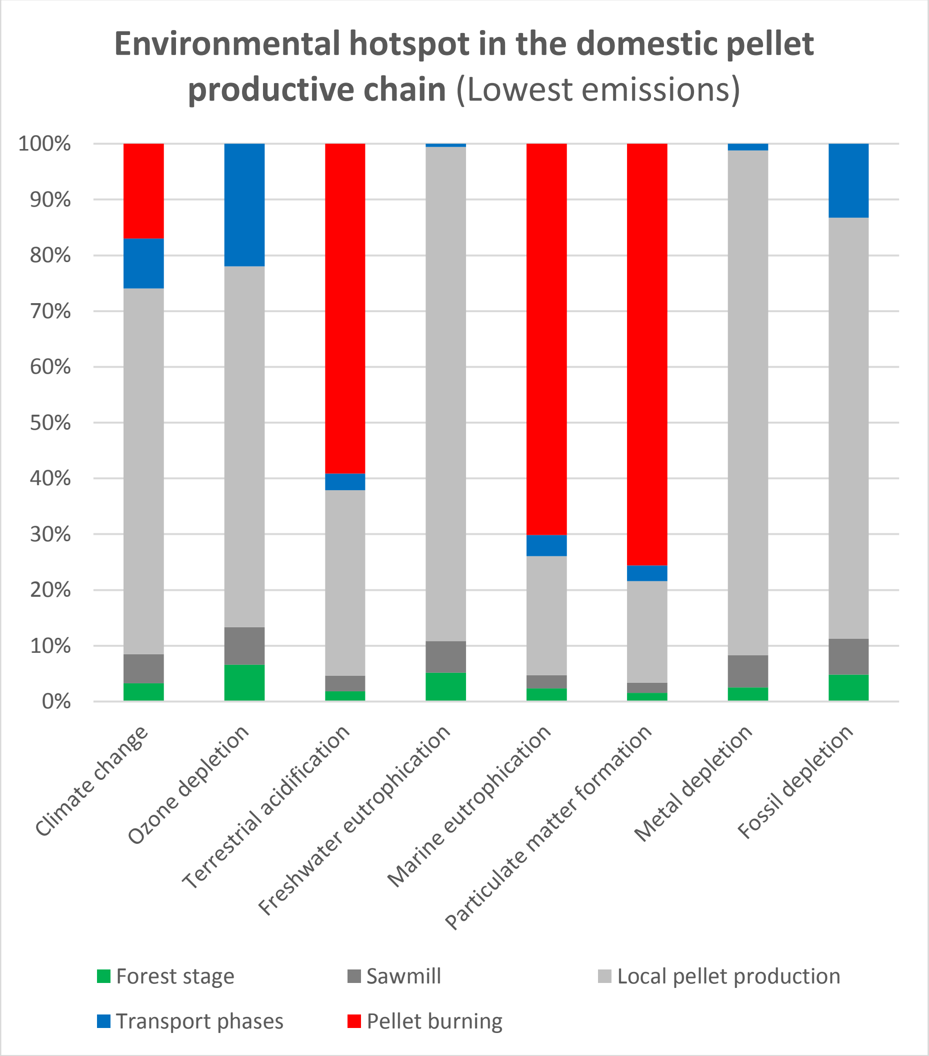


Figure 66: Impact assessment results obtained for the main stages of the domestic pellet production chain showed in 100% stacked column chart (lower emissions)

It Is possible to notice that, if compared to the other main stages of the production chain, forest stage is the less impacting process (no more than 5%). Sawdust production also has a small impact (around 5% -10% depending on the scenario)

The key phases in the production chain are the pellet production phase and the pellet burning phase, although pellet burning only affects some impact categories due to the use of virgin wood. The most impacting stage in the production chain is the pellet production phase, due to high machinery energy consumption during the palletisation processes.

In the extensive model the impacts from forest stage becomes irrelevant (2-3%).

In the highest emission scenario (fig 65), it is possible to notice that the impact of the pellet burning becomes the key phase in the production chain with a minimum overall impact that ranges from 50% to 90% in the affected categories, the pellet production also has a relevant impacting profile.

If the emissions are at the lowest, the pellet production phase has the most impacting environmental profile. It’s interesting to notice that despite the lower emissions scenario, pellet burning still accounts for 15 % of the climate change impact of the overall production chain and from 30% to 60% in the categories were the burning process has an impact, so the pellet burning phase is a key process, no matter the analysed scenario.

3.5 Comparison between the models for impact categories

The absolute results for each impact category are shown, in the tables (23, 24, 25, 26, 36, 37, 38, 39) of “Final pellet use” phase and “total” in each model.

Darkest bar in the figures (67, 68, 69, 70, 71, 72, 73, 74) are referred to the industrial model, the lightest to the domestic one.

The “Highest” transport distances scenario is analysed only in the industrial model, as the definition of a domestic scale production implies low distances between productors and final users.

3.5.1 Climate change

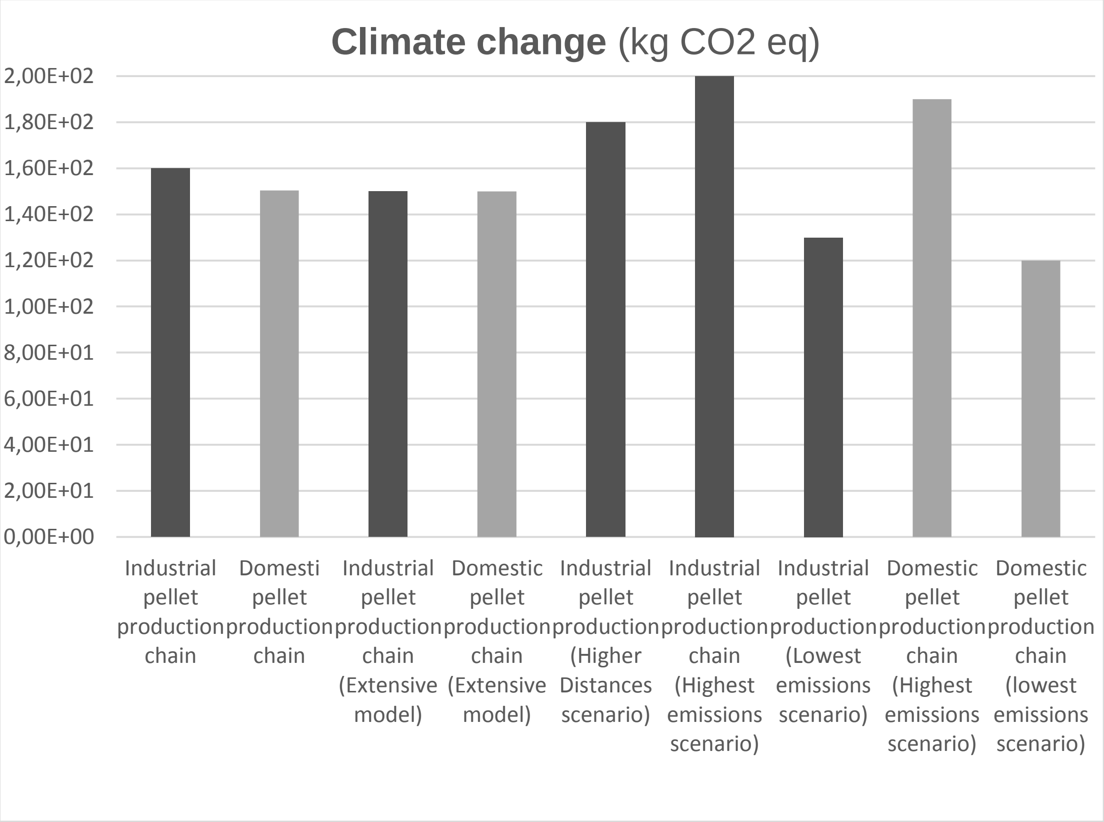


Figure 67: Comparison of the total impact for the models and scenarios studied in this thesis (For the impact category Climate Change)

The main contributors (for all the models) to climate change are CO_2 followed by CH_4 and N_2O, where about 65.1 kg of CO2 eq. were emitted to air only by electricity used in the pelletizing process (emissions derived from electricity production).

