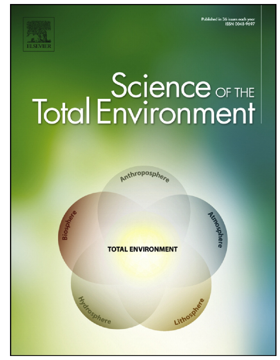
Accepted Manuscript



Life cycle assessment of wood pellets and wood split logs for residential heating

Paula Quinteiro, Luís Tarelho, Pedro Marques, Mario Martin-Gamboa, Fausto Freire, Luís Arroja, Ana Cláudia Dias

PII: S0048-9697(19)32993-6
DOI: https://doi.org/10.1016/j.scitotenv.2019.06.420
Reference: STOTEN 33074

To appear in: *Science of the Total Environment*

Received date: 25 January 2019
Revised date: 13 June 2019
Accepted date: 25 June 2019

Please cite this article as: P. Quinteiro, L. Tarelho, P. Marques, et al., Life cycle assessment of wood pellets and wood split logs for residential heating, Science of the Total Environment, https://doi.org/10.1016/j.scitotenv.2019.06.420

Life cycle assessment of wood pellets and wood split logs for residential heating

Paula Quinteiro[a,*,] Luís Tarelho[a], Pedro Marques[b], Mario Martin-Gamboa[a], Fausto Freire[b], Luís Arroja[a], Ana Cláudia Dias[a]

[a]Centre for Environmental and Marine Studies (CESAM), Department of Environment and Planning, University of Aveiro, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal

[b]ADAI-LAETA Department of Mechanical Engineering, University of Coimbra, 3030-788 Coimbra, Portugal

[*]Corresponding author at: CESAM Department of Environment and Planning, University of Aveiro, 3810-193 Aveiro, Portugal. Tel.: +351 234 370 349
E-mail address: p.sofia@ua.pt (Paula Quinteiro)

ABSTRACT

Wood-fuelled systems are commonly used all over the world for residential heating, and recently wood pellets have been replacing traditional firewood. This article presents an environmental life cycle assessment of five wood-based combustion systems for residential heating: i) a pellet stove using maritime pine pellets; a wood stove using ii) eucalyptus (*Eucalyptus globulus* Labill.) and iii) maritime pine (*Pinus pinaster* Ait.) split logs; and a fireplace using iv) eucalyptus and v) maritime pine split logs. The functional unit is 1 MJ of thermal energy for residential heating. System boundaries include four stages: (1) forest management; (2) pellet and wood split log production; (3) distribution; and (4) thermal energy generation. Environmental impacts were calculated for seven impact categories from the ReCiPe 2016 midpoint method, and a sensitivity analysis was performed using the Product Environmental Footprint (PEF) life cycle impact assessment method and modifying the distances travelled.

Of the five heating systems analysed, the fireplace presents the worst performance for all the impact categories with the exception of freshwater eutrophication and marine eutrophication, when maritime pine split logs are burned in the fireplace. Comparing the pellet stove with the wood stove, neither system is better for all the impact categories analysed. Regarding sensitivity analysis, the use of an alternative characterisation method leads to similar trends in the results in comparison with those obtained from the ReCiPe method, while changes in transport distances do not affect the total impacts to a large extent.

Keywords: biomass, fireplace, LCA, residential heating, wood pellets, wood stove

1. Introduction

The use of woody biomass for energy purposes has been increasing in recent decades, highlighting the importance of woody resources in sustainable economies (Branck, 2017; IEA Bioenergy, 2002), due to the potential to reduce fossil fuel dependency and greenhouse gas (GHG) emissions. Directive 2009/28/EC (Renewable Energy Directive) supports the use of woody biomass for achieving a 20% share of renewable energy sources in the European Union (EU) final energy mix by 2020. Recently, a new Renewable Energy Directive for the period beyond 2020 has been approved, with the purpose of reaching 32% renewable energy in the EU energy mix by 2030 and defining a 'bioenergy sustainability policy' (European Commission, 2018). In 2015, 46% of the total renewable energy produced in the EU came from woody biomass. Besides that, about half of the thermal energy produced from woody biomass was for residential heating (82,921 ktoe) (AEBIOM, 2017).

Wood-fuelled systems are commonly used all over the world for residential heating, and recently wood pellets have been replacing the firewood traditionally used for residential heating. Wood pellets are burned in pellet stoves with a higher combustion efficiency than traditional heating systems (wood stoves and fireplaces). Besides that, wood pellets have a higher energy density and thus require less storage space than firewood, considering an energy basis (Carvalho, 2016; Cespi et al., 2014; Loo and Koppejan, 2008). However, pellet production requires more complex industrial processing (Giuntoli et al., 2015; Marques et al., 2018), in principle leading to higher life cycle impacts.

Portugal is in the top ten of the largest producers of wood pellets in the EU, producing more than 1 million tonnes and consuming around 100,000 tonnes (AEBIOM, 2015). Portuguese forest covers an area of approximately 3.1 million hectares, which represents 35% of the national territory (ICNF, 2013), making Portugal a country with great potential for the exploitation of forest biomass, including for energy purposes (da Costa et al., 2018). The Portuguese national action plan for renewable energy promotes the use of forest biomass, namely pellets for residential heating, as a key to achieve GHG benefits compared to fossil fuel alternatives (European Commission, 2010). However, the use of woody fuels for residential heating leads to the emission of other air pollutants, namely carbon monoxide (CO), non-methane volatile organic compounds (NMVOC) and sulphur dioxide (SO_2) (Cespi et al., 2014; Kocbach Bølling et al., 2009; Nyström et al., 2017; Solli et al., 2009) which should be taken into account in the environmental assessment of forest biomass for residential heating. This can be accomplished by applying a life cycle assessment (LCA)-based methodology, which has been widely used to assess the environmental impacts of forest-based products (e.g. Dias, 2014; Dias and Arroja, 2012; González-García et al., 2014; Quinteiro et al., 2016; 2015).

In particular, several LCA studies on producing (e.g. Kylili et al., 2016; Laschi et al., 2016) and burning wood pellets for residential heating are available (e.g. Ferreira et al., 2018; Monteleone et al., 2015; Pa et al., 2013; Ruiz et al., 2018); however, the number of LCA studies on residential burning of traditional firewood is much smaller (Ferreira et al., 2018; Paolotti et al., 2017) and only a few compare the impacts of burning wood pellets against split wood logs (Cespi et al., 2014; Giuntoli et al., 2015).

So far, no LCA study comparing the environmental burdens of burning different wood fuels in a pellet stove, wood stove and fireplace, from a cradle-to-grave perspective, i.e. from forest management activities through pellet and wood split log production and distribution to thermal energy generation, has been performed. Therefore, the objective of this study was to assess the environmental impacts of five different wood-based residential heating systems in Portugal: i) a pellet stove using maritime pine (*Pinus pinaster* Ait.) pellets as feedstock; a wood stove using ii) eucalyptus (*Eucalyptus globulus* Labill.) and iii) maritime pine split logs as feedstocks; and a fireplace using iv) eucalyptus and v) maritime pine split logs as feedstocks. In addition, a sensitivity analysis was undertaken to assess how different impact assessment methods and assumed data (transport distances) influence the results. Maritime pine (softwood) is the most used raw material to produce wood pellets in Portugal, mainly because of its lower ash content, easier grindability and higher amount of extractives than eucalyptus (hardwood), and thus it is more suitable for pelletising. Maritime pine has an ash content of around 0.4 weight %, on a dry basis (average data from Alves et al. (2011) and Gonçalves et al. (2011)), which is lower than the ash content threshold required by the international wood pellet ENplus certification standard (≤ 0.7 weight %, dry basis) (ENplus, 2015). Wood extractives are the non-structural components of wood like resin, fatty compounds, sterols and phenolics. Softwood and hardwood have different types and quantities of extractives (Ekman and Holmbom, 2000), which contribute to differences in energy consumption during the pelletising operation (Nielsen et al., 2010). Softwood has a higher quantity of extractives than hardwood, which acts as lubricant, resulting in lower energy consumption in the pelletisation process and better agglomeration properties of the feedstock.

Wood stove, fireplace and pellet stove heating systems have been considered in this study. Wood stoves and fireplaces are the most used wood-based appliances in Portugal (Gonçalves et al., 2012), and the use of wood pellet stoves has been largely increasing over the last few years (Vicente et al., 2016).

