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Life Cycle Assessment of pellets production and combustion chain in the European context

(*LCA della filiera di produzione ed utilizzo dei pellets in Europa*)

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Abstract

The European Commission in the last years has undertaken some policies in order to reduce the impact on the global warming, increase the utilisation of the renewable energy sources and the energy efficiency and to reach the so-called *20-20-20 targets*.

One of these targets establishes that a share of the 20% in the final energy consumption has to be produced from renewable energy sources within the 2020.

This study was focused on the assessment of the environmental sustainability of the production and the combustion of a specific type of renewable energy rapidly increasing in Europe: the pellets.

Main goals of the study were: quantify the impacts on the impact categories recommended by the *International Reference Life Cycle Data System (ILCD) Handbook*, published by the European Commission and, compare the results for the impact on the global warming to the *Typical GHGs values* suggested by the Commission.

Data were taken from scientific literature and Ecoinvent database and an effort was made in order to collect data that can be considered as representative for the most common pathways in Europe.

Several scenarios, different for feedstock, distance of transport and combustion device were evaluated.

Both the feedstocks more commonly used (e.g. sawdust) and the feedstocks potentially available in the near future, such as energy crops and wheat straw were analysed. A particular attention was given to the collection of data for the cultivation phase.

These scenarios were compared to a reference scenario that included the extraction, the transport and the final combustion of natural gas in an equivalent combustion device.

The study was based on a typical *cradle to grave* LCA approach and calculations were done using the software Gabi 4.4 for LCA.

Results showed that the impact of using pellets instead of natural gas is positive for global warming and ozone layer depletion and it is negative for all the other impact categories analysed.

Abstract

The comparison with the typical values suggested by the European Commission, underlined that the methodology used by the Commission seems to underestimate the GHG emissions for forest residues collection and for pellets production.

Sommario e conclusioni

I cambiamenti climatici sono una problematica ambientale ormai largamente riconosciuta da parte della comunità scientifica internazionale e, al fine di ridurli, negli ultimi decenni sono state intraprese varie politiche sia a livello internazionale che europeo.

Dal canto suo l'Unione Europea si è posta l'ambizioso obiettivo di ridurre le emissioni di gas serra del 20% rispetto ai livelli del 1990 entro il 2020: per raggiungere tale obiettivo punta sia sul miglioramento delle prestazioni di edifici, di autovetture e dell'industria, sia su incremento nell'utilizzo delle energie rinnovabili.

La Direttiva 2009/28/CE annovera le biomasse tra le fonti energetiche che contribuiscono a raggiungere l'obiettivo del 20% di utilizzo di energie rinnovabili rispetto all'utilizzo complessivo di energia primaria.

La Commissione Europea ha stabilito dei criteri di sostenibilità e dei valori tipici di emissioni specifiche di gas serra per quantificare il vantaggio associato all'utilizzo di biomasse in sostituzione delle fonti fossili [9].

Tra le biomasse considerate rientrano anche i pellets, una forma di bio-energia derivata da residui legnosi o agricoli.

La politiche intraprese dall'Unione Europea, unite alla relativa economicità dei pellets, hanno portato ad un rapido e sensibile incremento nella produzione e nella domanda di pellets: le statistiche dell'AEBIOM [2] mostrano un aumento del 40% nei consumi europei dal 2008 al 2010.

I pellets, usati come combustibile sia in ambito industriale che domestico, derivano da un processo di essiccamento, triturazione e compattazione di biomasse legnose, residui di lavorazioni industriali del legno o residui agricoli.

Le emissioni di anidride carbonica in atmosfera dovute alla combustione dei pellets sono considerate nulle, in quanto corrispondono all'anidride carbonica assorbita dagli alberi durante la loro crescita attraverso la fotosintesi. Tuttavia, il processo di produzione dei pellets nonché il trasporto delle materie prime e dei pellets stessi, causano emissioni di gas serra che vanno in parte a ridurre l'impatto positivo dei pellets sul cambiamento climatico. Durante il loro utilizzo finale come combustibile, i pellets causano l'emissione di altri inquinanti, quali, ad esempio, ossidi di azoto e polveri sottili.

Descrizione del lavoro

Il presente lavoro è stato svolto presso l'Institute of Energy and Transport del Joint Research Centre (JRC) di Petten, in un gruppo di ricerca che si occupa di fornire un sostegno scientifico alla Commissione Europea nel determinare i valori tipici da inserire in futuri aggiornamenti della normativa inerente le bioenergie.

Gli scopi del lavoro sono stati, in primo luogo, quantificare le emissioni specifiche causate dalla filiera di produzione e utilizzo dei pellets attraverso un'analisi delle emissioni durante l'intero ciclo di vita (LCA) e, successivamente, di confrontare i risultati ottenuti dall'LCA inerenti l'impatto sul cambiamento globale e i *Typical GHGs values* proposti attualmente dalla Commissione Europea, al fine di evidenziare affinità e differenze con la metodologia attualmente utilizzata dalla Commissione.

L'analisi del ciclo di vita si è basata su un approccio *dalla culla alla tomba*, vale a dire che le emissioni dovute all'estrazione delle materie prime, alla creazione dei prodotti e al successivo utilizzo e smaltimento sono state conteggiate per la valutazione degli impatti.

La quantificazione degli impatti è avvenuta con l'ausilio del software Gabi 4.4 per LCA.

L'unità funzionale del lavoro è un mega-joule di calore prodotto dalla combustione dei pellets.

Lo scenario di riferimento per il confronto dei dati è il ciclo di vita del gas naturale bruciato in un impianto di combustione equivalente a quello dello scenario analizzato.

Le categorie d'impatto analizzate e i metodi di caratterizzazione utilizzati sono stati scelti sulla base delle raccomandazioni dell'*International Reference Life Cycle Data System (ILCD) Handbook,* pubblicato dalla Commissione Europea.

La filiera esaminata in questo studio comprende il processo di coltivazione o di produzione della materia prima, il trasporto di quest'ultima all'impianto di produzione dei pellets, la produzione dei pellets, il trasporto all'impianto di combustione (in caso di impianti a larga scala) o al negozio (in caso di utilizzo domestico) e l'uso finale.

Vari scenari sono stati analizzati, diversi per materia prima, distanza di trasporto e apparato di combustione, come illustrato nella seguente tabella.

	Denominazione	**Materia prima**	**Provenienza dei pellets**	**Impianto di combustione**
1	*FR, EU, DS*	Cippato da residui forestali	Europa	Stufa domestica
2	*FR, EU, DH*	Cippato da residui forestali	Europa	Teleriscaldamento
3	*FR, EU, CHP*	Cippato da residui forestali	Europa	Imp. di cogenerazione
4	*FR, Canada, DS*	Cippato da residui forestali	Canada	Stufa domestica
5	*FR, Canada, DH*	Cippato da residui forestali	Canada	Teleriscaldamento
6	*FR, Canada, CHP*	Cippato da residui forestali	Canada	Imp. di cogenerazione
7	*Poplar, DS*	Cippato da pioppo	Europa	Stufa domestica
8	*Poplar, DH*	Cippato da pioppo	Europa	Teleriscaldamento
9	*Poplar, CHP*	Cippato da pioppo	Europa	Imp. di cogenerazione
10	*SD, all mass, DS*	Segatura umida, allocazione secondo la massa	Europa	Stufa domestica
11	*SD, all mass, DH*	Segatura umida, allocazione secondo la massa	Europa	Teleriscaldamento
12	*SD, all mass, CHP*	Segatura umida, allocazione secondo la massa	Europa	Imp. di cogenerazione
13	*SD, all price, DS*	Segatura umida, allocazione economica	Europa	Stufa domestica
14	*SD, all price, DH*	Segatura umida, allocazione economica	Europa	Teleriscaldamento
15	*SD, all price, CHP*	Segatura umida, allocazione economica	Europa	Imp. di cogenerazione
16	*SD, 40% dry, all price, DS*	Mix di segatura: 60% umida e 40% asciutta (umidità=10%)	Europa	Stufa domestica
17	*SD, 40% dry, all price, DH*	Mix di segatura: 60% umida e 40% asciutta (umidità=10%)	Europa	Teleriscaldamento
18	*SD, 40% dry, all price, CHP*	Mix di segatura: 60% umida e 40% asciutta (umidità=10%)	Europa	Imp. di cogenerazione
19	*Straw, DE, DH*	Paglia di frumento	Germania	Teleriscaldamento
20	*Straw, PL, DH*	Paglia di frumento	Polonia	Teleriscaldamento
21	*Straw, ES, DH*	Paglia di frumento	Spagna	Teleriscaldamento
22	*Straw, NL, DH*	Paglia di frumento	Paesi Bassi	Teleriscaldamento
23	*Straw, UK, DH*	Paglia di frumento	Regno Unito	Teleriscaldamento
24	*Straw, DE, CHP*	Paglia di frumento	Germania	Imp. di cogenerazione
25	*Straw, PL, CHP*	Paglia di frumento	Polonia	Imp. di cogenerazione
26	*Straw, ES, CHP*	Paglia di frumento	Spagna	Imp. di cogenerazione
27	*Straw, NL, CHP*	Paglia di frumento	Paesi Bassi	Imp. di cogenerazione
28	*Straw, UK, CHP*	Paglia di frumento	Regno Unito	Imp. di cogenerazione

La scelta delle materie prime da includere negli scenari si è basata sull'ipotesi che a breve i residui dell'industria del legno non saranno più sufficienti a soddisfare la crescente richiesta di materie prime per la produzione di pellets, quindi, in questo studio sono stati calcolati gli impatti ambientali dovuti all'utilizzo sia di materie prime 'tradizionali', quali la segatura da lavorazioni del legno, sia di materie prime potenzialmente disponibili in un futuro molto prossimo, come il cippato da residui forestali e da pioppo e la paglia di frumento. Una particolare attenzione è stata dedicata al processo di coltivazione, necessario per il pioppo e il frumento, da cui si ricava la paglia, in quanto si è ritenuto ch tale fase potesse avere impatti significativi dovuti all'utilizzo di fertilizzanti e prodotti chimici. Le emissioni della coltivazione sono state allocate alla paglia su base economica.

Sono stati considerati due scenari per il trasporto dei pellets e delle materie prime: pellets prodotti e utilizzati in Europa e pellets prodotti in Canada e successivamente esportati in Europa.

La raccolta dei dati è stata una fase cruciale dello studio; è stata svolta un'accurata ricerca bibliografica di valori che potessero essere considerati rappresentativi delle pratiche più comunemente adottate in Europa. Per i processi non ricostruibili esaustivamente con le informazioni da letteratura, i dati sono stati presi dal database *Ecoinvent 2.2*, mantenendo sempre un atteggiamento critico nei confronti delle assunzioni e dei valori utilizzati.

Si evidenzia il fatto che il processo di coltivazione del pioppo non era considerato nei database commerciali disponibili e, quindi, è stato interamente modellato sulla base di dati di letteratura e dell'applicazione del modello di Mackay per la valutazione del destino ambientale degli erbicidi.

Inoltre, è stata valutata anche l'influenza sui risultati finali della scelta del metodo allocazione delle emissioni nel caso di utilizzo di segatura ottenuta come sottoprodotto dall'industria di lavorazione del legno del legno.

Lo studio si è concluso con un'analisi di sensitività e la successiva interpretazione dei risultati ottenuti.

Risultati dello studio

I risultati dello studio hanno confermato l'impatto positivo sul riscaldamento globale che ha l'utilizzo dei pellets rispetto a quello del gas naturale, ma ne hanno anche evidenziato una serie di criticità, legate prevalentemente alle emissioni di polveri sottili, metalli pesanti e ossidi di azoto durante la combustione. I pellets, infatti, causano un maggiore impatto su tutte le categorie considerate, eccetto nel caso di riscaldamento globale e deplezione dello strato di ozono.

La Figura 1 riporta la media dei risultati per alcune delle principali categorie d'impatto considerate, in termini di aumento/decremento percentuale dell'impatto dovuto all'utilizzo di pellets rispetto al gas naturale. Tale grafico non permette di visualizzare la variabilità tra i vari scenari analizzati, ma la differenza media percentuale tra gli impatti analizzati rapportati allo scenario di riferimento.

Ad esempio, un valore di -72%per il riscaldamento globale per la stufa domestica, indica che mediamente l'utilizzo di diversi tipi di pellets in una stufa permette di evitare il 72% delle emissioni dovute alla produzione della stessa quantità di calore, ottenuto bruciando gas naturale.

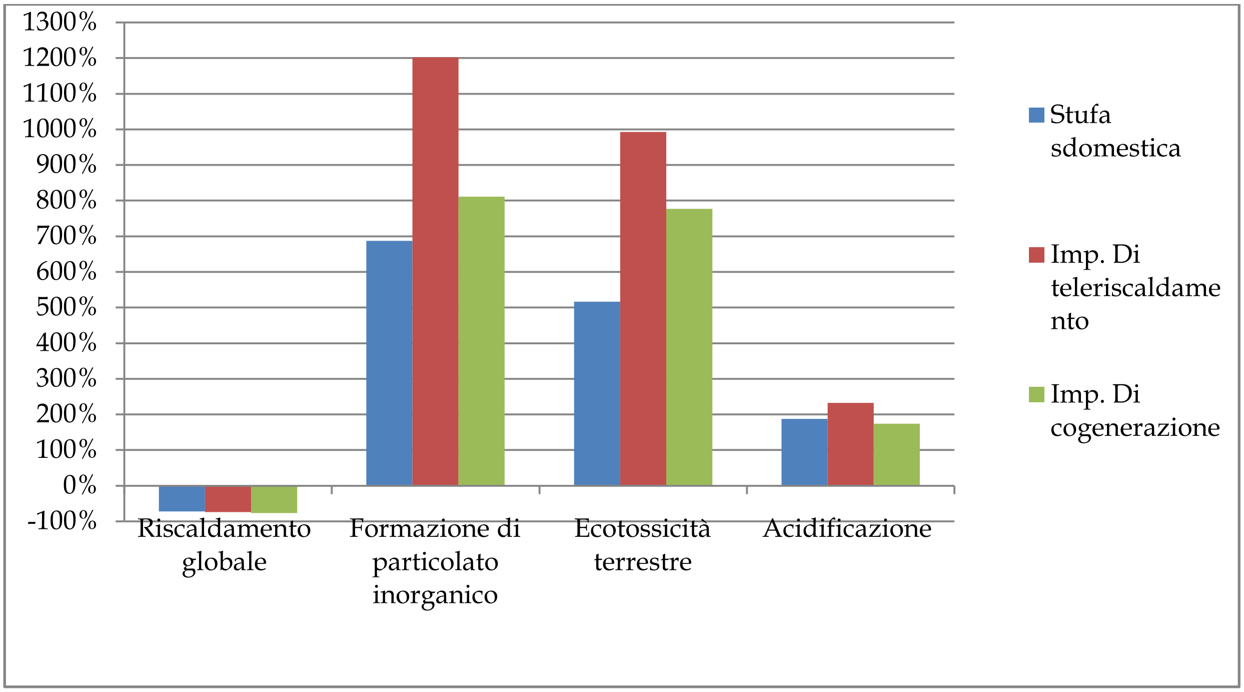

Figura 1: Differenze percentuali tra gli scenari analizzati e lo scenario di riferimento

Le emissioni di gas serra evitate rispetto allo scenario di riferimento sono comprese tra 64% e 85%, a seconda degli scenari, anche per lo scenario di pellets importati dal Canada.

I risultati in termini di emissioni evitate rispetto allo scenario di riferimento sono riportati in Figura 2.

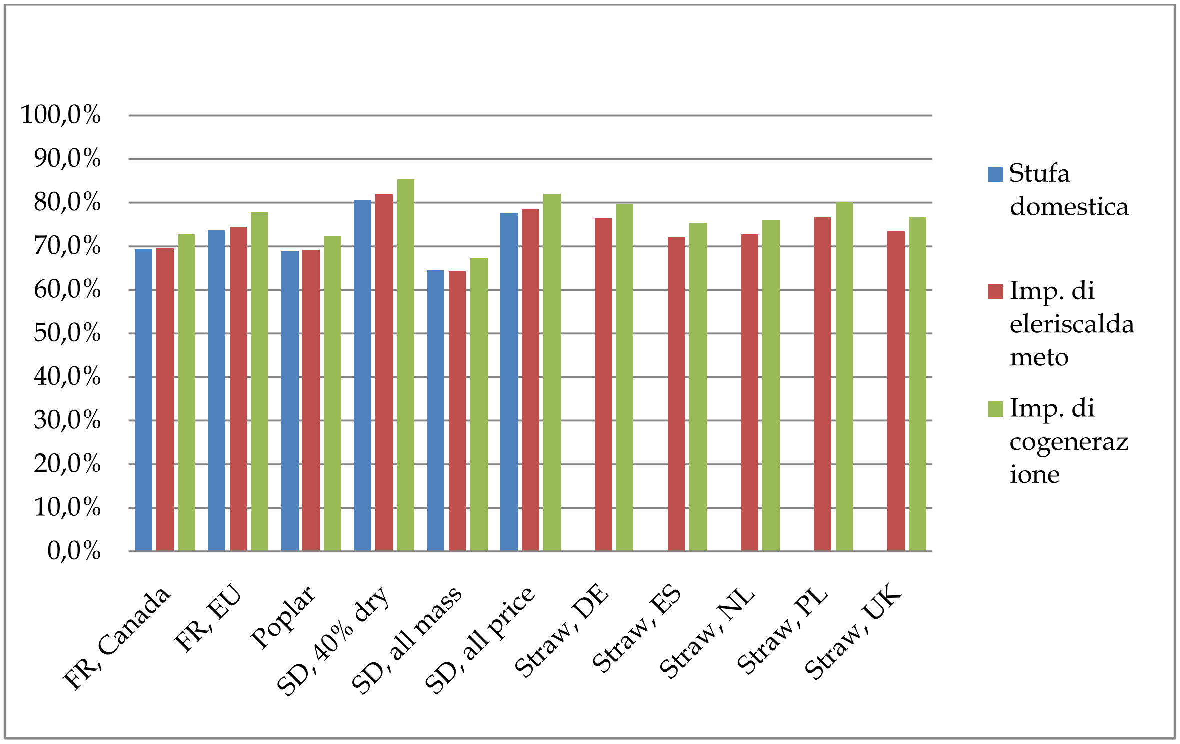

Figura 2: Emissioni di gas serra evitate rispetto allo scenario di riferimento [%]

L'utilizzo dei pellets in sostituzione del gas naturale provoca un aumento nelle emissioni di polveri sottili che varia tra il 500% e il 1500%.