A large quantity of CO_2 eq. is emitted during pellet combustion process (54.6 kg). Thus, if we consider the industrial model, highest emission scenario, is the most impacting model for climate change analysed in this thesis. If compared to the default industrial model 25% more of CO_2 eq. is emitted. In details in this scenario 89.8 Kg of CO_2 eq. are emitted to air in the combustion of 1 ton of pellet. The less impacting is the domestic production chain model, with lowest emissions scenario (19.5 kg of CO_2 eq. for the pellet burning).

The transport phase with truck is also a relevant process, only the transport of wood logs from the forest until the pellet factory emits 7.09 kg of CO_2 eq.

3.5.2 Ozone depletion

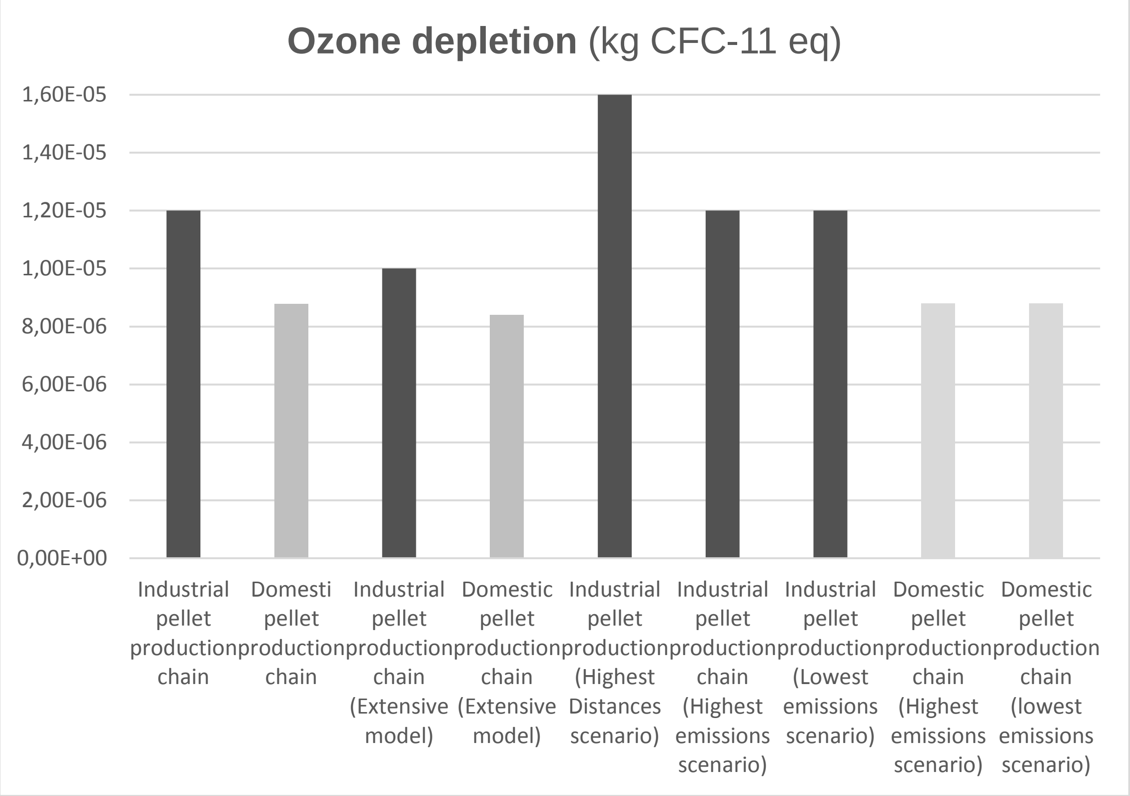


Figure 68: Comparison of the total impact for the models and scenarios studied in this thesis (For the impact category Ozone depletion)

Transport phases are a great contributor to ozone depletion due to the trucks emissions (or emissions derived from fuel refinery) of: methane bromotrifuoro, halon 1301, methane bromochlorodifuoro, halon 1211 and 1,2 s-dichloro-1,1,2,2-tetrafluoroethane (CFC 114), if high distances are used, the transport phases becomes the environmental hotspot for ozone depletion impact category, if the distances are low, such as the default model, or the domestic production chain, the pellet production phase becomes the hotspot. Those results are showed better in the previous “environmental production chain hotspot” sections.

Fig 66 confirms the previous considerations showing that the most impacting production chain for this category is the high transport distances scenario showing an increasing of 33.3% in CFC^{-11} eq. emitted with $8.6*10^{-6}$ kg CFC^{-11} eq. emitted only by transport phases. The less impacting model is the domestic production chain (extensive model) due to reduced transport distances compared to the industrial model. The extensive model also has reduction in emissions due to less machineries used during the forest stage.

3.5.3 Terrestrial acidification

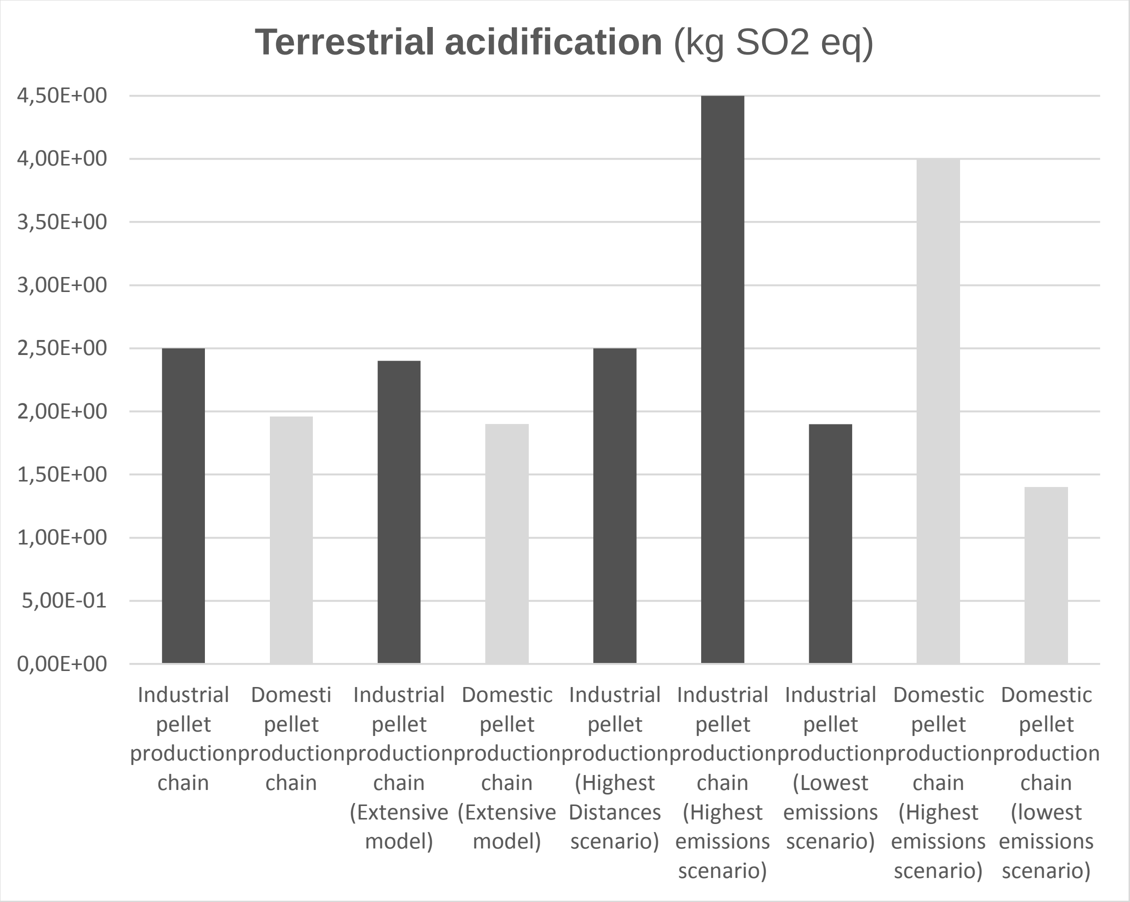


Figure 69: Comparison of the total impact for the models and scenarios studied in this thesis (For the impact category terrestrial acidification)

The processes that main contributes to this category are pellet burning (1.39 kg of SO_2 eq.) and forest residues burning (that is performed only in the industrial model) with 0.472 kg of SO_2 eq.