2. Methods

The LCA methodology assesses the environmental aspects and potential impacts associated with a product by compiling an inventory of the relevant inputs and outputs of a product system, evaluating the potential environmental impacts associated with those inputs and outputs, and interpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of the study. The LCA was performed following ISO 14040 and 14044 standards (ISO, 2006a, 2006b).

2.1. *Systems analysed, functional unit and system boundaries*

Five different wood-based residential heating systems were evaluated as follows:

– PS-MP: thermal energy generation through combustion of maritime pine pellets in a pellet stove;

– WS-E: thermal energy generation through combustion of eucalyptus split logs in a wood stove;

– WS-MP: thermal energy generation through combustion of maritime pine split logs in a wood stove;

– F-E: thermal energy generation through combustion of eucalyptus split logs in a fireplace;

– F-MP: thermal energy generation through combustion of maritime pine split logs in a fireplace.

Table 1 shows the biomass characteristics (elemental analysis, moisture and ash, and lower heating value) used in the five wood-based residential systems. Table 2 presents the main characteristics of the pellet and split log combustion appliances.

The functional unit is 1 MJ of thermal energy for residential heating. A cradle-to-grave approach was applied, i.e. from forest management activities through the pellet and wood split log production and distribution to thermal energy generation. System boundaries, shown in Fig. 1, include four stages as follows: (1) forest management of both eucalyptus and maritime pine species up to log loading onto trucks; (2) pellet and wood split log production; (3) distribution of pellets and wood split logs; and (4) thermal energy generation. The production of fuels, lubricants and fertilisers was also considered, as well as disposal of ashes from biomass burning. Moreover, in the case of pellets, the production of low-density polyethylene (LDPE) bags and maritime pine logging residues (used for producing the heat required in drying operations) was also included. The transport of workers and machinery was excluded, as was the production of capital goods (buildings, machinery and equipment).

2.2. *System description*

2.2.1. Wood pellets

The forest management stage includes all operations carried out during infrastructure establishment, stand establishment, stand tending and wood felling, forwarding and loading onto trucks. In the case of the wood pellet system, it also includes operations related to forwarding, forest roadside chipping and loading of residual forest biomass from maritime pine logging activities onto trucks. Following Dias and Arroja (2012), for the maritime pine forest, a high-intensity management model was considered, characterised by adoption of the best management practices recommended for the forest stands, and in which logging is accomplished by harvesters and forwarders for felling and forwarding. Maritime pine stands are managed as high forest with final cutting at the average age of 45 years. A more detailed description of the operations carried out is given by Dias et al. (2007) and Dias and Arroja (2012).

The production stage includes the production of wood pellets from maritime pine wood. Five main operations are considered: (1) log chipping; (2) milling; (3) drying, using the heat produced from the combustion of maritime pine logging residues, chipped at the forest roadside; (4) pelletising; and (5) packaging.

The distribution stage considers the distribution to stores of wood pellets packed in LDPE bags (15 kg of pellets per bag) by truck and the subsequent transport by final consumers by private cars. The last stage of thermal energy generation consists of wood pellet burning in a pellet stove with a nominal power of 9.5 kW_{th} for residential heating. The pellet stove has an internal pellet storage tank, and pellets are supplied to the burner by an auger screw.

The primary combustion air is supplied through holes in the bottom of the basket, while the secondary air is fed at the flame level. Ignition of the wood pellets is done by heating the air with an electrical resistance heater (Vicente et al., 2016). The pellet stove requires electricity to start up and for the operation of a fan to admit atmospheric air into the combustion chamber, that is the combustion air, and another fan to circulate the building's indoor air throughout the pellet stove heat exchanger to be heated (Vicente et al., 2015). The resulting ashes were considered to be landfilled at a sanitary landfill.

2.2.2. Wood split logs

Regarding the eucalyptus and maritime pine split log systems, they encompass forest management, split log production, distribution and thermal energy generation by households (Fig. 1).

The forest management stage includes all operations accomplished during infrastructure establishment, stand establishment, stand tending and wood felling, forwarding and loading onto trucks, both for eucalyptus and maritime pine. High-intensity management was considered for both species (Dias and Arroja, 2012), as in the case of the pellet system. Eucalyptus stands are managed as coppiced stands in three successive rotations, each one of 12 years, while maritime pine stands are managed as high forest with final cutting at the average age of 45 years, as mentioned above (Dias et al., 2007; Dias and Arroja, 2012). Fertiliser requirements in eucalyptus stands are higher than in maritime pine stands. Besides that, both phosphorus- and nitrogen-based fertilisers were considered for eucalyptus, while for maritime pine only phosphorus-based fertilisers were considered.

Split log production consists of splitting the wood logs into smaller portions of wood ready for burning. The thermal energy generation encompasses the combustion of split logs in a wood stove or a fireplace, depending on the system. The wood stove has manual control of combustion air that enters below the grate, and is equipped with two electric fans to force the building's indoor air through the heat exchanger to be heated. The driving force for the air flow rate through the combustion chamber is the natural draught resulting from the up-flowing stream of hot combustion flue gases through the woodstove chimney (Calvo et al., 2014).

The fireplace is a traditional Portuguese brick open fireplace operated manually in batch mode and with no control of combustion air. In both cases, the ashes produced were considered to be disposed at a sanitary landfill.

2.3. *Allocation*

Forest management is a multifunctional process that generates both wood and residual material produced during harvesting such as bark, logging residues (branches, tops and foliage) and stumps (only in eucalyptus). Mass allocation (dry basis) was applied for allocating the environmental burdens associated with the operations undertaken up to felling among the forest biomass components that leave the forest. All wood and bark leaving the forest was considered to be used by industry, while half of the logging forest residues and stumps was considered to remain on the forest floor due to ecological, technical and logistical reasons (Dias, 2014). The allocation factors adopted are shown in Table 3. In the case of eucalyptus, the mass proportions of each biomass component (wood, bark, logging residues and stumps) were taken from Dias (2014), whereas in the case of maritime pine, the allocation factors were estimated based on González-García et al. (2014) and Faias (2009).

2.4. *Inventory analysis*

2.4.1. Wood pellets

The inventory data for the production of maritime pine wood were taken from Dias and Arroja (2012) and complemented with data from González-García et al. (2014) for thinning operations. Regarding the production of maritime pine logging residues, data up to tree felling are the same as for wood but the respective allocation factor was applied. Data for the subsequent operations of forwarding (with a forwarder), forest roadside chipping and loading onto trucks were retrieved from Dias (2014). A neutral biogenic CO_2 balance was considered, as the CO_2 assimilated during forest growth was assumed to be equal to the CO_2 that is emitted to the atmosphere during the combustion of logging residues and wood pellets.

Table 4 presents the inventory data for the production of 1 tonne of wood pellets. All data other than for packaging material and air emissions are average primary data obtained based on surveys of two wood pellet mills in Portugal. The quantity of LDPE bags was taken from Laschi et al. (2016). Regarding air emissions from logging residue burning, data on CO, nitrogen oxides (NO_x), methane (CH_4) and NMVOC were calculated based on emission factors taken from EMEP/EEA (2017). The SO_2 was calculated based on a sulphur content in the logging residues of 0.01 weight % (dry basis) (Energy Research Centre of the Netherlands, 2017). Data for the production diesel and bags, as well as for ash transport and disposal, were taken from the Ecoinvent database (2017). Data for electricity generation in Portugal (for the period 2012 to 2016), including the life cycle impact assessment of electricity, were taken from Garcia et al. (2014) and Kabayo et al. (2018).

In the distribution stage, a distance of 15 km by truck from pellet mill to store and another 15 km by private car from store to households were considered, according to a 'short chain topology'. This implies proximity between the places of energy consumption and production (Paolotti et al., 2017). Data on environmental impacts for the trucks and private cars used in pellet transport were taken from the Ecoinvent database (2017).

In the thermal energy generation stage, the amount of pellets consumed was estimated based on a typical energy conversion efficiency of 82%, while electricity consumption was taken from Kruse (2016). The pellet stove was operated at three levels of power output (lowest, medium and highest) to cover different behaviours by users, with an average rate of feedstock consumption of around 1 kg.h^{-1}. The combustion of wood pellets emits several gaseous pollutants, namely CO, NO_x, SO_2, CH_4 and NMVOC, to the air (Table 5). Data on NO_x were calculated from our own measurements from Fourier-transform infrared spectroscopy conducted in a top-feed pellet stove burning maritime pine pellets. As SO_2 emissions depend on the sulphur content of the feedstock, they were calculated based on an average sulphur content of 0.01 weight % (dry basis), which corresponds to the lower detection level of the equipment used for elemental analysis (Table 1). Data for CH_4 and NMVOC (expressed as mass of CH_4 and NMVOC per unit energy in wood) were calculated based on emission factors taken from EMEP/EEA (2017). The CO emissions were also measured by Fourier-transform infrared spectroscopy. Finally, the ashes generated during the combustion process in the pellet stove were transported for an average distance of 40 km to the sanitary landfill site by a waste collection truck. Data on the ash transport and disposal were taken from the Ecoinvent database (2017).