La combustione dei pellets causa maggiori emissioni di NO_x rispetto a quella del metano, dovute alla presenza di azoto nel legno, inoltre, il trasporto delle materie prime e dei pellets dà un contributo aggiuntivo alle emissioni di ossidi di azoto di ciascun scenario. Questo porta ad un incremento dell'impatto sull'acidificazione dell'aria, che varia tra 80% e 380% a seconda degli scenari considerati.

Le emissioni di metalli pesanti influiscono sull'impatto sull'ecotossicità terrestre, calcolato con il metodo di caratterizzazione CML, che quantifica l'impatto in termini di emissioni di DCB equivalente. Tale impatto è risultato essere di un ordine di grandezza superiore per l'utilizzo di pellets rispetto a quello del gas naturale.

La materia prima meno impattante dal punto di vista ambientale è risultata essere la segatura, già parzialmente asciugata durante il processo industriale in cui è stata generata. Il suo utilizzo infatti permette un inferiore consumo di elettricità per la produzione dei pellets e un'inferiore richiesta di calore per diminuirne l'umidità.

Tra gli impianti di combustione considerati, la combustione in un impianto di cogenerazione (CHP) è risultata essere la soluzione migliore in quanto, contemporaneamente alla produzione di calore, produce elettricità per l'impianto stesso, garantisce migliori condizioni di combustione e le emissioni associate con la costruzione, la manutenzione e il funzionamento dell'impianto sono ripartite su una maggiore quantità di energia prodotta rispetto ad un'applicazione su scala minore.

È emerso anche che la realizzazione di una coltivazione di pioppo ad uso energetico è più impattante di tutte le altre materie prime considerate. In particolare l'impatto sull'ecotossictà, valutato con il metodo USEtox (suggerito dall'ILCD) è principalmente dovuto all'applicazione di erbicidi e alla loro dispersione nel suolo. Questo fa si che gli scenari del pioppo abbiano un impatto sull'ecotossicità circa 10 volte superiore rispetto a tutti gli altri scenari.

Per quanto riguarda l'impatto sulla tossicità umana, invece, l'utilizzo di pesticidi incide solo sull'1%del totale, sempre utilizzando il metodo di caratterizzazione suggerito dall'ILCD, USEtox.

L'utilizzo di fertilizzanti azotati causa emissioni di ossidi di azoto e protossido di azoto in atmosfera e di nitrati in falda. Tali composti vanno rispettivamente ad influire sull'acidificazione dell'aria, la formazione di ozono troposferico (di cui gli NO_x sono precursori), il riscaldamento globale e l'eutrofizzazione.

Due tra le materie prime considerate necessitano di una fase di coltivazione: la paglia e il pioppo. L'impiego della paglia ha un impatto inferiore rispetto al pioppo, in quanto le emissioni della coltivazione del frumento, pur essendo generalmente maggiori di quelle del pioppo, sono allocate a paglia e frumento su base economica e in quanto la paglia ha un'umidità inferiore rispetto al cippato, quindi richiede meno calore e meno elettricità per la produzione dei pellets.

Ulteriori considerazioni sono state effettuate riguardo la scelta del metodo di allocazione, in caso di processi multi-output in cui non sia applicabile alcuna espansione, come negli scenari riguardanti l'utilizzo della segatura. Si è giunti alla conclusione che l'allocazione economica è preferibile a quella energetica nel caso di utilizzo di un sottoprodotto perché rispecchia l'inferiore valore dello scarto rispetto al principale output del processo e, quindi, associa al sottoprodotto una frazione inferiore delle emissioni totali rispetto all'allocazione energetica. L'allocazione energetica, invece, può portare al paradosso che l'utilizzo di uno scarto sia ritenuto sfavorevole dal punto di vista ambientale rispetto all'impiego di una materia prima.

Per quanto riguarda il confronto con i Valori tipici proposti dalla Commissione Europea, sono emerse significative differenze tra le due metodologie che hanno portato a sostanziali discrepanze nei risultati.

In particolare, i valori tipici non conteggiano le emissioni associate alla produzione di residui e alla costruzione di macchinari e infrastrutture necessari alla produzione dei pellets. Inoltre nella metodologia della Commissione si assume che i pellets siano prodotti in un impianto dotato di un sistema di cogenerazione alimentato a cippato, così da annullare le emissioni di gas serra dovuti alla produzione di elettricità, in quanto biogeniche. Tale ipotesi è considerata alquanto 'ottimistica' poiché è raro trovare impianti di tal genere in ambito europeo.

Nella seguente tabella è riportato il confronto tra i risultati dello studio e i valori tipici di emissione di gas serra proposti dalla Commissione Europea.

		Valori tipici	**Questo studio**
		gCO2eq/MJ	
Residui forestali Europa	Cultivation	0	2,1
	Processing	0,5	8,3
	Transport and distribution	0,7	1,7
	TOT	**2**	**12**
Residui forestali Canada	Cultivation	0	2,1
	Processing	0,5	8,3
	Transport and distribution	13,7	4,8
	TOT	**15**	**15**
Pioppo	Cultivation	2,1	5,1
	Processing	0,5	8,6
	Transport and distribution	0,7	1,7
	TOT	**4**	**15**

In conclusione, quindi, i Valori tipici sottostimano in larga misura le emissioni di gas serra generate durante il ciclo di vita dei pellets, rispetto ai risultati ottenuti dallo studio svolto con un approccio LCA.

Ulteriori approfondimenti sono necessari in futuri studi per approfondire alcuni aspetti che in questo lavoro sono stati considerati solo marginalmente o non sono stati inclusi, quali, ad esempio, l'impatto dovuto al cambio di uso del suolo e l'analisi dell'impatto associato all'uso di altre materie prime.

Introduction

Almost all the members of the scientific community largely agree on the fact that the emissions caused by anthropic activities in the last century had a significant impact on the global warming, in fact in the last assessment report of the Intergovernmental Panel on Climate Change (IPCC), *Climate Change 2007*, [38] it has been stated that *"Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice and rising global average sea level"* and that *"Most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic GHG concentrations. It is likely that there has been significant anthropogenic warming over the past 50 years averaged over each continent (except Antarctica)"*.

In the last decades several policies on medium-long term to reduce the anthropic emissions of GHGs have been undertaken both at international and European level.

Probably the most important step towards the reduction of GHGs emissions at global level is the Kyoto protocol, an international agreement linked to the United Nations Framework Convention on Climate Change (UNFCCC). The major feature of the Kyoto Protocol is that it sets binding targets for 37 industrialised countries and the European Community for reducing greenhouse gas (GHG) emissions: this amounts to an average of five percent against 1990 levels over the five-year period between 2008-2012.

The Kyoto Protocol was adopted in Kyoto, Japan, on 11th December 1997 and entered into force on 16 February 2005, signed by 157 countries.

The sharing of the percentage of the emissions to be reduced is based on the *principle of common, but differentiated responsibilities*, and, in particular, the 15 countries, that were EU members at the time (EU-15), are requested to reduce their GHGs emissions in the 2008-2012 period to 8% below the 1990 levels.

This year the first commitment period of the Kyoto Protocol is going to expire. In 2011, at the Conference of the parties (COP) in Durban, the delegates of several counties established that the Kyoto Protocol will be extended from 1st January 2013 onwards and will end in 2017 or 2020. The length of the second commitment period as well as many technicalities, however, will need to be negotiated in 2012 and it is not going to be easy to find an agreement between the many interests in the international community.

In the meanwhile, the European Union overtook other policies, with even stricter objectives than the ones of the Kyoto protocol itself. In fact, in 2007 EU leaders endorsed an integrated approach to climate and energy policy to reduce GHGs emissions. In the 2008 the *Climate and renewable energy package* was approved. It established the so called *20-20-20 targets* that require a 20% of reduction of the GHG emissions, the 20% of reduction of the use of primary energy and a share of the 20% in the final energy consumption (FEC) to be produced from renewable energy sources within the 2020.

The use of biomass, if biomass systems are managed properly, contributes to meet the requirement of increasing the utilisation of renewable energy sources and GHGs savings.

In this study, in particular, we wanted to focus the attention on the impacts due to the use of wood pellets and agri-pellets, which is forecasted to strongly increase in Europe in the next years.

Pellets are produced from biomass, thus they have the advantage, compared with fossil fuels, that their combustion can be considered carbon dioxide neutral, because the carbon dioxide emitted in the combustion is the same amount that has been absorbed by the feedstock during its life via photosynthesis.

Some doubts have recently been raised on the actual validity of this assumption. Especially when considering the use of standing wood for bioenergy. This could create a temporary loss of carbon stock that would be balanced out by the GHG savings achieved only in a very long term (some studies indicate 100–300 years). However, this issue is not as relevant when considering wood residues or short rotation forestry which are anyway grown on an agricultural land and would therefore only displace other annual crops.

The production of pellets requires electrical energy, fossil fuels for the transportation of the raw material, infrastructures etc. that causes emissions of GHGs and other pollutants.

Some scientific studies have already investigated the environmental sustainability of the use of pellets. However, existing studies are mainly focused on pellets produced from traditional feedstocks, such as residues of the wood industry. Since the consumption of pellets is steadily increasing worldwide, the availability of additional raw materials, such as sawdust and wood shavings is rapidly decreasing in the countries where the production of pellets is very intense (e.g. Sweden). That is why the use of other types of feedstocks for pellets production is forecasted to grow in the near future [52].

This study aims at giving an additional contribution to consolidated knowledge by comparing different pellets production chains, based on the use of both *common* feedstocks, suck as sawdust and *novel* raw materials such as forest residues, energy crops (poplar) [52] and agricultural residues (straw) [17].

- A particular attention is given to the emissions due to the cultivation as they might be important, especially when pellets from energy crops and straw are considered. In particular, a new process for poplar cultivation will be created.
- In order to have a complete outlook of the environmental impact of pellets, not only the global warming will be analysed, but also other impacts which are considered significant in the Life Cycle Assessment. Especially end-use emissions of biomass might have a significant impact compared to natural gas combustion.
- Furthermore, the geographic origin of biomass is an important parameter as it influences for example, fertilizers needs, yield, elemental composition and distribution. This parameter is often overlooked in LCA analysis since it is complex and expensive to obtain differentiate geographical data for several locations. In this study an analysis is carried out comparing the global environmental impacts of straw pellets produced from wheat cultivated in five different European countries.
- Additionally, import is growing steadily and this study has also the objective to verify whether emissions from transport might even offset the total GHG balance and how much would they influence the final GHGs savings.
- The effect of different allocation methods is also studied for a chosen pathway in order to analyse the impact of such methodological decision on the final result and compare it with the decision of the European Commission to consider sawdust as residue (No emissions from the processing of timber) rather than allocation.
- Finally, a comparison is carried out between the results from a full LCA and the ones indicated by the European Commission as Typical GHG values for wood pellets, in order to underline both the strong and weak points of the RED methodology.

This study has been done with the support and in support to a working group of the Institute for Energy and Transport of the Joint Research Centre (JRC), which is working at the calculations for the Typical GHG emissions in the RED and related documents. A part of this study is in fact aimed at comparing the results of a full LCA with the results presented by the European Commission for solid biomass sustainability. Out of this comparison it will be evident which are the limitations and which the advantages of the Directive methodology to assess biomass sustainability.

Additionally, this study aimed, not only at quantifying the net impact on climate change of the pellets production and combustion chain, but also at highlighting the other environmental impacts associated with the production and use of pellets. These impacts are sometimes forgotten/neglected as the political discussion is mostly focused on Climate Change. However, the effects of the impacts due to the use of bioenergies, such as acidification and eutrophication, which are generally associated with agricultural processes, should be carefully evaluated.

This study analysed the pathways in all their impacts in order to draw a complete picture of pellets environmental sustainability.

In particular, the thesis is structured as follows.

Chapter 1 is a general introduction about what pellets are, their characteristics and their uses. It gives also information about the European standards for pellets and about the European pellets market.

Chapter 2 shows the principal actions undertaken by Europe in order to reach the *20-20-20 targets*. In particular, the attention is focused on the so called *Renewable Energy Direct*ive (Directive 2009/28/CE) in which the methodology to define the emissions of GHGs from biofuels is defined.

Chapter 3 deals with the description of the Life Cycle Assessment approach in general terms, following the recommendations of the standards ISO14040 and 14044 and of the ILCD Handbook [18]. In this chapter the main phases of the Life Cycle Analysis (LCA) are described.

Chapter 4 contains the review of the scientific studies available in the existing literature that deal with the analysis of the environmental impacts due to the use of pellets. This was an important phase of the work because it was aimed at identify which are the main open issues left to be investigated further. This was the starting point for the definition of the goal of this study, described in details in Chapter 5. Paragraph 5.4, specifically formulates the main research questions that were studied in this work.

Chapter 5 follows the framework recommended by the standards ISO14040 and ISO14044 for the LCA and it gives a detailed description of how each phase were achieved during this study. This Chapter includes a detailed description of the Life Cycle Inventory used (Section 5.2) and the results obtained (Section 5.4).

A further analysis was done comparing the results of this study with the *typical values* of GHGs emissions suggested by the European Commission for some scenarios of pellets production. This analysis is described in Paragraph 5.5

Finally, in Chapter 6, the conclusion of this research is drawn and recommendations are formulated for future investigations and research.

1 The pellets

Pellets are a biofuel obtained through the densification process of wood or agricultural residues. Depending on the raw material, the product of this process is generally called wood pellets or agri-pellets.

Pelletisation creates a clean burning, convenient and energy- concentrated fuel from bulky fibrous waste such as sawdust and wood shavings [44] which could not be used efficiently on a large scale in their original form due to low bulk density and the high moisture and heterogeneous nature.

Figure 1 represent a scheme of the main input and output flows of the process of wood pellets manufacturing.

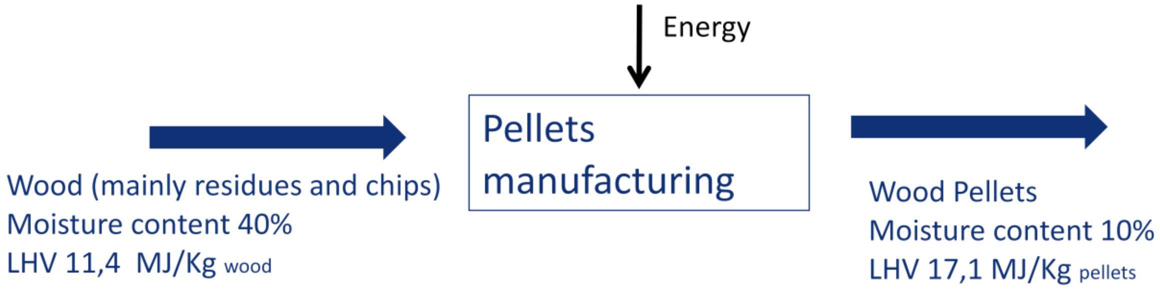

Figure 1: Scheme of wood pellets production

Figure 1 clearly highlights that during the process the moisture content of the feedstock decreases significantly and consequently its lower heating value increases. Obviously energy is needed to achieve this result and this is a key concept in order to evaluate the sustainability of the pellets pathways.

The output of the process is a biofuel that, compared to the raw material is more suitable for an efficient combustion and for trade on a large scale.

The main advantages with pelletised biofuels, in comparison with unprocessed biofuels, are the higher energy density due to a lower moisture content, which means also lower transport and storage costs; the higher quality, thanks, to the homogeneous physical and chemical parameters, such as moisture content; the higher mass fluidity, which means that automatic feeding equipment can be used even in small-scale boilers; the smaller fuel particles, which means more even boiler feeding, leading to lower emissions and better possibilities to fire at lower loads, resulting in longer boiler utilisation times [51] and higher combustion efficiencies.

Table 1 summarizes the main advantages and disadvantages associated with the life cycle of pellets.

PELLETS	
Strengths	**Weaknesses**
✓ Homogeneous moisture and energy content ✓ Regular shape ✓ Easy to handle and transport	✓ Energy requirement for pellets production ✓ Environmental emissions associated with the production of pellets (production of the feedstock, transport of the raw materials etc.)

Table 1: Strengths and weaknesses of pellets

1.1 The European pellets markets

Due to the Europe 2020 policy targets for renewable energy sources the production and consumption of pellets is largely increasing in Europe nowadays. This phenomenon implies large market flows of raw material and wood pellets not only through European countries but also from extra European regions.

The plot in Figure 2 shows the trend of the consumption of pellets in Europe, according to the *Annual statistical report* of AEBIOM (2011) [2].

In particular, the consumption of pellets in Europe increased by 40% from 2008 to 2010 and by 155% from 2005 to 2010.

Figure 3 shows the main trade flows of wood pellets in Europe, according to the study by Lamers et al. [42].

According to AEBIOM [2], the production of pellets in EU 27 in 2010 reached 9,2 million tons, representing the 62% of European production capacity. The main European producers of pellets are Germany and Sweden which, in 2010, produced respectively 1,75 and 1,64 million tons of pellets. They are also the countries with the highest availability of raw material.