Specifically the substances responsible of terrestrial acidification during pellet burning (considering high emissions) are NOx 0.94 Kg of SO_2 eq. ammonia 0,479 Kg of SO_2 eq. SO_x with 0,179 Kg of SO_2 eq. those substances leads to an increase of 80% in terms of g of SO_2 eq. emitted.

Also the processes related with the consumption electricity have a relevant impact in this category. Specifically they derive from the transformation of electricity from high to medium voltage, in details most of the impacts come from the hard coal used for the production of high voltage electricity. Scenarios with highest emissions are the most impacting in terrestrial acidification.

3.5.4 Freshwater eutrophication

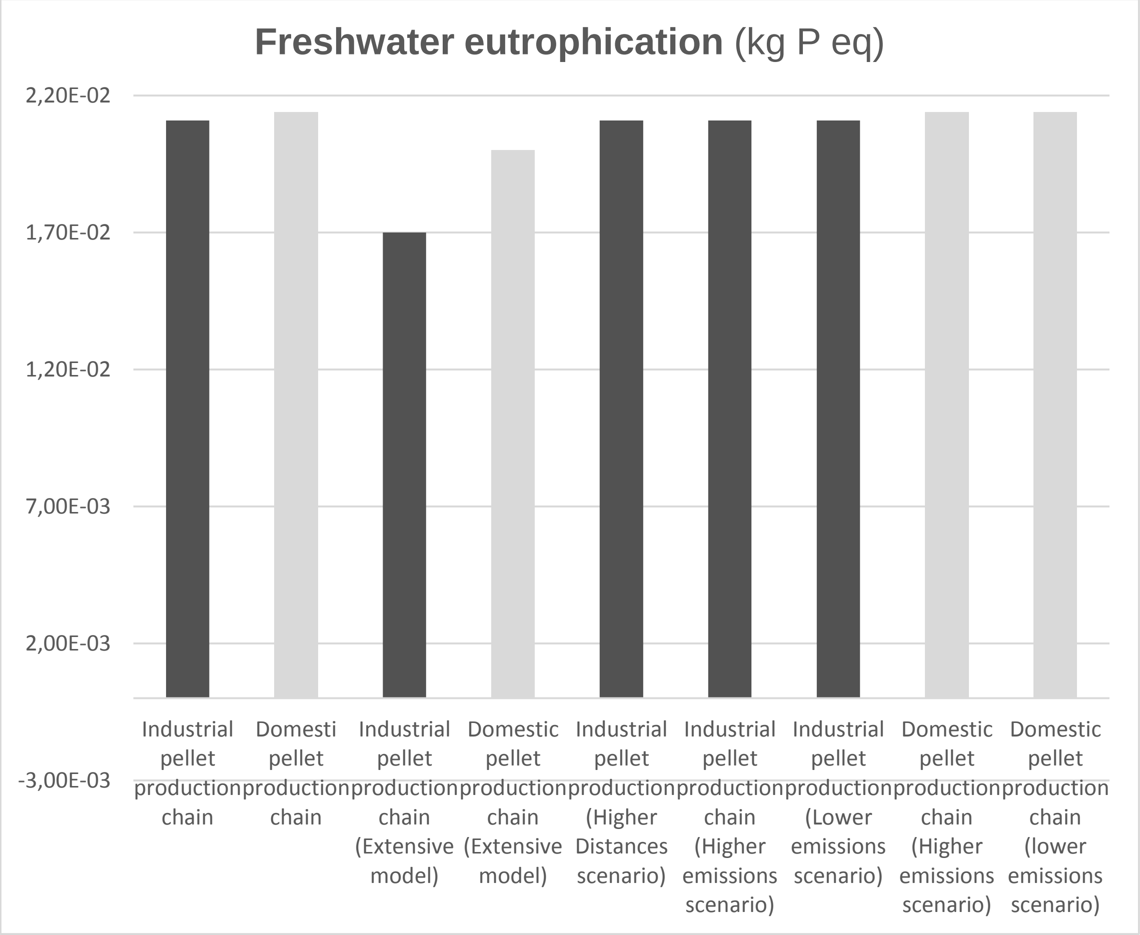


Figure 70: Comparison of the total impact for the models and scenarios studied in this thesis (For the impact category freshwater eutrophication)

For freshwater eutrophication $1.4*10^{-2}$ Kg of P equivalent comes from spoil from hard coal mining (operations related to coal extraction), that is a process involved in the production of electricity which is used in the pellet production. As the domestic model, uses a big amount of energy, has the greatest impact.

If we consider the intensive management model the forest management (logging) process discharge in the environment $3.3*10^{-3}$ kg of P equivalent and the phosphate fertilizer $4.6*10^{-4}$ kg of P equivalent. Obviously the industrial model with a low intensity management that excludes forest management processes is the lowest impactor in freshwater eutrophication.

3.5.5 Marine eutrophication

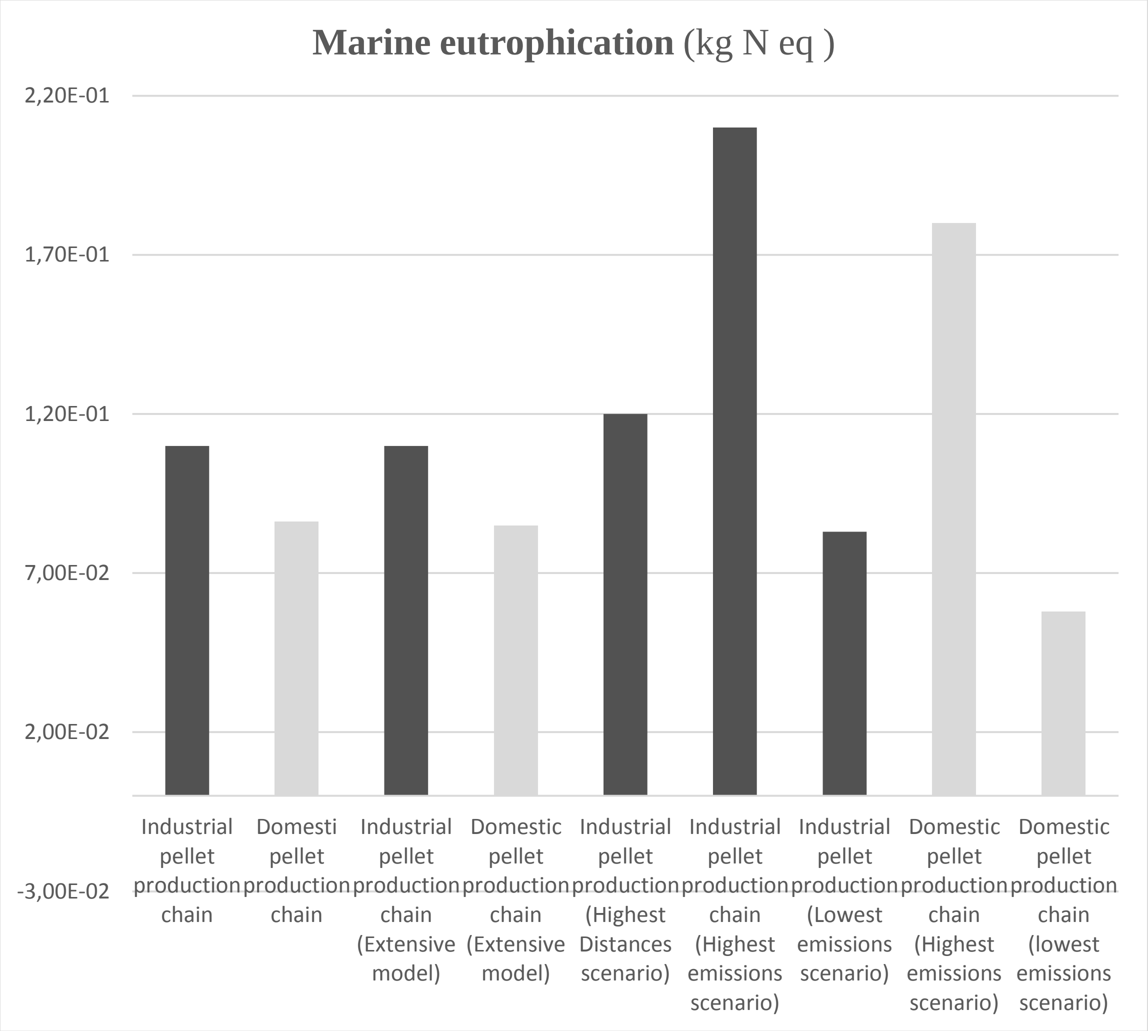


Figure 71: Comparison of the total impact for the models and scenarios studied in this thesis (For the impact category marine eutrophication)

Most of marine eutrophication comes from pellet burning with an emission of $6.8*10^{-2}$ kg of N eq. where $6.6 *10^{-2}$ kg of N eq. comes from nitrogen oxides and $1.8 *10^{-2}$ kg of N eq. comes from ammonia. Also the forest residues burning has a relevance with $2.1*10^{-2}$ kg of N eq. emitted. For those reasons the most impacting scenarios are those where highest emissions in the burning process are assumed. Is possible to observe that there is an increase of 90% in terms of kg of N eq. emitted comparing the default model and the highest emissions model.