2.4.2. Wood split logs

The inventory data for the forest management stage of maritime pine were the same as used for the pellet system, while those for eucalyptus forest were retrieved from Dias and Arroja (2012). As in the case of the pellet system, a neutral biogenic CO_2 balance was considered.

For the production of eucalyptus and maritime pine split logs (Table 4), an average value was used for the diesel consumed, resulting from data provided by two facilities. During the production of split logs, around 5% of the total wood is lost as wood chips during the log splitting process. Regarding air emissions from diesel combustion to deliver useful work in the machine producing the wood split logs, data on CO, CO_2, NO_x, CH_4 and NMVOC were calculated based on emission factors taken from EMEP/EEA (2017). Emissions of SO_2 were calculated based on the average sulphur content in the diesel (20 mg.kg^{-1}, Decree Law no. 142/2010, 2010). Inventory data for the production of diesel were sourced from the Ecoinvent database (2017).

An average distance of 15 km from the log splitting facilities to households was assumed. The split logs were transported by truck, and inventory data were taken from the Ecoinvent database (2017).

In the thermal energy generation stage (Table 5), the wood was burned as split logs. The wood stove and fireplace were operated with combustion cycles of between 45 and 90 min. About 6 kg of wood split logs was burned, using three consecutive batches of around 2 kg each. The amounts of split logs consumed were calculated based on typical energy conversion efficiencies of wood stoves and fireplaces, 65% and 10%, respectively (Carvalho, 2016; Loo and Koppejan, 2008). The energy conversion efficiency of the fireplace is much smaller than that of the wood stove, because the fireplace has no control of combustion air admission, and the combustion air flow rate is completely driven by the natural convection induced by the combustion flue gas through the chimney; this induces relatively high losses of thermal energy through the chimney. Electricity consumption for the wood stove was taken from Kruse (2016).

The NO_x emissions for WS-E and WS-P were calculated based on emission factors (expressed as mass of NO_x per mass of wood) obtained by Fernandes et al. (2011) considering the same feedstock as in this study and, therefore, presenting the same ultimate analysis (Table 1). Because no specific measurements of NO_x emissions are available for the fireplace, it was assumed that the NO_x emission factors (expressed as mass of NO_x per mass of wood) for F-E and F-WS are the same as those for WS-E and WS-MP, respectively. As in the case of the pellet stove, data on CH_4 and NMVOC were calculated based on emission factors (expressed as mass of CH_4 and NMVOC per unit energy in wood) taken from EMEP/EEA (2017), while emissions of SO_2 were calculated based on the sulphur content in the feedstock (0.01 weight %, dry basis), which corresponds to the lower detection level of the equipment used for elemental analysis. For CO emission factors, average values were obtained from Fernandes et al. (2011) and Gonçalves et al. (2012).

As in the case of pellet stove, the resulting ashes were transported to a sanitary landfill considering an average distance of 40 km. Data on the ash transport and disposal were taken from the Ecoinvent database (2017).

2.5. *Impact assessment*

A quantitative impact assessment was performed for seven impact categories – global warming, fossil resource scarcity, terrestrial acidification, freshwater eutrophication, marine eutrophication, ozone formation (human health) and ozone formation (terrestrial ecosystems) – applying the characterisation factors from the ReCiPe 2016 midpoint v.1.01 method (Huijbregts et al., 2016).

3. Results and discussion

3.1. *Comparison of systems*

Table 6 shows the impact assessment results obtained for the production of 1 MJ of thermal energy for residential heating under the five different wood-based heating systems. Fig. 2 shows the relative contribution of each stage within the system boundaries to the total impact. Overall, the results show that the fireplace produces the highest impacts for all the impact categories, with the exception of freshwater eutrophication and marine eutrophication, when maritime pine split logs are burned in the fireplace. Comparing the pellet stove with the wood stove, neither of the systems is better than the other, for all the impact categories analysed.

The pellet stove system presents the lowest environmental impacts for global warming, ozone formation (human health) and ozone formation (terrestrial ecosystems). For fossil resource scarcity, it performs better (2.15E−03 kg oil eq) than the fireplace system (5.95E−03 kg oil eq for maritime pine and 6.17E−03 kg oil eq for eucalyptus) but worst that when maritime pine and eucalyptus are burned in the wood stove (1.10E−03 kg oil eq and 1.14E−03 kg oil eq, respectively). For terrestrial acidification, it performs better (7.87E−05 kg SO_2 eq) than the fireplace system when maritime pine and eucalyptus split logs are burned (3.72E−04 kg SO_2 eq and 5.13E−04 kg SO_2 eq, respectively) and the wood stove system when eucalyptus is burned (8.03E−05 kg SO_2 eq), but it is worst when maritime pine is burned in the wood stove (5.84E−05 kg SO_2 eq). For freshwater eutrophication, it performs better (1.86E−06 kg P eq) than the fireplace when eucalyptus split logs are burned (2.31E−06 kg P eq) but worst that when maritime pine and eucalyptus split logs are burned in the wood stove (5.02E−07 kg P eq and 5.91E−07 kg P eq, respectively), and when maritime pine is burned in the fireplace (1.75E−06 kg P eq). For marine eutrophication, it performs better (2.16E−07 kg N eq) than the wood stove and fireplace systems when eucalyptus split logs are burned (4.87E−06 kg N eq and 3.14E−05 kg N eq, respectively) but it is worst when maritime pine split logs are burned in the woodstove and fireplace (3.68E−08 kg N eq and 4.31E−08 kg N eq, respectively).

The global warming impact of the pellet stove system is lower than that of the other systems mainly because the energy conversion efficiency during the combustion process for thermal energy generation is higher, resulting in lower GHG emissions. Regarding ozone formation (human health) and ozone formation (terrestrial ecosystems), the lowest environmental impact for the pellet stove system is mainly due to the lowest emission of NO_x during thermal energy generation due to higher combustion efficiency. The impacts of the pellet stove system for fossil resource scarcity and freshwater eutrophication result mainly from electricity consumption during the pellet production stage. The depletion of hard coal and natural gas for electricity generation are the main contributors to fossil resource scarcity, while for freshwater eutrophication it is the emission of phosphates to water, occurring primarily in hard coal mining. The impacts of the pellet stove system for terrestrial acidification result mainly from SO_2 emissions during the combustion process for thermal energy generation, while the impacts for marine eutrophication result mainly from the nitrates emitted to water during electricity generation.

Comparing wood stove and fireplace systems, the fireplace presents higher impacts for all impact categories because of the emission of gaseous pollutants during the combustion of wood split logs, with the exceptions of freshwater eutrophication and marine eutrophication, when maritime pine split logs are burned in the fireplace. These exceptions are due to the fact that during the maritime pine management stage, lower quantities of phosphorous-based fertilisers are applied compared to the ones applied during the eucalyptus management stage (freshwater eutrophication), and no fertilisers containing nitrogen are applied during the maritime pine management stage (marine eutrophication).

Additional research on the biogenic carbon balance should be carried out using a dynamic approach that takes into consideration the temporal profile of biogenic CO_2 sequestration during forest growth, instead of considering biogenic CO_2 neutrality (Demertzi et al., 2016).

A further step framed in the evaluation of residential heating systems based on wood biomass could be based on combination of the results obtained with economic and social indicators in order to enlarge the scope and to embrace a holistic vision of sustainability. In addition, since none of the heating systems studied is better in all the impact categories considered, further research will be needed to understand what is the best environmental, economic and social choice among the five residential heating systems studied. In this sense, the use of multi-criteria decision analysis tools is found to be appropriate for the prioritisation of alternatives, being a possible solution towards more robust and suitable choices within a future bio-economy context in Portugal.