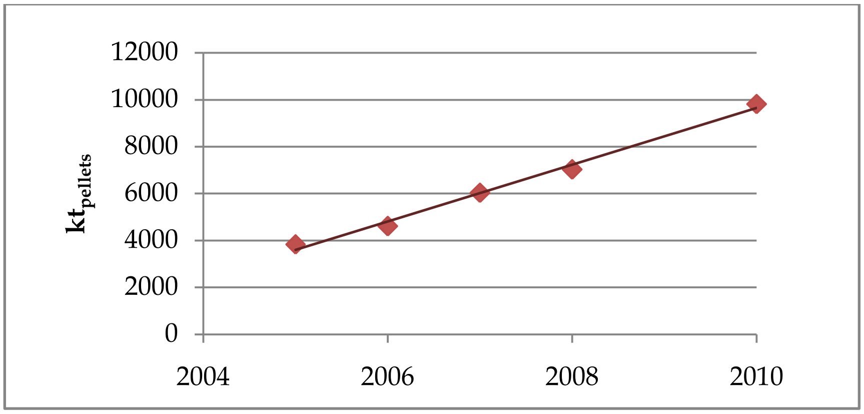

Figure 2: Consumption of pellets in EU27 from 2005 to 2010 [kt]

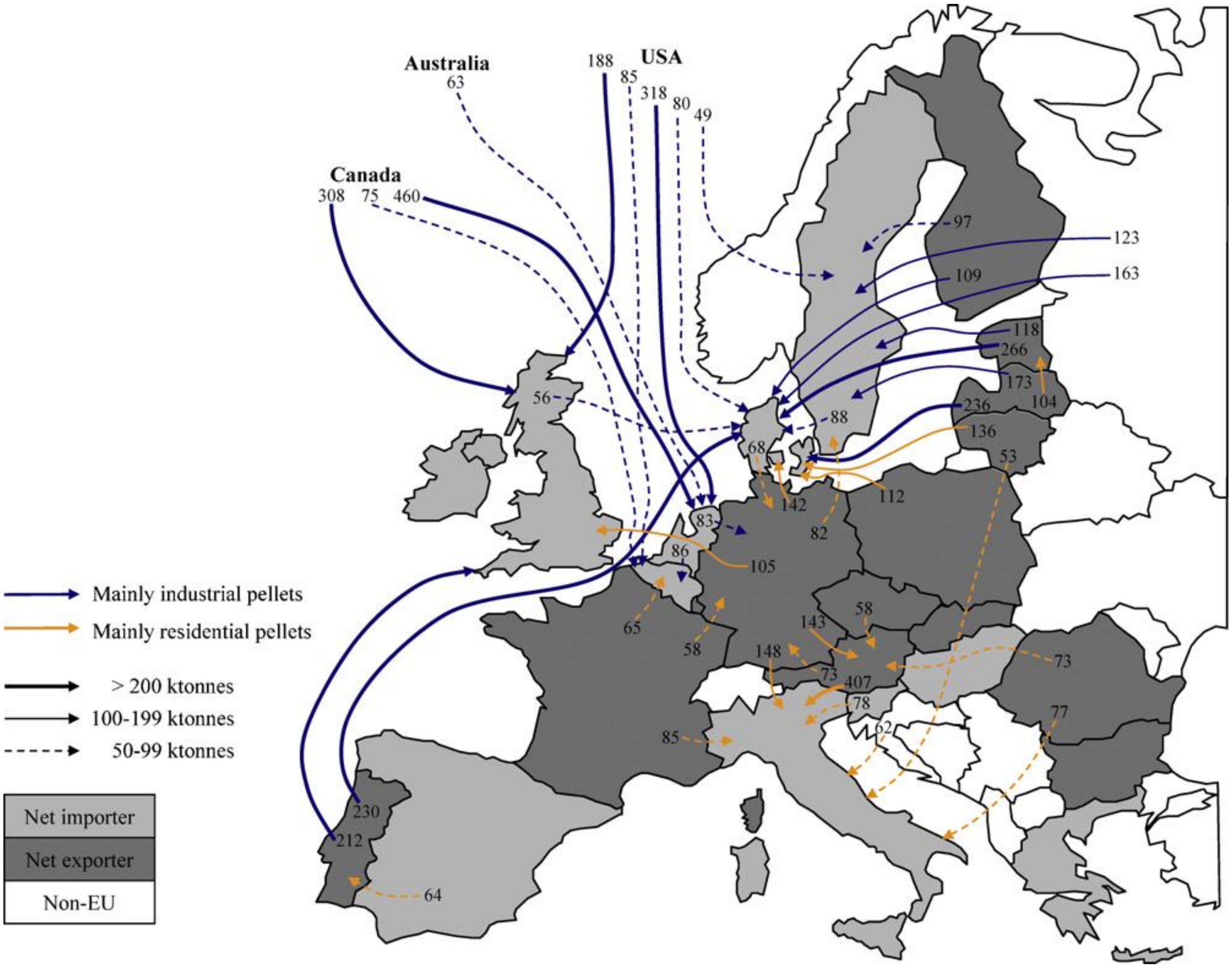

Figure 3: Main wood pellets trade flows in Europe [42]

Pellets consumption in EU27 in 2010 was equal to 9,8 million tons. The main consumers of pellets listed in descending order are Sweden, Denmark, Germany, Belgium, Netherlands, Italy and Austria. They accounted for the 56% of European pellets consumption.
Table 2 shows data concerning countries that have significant production or consumption of pellets.

	Production capacity (kt)	**Effective production (kt)**	**Consumption (kt)**
Austria	1200	850	660
Belgium	550	286	920
Czech Rep	300	223	3
Denmark	313	180	1600
Estonia	485	381	0
Finland	650	300	213
France	1040	495	400
Germany	2600	1750	1200
Hungary	200	162	10
Italy	725	600	850
Latvia	744	223	39
Netherlands	130	120	913
Poland	644	410	300
Portugal	875	430	10
Romania	260	157	25
Slovenia	185	154	112
Sweden	2500	1645	2200
UK	218	138	176

Table 2: Main pellets productions or consumption of EU27 countries in 2010

It can be noticed that there are countries that could satisfy their pellets demand with their own effective production or exploiting their potential capacity and other, such as Denmark, Netherlands and Italy, which currently depend on the import of pellets from foreign countries in order to satisfy their internal demand.

Actually, market dynamics are complicated and in some cases could be more economically convenient for a state to import pellets from other countries, even from extra European countries, than produce them domestically.

A significant fraction (2,5 millions of tons), correspondent to the 26% of the total amount of pellets combusted in Europe in 2010, was imported from extra-European countries. In particular, 0,9 millions of tons were imported from Canada, 0,7 millions of tons from USA, 0,4 millions of tons from Russia and 0.5 millions of tons from other countries.

If the trend of the imports from extra-European countries remains constant, the quantity of pellets from extra-European countries is supposed to increase in the next years, considering that the import of pellets increased by 42% from 2009 to 2010.

Also the flows from Canada and USA to Europe have already significantly increased between 2009 and 2010; this is an important point to evaluate because emissions from long distance transport could actually offset the GHG savings of using biomass.

Figure 4 shows the countries of origin of pellets exported to Europe from extra-European countries in terms of percentage.

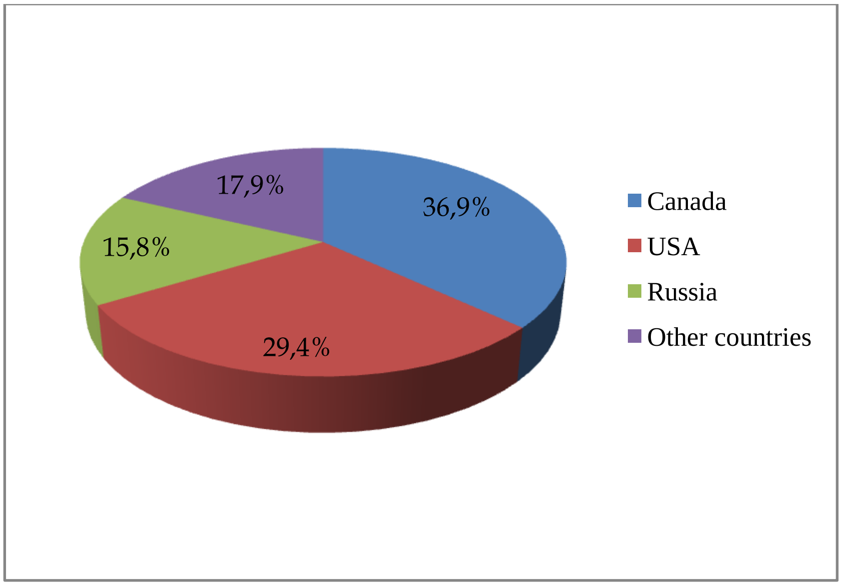

Figure 4: Total pellets import to EU27 in Kt in 2010

The main importer of pellets from extra European countries in 2010 were the Netherlands that imported 0.9 millions of tons, but also the United Kingdom, Denmark, Sweden and Belgium traded in a significant mass of pellets.

Figure 5 shows the main destinations of the 2.5 millions of tons of pellet imported in 2010.

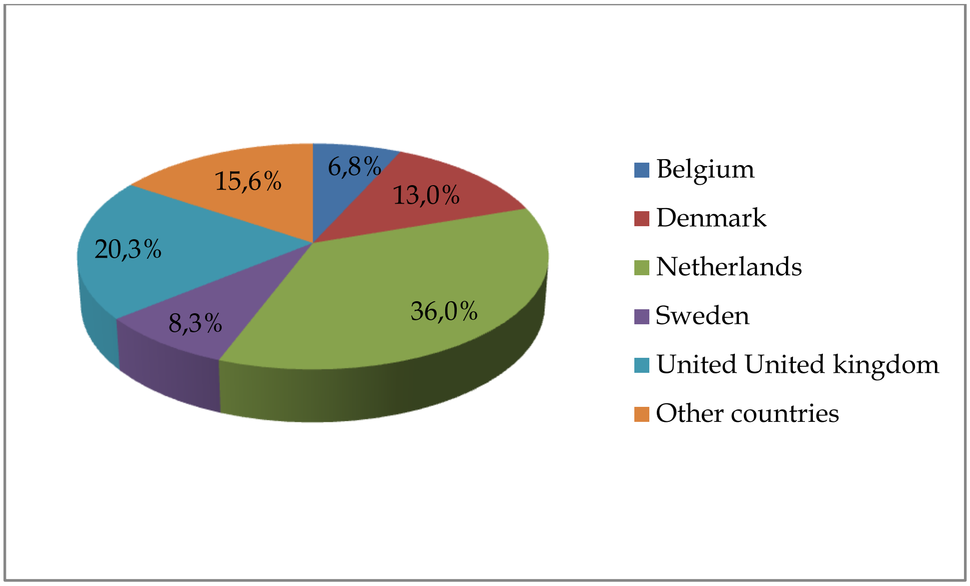

Figure 5: Destination of the 2,5 million of tons of pellets imported from extra European countries in 2010

1.2 *Standard for pellets quality*

The European Commission gave in 2000 a mandate to the European Committee for Standardisation CEN, under committee TC335, to prepare standards for solid biofuels.

During the period between 2003-2006 the European Committee for Standardisation has published 27 pre-standards (technical specifications). Recently these technical specifications have been upgraded to full European standards (EN).

In the past the vast majority of the European countries had few or no laws written specifically for the quality of pellets and often these came under the jurisdiction of only very general biomass laws. Actually only few European countries like Austria, Sweden and Germany had official and specific standards for densified biomass fuels. Now that EN-standards are in force, the national standards have to be withdrawn or adapted to EN-standards. This is a major development to guarantee a standard quality throughout Europe and this greatly facilitates trade and logistics.

The two most important technical specifications developed deal with classification and specification (EN 14961) and quality assurance for solid biofuels (EN 15234). Both these standards are published as multipart standards and are only for pellets for domestic use. Standards for pellets that are combusted in large plants are still lacking.

In particular, the parts of these standards that are referred specifically to pellets are:

- EN 14961-1:2010, Solid biofuels – Fuel specification and classes – Part 1: General requirements
- EN 14961-2:2011, Solid biofuels – Fuel specification and classes – Part 2: Wood pellets for non-industrial use
- EN 14961-6:2012, Solid biofuels – Fuel specification and classes – Part 2: Non -woody pellets for non-industrial use
- EN 15234-1:2011, Solid biofuels – Fuel quality assurance – Part 1: General requirements
- EN 15234-2:2012, Solid biofuels – Fuel quality assurance – Part 2: Wood pellets for non-industrial use

Part 1 of EN 14961 includes the general characteristics for all types of biomass pellets, such as moisture content, LHV, dimensions and content of some chemicals. It also clarifies the classification of solid biofuels, based on their origin and source.

Part 2 of EN 14961 defines three classes of quality for wood pellets for non-industrial use:

- EN plus-A1
- EN plus-A2
- EN B

The quality of wood pellets is strongly influenced by the feedstock, the physical and chemical characteristics of pellets, the use of additives in the production process and the content of some inorganic elements in the pellets.

The value of the thresholds to be respected in order to have pellets within the standards is listed in Table 3.

Part 6 of the standard 14961 is referred only to non-woody pellets for non-industrial use produced from these raw materials:

- Herbaceous biomass
- Fruit biomass
- Biomass blends and mixtures

As for wood pellets three quality classes have been identified.

This part of the standards includes also the specifications for straw, miscanthus and reed canary grass, that are reported in Table 4.

Parameter	**Unit**	**ENplus-A1**	**ENplus-A2**	**EN B**
Origin and source (14961-1)		Stemwood, Chemically untreated wood resides	Whole trees without roots, stemwood, logging residues, bark, chemically untreated wood residues	Forest, plantation and other virgin wood, by-products and residues from wood processing industry, used wood
Diameter D and Length, L	mm	D 6 ± 1 3,15 ≤ L ≤ 40 D 8 ± 1 3,15 ≤ L ≤ 40	D 6 ± 1 3,15 ≤ L ≤ 40 D 8 ± 1 3,15 ≤ L ≤ 40	D 6 ± 1 3,15 ≤ L ≤ 40 D 8 ± 1 3,15 ≤ L ≤ 40
Moisture, M	As received, w=% wet basis	M ≤ 10	M ≤ 10	M ≤ 10
Ash, A	w=%dry	A ≤ 0,7	A ≤ 1,5	A ≤ 3,5
Mechanical durability, DU	As received, w=%	DU ≥ 97,5	DU ≥ 97,5	DU ≥ 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	W% - as received	F≤1,0	F≤1,0	F≤1,0
Additives	W% - dry	≤ 2 w% Type and amount to be stated	≤ 2 w% Type and amount to be stated	≤ 2 w% Type and amount to be stated
Net calorific value, Q	As received, MJ/kg or kWh/kg	16,5≤Q≤19 or 4,6≤Q≤5,3	16,3≤Q≤19 or 4,5≤Q≤5,3	16,0≤Q≤19 or 4,4≤Q≤5,3
Bulk density, BD	Kg/m3	BD≥ 600	BD≥ 600	BD≥ 600
Nitrogen, N	w -% dry	N≤0,3	N≤0,5	N≤1,0
Sulphur, S	w -% dry	S≤0,03	S≤0,03	S≤0,04
Chlorine, Cl	w -% dry	Cl≤0,02	Cl≤0,02	Cl≤0,03
Arsenic, As	mg/kg dry	≤1	≤1	≤1
Cadmium, Cd	mg/kg dry	≤0,5	≤0,5	≤0,5
Chromium, Cr	mg/kg dry	≤ 10	≤ 10	≤ 10
Copper, Cu	mg/kg dry	≤ 10	≤ 10	≤ 10
Lead, Pb	mg/kg dry	≤ 10	≤ 10	≤ 10
Mercury, Hg	mg/kg dry	≤ 0,1	≤ 0,1	≤ 0,1
Nickel, Ni	mg/kg dry	≤ 10	≤ 10	≤ 10
Zinc	mg/kg dry	≤ 100	≤ 100	≤ 100
Ash melting behaviour	°C	Should be stated	Should be stated	Should be stated

Table 3: Specification of wood pellets for non-industrial use (EN 14961-2) [3]

Property class	**Unit**	**Cereal straw pellets**	**Miscanthus pellets**	**Reed canary grass pellets**
Origin and source (14961-1)		Straw parts	Grasses, whole plant	Grasses, whole plant
Diameter D and Length, L	mm	D 6 to 10 ± 1 3,15 ≤ L ≤ 40 D 12 ± 25 3,15 ≤ L ≤ 50	D 6 to 10 ± 1 3,15 ≤ L ≤ 40 D 12 ± 25 3,15 ≤ L ≤ 50	D 6 to 10 ± 1 3,15 ≤ L ≤ 40 D 12 ± 25 3,15 ≤ L ≤ 50
Moisture, M	As received, w=% wet basis	M ≤ 10	M ≤ 10	M ≤ 12
Ash, A	w=%dry	A ≤ 6	A ≤ 4	A ≤8
Mechanical durability, DU	As received, w=%	DU ≥ 97,5	DU ≥ 97,5	DU ≥ 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	W% - as received	F≤1,0	F≤1,0	F≤1,0
Additives	W% - dry	Type and amount to be stated	Type and amount to be stated	Type and amount to be stated
Net calorific value, Q	MJ/kg or kWh/kg	Minimum value to be stated	Minimum value to be stated	Q≥14,5 Q≥4,0
Bulk density, BD	Kg/m3	BD≥ 600	BD≥ 580	BD≥ 550
Nitrogen, N	w -% dry	N≤0,7	N≤0,5	N≤2,0
Sulphur, S	w -% dry	S≤0,10	S≤0,05	S≤0,20
Chlorine, Cl	w -% dry	Cl≤0,10	Cl≤0,08	Cl≤0,10
Arsenic, As	mg/kg dry	≤1	≤1	≤1
Cadmium, Cd	mg/kg dry	≤0,5	≤0,5	≤0,5
Chromium, Cr	mg/kg dry	≤ 50	≤ 50	≤ 50
Copper, Cu	mg/kg dry	≤ 20	≤ 20	≤ 20
Lead, Pb	mg/kg dry	≤ 10	≤ 10	≤ 10
Mercury, Hg	mg/kg dry	≤ 0,1	≤ 0,1	≤ 0,1
Nickel, Ni	mg/kg dry	≤ 10	≤ 10	≤ 10
Zinc	mg/kg dry	≤ 100	≤ 100	≤ 100
Ash melting behaviour	°C	Should be stated	Should be stated	Should be stated

Table 4: Specification for pellets produced from cereal straw, miscanthus and reed canary grass (final draft FprEN 14961 – 6) [3]

The multipart standard EN 15234 has the main aim to guarantee the solid biofuels quality trough the whole supply chain, from the origin to the delivery of the solid biofuels and provide adequate confidence that specified quality requirements are fulfilled.