3.5.6 Particulate matter formation

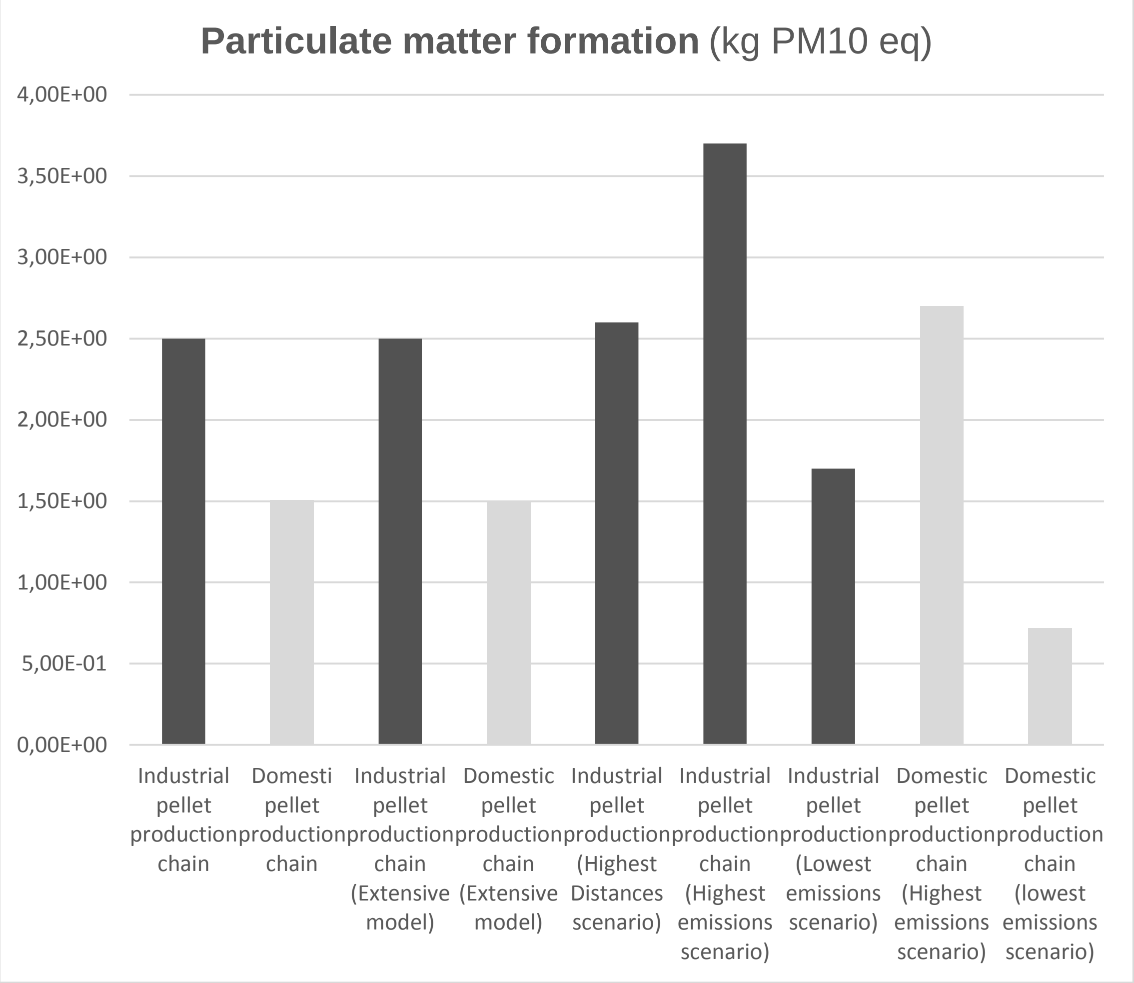


Figure 72: Comparison of the total impact for the models and scenarios studied in this thesis (For the impact category particulate matter formation)

Most of the PM 10 comes from burning processes, 1.33 kg of PM 10 eq. comes from pellet burning with 2.3 Kg of PM 10 and 0,473 kg of PM 2.5 and 0.981 kg of PM 10 eq. comes from forest residues burning. Also a percentage of PM 10 derives from the coal used in the electricity production. We can conclude that the most impacting model in particulate matter formation is the industrial model with high emissions scenario, which leads to an increase of 48% in PM 10 eq. respect to the default model. The lowest one is the domestic (that excludes also the forest residues burning) with low emissions.

3.5.7 Metal depletion

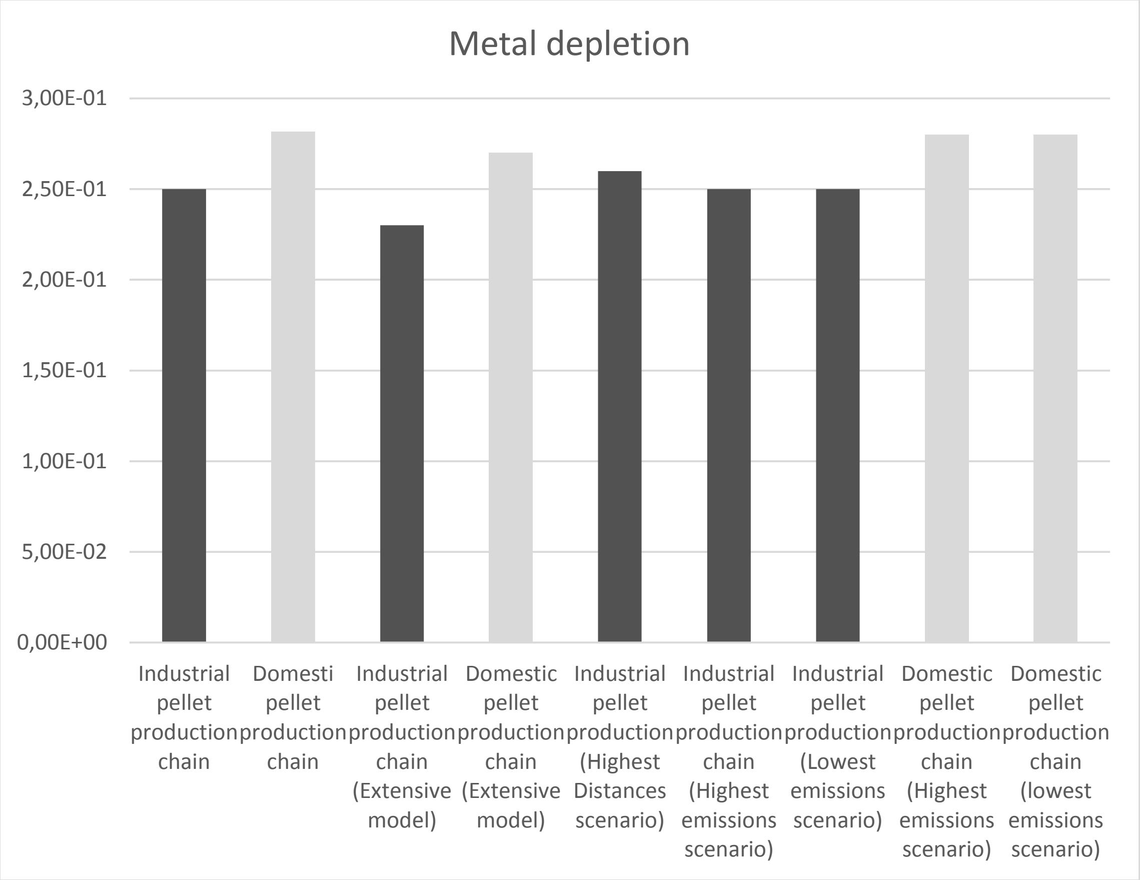


Figure 73: Comparison of the total impact for the models and scenarios studied in this thesis (For the impact category metal depletion)

Most of the metal depletion comes from electricity mix, in particular to the processes related to electricity production, those processes includes the consumption of tin (1.1x10^{-4} kg of fe eq.) and ore (1.2x10^{-4} kg of fe eq.). Based on those results, the models with high energy requirements are the most impacting ones. (domestic models).