3.2. *Hotspot analysis*

For the pellet stove system, the pellet production stage was particularly relevant for the impact categories of global warming, fossil resource scarcity, freshwater eutrophication and marine eutrophication, presenting contributions that range from 46% to 64% of the total impact (Fig. 2). These impacts result essentially from the electricity consumption and combustion of logging residues related to the process of pellet production. For global warming, the main contributor is the combustion of logging residues associated with heat generation for wood drying during the process of pellet production (due to CH_4 emission), while for fossil resource scarcity and freshwater eutrophication, electricity consumption in the pellet production process represents the major contribution to the total impacts. For terrestrial acidification, ozone formation (human health) and ozone formation (terrestrial ecosystems), thermal energy generation is the hotspot, ranging from 62% to 74% of the total impact, mainly due to NO_x emissions, for the three impact categories. The forest management stage presents the lowest impacts of all impact categories (2% to 14%), except for terrestrial acidification, freshwater eutrophication and marine eutrophication, in which the pellet distribution stage has the smallest impacts (0.6% to 4% of the total impacts, respectively).

For both wood stove systems, the stage of eucalyptus and pine split log combustion for thermal energy generation is the most relevant for all impact categories other than fossil resource scarcity, freshwater eutrophication (with the exception of the WS-MP system) and marine eutrophication (with the exception pf the WS-MP system), with contributions that range from 51% to 96% of the total impacts. These contributions are mainly due to gaseous pollutant emissions during wood combustion. Regarding fossil resource scarcity, the stage of split log production is the one that contributes most to the total impact (49% for maritime pine and 52% for eucalyptus), as a result of diesel consumption to operate the equipment to produce the wood split logs. For freshwater eutrophication and marine eutrophication, in the case of eucalyptus wood, the forest stage is the main hotspot, with 51% (freshwater eutrophication) and 99% (marine eutrophication) of impacts mainly resulting from application of phosphorus- and nitrogen-based fertiliser, respectively. For freshwater eutrophication, in the case of maritime pine, the main stage is thermal energy production from the maritime pine burned in the woodstove. This contribution comes from the electricity consumed by the stove fans, mainly because of phosphates emitted to water during electricity generation, in particular from the ones emitted during hard coal exploitation. For marine eutrophication, in the case of maritime pine wood, nitrogen-based fertilisers are not applied and, thus considering the maritime pine burned in the wood stove system, the main contributor is thermal energy generation, with 82% of the total impact due to NO_x emission during combustion. The least relevant stage for all the impact categories is the distribution of wood split logs (0.3% to 11% of the total impact), for both eucalyptus and maritime pine wood stove systems.

For both fireplace systems, the stage of eucalyptus and pine split log combustion for thermal energy generation is the most relevant to most impact categories (70% to 96% of the total impacts), with the only exceptions being fossil resource scarcity, freshwater eutrophication and marine eutrophication. These contributions are mainly due to gaseous pollutant emission during wood split log combustion. For fossil resource depletion, the wood split log production stage is the main hotspot, contributing 52% (F-E) and 59% (F-MP) of the total impact because of diesel consumption to operate the equipment to produce split logs. For freshwater eutrophication, the forest management stage is the one that contributes most to the total impact, with 84% for eucalyptus and maritime pine because of the phosphorous-based fertiliser applied during the forest management stage. Regarding marine eutrophication, for the eucalyptus burned in the fireplace, the hotspot is the forest management stage (99%), resulting from the application of nitrogen-based fertiliser, while for maritime pine burned in the fireplace the main contributor is split log production, with 49% of the total impact due to diesel consumption to split the logs.

Other studies have compared the environmental burdens resulting from thermal energy generation for residential heating, using wood pellets and wood stoves (Cespi et al., 2014; Giuntoli et al., 2015). However, it is important to note that a comparison between the results of these earlier studies with those of the present study should be considered with caution because different wood feedstocks and impact assessment methods, considering different impact categories, were used.

Cespi et al. (2014) compared the environmental impacts of burning wood split logs and wood residues in a wood stove and wood pellets in a pellet stove in the region of Lombardy (Italy), using poplar and beech as feedstocks. Based on their results obtained with the ReCiPe endpoint 2008 method (Goedkoop et al., 2013), Cespi et al. (2014) found that the wood stove had the highest impacts for human toxicity, due to a lower combustion efficiency. However, for global warming (global warming to human health and to ecosystems), the pellet stove presented higher impacts due to the energy consumption during pellet production.

Giuntoli et al. (2015) also compared the environmental impacts of burning wood pellets in a pellet stove and wood residues in a wood stove, but without identifying either the biomass species or the country where feedstock was grown. The environmental impacts obtained with the ILCD method (European Commission/Joint Research Centre/Institute for Environment and Sustainability, 2011) at midpoint level show that the pellet stove system had lower impacts for photochemical ozone formation, and higher impacts for global warming change and acidification than the wood stove. In the present study, the same trend was observed for ozone formation and terrestrial acidification (Fig. 2), whereas for global warming, the pellet stove presented lower impacts when compared with the wood stove. Both Cespi et al.'s (2014) and Giuntoli et al.'s (2015) studies show that there is no best environmental option; one option is better in some impact categories but worse in others.

3.3. *Sensitivity analysis*

To evaluate the influence of methodological assumptions and data on the impact results, two sensitivity analyses were performed. The first one consists of applying a different impact assessment method to evaluate whether the same trends in results are observed. The alternative method selected was the Product Environmental Footprint (PEF) life cycle impact assessment method (European Commission, 2017). Fig. 3 presents the environmental impact results obtained by applying the PEF method.

The absolute results obtained with the PEF method are not directly comparable with those obtained with the ReCiPe method (Fig. 2) due to differences in the characterisation factors, but trends can be evaluated. Besides that, fossil resource scarcity is replaced in the PEF method by abiotic depletion, in which characterisation factors for fossil fuels are expressed as $MJ.MJ_{th}^{-1}$. Also, the ozone formation (human health) and ozone formation (terrestrial ecosystems) impact categories from the ReCiPe method are replaced in the PEF method by photochemical oxidant formation. The ozone formation impact categories use NO_x equivalents instead of NMVOC equivalents (used in the formation of photochemical oxidants in the PEF) because NMVOC is a mixture of substances.

The results show that the fireplace leads to the highest impacts for all categories, with the exception of freshwater eutrophication, when maritime pine split logs are burned in the fireplace. Comparing the pellet stove and wood stove, neither system presents a better environmental performance for all the impact categories analysed.

For all the systems under study, the trend is similar in all impact categories using the PEF method, with the exception of marine eutrophication, which confirms the results obtained for the impact categories using the ReCiPe method. For marine eutrophication predicted using the PEF method, the emissions from the thermal energy generation stage are the most relevant (55% to 82% for all the systems considered). For marine eutrophication using the ReCiPe method, the emissions from the forest management stage for eucalyptus production are more relevant than those from wood combustion for the thermal energy generation stage. This finding is due to the fact that the PEF method considers that NO_x emissions are more relevant to this impact category, while the ReCiPe method considers that nitrate emissions from forest fertilisation are more relevant.

Another sensitivity analysis is related to the distances travelled by raw wood, logging residues, pellets and split logs. Based on an optimal ‘short chain typology’, and since real ranges of distance variation are not available, the distances were assumed to decrease by 50% for the transport of logged wood and logging residues, and by 30% for the transport of packed pellets and wood split logs. Only the production and distribution stages were affected by this change because they include the transport steps. The decreases in the impacts are very small, varying from 0.02% to 16% in relation to the total impact of the baseline scenario. The impact category of fossil resource scarcity is most affected.

4. Conclusions

The analysis performed for the five heating systems shows that the fireplace presents the worst performance for all the impact categories, with the exception of freshwater eutrophication and marine eutrophication, when maritime pine split logs are burned in the fireplace. Comparing the pellet stove with the wood stove, neither system is better for all the impact categories analysed.

Regarding the sensitivity analysis, the PEF method was used to evaluate whether the same trends in results are observed as using the ReCiPe method. The results obtained with the PEF method show that the fireplace leads to the highest impacts for all the impact categories, with the exception of freshwater eutrophication, when maritime pine split logs are burned in the fireplace. Comparing the pellet stove and wood stove, once again neither system presents a better environmental performance for all the impact categories analysed. The sensitivity analysis performed for the distances travelled by raw wood, logging residues, pellets and split logs under analysis assuming a 50% distance decrease shows a very small reduction in impacts, varying from 0.02% to 16% in relation to the total impact of the baseline scenario.