The object of EN 15234-1 is to serve as a tool to enable the efficient trading of biofuels.

The users of this European Standard may integrate the EN 15234-1 in their general quality assurance scheme, e.g. the ISO 9000 series. If the company does not have a quality management system, EN 15234-1 can be used on its own to help the supplier in documenting fuel quality and creating adequate confidence between the supplier and the end-user.

Fuel product declaration (EN 15234-1) for the solid biofuels shall be issued by the supplier to the end-user or the retailer [3].

It is to be noticed that the standards for pellets for industrial wood is still lacking.

2 European policy

2.1 *The European 20-20-20 policy*

At the European Council's March 2007 summit, the EU's leaders endorsed an integrated approach to climate and energy policy that aims to combat climate change and increase the EU's energy security while strengthening its competitiveness. They committed Europe to transforming itself into a highly energy-efficient, low carbon economy.

The 12th December 2008 the European Council approved the *Climate and renewable energy package* that is a series of demanding climate and energy targets to be met by 2020, known as the *20-20-20 targets*. These targets are:

- 20% reduction of green house gas emissions compared to 1990 levels
- 20% reduction in primary energy compared with projected levels to be achieved through improving energy efficiency
- 20% share of energy consumption originating from renewable energy sources.

Reduction of green house gas emission

In March 2007 a target was agreed upon by the member states of the EU, that there should be a 20% (from 1990 levels) reduction in GHG emission by 2020.

The EU leaders also offered to increase the EU's emissions reduction to 30%, on condition that other major emitting countries in the developed and developing worlds commit to do their fair share under a global climate agreement. United Nations negotiations on such agreement are ongoing.

The ultimate target for developed countries is a 60% to 80% (from the 1990 levels) reduction of GHG by 2050. To achieve these targets, several binding measures were adopted in 2009. These included the revised Emission Trading Scheme (ETS) Directive, the Effort Sharing Decision and the Carbon Capture and Storage (CCS) Directive.

Improvement of energy efficiency

This measure aims at decreasing the utilization of energy whilst preserving an equivalent pace of economic activities. This target is particularly meant for the transport sector, energy-using equipments, energy consumer's behaviour, buildings and energy technologies/innovations.

Steps like the adoption of the *Energy Efficiency Plan 2011*,which encourages further use of energy management systems, and the proposed amendment to *Energy Taxation Directive* (April 2011) which aims at including CO_2 emissions in the structure of the energy tax, are aimed at pushing different industries into a more energy efficient economy.

Increase use of energy from renewable sources

The 2009 *Renewable Energy Directive* (Directive 2009/28/EC) has mandated an EU-wide mandatory target for the overall consumption of renewable energy and while targets vary for individual member states, the overall renewable energy consumption over the EU should be 20% of the gross final energy consumption by 2020.

The adoption of the *Communication on Renewable Energy* and the *Roadmap* in 2011 invites further investments in renewable-specific technologies through supplementary financing sources. The roadmap also encourages the EU to dedicate, by 2050, 1.5% of its total GDP per annum in low carbon energy sources, low carbon infrastructures and low carbon supporting systems (in addition to the 19% investments based on the 2009 GDP).

Other future initiatives include the EU endorsed *Low carbon 2050 strategy* for reducing GHG in the EU by 80%-95% from the 1990 levels, by 2050.

2.2 *Renewable Energy Directive*

The main goal of the Directive 2009/28/EC, also called *Renewable Energy Directive* (RED), is to promote the use of energy from renewable sources.

The article 1 of the Directive establishes that within 2020 each Member State has to ensure a share of gross energy consumption from renewable sources at least equal to its own target quantified in Annex I. Such mandatory national overall targets are consistent with a target of at least a 20% share of energy from renewable sources in the Community's gross final consumption of energy in 2020, which is imposed by the *Climate and renewable energy package*.

The gross energy consumption of energy from renewable sources is obtained as sum of three addends (Art. 5):

- Gross final consumption of electricity from renewable energy sources
- Gross final consumption of energy from renewable sources for heating and cooling
- Final consumption of energy from renewable sources in transport.

Each member State has also to guarantee a share of energy from renewable sources in all form of transport at least equal to 10% of the final consumption of energy used for transport in that Member State.

Articles 17, 18 and 19 set out the *sustainability criteria* for biofuels related to greenhouse gas savings, land with high biodiversity value, land with high carbon stock and agro-environmental practices.

The article 17 establishes that biofuels which shall be accounted towards the national targets need to comply with a number of sustainability criteria. The minimum greenhouse gas emissions saving from the use of biofuels must be 35 %. From 2017 on, it must be 50 %, and from 2018 it must be 60% for new installations.

Raw materials for biofuels must not come from land that had one of the following statuses in 2008 and no longer has that status: primary forest, protected area, highly biodiverse grassland, areas with high stocks of carbon, or peatlands.

For social and economical sustainability, the RED does not set any must-criteria. However, it requests, every two years, a report of the European Commission on the impact of EU's biofuels policy on the availability of foodstuffs at affordable prices, in particular for people living in developing countries, as well as on land rights, and whether main producer countries have ratified a number of international labour conventions. The Commission shall, if appropriate, propose corrective actions, in particular if evidence shows that biofuels production has a significant impact on food prices.

The Article 18 of the RED deals with the verification of the compliance with the sustainability criteria.

Member States shall require economic operators to show that the sustainability criteria have been fulfilled. Economic operators therefore have to use a mass balance system which allows consignments of raw material or biofuel with differing sustainability characteristics to be mixed, and they have to arrange for an adequate standard of independent auditing of the information.

Regarding imports of raw material or biofuels, the EU shall seek to make bilateral or multilateral agreements with third countries that guarantee compliance with the sustainability criteria; the Commission may then decide that those agreements demonstrate that biofuels produced from raw materials cultivated in those countries comply with the sustainability criteria.

The Article 19 of the Directive refers to the calculations of the greenhouse gas impact of biofuels and bioliquids that are explicated in the Annex V

Annex V gives the Typical and the Default values of 22 biofuels production pathways that may be used. For other production pathways economic operators have to do their own calculations according to the methodology in the same Annex, point C.

Default values are only valid if no land use change has taken place for cultivation of the raw materials, and when raw materials are cultivated outside the EU or in the EU in areas included in one of the lists that are provided by Member States in March 2010. The areas in these lists should follow the regions classified as level 2 or a more disaggregated level in the nomenclature of territorial units for statistics (NUTS). The lists give the NUTS-2 regions where the typical GHG emissions from cultivation of agricultural raw materials can be expected to be lower than or equal to the emissions reported under the heading "*Disaggregated default values for cultivation*" in part D of RED Annex V.

The point C of Annex V establishes the methodology to calculate emissions from biofuels and bioliquids production and consumption. In doing so disaggregated default values may be used for some factors (e.g. for the transportation of biofuels). Total GHG emissions are the sum of emissions from cultivation, processing and transportation of biofuels. [66]

Greenhouse gas emissions from the production and the use of transport fuels and bioliquids shall be calculated as

$E = e_{ec} + e_l + e_p + e_{td} + e_u - e_{sca} - e_{ccs} - e_{ccr} - e_{ee}$

Where:

E = total emissions from the use of the fuel expressed in terms of carbon dioxide equivalent per MJ of fuel, g CO_{2eq}/MJ

e_{ec} = emissions from the extraction or cultivation of raw materials

e_l = annualized emissions from carbon stock changes caused by land-use change

e_p = emissions from processing

e_{td} = emissions from transport and distribution

e_u = emissions from the fuel in use

e_{sca}=emission saving from soil carbon accumulation via improved agricultural management

e_{ccs} = emission saving from carbon capture and geological storage

e_{ccr} = emission saving from carbon capture and replacement

e_{ee} = emission saving from excess electricity from cogeneration

It is important to underline that RED Directive is the first regulation which refers to such sustainability criteria.

2.3 Solid biofuels

The Directive 2009/28 EC, art. 17, established that the Commission should report by December 2009 on requirements for a sustainability scheme for energy uses of biomass other than biofuels and bioliquids (i.e. solid and gaseous fuels in electricity, heating and cooling).

The *Report from the Commission to the Council and the European Parliament on sustainability requirements for the use of solid and gaseous biomass sources in electricity, heating and cooling*, adopted the 25th of February 2010, fulfilled this obligation.

The report is accompanied by an impact assessment which shows that binding criteria would impose substantial costs on European economic actors, bearing in mind that at least 90 % of biomass consumed in the EU comes from European forest residues and by-products of industries. Hence, the Report concludes that, at this stage, more strict legislation is not necessary. In the absence of harmonised rules at European level, Member States are free to put in place their own national schemes for solid and gaseous biomass used in electricity, heating and cooling. The report provides recommendations for Member States to follow similar patterns and most importantly to be guided by the sustainability criteria explained in the Report. In this way, it will be possible to minimise the risk of the development of varied and possibly incompatible criteria at national level, leading to barriers to trade and limiting the growth of the bio-energy sector.

The recommended criteria relate to:

- A general prohibition on the use of biomass from land converted from forest, other high carbon stock areas and highly bio-diverse areas

- A common greenhouse gas calculation methodology which could be used to ensure that the minimum greenhouse gas savings from biomass are at least 35% (rising to 50% in 2017 and 60% in 2018 for new installations) compared to the EU's fossil energy mix
- The differentiation of national support schemes in favour of installations that achieve high energy conversion efficiencies
- Monitoring of the origin of biomass chain.

It is also recommended not to apply sustainability criteria to wastes, as these must already fulfil environmental rules in accordance with waste legislation at national and at European level, and that the sustainability requirements should apply to larger energy producers of 1 MW thermal or 1MW electrical capacity or above.

Under the Renewable Energy Directive, Member States must submit National Renewable Energy Action Plans in June 2010. These will be a key tool for identifying the EU's ambitions for exploiting its biomass potentials, whether in electricity, heating or transport. Following the submission of these plans and analysis of emerging national schemes, the Commission will consider in 2011 whether additional measures such as common sustainability criteria at EU level would be appropriate.

3 Life Cycle Assessment

Life Cycle Assessment (LCA) is a structured, comprehensive and internationally standardised method. It quantifies all relevant emissions and resources consumed and the related environmental and health impacts and resource depletion issues that are associated with any goods or services (*products*).

Life Cycle Assessment takes into account a product's full life cycle: from the extraction of resources, through production, use, and recycling, up to the disposal of remaining waste.

Life Cycle Assessment is therefore a vital and powerful decision support tool, complementing other methods, which are equally necessary to help effectively and efficiently make consumption and production more sustainable [18].

Life Cycle Assessment follows the standards ISO 14040:2006 (Environmental management- Life cycle assessment – Principle and framework) and ISO 14044:2006 (Environmental management- Life cycle assessment –Requirements and guidelines).

The principles of the standards are detailed in the ILCD Handbook [18], a document that has been developed by the European Commission and that has been carried out through a broad international consultation process with experts, stakeholders, and the public.

The ILCD Handbook is a series of technical documents providing guidance for good practice in Life Cycle Assessment in business and government. It is supported by templates, tools, and other components.

According to ISO standard the Life Cycle Assessment is an iterative process and it is carried out in four distinct phases. Figure 6 represents the framework for the life cycle assessment. The framework underlines that the life cycle assessment almost always needs to be improved while doing it. In fact, during the life cycle inventory phase of data collection and during the subsequent impact assessment and interpretation more information becomes available, the initial scope settings will typically need to be refined and sometimes also revised.

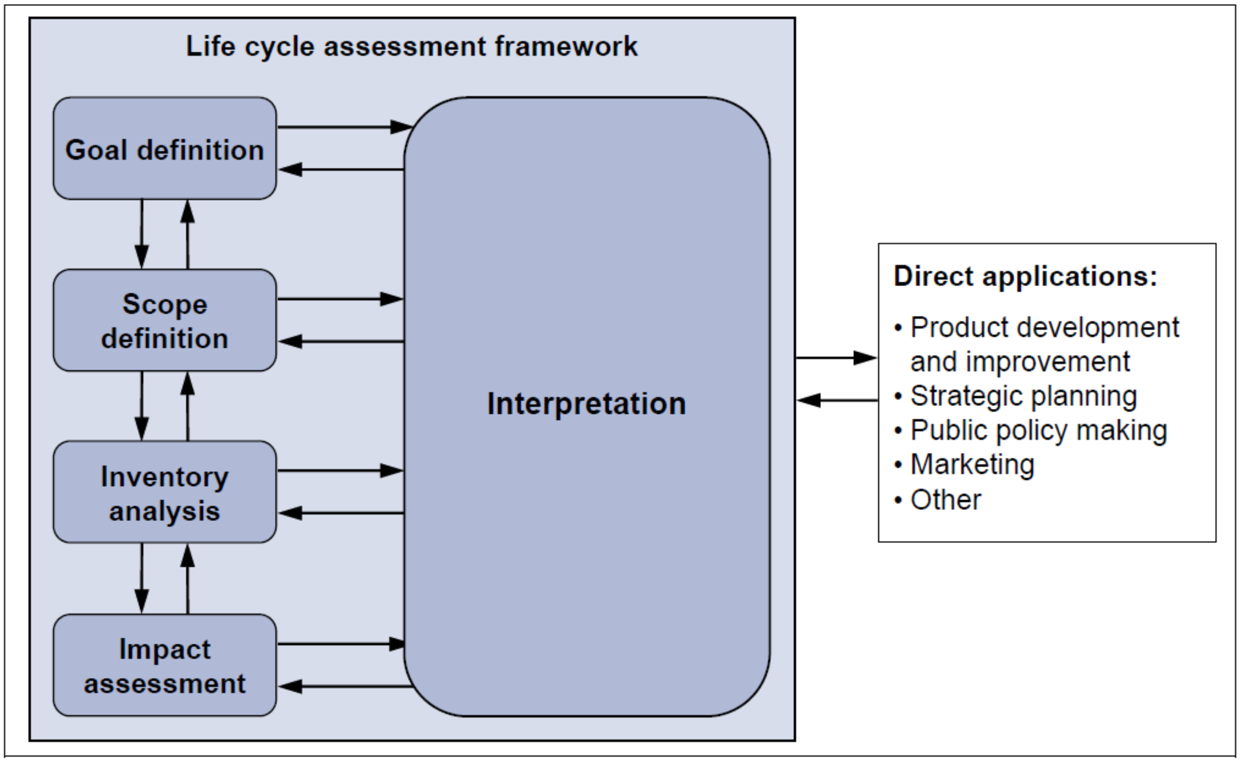

Figure 6: Framework for life cycle assessment [18]

3.1 Definition of the goal and the scope

An LCA starts with an explicit statement of the goal and scope of the study, which sets out the context of the study and explains how and to whom the results are to be communicated. This is a key step and the ISO Standards require that the goal and scope of an LCA be clearly defined and consistent with the intended application.

According to the ILCD Handbook [18] six aspects shall be addressed and documented during the goal definition:

- Intended application(s) of the deliverables / results;
- Limitations due to the method, assumptions, and impact coverage;
- Reasons for carrying out the study and decision-context;
- Target audience of the deliverables / results ;
- Comparative studies to be disclosed to the public;
- Commissioner of the study and other influential actors.

Whereas the declaration of the scope of the study shall include and describe:

- The type(s) of the deliverable(s) of the LCI/LCA study, in line with the intend application(s);
- The system or process that is studied and its function(s), functional unit, and reference flow(s);
- LCI modelling framework and handling of multifunctional processes and products;
- System boundaries, completeness requirements, and related cut-off rules;
- LCIA impact categories to be covered and selection of specific LCIA methods to be applied as well as, if included, normalisation data and weighting set;
- Other LCI data quality requirements regarding technological, geographical and time-related representativeness and appropriateness
- Types, quality and sources of required data and information, and here especially the required precision and maximum permitted uncertainties
- Special requirements for comparisons between systems
- Identifying critical review needs
- Planning reporting of the results.

The functional unit names and quantifies the qualitative and quantitative aspects of the function(s) along the questions *what, how much, how well*, and for *how long* [18].

The reference flow provides a reference to which inputs and outputs are related, thus allowing comparison between two or more different system. Examples of reference flows for LCA about wood manufacture can be a unit of energy content (1 MJ wood) or a unit of mass (1 t wood).

A multifunctional process is a process that provides more than one function such as delivering more than one goods or service. The environment impact due to one of these outputs must be calculated using different approaches that are listed in the hierarchy of the standard ISO 14044:

- Subdivision of multifunctional processes
- System expansion/substitution
- Allocation

The first alternative consists in splitting the multifunctional process in more than one process that has just one process. This is not always possible.

The second option is to the system expansion. This can mean to add another, not provided function to make to system comparable (i.e. system expansion in the stricter sense) or to subtract not required function(s) substituting them by the ones that are superseded / replaced (i.e. substitution by system expansion).

The allocation method is necessary to partition the environmental load of a multifunctional process when the others option to associate the emissions to one output are not applicable.

Following this approach, the emissions of the process are associated with each product depending on its mass, its heating value, its market value or following other criteria.

The system boundaries determine which unit processes are to be included in the LCA study. Defining system boundaries is partly based on a subjective choice, made during the scope phase when the boundaries are initially set.

The impact categories represent environmental issues of concern to which product's impact can be associated such as the global warming or the rain acidification. The choice of the impact categories to be considered is made in this initial phase, however, during the life cycle assessment, on the basis of the outcomes of next iterations, it could be possible to exclude irrelevant impact categories or to include ones initially neglected [18].

3.2 *Life Cycle Inventory (LCI)*

During the life cycle inventory phase the actual data collection and modelling of the system (e.g. product) is to be done. This is to be done in line with the goal definition and meeting the requirements derived in the scope phase. The LCI results are the input to the subsequent LCIA phase. The results of the LCI work also provide feedback to the scope phase as initial scope settings often needs adjustments.