3.5.8 Fossil depletion

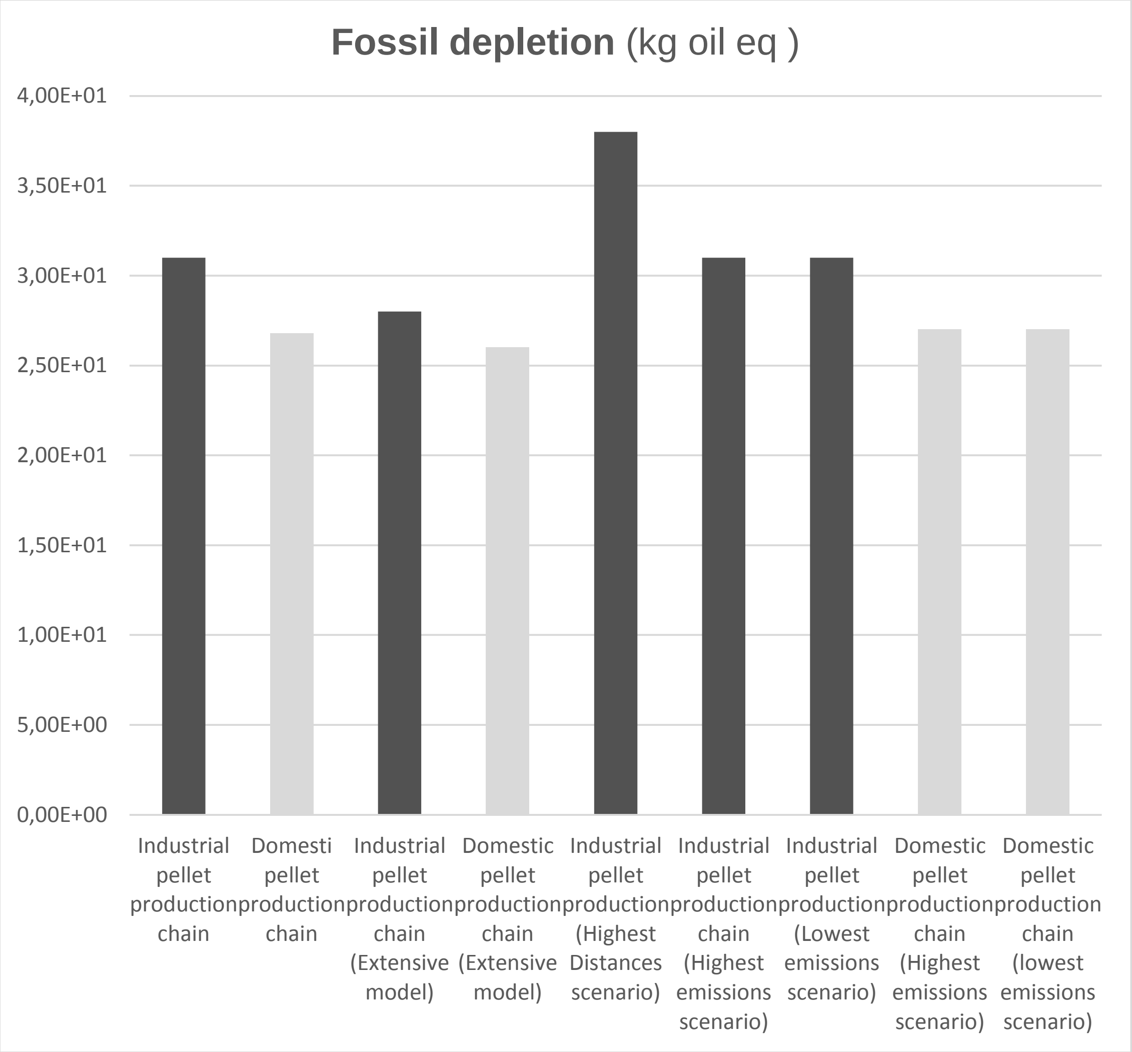


Figure 74: Comparison of the total impact for the models and scenarios studied in this thesis (For the impact category fossil depletion)

The most impacting singular process, is related to fossil resources depletion due to electricity production (electricity in a certain percentage comes from fossil source, mostly hard coal $1.8*10^{-2}$ kg of oil eq. and natural gas $3.6*10^{-2}$ kg of oil eq. following the electricity mix of Portugal used in this model). Also a part of the impacts comes from the transport phases due to gasoline consumption that is a fossil source. The most impacting model is the industrial one with higher transport distances assumed with an increase in kg of oil eq. consumed of 23% (16 kg oil eq. derives only from transport phases, that is mainly due to consumption of crude oil)

4 Discussions and conclusions

This study identifies the environmental impacts of the processes of two pellet production chains. Moreover it performs a comparison between the two production chains: industrial scale production and a domestic production.

This study included three main stages (four, with the sawmill in the domestic model), forest stage, pellet production, and pellet use.

Together with the default model, an extensive model was analysed for the forest stage, and a sensitivity analysis was performed to check the model variations when emissions and transport distances are allowed to vary.

4.1 Industrial pellet and domestic pellet production

The comparison between of the results obtained for the domestic and industrial models, based on a multicriteria analysis, shows that the domestic model is better for most of the impact categories, having better performances on 6 impact categories of 8. The main problem of the domestic model is the highest consumption of electricity, that leads to higher environmental impacts in freshwater eutrophication and metal depletion. Another point is the fact that the wood compression in case of a domestic machinery is less if compared to an industrial one, so a pellet produced locally is less mechanically durable, and can be transported only locally, not to great distances. But this point should not be seen as an disadvantage, as low transport distances that are characteristic of a domestic model, lead to saves in transport costs and emissions.

Besides that, one of the main purposes of biomass use, instead of fossil fuel, is to reduce the GHG emissions, as CO_2, that contributes to climate changes. If we look at this environmental problem, the domestic model is a better choice contributing to save 10 kg of CO_2 equivalent for each ton of pellet used.

Great differences can be seen in particulate matter formation, (that is one of the most problematic issues related to biomass use). In the industrial model, there is an increase of 67% of kg of PM 10 eq. emitted, mainly to the forest residues burning process (raw material drying) that emits great quantities of particulate matter. In the domestic model the raw material is atmospherically dried, and those emissions are avoided.

Also in terms of ozone depletion, the industrial model is 50% more impacting (100% if we consider high transport distances) than the domestic one.

As LCA is continually evolving, the normalizing and weighting phase that allows to remove the measure unit from impact categories and perform a comparison between categories to choose the most relevant, are still not perfectly developed. A better answer to the impacts related to pellet production could be done when those phases could be applied to the results of this study.

4.2 Intensive and extensive model

As reported by *González-García et al. (2013)* “the intensive scenario is a highly mechanized forest system, which requires a dosage of fertilizers, as a consequence the trees quality and growth are increased”

If we compare the intensive and the extensive forest models, considering only the operations taken inside the forest, (excluding the transport phase of the wood logs), the intensive one has 15-25% more impact in all categories, except in freshwater eutrophication and metal depletion, where accounts for 95 % of the impacts if compared to the low management one because of the forest management stage, where fertilizers and forestry operations with large machineries are applied. However the disadvantage of the low intensity model is a reduction in the wood productivity. This study is not focused on wood production, but considering the study of *Dias and Arroja (2012)* where they focused on wood production and performed a sensitivity analysis on this parameter, they conclude that: *“if wood productivity decreases due to the less intensive forest practices, the results of the sensitivity analysis show that the difference between the more intensive scenarios and the less intensive scenario may decrease considerably.”*

4.3 Environmental hotspots in the production chain

1. The results underline the fact that the energy used in the machines used in pelletizing process is the most impacting process during the production chain, which is in accordance with the study of *Laschi et al. (2016)* who studied the environmental performance of wood pellets production through LCA, followed by the pellet burning. This important contribution is mainly due to the non-renewable source of the electricity consumed, because it is taken from the Portuguese grid, which depends in a part on fossil fuels.