Acknowledgments

This work is a contribution to the projects SABIOS (PTDC/AAGMAA/6234/2014) and SustainFor (PTDC/AGR-FOR/1510/2014), both funded under the project 3599-PPCDT, by FEDER, through COMPETE2020 - Programa Operacional Competitividade e Internacionalização (POCI), and by national funds (OE), through FCT/MCTES. Thanks are due to FCT/MCTES for the financial support to CESAM (UID/AMB/50017/2019), through national funds. Thanks are also due to FCT and POHP/FSE funding program for the scholarship granted and contract to Paula Quinteiro (SFRH/BPD/114992/2016;

CEECIND/02174/2017) and contracts granted to Ana Cláudia Dias (IF/00587/2013; CEECIND/00143/2017).

References

AEBIOM (2017) Key Findings. Euroepan Bioenergy. AEBIOM statistical report Outlook. Brussels

Alves, C., Gonçalves, C., Fernandes, A.P., Tarelho, L., Pio, C., 2011. Fireplace and woodstove fine particle emissions from combustion of western Mediterranean wood types. Atmos. Res. 101, 692–700. doi:10.1016/j.atmosres.2011.04.015

Branck D (2017) Woody biomass for power and heat impacts on the global climate. Chatham House. The Royal Institute of International Affairs. London

Calvo AI, Tarelho LAC, Alves CA, et al (2014) Characterization of operating conditions of two residential wood combustion appliances. Fuel Process Technol 126:222–232. doi: 10.1016/j.fuproc.2014.05.001

Carvalho RL (2016) Wood-burning stoves worldwide: technology, innovation, and policy. Ph.D. thesis. Aalborg University of Denmark

Carvalho RL, Vicente ED, Tarelho LAC, Jensen OM (2018) Energy & Buildings Wood stove combustion air retrofits : A low cost way to increase energy savings in dwellings. Energy Build 164:140–152. doi: 10.1016/j.enbuild.2018.01.002

Cespi D, Passarini F, Ciacci L, et al (2014) Heating systems LCA: Comparison of biomass-based appliances. Int J Life Cycle Assess 19:89–99. doi: 10.1007/s11367-013-0611-3 da Costa TP, Quinteiro P, Tarelho LA da C, et al (2018) Environmental impacts of forest biomass-to-energy conversion technologies: Grate furnace vs. fluidised bed furnace. J Clean Prod 171:153–162. doi: 10.1016/j.jclepro.2017.09.287

Decree Law no 142/2010 (2010) Decreto-Lei n.º 142/2010 de 31 de Dezembro. Diário da República: I série, Nº 253 (in Portuguese)

Demertzi M, Paulo JA, Faias, SP, Arroja L, Dias AC (2018) Evaluating the carbon footprint of the cork sector with a dynamic approach including biogenic carbon flows., Int J Life Cycle Assess, 23, (7), 1448-1459. doi:10.1007/s11367-017-1406-8

Dias AC (2014) Life cycle assessment of fuel chip production from eucalypt forest residues. Int J Life Cycle Assess 19:705–717. doi: 10.1007/s11367-013-0671-4

Dias AC, Arroja L (2012) Environmental impacts of eucalypt and maritime pine wood production in Portugal. J Clean Prod 37:368–376. doi: 10.1016/j.jclepro.2012.07.056

Dias AC, Arroja L, Capela I (2007) Carbon dioxide emissions from forest operations in Portuguese eucalypt and maritime pine stands. Scand J For Res 22:422–432. doi: 10.1080/02827580701582692

Ecoinvent (2017) Ecoinvent Database v.3.4 Swiss Centre for life cycle inventories. Dübendorf

EMEP/EEA (2017) EMEP/EEA air pollutant emission inventory guidebook 2016: technical guidance to prepare national emission inventories. European Monitoring and Evaluation Programme/European Environment Agency. Luxembourg

Ekman, R., Holmbom, B., 2000. The chemistry of wood resin, in: Back EI, Allen LH (Eds.), Pitch Control, Wood Resin and Deracination. Atlanta: Tappi Press, pp. 37–76.

Energy Research Centre of the Netherlands (2017) Phyllis2, database for biomass and waste. https://www.ecn.nl/phyllis2/. Accessed 27 Feb 2018

European Commission/Joint Research Centre/Institute for Environment and Sustainability (2011) International Reference Life Cycle Data System (ILCD) Handbook – recommendations for life cycle impact assessment in the European context. First edition November 2011. EUR 24571 EN. Luxemburg. Publications Office of the European Union

European Commission (2018) Europe leads the global clean energy transition: Commission welcomes ambitious agreement on further renewable energy development in the EU. http://europa.eu/rapid/press-release_STATEMENT-18-4155_en.htm. Accessed 20 Jun 2018

European Commission (2010) National action plans. https://ec.europa.eu/energy/en/topics/renewable-energy/national-action-plans. Accessed 21 Feb 2018

European Commission (2017) PEFCR Guidance document, - Guidance for the development of Product Environmental Footprint Category Rules (PEFCRs), version 6.3.

Faias SMMP (2009) Analysis of biomass expansion factors for the most important tree species in Portugal. ISA - Instituto Superior de Agronomia

Fernandes AP, Alves CA, Gonçalves C, et al (2011) Emission factors from residential combustion appliances burning Portuguese biomass fuels. J Environ Monit 13:3196. doi: 10.1039/c1em10500k

Ferreira J, Esteves B, Cruz-Lopes L, et al (2018) Environmental advantages through producing energy from grape stalk pellets instead of wood pellets and other sources. Int J Environ Stud 7233:1–15. doi: 10.1080/00207233.2018.1446646

Garcia R, Marques P, Freire F (2014) Life-cycle assessment of electricity in Portugal. Appl Energy 134:563–572.

Giuntoli J, Caserini S, Marelli L, et al (2015) Domestic heating from forest logging residues: Environmental risks and benefits. J Clean Prod 99:206–216. doi: 10.1016/j.jclepro.2015.03.025

Goedkoop M, Heijungs R, Huijbregts M, et al (2013) ReCiPe 2008. A life cycle impact Assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. First edition (version 1.08).

Gonçalves C, Alves C, Pio C (2012) Inventory of fine particulate organic compound emissions from residential wood combustion in Portugal. Atmos Environ 50:297–306. doi: 10.1016/j.atmosenv.2011.12.013

Gonçalves C, Alves C, Fernandes AP, Monteiro C, Tarelho L, Evtyugina M, Pio C (2011) Organic compounds in PM2.5 emitted from fireplace and woodstove combustion of typical Portuguese wood species. Atmos. Environ. 45, 4533–4545. doi:10.1016/j.atmosenv.2011.05.071

González-García S, Dias AC, Feijoo G, et al (2014) Divergences on the environmental impact associated to the production of maritime pine wood in Europe: French and Portuguese case studies. Sci Total Environ 472:324–337. doi: 10.1016/j.scitotenv.2013.11.034

Huijbregts MAJ, Steinmann ZJN, Elshout PMFM, et al (2016) ReCiPe 2016: A harmonized life cycle impact assessment method at midpoint and enpoint level - Report 1 : characterization. Natl Inst Public Heal Environ 194. doi: 10.1007/s11367-016-1246-y

IEA Bioenergy (2002) Sustainable Production of woody biomass for energy, A position paper prepared by IEA Bioenergy. Exec Comm IEA Bioenergy with Valuab Assist from Tasks 29:30–31.