Typically, the LCI phase requires the highest efforts and resources of an LCA: for data collection, acquisition, and modelling.

According to the ISO standard 14044 the specific kind of life cycle inventory work depends on the deliverable of the study; not all of the following steps are required for all of these. In its entirety, life cycle inventory work means:

- Identifying the processes that are required for the system
- Planning of the collection of the raw data and information, and of data sets from secondary sources

- Collecting (typically) for the foreground system unit process inventory data for these processes. An important aspect is the interim quality control and how to deal with missing inventory data
- Developing generic LCI data, especially where average or specific data are not available and cannot be developed, typically due to restrictions in data access or budget
- Obtaining complementary background data as unit process or LCI result data sets from data providers
- Averaging LCI data across process or products, including for developing production, supply and consumption mixes
- Modelling the system by connecting and scaling the data sets correctly, so that the system is providing its functional unit
- This modelling includes solving multifunctionality of processes in the system.
  Calculating LCI results, i.e. summing up all inputs and outputs of all processes within the system boundaries. If entirely modelled, only the reference flow ("final product") and elementary flows remain in the inventory [18].

These steps are done in an iterative procedure, as illustrated in Figure 6.

While developing the inventory, a flow model of the technical system helps to identify all the process within a system and to visualize all the flows between different processes and to the environment.

The flow model is typically illustrated with a flow chart that includes the activities that are going to be assessed in the relevant supply chain and gives a clear picture of the technical system boundaries. The input and output data needed for the construction of the model are collected for all activities within the system boundary, including from the supply chain.

The data must be related to the reference flow defined in the goal and scope definition. The results of the inventory is the LCI which provides information about all inputs and outputs in the form of elementary flows to and from the environment from all the unit processes involved in the study.

3.3 Life Cycle Impact Assessment (LCIA)

Life Cycle Impact Assessment (LCIA) is the phase in an LCA where the inputs and outputs of elementary flows that have been collected and reported in the inventory are translated into impact indicator results related to human health, natural environment, and resource depletion. Impacts are related both with input and output flows.

The Standard ISO14044 states that LCIA is composed by mandatory and optional steps.

Mandatory steps:

- Selection of impact categories, category indicators and characterization models.
- Classification: assigning LCI results to the impact categories
- Characterisation: modelling LCI impacts within impact categories using science-based conversion factor.

Optional elements (dependent on the goal and scope of the study):

- Normalisation: expressing potential impacts in ways that can be compared.
- Weighting: emphasizing the most important potential impacts.
- Grouping: sorting or ranking the indicators after geographic relevance, company priorities etc.

3.4 Interpretation of the results

The Interpretation phase of an LCA has two main purposes that fundamentally differ:

- During the iterative steps of the LCA and for all kinds of deliverables, the interpretation phase serves to steer the work towards improving the Life Cycle Inventory model to meet the needs derived from the study goal.
- If the iterative steps of the LCA have resulted in the final LCI model and results, and especially for comparative LCA studies (while partly also applicable to other types of studies), the interpretation phase serves to derive robust conclusions and, often, recommendations. In life cycle interpretation, the results of the life cycle assessment are appraised in order to answer questions posed in the goal definition. The interpretation relates to the intended applications of the LCI/LCA study and is used to develop recommendations. Interpretation of the results allows to make comparisons between two

or more products as far as environmental impact is concerned and to identify the most environmentally impacting phase or phases of a process.

The life cycle interpretation is the phase of the LCA where the results of the other phases are hence considered collectively and analysed in the light of the achieved accuracy, completeness and precision of the applied data, and the assumptions, which have been made throughout the LCI/LCA study. As said, in parallel to performing the LCI work this serves to improve the LCI model.

4 Literature review

Several studies have investigated the environmental impact of pellets production chain. The main features of some of them are briefly described afterwards. . This will identify the open issues in the field and it will make clear how the present work will help fill such gaps.

Hagberg et al. [31] dealt with the calculation of life cycle emissions of greenhouse gases for some representative Swedish pellets production chains according to the methodology laid out in the Annex V of the Renewable Energy Directive (RED).

The main goals of this study were, firstly, to calculate the greenhouse gas emissions for different Swedish pellet production chains following the guidelines in the RED and, secondly, to underline problems and ambiguous aspects of the RED methodology, originally designed for liquid biofuels, applied to wood pellets.

A large number of alternatives were investigated, considering the effects of different raw materials (wet and dry feedstocks and roundwood), the type of fuel used to dry the raw material, the transport distances, the fuel mix for purchased electricity and the type of pellet plant.

Calculations were based on actual data from 11 Swedish pellet plants as well as data from literature.

The study identified some critical points of the RED methodology, one of which refers to the accounting of GHG emissions during combustion. The RED states that emissions of GHG during combustion should not be included. However while this might be correct for liquid biofuels, where emissions of N_2O are very low or absent, it is more important for solid biofuels where emissions of N_2O can be significant due to their fuel-N content. Also emissions of incombusted methane can be significant, especially for biogas combustion.

Additionally it is not clear whether the raw material from sawmills should be considered a residue and thus with no emissions up to the collection point or whether the emissions from the sawmill should be allocated also to the sawdust. This could have a relevant effect on the final account of emissions from pellets pathways.

In this work it was assumed that emissions of CH_4 and N_2O during combustion would have to be accounted and that emissions from sawmills would have to be allocated also to sawdust since this product has a significant economic value and often it has also an alternative utilisation (such as animal bedding)

Many scenarios were analysed, the results of the base case are reported in the Table 5.

	Wet Sawdust.. Biomass used for drying	**Dry raw material (cutterdust/dry chips)**	**Wet (roundwood chips) Biomass used for drying**
	Total emissions ($g_{CO2\ eq}$/$MJ_{pellets}$)		
End use - large scale heating plant	3,35	3,74	3,6
Excluding end use emissions	3,17	3,56	3,43
Excluding distribution of pellets and use emissions	2,73	3,12	2,98

Table 5: Results of the calculation of greenhouse gases emissions from Swedish wood pellets production chains using RED methodology [31]

Caserini et al. [7] analysed the situation of Lombardy, a northern Italian region, with a *cradle to grave approach.*

A mix of primary and secondary data was used. Several environmental impacts, according to the characterization method CML2001, were considered: global warming, human toxicity, air acidification and photochemical ozone formation.

Seven scenarios were analysed based on different feedstock, raw material processing and combustion equipment. One of the scenarios considered referred to pellet production from forest residual chips and combustion in a residential stove equipped with the Best Available Technologies (BAT). The other six scenarios dealt with the combustion of wood logs, wood chips, and forest residues in different CHP industrial and residential devices.

The main results are reported in the Table 6, and they indicate that, regardless of the material used, industrial plants have lower environmental impacts thanks to the emissions abatement system, and that the combustion of pellets has lower impacts than wood logs burned in domestic stoves, in terms of human toxicity and photochemical ozone formation potential.

Results are expressed as difference between the emission of the technology analysed and the reference system that is assumed to be the combustion of fossil fuels represented by the 2004 thermo-electric Italian mix.

			Impact categories			
			Global warming	**Human toxicity**	**Air acidificatio n**	**Photochemical ozone formation**
	Device	**Fuel**	**Kg $CO_{2\,eq}$**	**Kg $_{1,4\,DCB\,eq}$**	**Kg $SO_{2\,eq}$**	**Kg $C_2H_{4\,eq}$**
1	Open fireplace	Wood log - forest residues	-80.4	2870	3.05	44.5
2	Conventional wood stove	Wood log - forest residues	-698	2801	2.26	11
3	Low emission wood stove	Wood log - forest residues	-932	2782	1.17	5.17
4	Pellet stove (BAT)	Pellets - forest residues	-1080	96.3	1.63	0.762
5	CHP plant (8 MW)	Chip - forest and industrial residues	-1020	-106	-2.28	-0.305
6	CHP plant (8 MW)	Chip - energy crops	-850	-69	-1.26	-0.195
7	CHP plant (100 MW)	Varying - wood wastes	-914	-116	-2.68	-0.227

Table 6: Impacts of different scenarios considered in [7] expressed per tonne of dry biomass

Fantozzi at al. [22] evaluated the environmental impact due to the production of pellets from short rotation coppice and the subsequent combustion in a residential boiler, using different assessment methodologies.

The main processes analysed in the study were: cultivation, transportation and storage to the pellet mill, pelletisation, transportation to the user, combustion and ash disposal.

The data for the pellet production plant were taken from an Italian pellets plant, while other data were taken from literature.

Results show that the process of cultivation accounts for most of the environmental impacts, even though for the *Ecoindicator 99* methodology, the higher impact is related to *Human Health* while for *EPS 2000* it is related to *Resources Consumption*.

This work also assessed that accounting infrastructures and machineries would increase the final result only by 2%. These factors are, thus, of little relevance for the final result, as it is common for energetic systems. In the present study, however, it was decided to include also these contributions in an attempt to be as thorough as possible.

Moreover the study showed how the estimated environmental impacts resulted significantly lower (23%) using input data from a real plant rather than data from literature, underlining the importance of reliable data.

Mani [45] analysed the emissions from a pellet production system considering as feedstocks sawdust with 40% of moisture content and dry wood shavings with 10% of moisture content. Alternative fuels considered for drying, when necessary, were pellets, wet sawdust, dry sawdust, coal, natural gas and wood shavings.

The main processes considered were: drying using a rotary drum dryer, grinding by a hammer mill and densification with a pellet mill.

Data were mainly taken from experimental measurements and, when necessary, from literature.

The results show that drying using coal as a fuel has a higher environmental impact in terms of all the impact categories considered, due to higher environmental emissions.

The lower environmental impact, considering all the impact categories, is associated with the scenario without drying. This is due to the fact that the drying phase causes significant emissions of terphene, which have the highest influence on smog formation potential in all the scenarios considered and which has an important weight in the human toxicity impact assessment, due to its the carcinogenic effect. Additionally the scenario without drying has a lower pressure also on global warming and rain acidification impact categories.

Ghafghazi et al. [27] dealt with the assessment and the comparison of the environmental performances of four heat sources options for a district heating centre in Vancouver, British Columbia, Canada. In particular the fuels considered were natural gas, wood pellets, sewer heat and ground heat.

Sawdust received from a sawmill was considered as the feedstock for the production of wood pellets.

The processes analysed included harvesting activities, the transportation of wood logs to the sawmill and the production of both sawdust and pellets. The emissions from the sawmill were allocated to the sawdust on a mass basis.

The final utilisation of the pellets was considered to be the combustion of pellets to produce district heating.

The comparison between the four fuels considered underlines that wood pellets have a higher impact for *respiratory of inorganics*, *terrestrial ecotoxicity* and *terrestrial acidification and nitrification* compared to the other fuels.

In particular, the main contribution to the *respiratory of inorganics* category is given by the particulate and nitrogen oxides emissions resulting from pellet combustion.

Copper emissions to soil and, to a lesser degree, to the atmosphere have a relevant weight on *aquatic and terrestrial ecotoxicity* categories. During the life cycle of wood pellets seems to be an important contribution due to copper emissions in the flue gases and especially in the bottom ash during sawdust production, pelletisation and facility operation. Other emissions which appear to have a significant contribution to *terrestrial ecotoxicity* category are the presence of trace of heavy metals in the flue gases and in the ashes of the wood combusted during the pelletisation process. As evidenced in these studies, the environmental effects of wood pellets might be even worse than fossil fuels in some categories and this should not be forgotten when judging the sustainability of such sources. Focusing solely on the global warming impact category can many times overshadow the contributions of other impacts.

Moreover, the results of the study point out that although emissions of carbon dioxide during pellets combustion are considered zero, in this process there is a contribution to the global warming due to emissions of methane from incomplete combustion.

About 50% of the *global warming* impact is associated with the emissions related to the fossil fuels consumption during harvesting, sawmilling operation and the pelletisation process. Transport accounts for less than 25% of the *global warming* impact.

In conclusion, Ghafghazi et al. stated that there is not a fuel between the four analysed which could be considered the best on an environmental basis, and underlined that every fuel has many impacts not only related with the combustion and the resources depletion, but with all its life cycle.

The study by Sikkema et al [59] assessed the avoided greenhouse gases emissions of a pellets production chain and their conversion into heat or electricity. Three main scenarios were considered as typical cases for three European countries.

The calculation of avoided greenhouse gases emissions was based on the comparison with emissions due to the fossil fuel used in each country with the same purpose.

Input data were taken from scientific literature.

Hereunder a brief description of the three main scenarios is given.

1. Pellets for district heating, sold in non industrial bulk. This is considered to be the representative case for Sweden. The calculation of avoided greenhouse gases emissions was made by comparison with emissions due to the production of heat using heavy oil.
2. Pellets for residential heating, sold in plastic bags of 10-15 Kg, burned in small scale heater at home. This market is typical of Italy, where pellets are supposed to partly replace natural gas which is the fossil fuel generally used for household heating
3. Pellets for electricity production, sold in industrial bulk and burned in large scale devices. This is considered the typical case of the Netherlands, where pellets are mainly imported from Canada. These pellets, compared with pellets burned in the two previous cases, are allowed to have lower quality, because they are combusted in a large scale power plant with an air emissions abatement system. The fuel comparator is hard coal because pellets can only partly substitute fossil fuel in coal-fired power plants. It has been assumed that the share of pellets in co-combustion is $10\%_{th}$, even though many efforts are in place to increase this share.

The processes analysed for each scenario were: supply of feedstock, production of wood pellets, distribution of wood pellets, conversion to power and heat.

In all the cases considered, the pellet plant was fed with sawdust and relatively dry shavings.

No emissions were allocated to the feedstocks because they were considered as residues.

The drying phase was carried out with the use of biofuels, such as wet sawdust or bark.

The results of the study show that the avoided GHG emissions, compared to the emission due to the combustion of the fossil fuel traditionally used in each scenario, expressed in absolute terms, are higher for the scenario 3, whereas to the scenario 1 is associated the lower quantity of avoided emissions.

That is due to the fact that the use of pellets for the production of electricity is assumed to replace the use of coal that causes more emissions of GHG in comparison with the use of oil and natural gas, respectively, used for district heating and residential heating.

Table 7 shows the results of the study, in terms of avoided greenhouse gases emissions per unit of heat or electricity produced in the three main cases considered.

Scenario 1	**Scenario 2**	**Scenario 3**
kg $_{CO2eq}$/GJ$_{th}$	**kg $_{CO2eq}$/GJ $_{th}$**	**g $_{CO2eq}$/kWh**
92	62	988

Table 7: Avoided greenhouse gases emission [59]

Concerning straw pellets, just few studies are available in scientific literature.

Actually, only one study was found in literature where the authors carried out a proper Life Cycle Assessment of agri-pellets [63]. Some studies are more focused on the economical aspects such as the studies by Mupondwa et al. [49] and the one by Nillson et al. [51].

In particular, the study of Sultana et al. [6363] dealt with the estimation of the GHGs emissions emitted during the life cycle of straw pellet. Only the global warming impact was considered.

Data were taken from literature and are considered to be specific for the situation in Western Canada.

The processes analysed were: crop production and harvesting, transportation of the crop residue from the field to the pellet plant, pellet production, transportation of the pellets to the user and combustion of the pellets in a small scale combustor and in a CHP plant.

Emissions of the cultivation process were allocated to straw according to the mass.

One base case and six scenarios were analysed. The scenarios differed depending on the use of different fertilisers during field operations (organic fertilisers, zero tillage option), on the emissions allocated to the cultivation of straw (null if straw is considered as a by-product), on the kind of fuel and the quantity of heat used for drying the pellets and, finally, on the means of transport assumed to be used.

The final results show that the emissions of GHG during the life cycle of straw pellets are equal to about 30 $gCO_{2eq}/MJ_{pellets}$. The main contribution (92%) is due to the field process, in particular to nitrogen fertilisers production, transportation and application.

A final comparison illustrates that straw pellets have a lower impact on global warming compared to wood pellets and fossil fuels. In particular they could avoid 50% of GHG emissions compared to wood pellets and 250% and 350% of GHG emissions compared respectively to natural gas and coal.

In Table 8 the main differences between the cited studies and the one carried out in this thesis are underlined.

Ref	Reference country /countries	Raw materials	Impact categories	Assessment methodology
[31]	Sweden	- Wet wood residues - Dry wood residues - Roundwood chips	Global warming	RED sustainability criteria
[7]	Italy (Lombardy)	Forest residues	- Global warming - Human toxicity - Acidification - Photochemical ozone formation	LCA, characterisation method CML 2001
[22]	Italy	Wood from Short rotation coppice	Different for the 3 methodology	LCA, comparison between three different characterisation methods: EcoIndicator 99, EPS 2000, EDIP
[45]	Canada (British Columbia)	- wet sawdust - shavings	- Global warming - Human toxicity - Acid rain formation - Smog formation	Simulations
[27]	Canada (British Columbia)	Sawdust and shavings	- Carcinogens - Non – carcinogens - Respiratory organics - Ozone layer depletion - Aquatic ecotoxicity -Terrestrial ecotoxicity -Terrestrial acidification-nutrification - Aquatic acidification - Aquatic eutrophication - Global warming - Non renewable energy - Mineral extraction	LCA, characterisation method IMPACT 2002
[59]	Sweden, Italy, the Netherlands	Sawdust	- Global warming	LCA
[63]	Western Canada	Straw	- Global warming	LCA
	This study	**- Woodchips from forest residues** **- Poplar woodchips** **- Wet sawdust** **- Partially dry sawdust** **-Straw**	**- Climate change** **- Ozone depletion** **- Human toxicity** **- Particulate matter/respiratory inorganics** **- Ionising radiation** **- Photochemical ozone formation** **- Air acidification** **- Terrestrial eutrophication** **- Aquatic eutrophication** **- Ecotoxicity** **- Resource depletion**	**LCA, characterisation method suggested by ILCD (see paragraph 5.3)**

Table 8: Main differences between the cited studies

Other studies have been analysed, in particular for the collection of the data for the process of poplar cultivation. The one considered most important are briefly described hereunder.