2. The energy consumption used in the domestic production chain is higher than the industrial-scale requirements due to less efficiency of the process, and for the lack of quality control that a big scale industry can perform on the raw material, especially on the moisture level that has a key role in the energy that will be consumed during the pelletisation process.

3. The pellet burning stage has a large environmental impact, is therefore a must to use the best available technologies for pellet stoves, to prevent pollution from the combustion, especially in terms of NOx and Particulate matter.

4. The phases related with wood production (forest stage) are the stages with the lower environmental impacts, which comes mostly from the phases of forest management stage. Also *Laschi et al. (2016)* who studied environmental performance of wood pellets production found that "operations carried out in the forest produce a minor part of the impact (from 1% to less than 10% depending on the category)." If a low intensity management is considered, the impacts from wood production become negligible, however as explained in 4.2 the reduction in wood productivity, related to a low management model, is not taken into account.

5. The plastic use for the packaging phase also has a negligible impact if compared to the other processes related to pellet production.

4.4 Sensitivity analysis

As this study wants to be a general investigation of the pellet production chains, pellet factories can be located relatively near of far from the selling point, and from the source of raw material, depending on a multitude of factors. The sensitivity analysis applied to transport distances was performed to understand in which measure the increase in transport distances between the forest and the selling point can influence the total amount of impacts. This analysis was performed only to the industrial model, as the domestic one implies for definition low transport distances.

This analysis showed that transport distances generally do not have a large environmental impacts, except when big travel distances are used to transport the wood far from the production site (70 km instead of 35 and 80 km until the selling point instead of 40). In that case the transport phases (excluding the transport inside the forest) can account for the 60% in the impact category of fossil depletion due to diesel consumption and 50% in ozone depletion of the whole model. If we compare the default scenario and the scenario with highest distances there is an increase of 33% in ozone depletion potential and of 12 % in climate change potential.

Considering the previous results, improvement in transportation phases like using new types of truck (Euro 6, or hybrid) can be important in reducing the environmental impacts associated with the movement of the material, especially when a long travelling distance is needed.

The sensitivity analysis was applied also to pellet burning, due to the fact that the emissions of pellet burning can vary in a certain range, due to several reasons, such as a different model of domestic pellet stove used by the final user, or a wood pine pellet produced by a different company, or different parameters settled in the stove, like the heating output etc.

Important substances were allowed to vary in a great range, such as particulates PM 10 from 29 to 141 g/Gj, NOx from 21 to 104 g/Gj and CO from 66 to 740 g/Gj. A substance that seems to have a relevant impact when emitted in great quantities is NOx, that when assumed to be maximum 104 g/Gj greatly contributes to worsening the environmental performance of the model, especially for the marine eutrophication and terrestrial acidification impact categories. As far as particulate matter formation is concerned, if compared with the default model, in the "highest emissions scenario” there is a worsening of 48% in terms of total PM 10 eq. emitted, and of 80% in terms of terrestrial acidification, and 100% looking of marine eutrophication.

We can conclude that the pellet burning phase has a relevant impact even when the stove with the lower emissions scenario is considered. When emissions are assumed to be maximum, the contribution of some critical substances such as NOx, CO, and particulate, leads to a great worsening of the environmental performance of the model in climate change, terrestrial acidification, marine eutrophication, and particulate matter formation.

For those reasons, the pellet burning process has to be considered as a key phase in the production chain, and the best available emission saving technologies should be used for the pellet stove.

4.5 Conclusions

The main conclusions are listed hereunder:

The most environmental impacting scenario is the industrial model with high emissions assumed, due to the fact that it is the worst scenario in three of the eight impact categories analysed, namely climate change, terrestrial eutrophication, and particulate matter formation.

The Industrial model with high transport distances scenario, is the most impacting scenario in ozone depletion and fossil depletion impact categories.

The domestic model is generally less impacting than the industrial model except to freshwater eutrophication and metal depletion due to the fact that electricity has a large contribution in these impact categories.

The pellet burning stage and the electricity consumption during pelletizing process are environmental hotspots of both the production chains.

4.6 Recommendations

Based on the finding of this study, developing local productive chain and exploring domestic application for wood pellet hold potential in reducing environmental impacts of pellet production, especially in climate change, particulate matter formation, ozone depletion and fossil depletion impact categories.

This is mainly due to reductions in the transport distances, and the avoidance of forest residues burning for raw material drying.

New technologies should be used to reduce to the minimum the usage of fossil fuel derived electricity in the pelletization process, which is the worst problem of the domestic model. Such technologies include solar panels or other forms of green energy source, and they could be chosen from performing an LCA.

As showed in the results part, a great quantity of impacts comes from the pellet burning, and a usage of a bad quality pellet, or worse, a pellet made by contaminated wood (such as metals) can lead to great impacts, and can determine who will be the most impacting production chain.

As well known, the usage of biomass is nowadays incentivised, in relation to their benefits in climate change fighting, due to neutral CO2 emissions. However, other concerns are now appearing with the increasing of their usage, as for example the emissions of fine particulate matter are arising, with the consequence of decreasing air quality. If we have a look at the emissions related to wood combustion, in the Po valley (Italy), wood burning can account for more than 60% of the primary emissions of particulate matter of the region. Some plans for the air quality were approved, for limiting the wood burning impacts, but with the risk of increasing the doubts and concerns of people, related to those new forms of energies, the use of biomass needs to be paired with an efficiency in the emissions reducing system, as new generation pellet stoves.
An interesting expansion of this study could be comparing the impact assessment results in terms of particulate matter formation with other type of biomass, to understand the differences between the environmental performance of A1 wood pine pellet, respect to other biomass, and how convenient is their usage in terms of air quality*. Zinoni (2015)*

5 Annex

5.1 **Impact assessment** (midpoint level)

The impact assessment method used in the SimaPro software v 8.2.3.0 is the ReCiPe 2008 Midpoint v 1.12. The impact categories are taken from *Goedkoop et al. (2009) and Huijbregts et al. (2016)* who created and actualized the report 'Recipe': A life cycle impact assessment method which comprises harmonized category indicators at the midpoint and the endpoint level.

5.1.1 Climate change

For the climate change impact category, the damage modelling is subdivided into several steps. An emission of a greenhouse gas (kg) will lead to an increased atmospheric concentration of greenhouse gases (ppb) which, in turn, will increase the radiative forcing capacity (W/m^2), *Goedkoop et al. (2009)*.

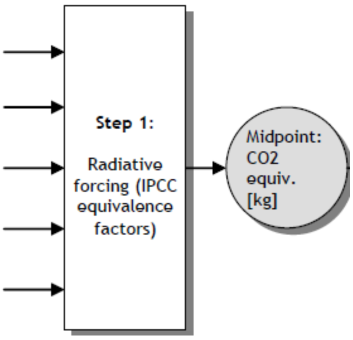


Figure 75: Cause-and-effect chain, climate change

The midpoint characterization factor for climate change is the widely used Global Warming Potential (GWP). The GWP expresses the amount of additional radiative forcing integrated over time (here 100 years) caused by an emission of 1kg of GHG relative to the additional radiative forcing integrated over that same time horizon caused by the release of 1 kg of CO_2. The amount of radiative forcing integrated over time caused by the emission of 1 kg of GHG is called the Absolute Global Warming Potential (AGWP) and is expressed in the unit W m^{-2} yr kg$^{-1.}$ The midpoint characterization factor of any GHG (x) and any time horizon (TH) can then be calculated as follows:

$$GWP_{x,TH} = \frac{AGWP_{x,TH,}}{AGWP_{CO_2,TH}}$$

Equation 2: Global warming potential

Which yields a time-horizon-specific GWP with the unit *kg CO2 eq/kg GHG*. *Huijbregts et al. (2016)*