ISO (2006a) Environmental management – life cycle assessment – principles and frameworks. ISO 14040. International Organization for Standardization, Geneva, Switzerland

ISO (2006b) Environmental management – life cycle assessment – requirements and guidelines. ISO 14044. International Organization for Standardization, Geneva, Switzerland

Kabayo J, Marques P, Garcia R, Freire F (2018) Avaliação ambiental de ciclo de vida dos principais sistemas de geração de eletricidade em Portugal. In: GCV 2018 – VI Congresso Brasileiro sobre Gestão do Ciclo de Vida. 17-20 Junho, Brasília, Brasil,

Kocbach Bølling A, Pagels J, Yttri KE, et al (2009) Health effects of residential wood smoke particles: the importance of combustion conditions and physicochemical particle properties. Part Fibre Toxicol. doi: 10.1186/1743-8977-6-29

Kruse J (2016) Analysis of a portuguese pellet stove . An investigation of all energy flows, the Technical efficiency and the economic viability in comparison to conventional heating solutions. Hamburg University of technology

Kylili A, Christoforou E, Fokaides PA (2016) Environmental evaluation of biomass pelleting using life cycle assessment. Biomass and Bioenergy 84:107–117. doi: 10.1016/j.biombioe.2015.11.018

Laschi A, Marchi E, González-García S (2016) Environmental performance of wood pellets' production through life cycle analysis. Energy 103:469–480. doi: 10.1016/j.energy.2016.02.165

Loo SV, Koppejan J (2008) The handbook of biomass combustion and co-firing. Earthscan, Sterling

Marques P, Quinteiro P, Dias AC, Freire F (2018) Avaliação de ciclo de vida de péletes de biomassa: uma revisão analisando a variabilidade dos resultados. In: CIALP-Conferência Internacional de Ambiente em Língua Portuguesa / XX Encontro REALP / XI Conferência Nacional do Ambiente. 8-10 May, Aveiro, Portugal,

Monteleone B, Chiesa M, Marzuoli R, et al (2015) Life cycle analysis of small scale pellet boilers characterized by high efficiency and low emissions. Appl Energy 155:160–170. doi: 10.1016/j.apenergy.2015.05.089

Nielsen, N.P.K., Gardner, D.J., Felby, C., 2010. Effect of extractives and storage on the pelletizing process of sawdust. Fuel 89, 94–98. doi:10.1016/J.FUEL.2009.06.025

Nyström R, Lindgren R, Avagyan R, et al (2017) Influence of Wood Species and Burning Conditions on Particle Emission Characteristics in a Residential Wood Stove. Energy and Fuels 31:5514–5524. doi: 10.1021/acs.energyfuels.6b02751

Pa A, Bi XT, Sokhansanj S (2013) Evaluation of wood pellet application for residential heating in British Columbia based on a streamlined life cycle analysis. Biomass and Bioenergy 49:109–122. doi: 10.1016/j.biombioe.2012.11.009

Paolotti L, Martino G, Marchini A, Boggia A (2017) Economic and environmental assessment of agro-energy wood biomass supply chains. Biomass and Bioenergy 97:172–185. doi: 10.1016/j.biombioe.2016.12.020

Quinteiro P, Dias AC, Silva M, et al (2015) A contribution to the environmental impact assessment of green water flows. J Clean Prod 93:318–329. doi: 10.1016/j.jclepro.2015.01.022

Quinteiro P, Van de Broek M, Dias AC, et al (2016) Life cycle impacts of topsoil erosion on aquatic biota: case study on Eucalyptus globulus forest. Int J Life Cycle Assess. doi: 10.1007/s11367-016-1146-1

Ruiz D, San Miguel G, Corona B, López FR (2018) LCA of a multifunctional bioenergy chain based on pellet production. Fuel 215:601–611. doi:

10.1016/j.fuel.2017.11.050

Solli C, Reenaas M, Strømman AH, Hertwich EG (2009) Life cycle assessment of wood-based heating in Norway. Int J Life Cycle Assess 14:517–528. doi: 10.1007/s11367-009-0086-4

Tarelho, L.A.C., Teixeira, E.R., Silva, D.F.R., Modolo, R.C.E., Labrincha, J.A., Rocha, F., 2015. Characteristics of distinct ash flows in a biomass thermal power plant with bubbling fluidised bed combustor. Energy 90, 387–402. doi:10.1016/j.energy.2015.07.036

Vicente ED, Vicente AM, Musa Bandowe BA, Alves CA (2016) Particulate phase emission of parent polycyclic aromatic hydrocarbons (PAHs) and their derivatives (alkyl-PAHs, oxygenated-PAHs, azaarenes and nitrated PAHs) from manually and automatically fired combustion appliances. Air Qual Atmos Heal 9:653–668. doi: 10.1007/s11869-015-0364-1

Table 1. Elemental composition, ash and moisture content, and lower heating values of feedstock.

		Pellets	Eucalyptus	Maritime Pine
Proximate analysis (weight %, wet basis)	Moisture	4.6	11.3[a]	9.1[a]
Ultimate analysis (weight %, dry basis)	Ash	0.32	0.58[a]	0.37[a]
	C	47.5	51.4[a]	48.6[a]
	H	6.20	6.20[a]	6.20[a]
	N	0.09	0.16[a]	0.16[a]
	S	<0.01	<0.01[a]	<0.01[a]
	O (by difference)	45.9	41.7	46.7
Lower heating value of feedstock (MJ/kg, dry basis)		18.3[b]	17.5[c]	18.5[c]

[a]Average data from Alves et al. (2011) and Gonçalves et al. (2011)

[b]Vicente et al. (2016)

[c]Tarelho et al. (2015)

Table 2. Characteristics of the pellets and split logs combustion appliances.

	Pellet stove	Wood stove		Fireplace	
Feedstock	Maritime pine pellets	Eucalyptus split logs	Maritime pine split logs	Eucalyptus split logs	Maritime pine split logs
Nominal power (kW_{th})	9.5[a]	10.8[b]	10.8[b]	-	-
Energy conversion efficiency (%)	82	65[c]	65[c]	10[d]	10[d]
Temperature in the combustion chamber (on average) (ºC)	683[e]	425[e]	390[e]	300[f]	200[f]

[a]Vicente et al. (2015)

[b]Carvalho et al. (2018)

[c]Carvalho (2016)

[d]Loo and Koppejan (2008)

[e]Vicente et al. (2016)

[f]Calvo et al. (2014)

Table 3. Allocation factors for the forest management stage.

Tree compartment	Mass allocation factors (%)	
	Eucalyptus	Maritime pine
Wood from final cutting	75.3	52.0
Wood from thinnings	-	25.
Bark	10.0	8.6
Logging residues	10.3	14.3
Stumps	4.4	-

Table 4. Inventory data for the production of 1 t of wood pellets and split logs.

	Unit	Pellets	Split logs	
			Eucalyptus	Maritime pine
Inputs				
Feedstock				
Maritime pine wood from final felling (dry basis)	t	1.00	-	1.05
Eucalyptus wood (dry basis)	t		1.05	-
Energy				-
Electricity	kWh	158	-	
Diesel	kg	0.860	3.75	4.51
Logging residues – chips (dry basis)	t	0.200	-	-
Ancillary materials				
LDPE bags	kg	3.57E-04	-	-
Outputs				
Pellets packed (dry basis)	t	1.00	-	-
Split eucalyptus logs (dry basis)	t	-	1.00	-
Split maritime pine logs (dry basis)	t	-	-	1.00
Loses of wood (dry basis)	t	-	0.05	0.05
Air emissions				
CO	kg	2.43E-03	1.06E-2	1.28E-02
CO_2 fossil	kg	2.73	11.9	14.2
NO_x	kg	0.309	8.42E-02	0.100
SO_2	kg	4.00E-02	6.86E-05	8.38E-05
CH_4 biogenic	kg	3.60E-03	-	-
CH_4 fossil	kg	5.53E-05	2.42E-04	2.91E-04
NMVOC	kg	2.72E-02	4.03E-03	4.84E-03
Ashes to landfill	kg	2.14	-	-

Table 5. Inventory data for the generation of 1 MJ of thermal energy for the five biomass heating scenarios: maritime pine pellets burned in a pellet stove (PS-MP), eucalyptus logs burned in a wood stove (WS-E), maritime pine burned in a wood stove (WS-MP), eucalyptus logs burned in a fireplace (F-E), maritime pine burned in a fireplace (F-MP).

		Scenarios				
	Unit	**PS-MS**	**WS-E**	**WS-MP**	**F-E**	**F-MP**
Inputs						
Feedstock	t (dry basis)	6.66E-05	8.79E-05	8.32E-05	5.71E-04	5.41E-04
Electricity	kWh	5.24E-03	2.25E-03	2.25E-03	-	-
Outputs						
Air emissions						
CO	g	0.906	5.68	4.55	48.1	29.7
NO_x	g	0.106	0.105	8.42E-02	0.683	0.547
SO_2	g	1.33E-02	1.76E-02	1.66E-02	0.114	0.108
CH_4 biogenic	g	8.54E-03	0.559	0.559	3.03	3.03
NMVOC	g	1.22E-02	0.923	0.923	6.00	6.00
Ashes to landfill	g	0.192	0.462	0.308	3.00	1.80

Table 6. Impact assessment results associated with the generation of 1 MJ of thermal energy for residential heating under five different scenarios: maritime pine pellets burned in a pellet stove (PS-MP), eucalyptus logs burned in a wood stove (WS-E), maritime pine burned in a wood stove (WS-MP), eucalyptus logs burned in a fireplace (F-E), maritime pine burned in a fireplace (F-MP).