Heller et al [32] made an LCA of a willow bioenergy cropping system in the State of New York (US), focusing their attention only on the cultivation phase. In fact the boundaries of the study included the field operations from the site plantation to the removal of the stumps, whereas the environmental impacts of the energy conversion of the biomass were neglected.

All the impact related to the manufacturing and the use of the agrarian machineries, fertilisers and herbicides were accounted for.

In this study it was calculated that the total amount of non-renewable energy needed for the cultivation of willow was 1,8% of the total energy content of the wood delivered and that the production of nitrogen inorganic fertilisers accounted for nearly the 40% of the energy cost of producing willow biomass.

Roedl [57] investigated the production of woodchips from short rotation coppice of poplar and its consequent conversion to heat, power or to diesel, using the Fischer Tropsch sysntesis.

The study was divided in two parts: the first one included the analysis of the site plantation, the field operations, the harvesting and the chipping of the biomass. The second part, instead, evaluated the environmental impact of the conversion of wood chips to energy, power or bio-diesel.

This study found that the energy needed to produce 1 mega-joule of poplar woodchips was higher than the one estimated by Heller et al.[32] and, in particular, it was equal to 2,3% of the energy content of the wood.

The study by Rafaschieri et al [55] investigated the environmental impacts associated with an integrated gasification combined cycle for power generation using poplar biomass growing on a short rotation coppice. The emissions associated to the use of energy, fertilisers, chemicals and agrarian machineries were accounted in the impacts of the cultivation phase, whereas the emissions of their production were excluded.

It was concluded that the use of fertilisers and chemicals during the cultivation phase caused the most negative environmental impacts associated with the conversion of the biomass in power by the gasification.

5 Description of the study

5.1 *Goal and scope of the study*

The goals of this study are to analyse, using an LCA approach, the environmental impact of different pellets production chains, including the effects of the use of different feedstocks, long-range transportation and end use emissions and to compare the results of the impact on global warming to the typical values suggested by the European Commissions.

The first part of the study aims at accounting and describing all the emissions and the consequent environmental impacts due to the production of pellets, starting from the cultivation of raw materials and including every step of pellets manufacture up to the combustion in apposite stoves or boilers. This is a typical *cradle to grave* LCA approach.

An attempt has been made in order to collect wide-ranging input data with the purpose of giving a general idea of which would be a typical impact of an average production and utilisation chain of pellets in Europe. This implies that also import from extra European Countries and internal commercial flows in Europe have to be considered.

The evaluation of the impacts has been done using the software GaBi 4.0, that allows modelling the energy and mass flows of the pathway analysed and then to evaluate its environmental impacts, based on different methods.

The second part of the study deals with the comparison of the results obtained following the methodology recommended by the Directive 2009/28/EC (RED) and published by the Commission and the results obtained in this work.

Actually the Directive does not include the pellets production process because the sustainability criteria laid down in the RED currently refer only to biofuels and bioliquids. However, the Commission has published in 2010 an additional Report [9], in which it recommends a methodology similar to the one of the RED in order to evaluate the GHG balance of solid biomass for power and heat. In these documents the European Commission has also published a series of typical GHG values for different pathways and they will be the basis for the comparison in Paragraph 5.5.

The deliverable of the work is this thesis.

This study is carried out to investigate particular scenarios that have not been analysed in existing studies, to add a new contribution to consolidate knowledge about pellets environmental sustainability and, additionally, to make a critical analysis of the methodology of the European Commission used to calculate the typical values that can be a starting point for a next updating of the normative.

The functional unit of the study is a unit of heat produced with the combustion of pellets. In particular, every flow is expressed in terms of dry matter; this means that it does not consider the quantity of heat necessary to evaporate the water present in the pellets.
In fact the lower heating value (LHV) of a material on wet basis shall be calculated considering also the contribution of the latent heat of vaporisation of water [61]:

$$LHV_{\text{wet basis}} = LHV_{\text{dry}} * (1\text{-}MC) – 2{,}442 * (MC)$$

Where: MC = moisture content [% on wet basis]
2,442 = latent heat of vaporisation of water at 25°C [MJ/kg_{water}]
Considering that the moisture content of the feedstock varies during the pellets production chain, also the actual LHV would change during the process. This makes it very difficult to refer to this parameter during all the steps of the study.
For this reason, every quantity is referred to the dry matter, so that the basis of calculation is:

$$Kg_{\text{fresh matter}} * LHV_{\text{dry}} * (1\text{-}MC)$$

The reference scenario is the production of one-mega joule of heat produced by the combustion of natural gas in a domestic device that can be considered equivalent to the one of the pathway analysed.

In case of multifunctional processes, the emissions associated with one output are calculated using different allocation approaches, because the other approaches, suggested by the ISO14044, are not applicable in this study.
In particular, for a specific feedstock (sawdust) three allocation methodologies are compared, whereas the economic allocation and the allocation by exergy have been considered more

suitable respectively for the multi-outputs industrial and the combustion of pellets in a CHP that delivers electricity and heat.

Referring to the boundaries of the study, this study is characterised by a *cradle to grave* approach, so all the operations within the pellets production and utilisation chains have to be considered. The boundaries of the studies include also the process of the production of the machineries, the energy and the raw materials used in the whole 'life' of the pellets.

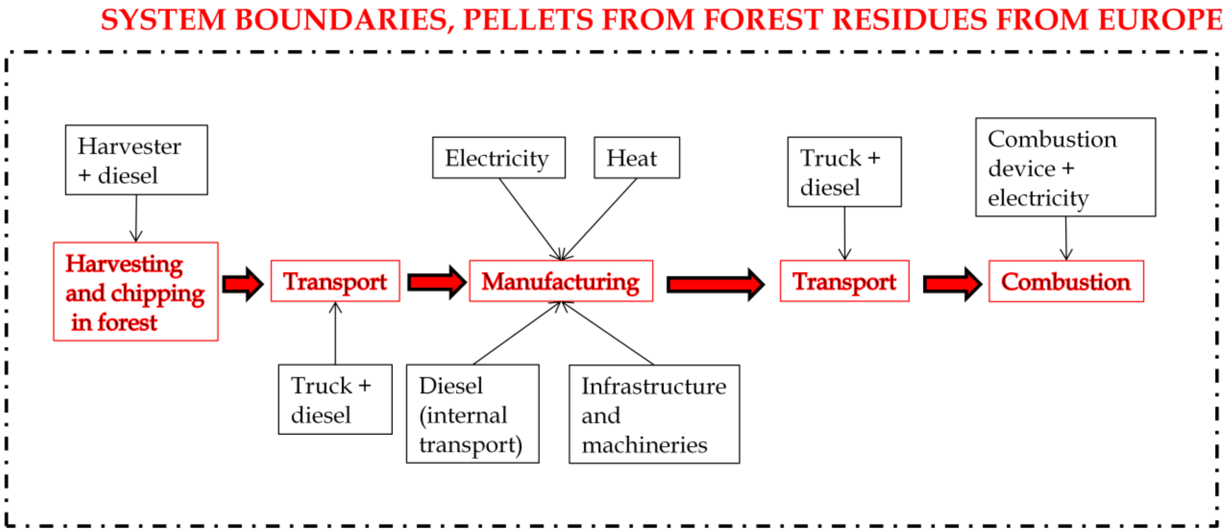

Figure 7: System boundaries for the scenario of wood pellets produced from forest residues from Europe

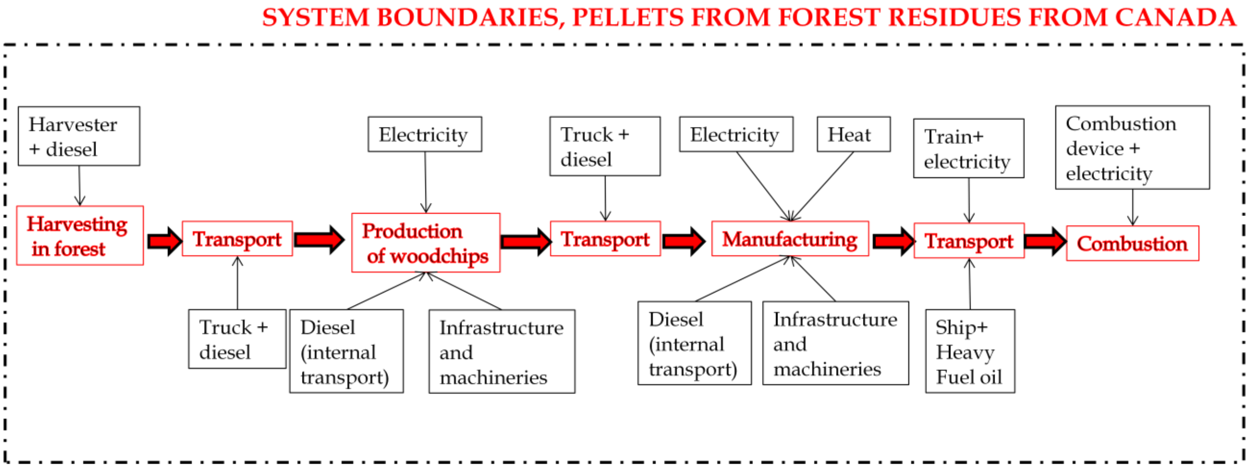

Figure 8: System boundaries for the scenario of wood pellets imported from Canada

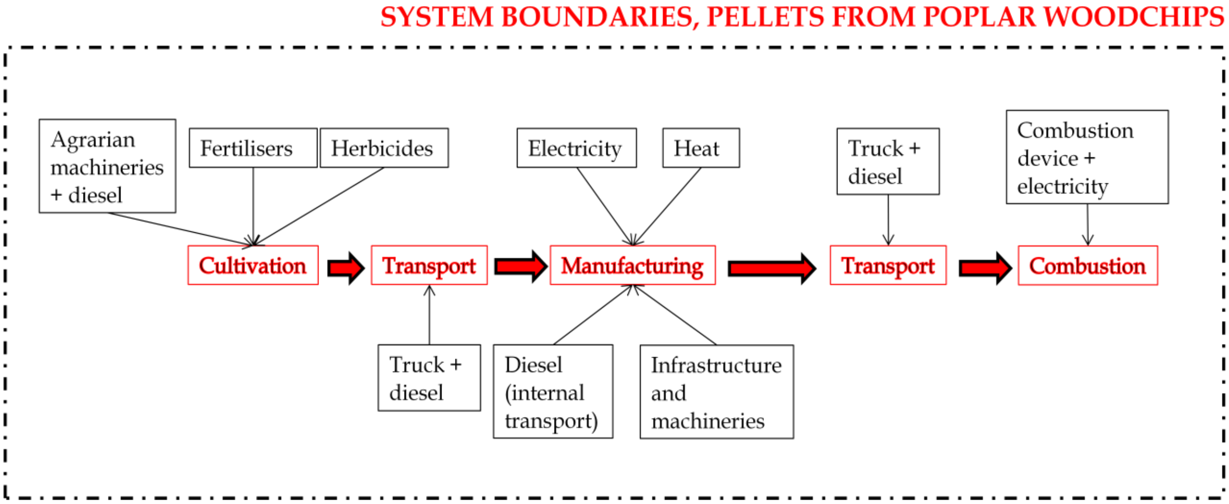

Figure 9: System boundaries for the scenario of wood pellets produced from poplar woodchips

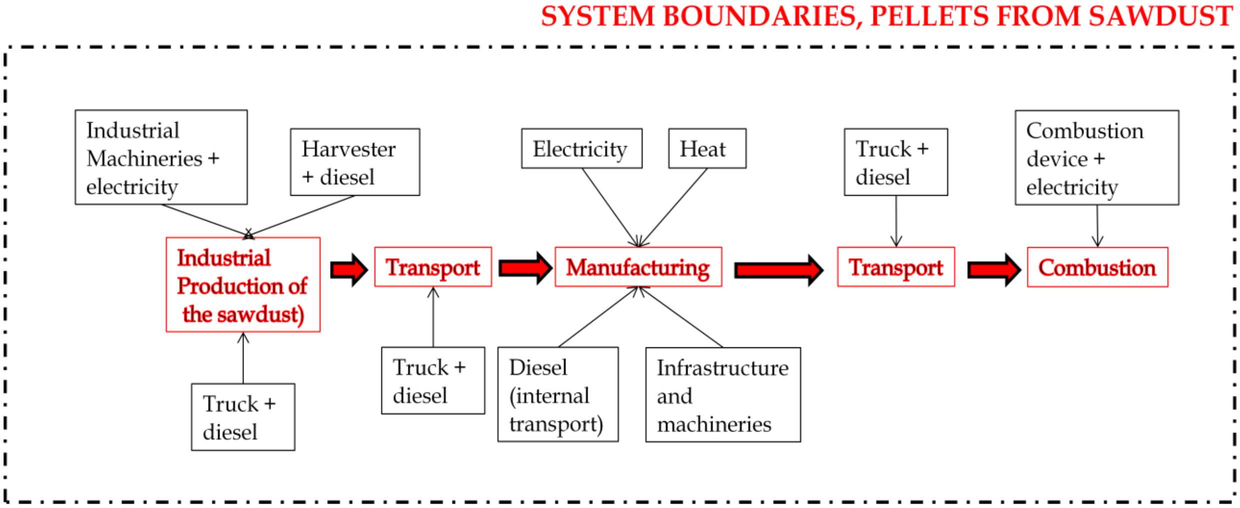

Figure 10: System boundaries for the scenario of wood pellets produced from sawdust

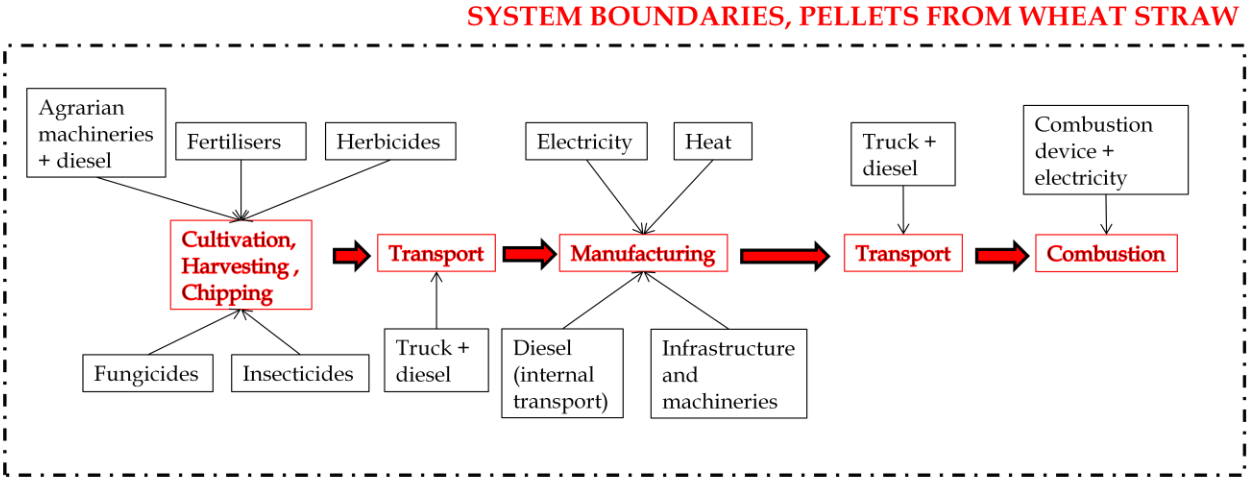

Figure 11: System boundaries for the scenario of wood pellets produced from wheat straw

Concerning the processes that have been created for this study, a default value of a cut-off rule of 1% shall be applied. This means that for the overall LCI result of the product 99% of the environmental impacts are included. For the other processes, taken from the Ecoinvent database, the cut-off rules are implied in the process itself.

The impact categories to be considered and the methods to be used to evaluate such impacts have been chosen following the indications of the *ILCD handbook, Recommendations for life cycle impact Assessment in the European context* [19].

The impact categories analysed in this study are:

- Climate change
- Ozone depletion
- Human ecotoxicity
- Particulate matter/ Respiratory inorganics
- Ionising radiation
- Photochemical ozone formation
- Acidification
- Eutrophication, terrestrial
- Eutrophication, aquatic
- Ecotoxicity (freshwater)
- Ecotoxicity (terrestrial)
- Resource depletion, mineral, fossil and renewable

A list of all the scenarios analysed in this study is reported in Table 9.

	Name	**Feedstock**	**Provenience of the pellets**	**Combustion facilities**
1	*FR, EU, DS*	Woodchips from forest residues	Europe	Domestic stove
2	*FR, EU, DH*	Woodchips from forest residues	Europe	District heating
3	*FR, EU, CHP*	Woodchips from forest residues	Europe	Combined heat and power
4	*FR, Canada, DS*	Woodchips from forest residues	Canada	Domestic stove
5	*FR, Canada, DH*	Woodchips from forest residues	Canada	District heating
6	*FR, Canada, CHP*	Woodchips from forest residues	Canada	Combined heat and power
7	*Poplar, DS*	Woodchips from poplar	Europe	Domestic stove
8	*Poplar, DH*	Woodchips from poplar	Europe	District heating
9	*Poplar, CHP*	Woodchips from poplar	Europe	Combined heat and power
10	*SD, all mass, DS*	Sawdust wet, emissions allocated by mass	Europe	Domestic stove
11	*SD, all mass, DH*	Sawdust wet, emissions allocated by mass	Europe	District heating
12	*SD, all mass, CHP*	Sawdust wet, emissions allocated by mass	Europe	Combined heat and power
13	*SD, all price, DS*	Sawdust wet, emissions allocated by price	Europe	Domestic stove
14	*SD, all price, DH*	Sawdust wet, emissions allocated by price	Europe	District heating
15	*SD, all price, CHP*	Sawdust wet, emissions allocated by price	Europe	Combined heat and power
16	*SD, 40% dry, all price, DS*	Sawdust, 40% dry	Europe	Domestic stove
17	*SD, 40% dry, all price, DH*	Sawdust, 40% dry	Europe	District heating
18	*SD, 40% dry, all price, CHP*	Sawdust, 40% dry	Europe	Combined heat and power
19	*Straw, DE, DH*	Straw	Germany	District heating
20	*Straw, PL, DH*	Straw	Poland	District heating
21	*Straw, ES, DH*	Straw	Spain	District heating
22	*Straw, NL, DH*	Straw	Netherlands	District heating
23	*Straw, UK, DH*	Straw	United Kingdom	District heating
24	*Straw, DE, CHP*	Straw	Germany	Combined heat and power
25	*Straw, PL, CHP*	Straw	Poland	Combined heat and power
26	*Straw, ES, CHP*	Straw	Spain	Combined heat and power
27	*Straw, NL, CHP*	Straw	Netherlands	Combined heat and power
28	*Straw, UK, CHP*	Straw	United Kingdom	Combined heat and power

Table 9: Scenarios analysed in this study

The environmental impacts of these pathways have been compared to a reference scenario. It was assumed that all the scenarios analysed substitute heat by natural gas, so they are compared with an equivalent system that delivers 1 MJ of heat, fed with natural gas.