5.1.2 Ozone depletion

Emissions of Ozone Depleting Substances (ODSs) ultimately lead to damage to human health because of the resultant increase in UV radiation. Chemicals that deplete ozone are relatively persistent and have chlorine or bromine groups in their molecules that interact with ozone (mainly) in the stratosphere. After an emission of an ODS, the tropospheric concentrations of all ODSs increase and, after a time, the stratospheric concentration of ODS also increases. This increase in ozone depleting potential leads to a decrease in the atmospheric ozone concentration, which in turn causes a larger portion of the UVB radiation to hit the earth. This increased radiation negatively affects human health, thus increasing the incidence of skin cancer and cataracts. *Huijbregts et al. (2016)*

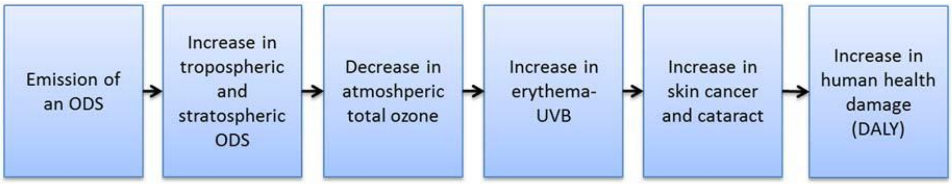


Figure 76: Cause-and-effect chain, ozone depletion

The Ozone Depleting Potential (ODP), expressed in kg CFC-11 equivalents, is used as a characterization factor at midpoint level. The ODP quantifies the amount of ozone a substance can deplete relative to CFC-11 for a specific time horizon and is therefore largely related to the molecular structure of the ODS and especially to the number of chlorine and bromine groups in the molecule, as well as the atmospheric lifetime of the chemical. ODPs are calculated by the World Meteorological Organization.

ODPs were calculated in a semi-empirical way by WMO, whereby the fractional release of chlorine and bromine groups from the molecule of an ODS is based on observational data for air layers with different ages. The ozone destruction potency of bromine is 60 times higher than the destruction potency of chlorine (65 in arctic regions). By combining the fractional release and the number of bromine and chlorine groups in the molecule, the effect on the equivalent effective stratospheric chlorine (EESC) can be calculated for each ODS. From this change in EESC, the ODP can be calculated as follows:

$$ODP_{inf,x} = \frac{\Delta EESC_x}{\Delta EESC_{CFC-11}}$$

Equation 3: Ozone Depleting Potentia for an infinite time horizon for ODS x l, ΔEESCx and ΔEESCcfc-11 are the changes in EESC caused by the emission of 1 kg of ODS x and 1 kg of CFC-11, respectively Huijbregts et al. (2016).

5.1.3 Particulate matter formation

Fine Particulate Matter with a diameter of less than 10 μm (PM10) represents a complex mixture of organic and inorganic substances. PM10 causes health problems as it reaches the upper part of the airways and lungs when inhaled. Secondary PM10 aerosols are formed in air from emissions of sulfur dioxide (SO2), ammonia (NH3), and nitrogen oxides (NOx) among others. Inhalation of different particulate sizes can cause different health problems. From recent WHO studies, the effects of chronic PM exposure on mortality (life expectancy) seem to be attributable to PM2.5 rather than to coarser particles. Particles with a diameter of 2.5–10 μm (PM2.5–10), may have more visible impacts on respiratory morbidity. PM has both anthropogenic and natural sources. Although both may contribute significantly to PM levels in the atmosphere, this chapter focuses on attributive effects of PM from anthropogenic sources, since only this fraction may be influenced by human activity. *Goedkoop et al. (2009)*

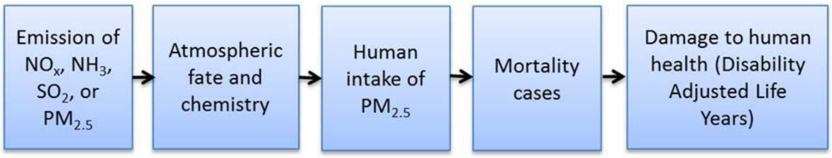


Figure 77. Cause-and-effect chain, from fine dust formatting emissions to damage to human health

The modelling from emission to damage was divided into five consecutive steps, 1) an emission of NOx, NH_3, SO_2 or primary PM2.5 is followed by 2) atmospheric fate and chemistry in the air; NOx, NH_3, and SO_2 are transformed in air to secondary aerosols. 3) PM2.5 can be inhaled by the human population, leading to 4) increased number of mortality cases in humans, and 5) final damage to human health. No thresholds for PM2.5 effects were assumed in the effect calculations. After thorough examination of all available evidence, a review by a WHO working group concluded that most epidemiological studies on large populations have been unable to identify a threshold concentration below which ambient PM has no effect on mortality and morbidity. To express the life years affected by respiratory health damage due to exposure to PM2.5, Disability Adjusted Life Years (DALY) are used as a measure.

On the midpoint level the intake fraction of PM10 is of importance, as the effect and damage factors are substance independent. Particulate matter formating potentials (PMFP) are expressed in PM10-equivalents: *Goedkoop et al. (2009), Huijbregts et al. (2016)*

$$PMFP = \frac{iF_x}{iF_{PM10}}$$

Equation 4 PMFP midpoint characterization factor calculation, iF = intake factor

5.1.4 Terrestrial acidification

Atmospheric deposition of inorganic substances, such as sulphates, nitrates and phosphates, cause a change in acidity in the soil. For almost all plant species, there is a clearly defined optimum level of acidity. A serious deviation from this optimum level is harmful for that specific kind of species and is referred to as acidification. As a result, changes in levels of acidity will cause shifts in a species occurrence. Major acidifying emissions are NOx, NH_3, or SO_2. This chapter describes the calculation of characterization factors for acidification for vascular plant species in biomes worldwide. Fate factors, accounting for the environmental persistence of an acidifying substance, can be calculated with an atmospheric deposition model, combined with a geochemical soil acidification model. Effect factors, accounting for the ecosystem damage caused by an acidifying substance, can be calculated with dose-response curves of the potential occurrence of plant species, derived from logistic regression functions. For acidification, *Huijbregts et al. (2016)* divided the endpoint modelling from emission to damage into six consecutive steps. An emission of NOx, NH_3 or SO_2 is followed by atmospheric fate before it is deposited on the soil. Subsequently, it will leach into the soil, changing the soil solution H+ concentration. This change in acidity can affect the plant species living in the soil, causing them to disappear.

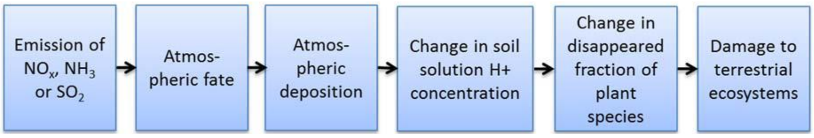


Figure 78: Cause-and-effect chain, from acidifying emissions to relative species

The fate factor (FF) for acidification due to emissions in grid It is determined per precursor x (FFx,i). The Acidification Potential (AP), expressed in kg SO_2 equivalents, is calculated by dividing FFx,i by the emission-weighted world average FF of SO_2:

$$AP_{x,i} = \frac{FF_{x,i}}{FF_{SO2,world\ average}}$$

Equation 5: Calculation of AP

The AP quantifies the soil acidity a substance emission can enhance relative to SO_2. The midpoint characterization factor was calculated in two steps. Firstly, grid-specific changes in acid deposition were calculated, following grid-specific changes in air emission. *Huijbregts et al. (2016)*

5.1.5 Freshwater eutrophication

Freshwater eutrophication occurs due to the discharge of nutrients into soil or into freshwater bodies and the subsequent rise in nutrient levels, i.e. phosphorus and nitrogen. Environmental impacts related to freshwater eutrophication are numerous. They follow a sequence of ecological impacts offset by increasing nutrient emissions into fresh water, thereby increasing nutrient uptake by autotrophic organisms such as cyanobacteria and algae, and heterotrophic species such as fish and invertebrates. This ultimately leads to relative loss of species. In *Huijbregts et al. (2016)* work, emission impacts to fresh water are based on the transfer of phosphorus from the soil to freshwater bodies, its residence time in freshwater systems and on the potentially disappeared fraction (PDF) following an increase in phosphorus concentrations in fresh water.