Impact category	Unit	Scenarios				
		PS-MP	WS-E	WS-MP	F-E	F-MP
Global warming	kg CO_2 eq	7.79E−03	2.27E−02	2.23E−02	1.22E−01	1.20E−01
Fossil resources scarcity	kg oil eq	2.15E−03	1.14E−03	1.10E−03	6.17E−03	5.95E−03
Terrestrial acidification	kg SO_2 eq	7.87E−05	8.03E−05	5.84E−05	5.13E−04	3.72E−04
Freshwater eutrophication	kg P eq	1.86E−06	5.91E−07	5.02E−07	2.31E−06	1.75E−06
Marine eutrophication	kg N eq	2.16E−07	4.87E−06	3.68E−08	3.14E−05	4.31E−08
Ozone formation, Human health	kg NOx eq	1.84E−04	2.89E−04	2.68E−04	1.86E−03	1.73E−03
Ozone formation, Terrestrial ecosystems	kg NOx eq	1.56E−04	3.90E−04	3.70E−04	2.52E−03	2.39E−03

Figure captions

Figure 1. System boundaries of the wood-based residential heating systems evaluated.

Figure 2. Impact assessment results associated with the generation of 1 MJ of thermal energy for residential heating, for the five biomass heating scenarios studied: maritime pine pellets burned in a pellet stove (PS-MP), eucalyptus logs burned in a wood stove (WS-E), maritime pine burned in a wood stove (WS-MP), eucalyptus logs burned in a fireplace (F-E), maritime pine burned in a fireplace (F-MP).

Figure 3. Results of the sensitivity analysis: effect of changing the impact assessment method – ReCiPe 2016 midpoint by the PEF, for the five biomass heating scenarios studied: maritime pine pellets burned in a pellet stove (PS-MP), eucalyptus logs burned in a wood stove (WS-E), maritime pine burned in a wood stove (WS-MP), eucalyptus logs burned in a fireplace (F-E), maritime pine burned in a fireplace (F-MP).

Life cycle assessment of wood pellets and wood split logs for residential heating

Paula Quinteiro[a,†], Luís Tarelho[a], Pedro Marques[b], Mario Martin-Gamboa[a], Fausto Freire[b], Luís Arroja[a], Ana Cláudia Dias[a]

[a]Centre for Environmental and Marine Studies (CESAM), Department of Environment and Planning, University of Aveiro, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal

[b]ADAI-LAETA Department of Mechanical Engineering, University of Coimbra, 3030-788 Coimbra, Portugal

Research highlights

- Five wood-based combustion systems for residential heating are assessed
- Fireplaces present the worst environmental performance for almost all the impact categories considered
- Pellet stove presents lower impacts than wood stoves for global warming and ozone formation
- Pellet stove presents higher impacts than wood stoves for the remaining impact categories
- A 50 % decrease in the distances travelled by feedstocks leads to a very small reduction in impacts

[†]Corresponding author at: CESAM Department of Environment and Planning, University of Aveiro, 3810-193 Aveiro, Portugal. Tel.: +351 234 370 349
E-mail address: p.sofia@ua.pt (Paula Quinteiro)

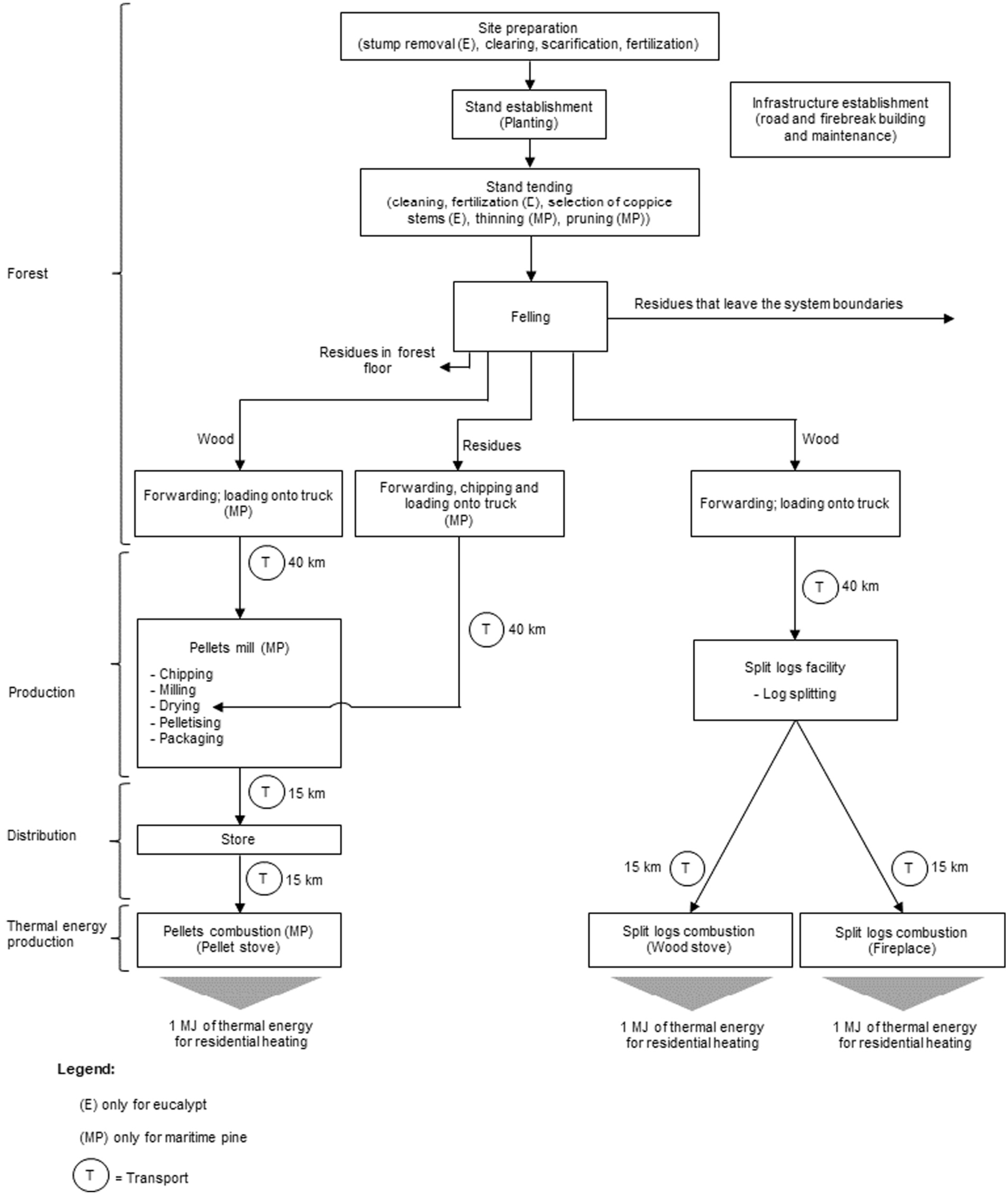
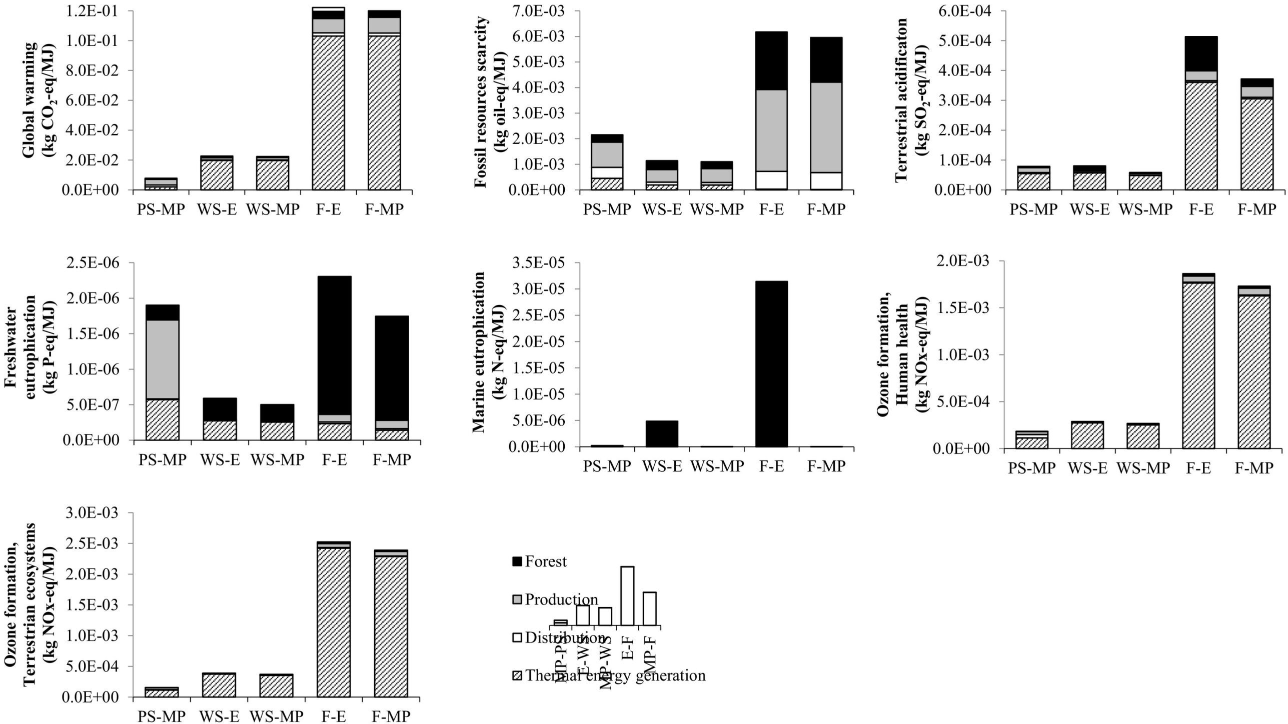