This is the system not likely to be replaced by wood pellets plants, above all the large-scale ones, and it is also the "cleanest" fossil fuel so that the comparison will be done towards the most efficient technology.

The three reference system for different three different combustion devices are reported in Figure 12, Figure 13 and Figure 14.

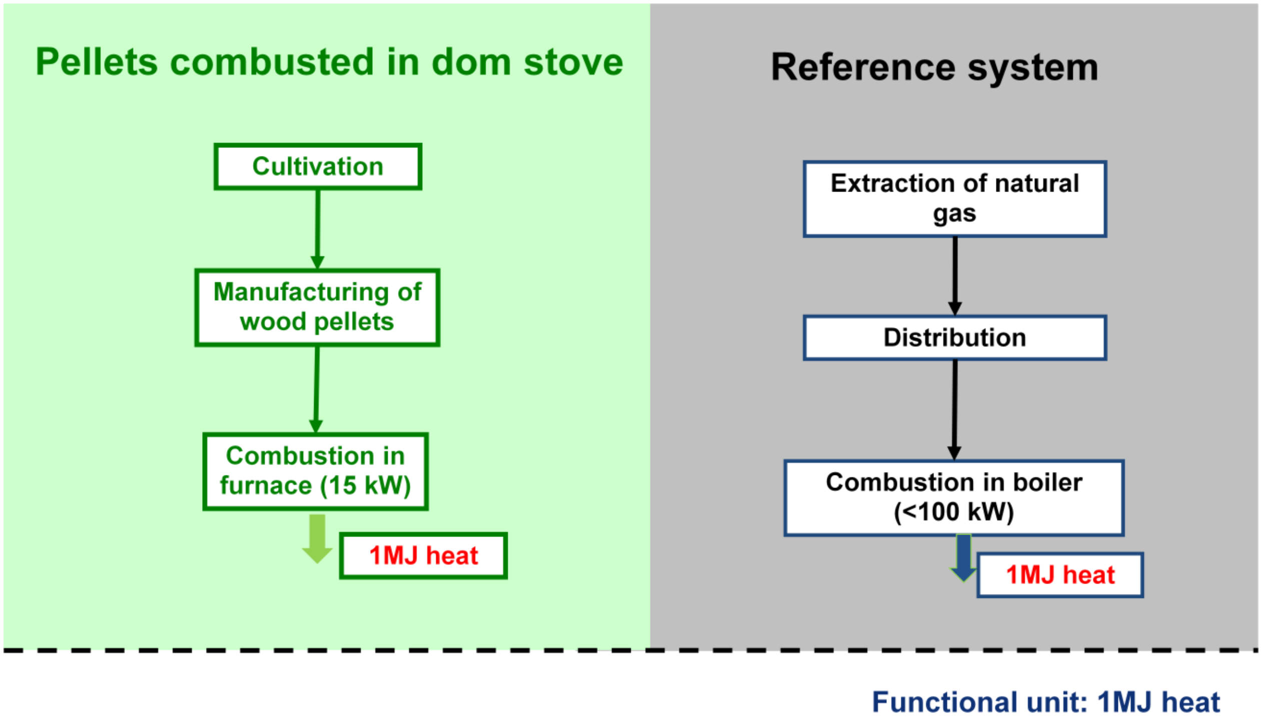

Figure 12: Reference system for the domestic stove pathways

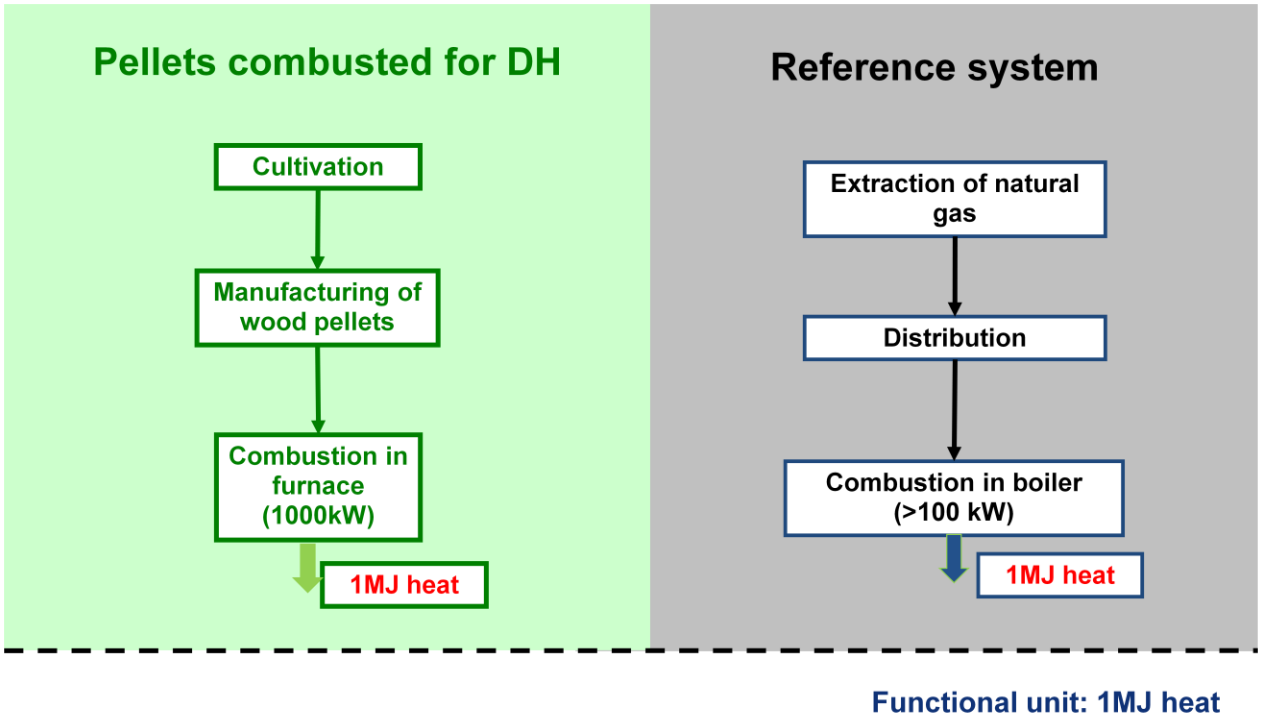

Figure 13: Reference system for the district heating pathways

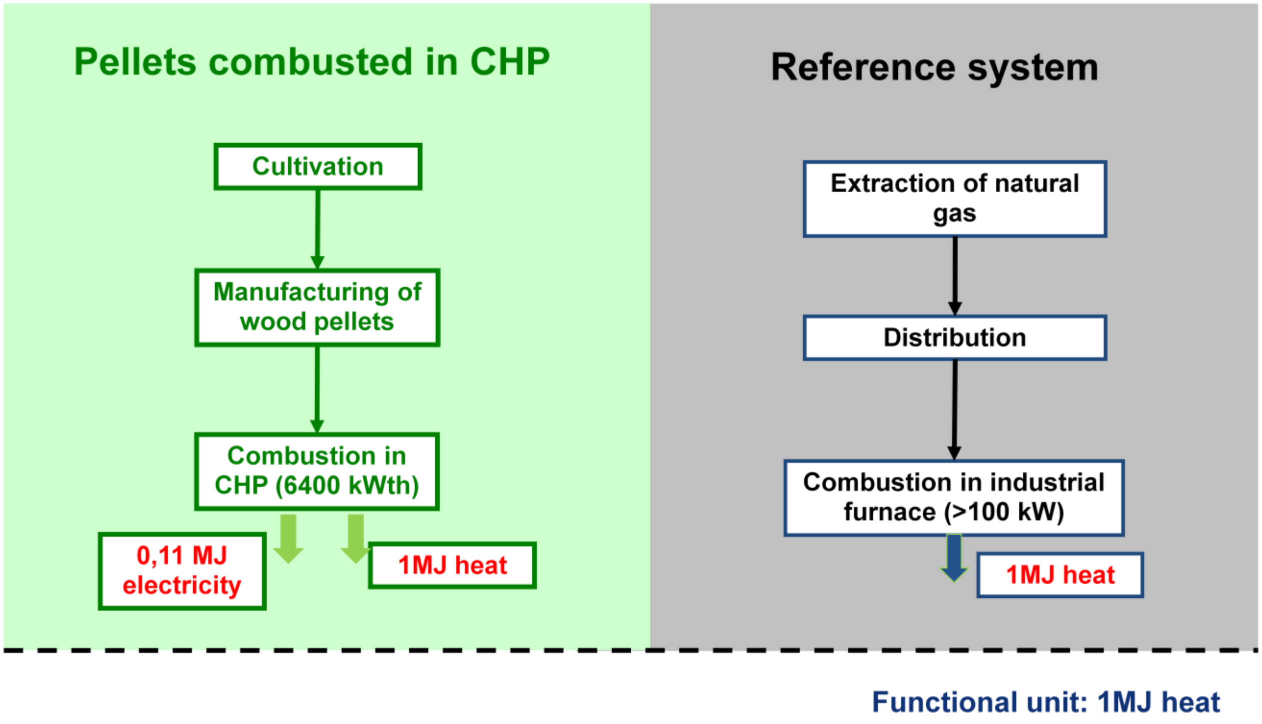

Figure 14: Reference system for the CHP pathways

The processes for reference scenario are taken from the Ecoinvent database v2.2 and the emissions factors for the main pollutants released during the combustion of natural gas are reported in Table 10 in terms of mass of nitrogen per one mega-joule of heat produced.

	CO_2	CO	Dust (>PM10)	Dust (PM2.5)	NMVOC	NOx	SO_X	CH_4
	mg/MJ_{heat}	mg/MJ_{heat}	mg/MJ_{heat}	mg/MJ_{heat}	mg/MJ_{heat}	mg/MJ_{heat}	mg/MJ_{heat}	mg/MJ_{heat}
Domestic boiler	59360	2,12	0,00	0,00	4,11	15,69	0,58	2,12
Boiler >100kW	69427	16,16	1,56	0,65	28,76	43,25	2,72	174,24
Industrial furnace >100kW	70094	17,08	1,58	0,65	29,04	46,07	27,50	175,92

Table 10: emissions factor of the reference scenarios [mg/MJ_{heat}]

5.2 Life Cycle Inventory

In this phase of the LCA all the processes are identified, described and modelled.

The study analyses various pathways, differing for the choice of the raw material, its origin and the size of the combustion facilities.

Figure 15 shows a general scheme of the processes analysed in this study.

In the next paragraphs all the pathways are described in details and analysed, in particular focusing on the process variables and the collection of data.

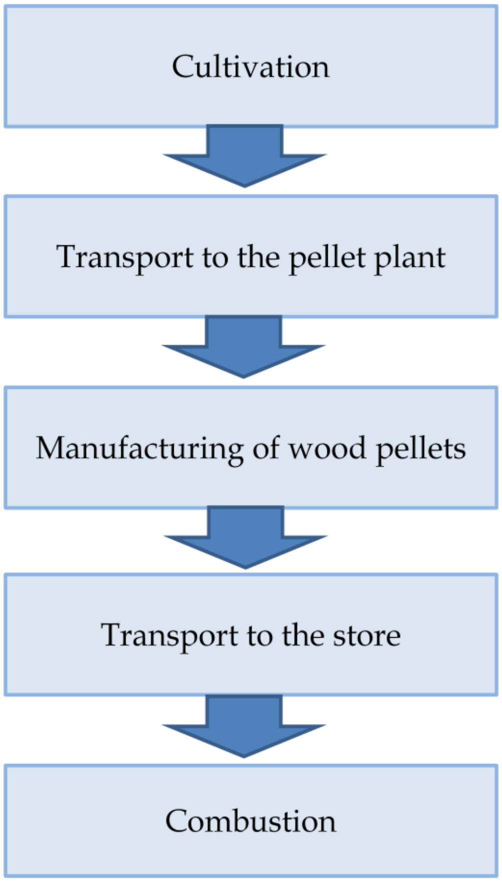

Figure 15: General scheme of the processes analysed

Although not all the feedstocks analysed require a proper cultivation phase, intended as the application of agrarian techniques to the field, in order to simplify the representation of the data, the *cultivation* in next plots and table includes also the processes of the production of a feedstock (e.g. the "cultivation" of the sawdust has to be intended as the sequence of processes that brings to the production of the sawdust: harvest of the trees, transport to the lumber meal and industrial production of the sawdust).

5.2.1 Cultivation

As described in the previous chapters, many feedstocks can be used to manufacture pellets. Having a densified fuel with standardised and homogeneous characteristics is advantageous for the many reasons described in the Chapter 1.

Any of such feedstocks is associated with a different pathway and processes. This study analysed both some of the most commonly used pathways and some others that will become increasingly relevant in the near-medium future.

Depending on the feedstocks, pellets are defined as wood pellets (generally from residues of wood industry), more commonly used, and agripellets from agricultural residues.

The raw materials used for wood pellets production used to be quite specific: until 2008 the sector used largely leftover feedstocks such as sawdust (mainly produced during the processing of logs) and wood shavings (processing of sawn wood) [60], [17], [52].

However, in the near future, forest chips from logging residues such as whole and tops (forest slash) from existing forests and new energy plantations, e.g. poplar and willow will become technically and economically feasible. They can be pelletized alongside traditional feedstocks [17], [60].

Another important residue potentially available for pelletization is straw that is already widely used as a fuel but mostly in dedicated plants near the fields and in bales form. With the increase in use of bioenergy, straw pellets might open up an important market for international trade [17]. According to EUBIA [17] near 23 million tons of dry biomass from straw could be available yearly in the EU. The most advanced European country in that field is undoubtedly Denmark, where more than 750,000 tons of straw (and 1.3 million tons of wood) are used every year in power plants, industries, district heating plants, farms and private households.

The analysis carried out in this thesis is focused on the following feedstocks:

- Wood chips from forest residues
- Wood chips from short rotation coppice

- Wet sawdust from industrial processes
- Partially dry sawdust from industrial processes (40% dry sawdust and 60% wet sawdust)
- Straw

5.2.1.1 *Wood chips from forest residues*

Forest residues typically are the parts of trees unsuitable for sawlogs, such as treetops, branches, small-diameter wood, stumps, dead wood and even misshapen whole trees, as well as undergrowth and low-value specie.

Woodchips are generally produced directly at forest, using a mobile chopper [65], but in certain cases they can also be produced at a more central location with larger equipment or even directly at the power plant [31].

The characteristics of wood chips assumed for this study and the sources of the data are shown in Table 11.

	Unit	Amount	Source
LHV dry	MJ/kg_{dm}	19	[1]
Moisture content	%	40	Pool of JRC sources
Bulk density	kg/m^3	238	[1]
Mass density	kg/m^3	580	[1]

Table 11: Characteristics of woodchips from forest residues

Data for the production of woodchips are taken from the process of Ecoinvent database v.2.2 *Wood chips, mixed, u=120%, at forest*. In this process, the moisture content is express as percentage of water on dry basis. The correspondent moisture content in term of kg_{water}/kg_{chips} is 0,54, that is higher than the one considered in this study, because it is assumed that during the storage in the forest a fraction of the water evaporates from the wood [1].

The mass density and the bulk density of the woodchips are calculated considering the saturation point of the fibres as indicated in the AEBIOM wood fuel handbook, 2009. [1]

Forests can be composed by different types of wood species; in this case it is assumed that wood chips from forest residues are made by a mix of softwood (72%) and hardwood (28%) [65], which is a reasonable assumption for European forests.

Magelli et al. [44] state that the wood resource can be an established forest or a natural one. The Ecoinvent process refers to a natural forest in which the trees grow up without the use of fertilizers and in this study the case of an established forest is not considered because it is not common in Europe.

The main inputs of the process are:

- Hardwood and softwood
- Energy and raw materials for the construction and the construction of the machinery for harvesting and chipping
- Energy and materials for the utilisation of the machinery for harvesting and chipping

The main output flows are woodchips and environmental emissions

5.2.1.2 *Wood chips from short rotation forestry*

Short rotation forestry indicates woody vegetation grown on a repeated coppice cycle of 3-4 years specifically for the production of biomass [25]. Poplars and willows are the short rotation species mainly used in pellets manufacture [52].

Given that the characteristics and the cultivation processes of poplar and willow are quite similar, data are taken from publications related to both the species. It is considered acceptable because the data of this work are an average of the European situation and the difference between data from different sources is actually a factor of higher uncertainty than the species of wood.

The establishment and the cultivation phases of short rotation forestry generally includes a step called *nursery phase* during which the field is ploughed, weeds are eliminated using herbicides or mechanical methods, the field is enriched of nutrients by means of synthetic or organic fertilizers, the seeds are sown and the trees start growing. In practise, trees of 1-2 years are bought directly from a plant nursery and then planted in the prepared field. For simplicity it is here considered that the trees grown from field directly from seeds. The duration of this phase varies from case to case and generally it lasts one to two years.