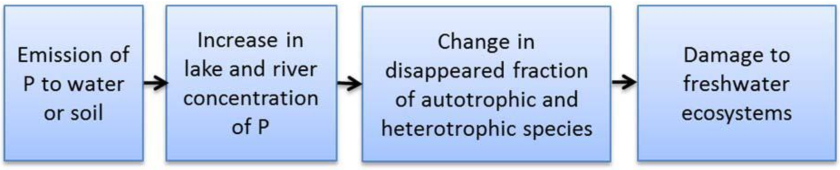


Figure 79: Cause-and-effect chain for Phosphorus emissions causing loss of freshwater species richness.

Fate factors (FFs) are used for phosphorus emissions to fresh water, based on a new global fate model on a half-degree grid resolution. The removal processes taken into account are grid-specific advection, phosphorus retention and water use. The FF represents the net residence time in the freshwater compartment (in years). The cumulative FF for an emission in a grid cell is the sum of the FFs for the individual cell of emission and of all downstream receptor grid cells j. Country and world aggregated fate factors were determined based on gridded population estimates, which served as a proxy for emission intensity of P in a grid.

0.5°×0.5° gridded population estimates of year 2015, were used for this purpose. With this method, *Huijbregts et al. (2016)* obtained a world average fate factor of P emissions to fresh water for 84 days (0.23 years). For emissions to agricultural soils, the FFs were multiplied by 0.1, as typically 10% of all P is transported from agricultural soil to surface waters. Emissions to seawater do not lead to freshwater eutrophication as there is no transport from seawater to fresh water. Here, we use the world average in the calculation of the freshwater eutrophication midpoint factors:

$$\mathrm{FEP}_{x,c,i} = \frac{\mathrm{FF}_{x,c,i}}{\mathrm{FF}_{P,fw,world\ average}}$$

Equation 6 FEPx,c,i is the freshwater eutrophication potential of substance x for emission to compartment c in grid cell i (in kg P to freshwater equivalents /kg of substance x to compartment c in grid i), FFx,c,i is the fate factor of substance x emitted to compartment c in grid cell i (years) and FFP,fw is the world average fate factor of P emission to fresh water (85 days) Huijbregts et al. (2016).

5.1.6 Marine eutrophication

Marine eutrophication occurs due to the runoff and leach of plant nutrients from soil, and to the discharge of those into riverine or marine systems, and the subsequent rise in nutrient levels, i.e. phosphorus and nitrogen (N). Here, *Huijbregts et al. (2016)* assume N as the limiting nutrient in marine waters.

Environmental impacts related to marine eutrophication due to nutrient enrichment point to a variety of ecosystem impacts, one being benthic oxygen depletion. This may lead to the onset of hypoxic waters and, if in excess, to anoxia and ‘dead zones’, which is one of the most severe and widespread causes of marine ecosystems disturbance.

In *Huijbregts et al. (2016)* work, impacts to marine water are based on the transfer of dissolved inorganic nitrogen (DIN) from the soil and freshwater bodies, or directly to marine water, its residence time in marine systems, on dissolved oxygen (DO) depletion, and on the potentially disappeared fraction (PDF), modelled as a function of DIN emitted

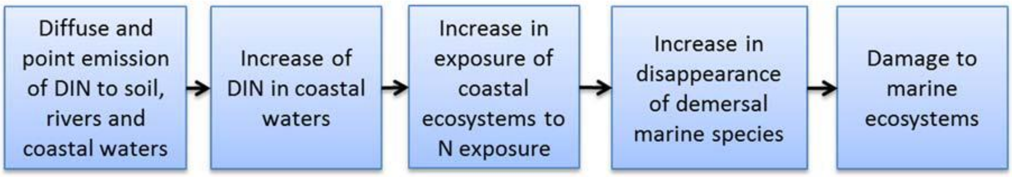


Figure 80: Cause-and-effect chain for marine euthropication

The marine eutrophication potential of substance x for emission to compartment c (MEPx,c) is the emission (E)-weighted combined fate factor and exposure factor, scaled to the world average of N emitted to marine water:

$$MEP_{x,c} = \frac{\frac{\sum\left(FF_{x,c,LME} \cdot XF_{x,c,LME} \cdot E_{x,c,LME}\right)}{\sum E_{x,c,LME}}}{\frac{\sum\left(FF_{N,mw,LME} \cdot XF_{N,mw,LME} \cdot E_{N,mw,LME}\right)}{\sum E_{N,mw,LME}}}$$

Equation 7: MEP calculation

The fate factor (FF) combines the persistence of DIN in the receiving coastal ecosystem, determined by the marine water removal rate (in years), and the fraction f of the original DIN emission entering the coastal environment. *Huijbregts et al. (2016)*

5.1.7 Metal depletion

For the impact category of metal depletion, the damage modelling is subdivided into several steps by *Goedkoop et al.* *(2009)*. The primary extraction of a mineral resource (ME) will lead to an overall decrease in ore grade (OG), meaning the concentration of that resource in the worldwide, which in turn will increase the ore produced per kilogram of mineral resource extracted (OP). This, when combined with the expected future extraction of that mineral resource, leads to an average surplus ore potential (SOP) which is the midpoint indicator for this impact category.

An increase in surplus ore potential will then lead to a surplus cost potential. These two indicators follow the principle that mining sites with higher grades or with lower costs, for SOP and SCP, respectively, are the first to be explored.

In the description of the Area of protection, the damage is defined as the additional costs society has to pay as a result of an extraction. This cost can be calculated by multiplying the marginal cost increase of a resource with an amount that is extracted during a certain period. This could be the annual production of a resource on a global basis, or the apparent consumption of a resource in a region.

The midpoint characterization factor is computed as:

$$CF_{c.kg.mid} = -\frac{\overline{M_c}}{\left(c_c\right)^2} \times V_c^2 \times P_{c.kg}$$

Equation 8: SOP calculation, *with Mc and Cc the slope and constant on deposit level recalculated to commodity level c, P/kg the produced amount of resource (kg) and V the value factor (yr).The characterization factor that expresses the increase in price ($/kg) as a result of an extraction. The unit of this characterization factor is 1/$.yr. The midpoint factors are given as Fe-equivalents Goedkoop et al. (2009).*

5.1.8 Fossil resource depletion

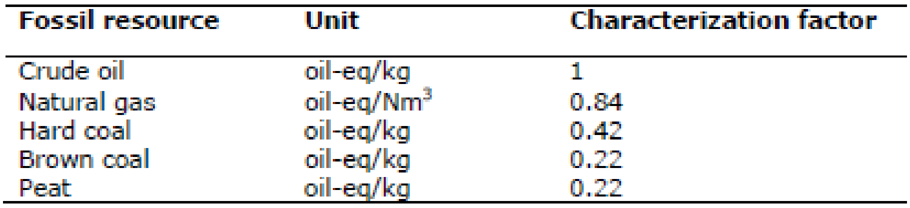
For the impact category fossil resource depletion, the damage modelling is subdivided into several steps by *Huijbregts et al. (2016)*. It is assumed in the endpoint modelling that fossil fuels with the lowest costs are extracted first. Consequently, the increase in fossil fuel extraction causes an increase in costs due either to a change in production technique or to sourcing from a costlier location. For example, when all conventional oil is depleted, alternative techniques, such as enhanced oil recovery, will be applied or oil will be produced in alternative geographical locations with higher costs, such as Arctic regions. This, when combined with the expected future extraction of a fossil resource, leads to a surplus cost potential (SCP) which is the endpoint indicator for this impact category. Here, we estimated the damage to natural resource scarcity. The fossil fuel potential (higher heating value) was used as midpoint indicator.

The midpoint indicator for fossil resource use, determined as the Fossil Fuel Potential of fossil resource x (kg oil-eq/unit of resource), is defined as the ratio between the energy content of fossil resource x and the energy content of crude oil, which is calculated by:

$$FFP_x = \frac{HHV_x}{HHV_{oil}}$$

Equation 9: FFP calculation

The fossil fuel potential (FFP) is based on the higher heating value (HHV) of each fossil resource and is provided for crude oil, natural gas, hard coal, brown coal and peat. We use the HHVs that were used in the ecoinvent database.



Fossil resource	Unit	Characterization factor
Crude oil	oil-eq/kg	1
Natural gas	oil-eq/Nm^3	0.84
Hard coal	oil-eq/kg	0.42
Brown coal	oil-eq/kg	0.22
Peat	oil-eq/kg	0.22

Figure 81: Fossil fuel potentials (in kg oil-eq/unit of resource) for 5 fossil resources. Huijbregts et al. (2016)

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