Site preparation
(stump removal (E), clearing, scarification, fertilization)
Stand establishment
(Planting)
Infrastructure establishment
(road and firebreak building
and maintenance)
Stand tending
(cleaning, fertilization (E), selection of coppice
stems (E), thinning (MP), pruning (MP))
Forest
Felling
Residues that leave the system boundaries
Residues in forest
floor
Wood
Residues
Wood
Forwarding; loading onto truck
(MP)
Forwarding, chipping and
loading onto truck
(MP)
Forwarding; loading onto truck
T 40 km
T 40 km
T 40 km
Production
Pellets mill (MP)
- Chipping
- Milling
- Drying
- Pelletising
- Packaging
Split logs facility
- Log splitting
T 15 km
Distribution
Store
T 15 km
15 km T
T 15 km
Thermal energy
production
Pellets combustion (MP)
(Pellet stove)
Split logs combustion
(Wood stove)
Split logs combustion
(Fireplace)
1 MJ of thermal energy
for residential heating
1 MJ of thermal energy
for residential heating
1 MJ of thermal energy
for residential heating
Legend:
(E) only for eucalypt
(MP) only for maritime pine
T = Transport

Figure 1



Global warming (kg CO_2-eq/MJ)
1.2E-01
1.0E-01
8.0E-02
6.0E-02
4.0E-02
2.0E-02
0.0E+00
Fossil resources scarcity (kg oil-eq/MJ)
7.0E-03
6.0E-03
5.0E-03
4.0E-03
3.0E-03
2.0E-03
1.0E-03
0.0E+00
Terrestrial acidificaton (kg SO_2-eq/MJ)
6.0E-04
5.0E-04
4.0E-04
3.0E-04
2.0E-04
1.0E-04
0.0E+00
Freshwater eutrophication (kg P-eq/MJ)
2.5E-06
2.0E-06
1.5E-06
1.0E-06
5.0E-07
0.0E+00
Marine eutrophication (kg N-eq/MJ)
3.5E-05
3.0E-05
2.5E-05
2.0E-05
1.5E-05
1.0E-05
5.0E-06
0.0E+00
Ozone formation, Human health (kg NOx-eq/MJ)
2.0E-03
1.5E-03
1.0E-03
5.0E-04
0.0E+00
Ozone formation, Terrestrian ecosystems (kg NOx-eq/MJ)
3.0E-03
2.5E-03
2.0E-03
1.5E-03
1.0E-03
5.0E-04
0.0E+00
PS-MP
WS-E
WS-MP
F-E
F-MP
Forest
Production
Distribution
Thermal energy generation

Figure 2

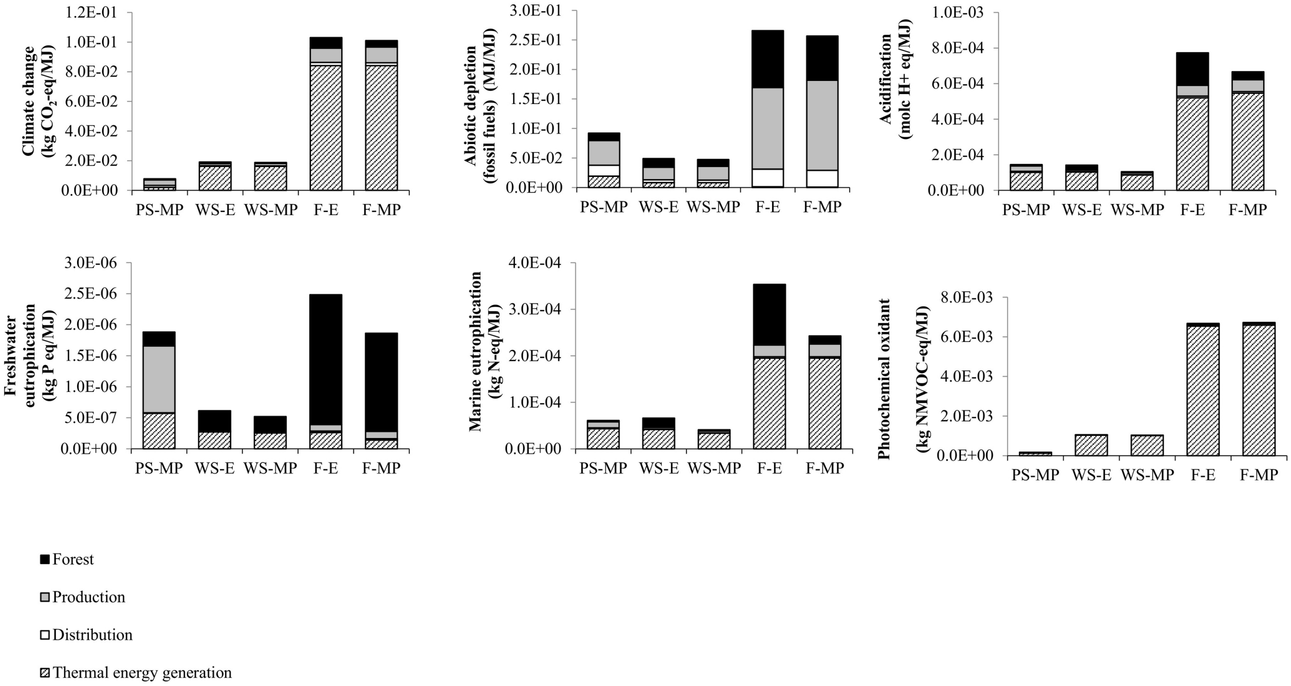

Climate change (kg CO_2-eq/MJ)
1.2E-01
1.0E-01
8.0E-02
6.0E-02
4.0E-02
2.0E-02
0.0E+00
PS-MP WS-E WS-MP F-E F-MP
Abiotic depletion (fossil fuels) (MJ/MJ)
3.0E-01
2.5E-01
2.0E-01
1.5E-01
1.0E-01
5.0E-02
0.0E+00
PS-MP WS-E WS-MP F-E F-MP
Acidification (molc H+ eq/MJ)
1.0E-03
8.0E-04
6.0E-04
4.0E-04
2.0E-04
0.0E+00
PS-MP WS-E WS-MP F-E F-MP
Freshwater eutrophication (kg P eq/MJ)
3.0E-06
2.5E-06
2.0E-06
1.5E-06
1.0E-06
5.0E-07
0.0E+00
PS-MP WS-E WS-MP F-E F-MP
Marine eutrophication (kg N-eq/MJ)
4.0E-04
3.0E-04
2.0E-04
1.0E-04
0.0E+00
PS-MP WS-E WS-MP F-E F-MP
Photochemical oxidant (kg NMVOC-eq/MJ)
8.0E-03
6.0E-03
4.0E-03
2.0E-03
0.0E+00
PS-MP WS-E WS-MP F-E F-MP
Forest
Production
Distribution
Thermal energy generation

Figure 3