It is important to underline that not all the operations described are strictly necessary, some of them such as fertilization, the use of pesticides and the use of herbicides are site-specific and mainly depend on the characteristics of the field.

Afterward, the actual rotation stars: trees are cultivated for a period that lasts from 2 to 4 years, depending on the management techniques adopted and then they are harvested. Depending on the context, a different number of rotations can be done, generally between 4 and 7 rotations are collected.

There are harvesters that can apply a direct-chip harvesting method in which stems are cut, chipped and blown into an accompanying trailer, using the same machinery. Hence chipping is considered as an operation that is made on the field included in the cultivation process [32], [55].

During each rotation the plantation might need an extra contribution of nutrients so, often, fertilisers are applied every year of the rotation or after every coppice.

At the end of the rotations, also stools must be removed from the field.

The characteristics of the wood chips from short rotation coppice are considered in this study to be the same as the ones of wood chips from forest residues, described in Table 11 as for coherence it is better to have a consistent flow across all the pathways.

Cultivation of poplar

It was not possible to find a reliable process of poplar cultivation and chipping in any commercial database, thus it has been necessary to model a completely new process.

Al the input data and their references are listed in Table 12

Flow	**Unit**	**Amount**	**Source**	**Comments**
N fertiliser	$kg_N/MJ_{woodchips}$	0,000379	Average [55], [62], [26], [34], [46], [32]	Urea
Glyphosate	$g_{AI}/MJ_{woodchips}$	0,000693	[32]	Herbicide
Oxyfluorfen	$g_{AI}/MJ_{woodchips}$	0,000311	[32]	Herbicide
Water	$l/MJ_{woodchips}$	0,004320	Average [55], [7]	
Mobile chopper	$Kg/MJ_{woodchips}$	0,088088	Ecoinvent	
Broadcaster	$m^2/MJ_{woodchips}$	0,002288	Calculated	
Spring harrow	$m^2/MJ_{woodchips}$	0,002288	Calculated	
Plough	$m^2/MJ_{woodchips}$	0,002288	Calculated	
Weeder	$m^2/MJ_{woodchips}$	0,002288	Calculated	
Carbon dioxide	$Kg/MJ_{woodchips}$	0,094561	[32]	Carbon uptake

Table 12: Input data to the short rotation coppice cultivation process

All the data related to the use of fertilisers and chemicals are taken from specific literature.

The nitrogen fertiliser can be spread on the field in different form such as Urea [46], Ammonium sulphate [32] etc.

In this work it is assumed to use Urea: this is the cheapest N-fertiliser available, thus it is also the most commonly used in Europe. [36].

The quantity of fertiliser used is expressed in terms of mass of nitrogen.

The quantity of nitrogen fertiliser considered in this study is calculated as average value of different literary values, that are listed in Table 13.

All the values are expressed in terms of $Kg_N/MJ_{woodchips}$ in order to make them comparable.

Unit	Amount	Source	Comment
$Kg_N/MJ_{woodchips}$	0,000718	[55]	Poplar
$Kg_N/MJ_{woodchips}$	0,000266	[26]	Poplar
$Kg_N/MJ_{woodchips}$	0,000541	[46]	Poplar
$Kg_N/MJ_{woodchips}$	0,000332	[34]	Poplar
$Kg_N/MJ_{woodchips}$	0,000341	[26]	Willow
$Kg_N/MJ_{woodchips}$	0,000278	[34]	Willow
$Kg_N/MJ_{woodchips}$	0,000120	[32]	Willow
$Kg_N/MJ_{woodchips}$	0,000437	[62]	Willow

Table 13: Literary value for nitrogen fertiliser calculation

The values indicated are relatively consistent, implying that the average data obtained can be considered robust. The use of other types of fertilisers, such as phosphorous and potassium based fertilisers, is not considered in this study because an extra-contribution of these nutrients is not always necessary for the cultivation of poplar and willow. It depends on the soil composition, as underlined before, thus it has been considered negligible for the European case.

Concerning the herbicides, data are taken only from the study by Heller at al. [32], because in other studies different kinds of chemical products are used and it is impossible to make quantities of different types of herbicides comparable, in order to make an average between them. The study of Heller et al. is referred to a cultivation of poplar located in the USA where Glyphosate, Simazine and Oxyfluorfen are used as herbicides. The use of Simazine has been forbidden in Europe years ago, so in this study it has been assumed that only the Glyphosate and the Oxyfluorfen are applied to the poplar cultivation. The total quantity of herbicides applied, in terms of mass of active ingredient, is assumed to be the same of the study by Heller et al. [32]: the mass of active ingredient of Simazine has been shared between Oxyfluorfen and Glyphosate in reason of their percentage on the total amount of herbicides and then added to the mass of active ingredient of the two herbicides.

The quantity of water used is calculated as an average between the values used in the study of Rafaschieri et al. [55] and Caserini et al. [7].

Table 14 includes the two values used in the mentioned studies.

Unit	Amount	Source
$l/MJ_{woodchips}$	0,004944	[55]
$l/MJ_{woodchips}$	0,003696	[7]

Table 14: Literary values for water calculation

Considering a LHV of woodchips of 19 MJ/kg_{dm} [1] and a biomass yield of 10 $t_{dm}/ha/y$ [46], the water request for short rotation forestry cultivation results to be equal to 820 l/ha/y.

Data regarding the use of agrarian machinery are expressed in terms of $m^2/MJ_{woodchips}$ and are calculated as:

$$A\,[ha] = \frac{1}{LHV\left[\frac{MJ}{t}\right] * Yield\left[\frac{t}{ha * y}\right] * Duration\ of\ the\ SRC\,[y]}$$

Where: Yield=10 $t_{dry}/ha/y$ [46]

Duration of the SRC= 23 years [32].

As mentioned earlier, the emissions due to the construction and use of the machinery and due to the production and spreading of the chemicals, are included in this study and the values are taken from the Ecoinvent database.

The quantities of mobile chopper expressed in terms of $Kg/MJ_{woodchips}$ is taken from the process of Ecoinvent database *Wood chips, hardwood, u=80% at forest,* described in the Ecoinvent report by Werner et al [65].

The carbon uptake is due to the photosynthesis that makes the trees able to absorb carbon dioxide from the atmosphere during their growth.

The quantity of carbon dioxide assumed to be stored during the life of the plantation has been calculated assuming a carbon content in wood of 49% on dry basis [32], and dividing this value for the LHV (19 MJ/kg_{dm}). The final result is 25,8 $g_C/MJ_{woodchips}$, that corresponds to 94,6 $g_{CO2}/MJ_{woodchips}$.

The use of pesticides for the short rotation forestry in this study has not been included mainly because the scientific community has not reached a consensus about this issue yet and also because in most of the scientific studies analysed their use has not been considered [29], [32] [57]. Due to the relative novelty of the use of short rotation forestry for energy purposes, it is not yet clear whether the use of pesticides will be economically viable. This is instead quite a common practice for poplar plantation for timber logging where protection is needed for poplar borer.

Modelling the fate of fertilisers in the environment

The use of fertilisers and herbicides implies their partial dispersion in the environment and subsequent environmental impacts.

It is assumed that the nitrogen is partly released in the environment in the form of:

- N_2O in the atmosphere
- NH_3 in the atmosphere
- NO_3^- in the groundwater [41], [32]

The amounts of these flows to the environment are calculated following the methods suggested in the literature by different references: the IPPC [37] is used for N_2O emissions, the Ecoinvent report about agriculture [50] for NH_3 and the study of Kern et al. [41] for NO_3^-.

The emissions of N2O are calculated as the sum of direct and indirect emissions, following the guidelines of IPPC [37].

In an average scenario, the direct emissions of N_2O from the field are assumed to be the 1% of the total quantity of nitrogen fertilisers applied.

Indirect emissions of N_2O take place through two different pathways.

The first of these mechanism is the volatilisation of N as ammonia (NH_3) and oxides of nitrogen (NO_x) from the field, and the deposition of these gases and their products, NH_4^+ and NO_3, onto the soils and the surfaces of lakes and other waters.

The sources of N as NH_3 and NO_x are not confined to agricultural fertilisers and manures, but also include fossil fuels combustion, biomass burning, and processes in the chemical industry. Thus, these processes cause N_2O emissions in an exactly analogous way to those resulting from deposition of agriculturally derived NH_3 and NO_x, following the application of synthetic and organic N fertilisers.

Considering that in this study the use of only one inorganic fertiliser has been assumed, this first contribution to indirect N_2O emissions is calculated as:

$$N_2O - N_{ATD} = F_{SN} * EF_4 * Frac_{GASM}$$

Where: $N_2O–N_{ATD}$= annual amount of $N_2O–N$ produced from atmospheric deposition of N volatilised from managed soils [kg_{N2O-N}/ y]

F_{SN}= annual amount of synthetic fertiliser N applied to soils [kg_N/y]

EF_4= emission factor for N_2O emissions from atmospheric deposition of N on soils and water surfaces [$kg_{N_2O\text{-}N}/kg_{NH_3\text{–}N + NO_x\text{–}N\ volatilised}$]

$Frac_{GASF}$= fraction of synthetic fertiliser N that volatilises as NH_3 and NO_x [$kg_{Nvolatilised}$ /$kg_{Napplied}$]

The specific values of IPPC parameters for an average scenario used in this study are 1% for EF4 and 10% for $Frac_{GASF}$, this implies that the contribution to indirect N_2O emissions, in terms of N, due to the volatilisation of NH_3 and NO_x is the 0,1% of the nitrogen fertiliser applied, expressed in mass of nitrogen.

The second pathway that contributes to indirect emissions of N_2O is the leaching and runoff from land of nitrogen from synthetic and organic fertiliser additions.

Some of the inorganic nitrogen in or on the soil, mainly in the form of NO_3^- , may bypass biological retention mechanisms in the soil/vegetation system by transport in overland water flow (runoff) and/or flow through soil macropores or pipe drains. Where NO_3^- is present in the soil in excess of biological demand, the excess leaches through the soil profile.

The contribution of this phenomenon to indirect emission of N_2O has been calculated as:

$$N_2O - N_L = F_{SN} * EF_5 * Frac_{LEACH}$$

Where: $N_2O\text{–}N_L$ = annual amount of N_2O–N produced from leaching and runoff of N additions to managed soils in regions where leaching/runoff occurs [$kg_{N2O\text{-}N}$/ y]

EF_5= emission factor from N leaching and runoff [$kg_{N_2O\text{-}N}$/kg $N_{leached+runoff}$]

$Frac_{LEACH}$= fraction of all N added to/mineralised in managed soils in regions where leaching/runoff occurs that is lost through leaching and runoff [$kg_N/kg_{Napplied}$]

In this study the parameters EF_5 and $Frac_{LEACH}$ in average conditions are assumed to be respectively 0,75% and 30%. This results in a final contribution to N_2O indirect emissions due to nitrates leaching that is 0,225% of the fertiliser applied expressed in terms of mass of nitrogen. Finally the emissions of N_2O in atmosphere in terms of mass of nitrogen are the 1,325% of the total mass of nitrogen applied with fertilisation and the specific contributes are:

- 1% from direct emission from the field
- 0,1% from the ammonia volatised
- 0,225% from the nitrates leached

Ammonium contained in fertiliser can easily be converted into ammonia and released to the atmosphere [50].

In this study the emissions of NH_3 in terms of mass of nitrogen are calculated as the 15% of fertiliser applied expressed in terms of mass of nitrogen [50]. It is important to note that Urea, compared to other nitrogen fertilisers, is the one that has the highest percentage of ammonia emitted, due to its specific chemical composition.

The quantity of nitrates that is leached in the underground water is strongly dependent on the granulometry of the soil and on the quantity of the rainfall during the year. The study by Braum [5], for example, shows that the nitrates leaching in two consecutive seasons on the same soil decreased of about 90% because the rainfall was lower.

In this study, the quantity of nitrate assumed to be leached in the soil is the 8% of the nitrogen fertiliser applied (in terms of mass of nitrogen) [41].

Data referred to the volatilisation and leaching of nitrogen are not the same used for the calculations of indirect emissions of nitrous oxide, for which the data suggested by the IPCC [37] are used. The choice to use other data is justified by the fact that these data are more specific: the percentage of volatilisation of ammonia is specific for the use of Urea and the percentage of nitrogen leached as nitrate is taken from an experimentation on a poplar cultivation.

Modelling the fate of herbicides in the environment

Regarding the distribution of the herbicides in the environment, the Mackay fugacity model has been used to estimate the fate of the chemical products applied to the short rotation coppice.

This model defines how the chemicals are going to distribute after their application in the environment, depending on their physical and chemical properties and on the characteristics of the environment.

The environmental compartments considered by this model are: soil, water, atmosphere, sediments, suspended solids and biota.

The estimation is based on the definition of a parameter called *fugacity (f)* that describes the "escaping" tendency of a chemical species from a particular environmental compartment in order to reach the equilibrium of the system.

The fugacity has a unit of pressure [Pa] and at the steady state the value of this parameter is the same for all the environmental compartments.

Each environmental medium is characterised by its own *fugacity capacity (Z) that* describes the relationship between chemical concentration and fugacity.

$$Z = \frac{C}{f}$$

Where: Z= fugacity capacity [mol/m^3/Pa]

C= concentration in the environmental compartment considered [mol/m^3]

f = fugacity [Pa]

The fugacity capacity represents the maximum concentration potentially kept in a compartment at the pressure of one Pa. It can be calculated for each compartment in function of the physical and chemical parameters of each substance and of the environmental conditions. In particular:

$$Z_{water} = \frac{1}{H}$$

$$Z_{soil} = Z_{SS} = Z_{sediment} = \frac{d * k_p}{H}$$

$$Z_{air} = \frac{1}{R * T}$$

$$Z_{biota} = \frac{d * k_b}{H}$$

Where: H =Henry's law constant [m^3*Pa/mol]

d = soil density [Kg/l]

k_p = partition coefficient between water and solids [l/Kg]

R = ideal gases law constant [Pa * m^3/mol/K]

T = temperature [K]

k_b= bioconcentration factor [l/kg]

Knowing the volume of each compartment, it is possible to evaluate the distribution of the chemical substances in the environment.

The Mackay fugacity model can be applied using three different level of complexity.

The first level is the less complex and it was assumed to be appropriate for the level of accuracy required in this study and is thus the one that has been used. It considers a closed system in its steady state in which there are no chemical reactions.

Considering the following equations:

$$M_t = \Sigma\, C_i * V_i$$

$$C_i = f * Z_i$$

it is possible to derive the formula of fugacity:

$$f = \frac{M_t}{\sum_i Z_i * V_i}$$

Where: M_t = moles of chemical spread in the environment [mol]

V_i = volume of the compartment i [m^3]

Once the fugacity has been calculated, the concentration of the chemicals in each compartment can be easily estimated.

The Mackay model can be applied only to organic compound that are not polymerizable.

In this study the model cannot be applied to Glyphosate [39], but it has been applied to Oxyfluorfen.

The repartition of Oxyfluorfen in the environmental compartments is reported in Table 15.

In this study the flows of Oxyfluorfen to the atmosphere, to the water and the suspended solid are considered as negligible and are not accounted, whereas the flows of chemicals to soil and sediments have been summed up, because the software GaBi, used for the LCIA does not make any difference between the two compartments.

To model the fate of Glyphosate in the environment, data are taken from the study of Rafaschieri et al. [55], that states that the 90% of the chemical persists in the soil, the 3% goes in the ground water for run-off and percolation phenomena, and no chemical migrates to the atmosphere. The remaining 7% of Glyphosate is assumed to be degraded in the soil and absorbed by weeds.

	% Oxyfluorfen
Atmosphere	4,2%
Water	12,3%
Soil	43,2%
Sediments	40,3%
SS	0,1%
Biota	0,0%

Table 15: Repartition of Oxyfluorfen in the environmental compartments

All the output values of the cultivation of the wood chips from short rotation coppice are shown in the Table 16.

Flow	**Unit**	**Amount**	**Source**	**% of the input flow**
N_2O	$kg_{N2O}/MJ_{woodchips}$	7,90E-06	[37]	1,33 % of N
NH_3	$kg_{NH3}/MJ_{woodchips}$	6,91E-05	[50]	15 % of N
NO_3^-	$kg_{NO3}/MJ_{woodchips}$	1,34E-04	[41]	8% of N
Oxyflourfen to soil	$g_{AI}/MJ_{woodchips}$	2,59E-04	Mackay model	83,46 % of Oxyflourfen
Glyphosate to soil	$g_{AI}/MJ_{woodchips}$	6,24E-04	[55]	90,00 %of Glyphosate
Glyphosate to water	$g_{AI}/MJ_{woodchips}$	2,08E-05	[55]	3,00 %of Glyphosate
Wood poplar chips	MJ_{chips}	1		

Table 16: Outputs data to the short rotation coppice cultivation process

The mass balance of the nitrogen is assumed to be closed considering that all the nitrogen fed to the cultivation is partly lost in the environment (24,3%), as highlighted in Table 16, and the remaining part (75,7%) is absorbed by the trees as nutrient. This means that the quantity of nitrogen absorbed by the trees during their life is about 5,4 kg_N/t_{dry}.

The herbicides instead are not absorbed by the trees so their fate is to be lost in different environmental compartments depending on their chemical and physical properties, and to be partially degraded or absorbed by the weeds that they are supposed to kill.

5.2.1.3 *Wet sawdust from industrial processes*

The sawdust used for the production of wood pellets analyzed in this study is a by-product of the production of sawn timber in Scandinavia. Data referring to the production of sawdust are taken from the Ecoinvent process *Sawdust, Scandinavian softwood (plant debarked), u=70%, at plant* that is described in details in one of the Ecoinvent report by Hischier [33]. It is important to notice that the moisture content in Ecoinvent database is expressed in terms of Kg_{water}/Kg_{dm}, that means that the wood considered has a moisture content of 0,41 Kg_{water}/Kg_{wood}.

The characteristics of the sawdust as used in this work are listed in the Table 17.

	Unit	Amount	Source
LHV dry	MJ/kg_{dm}	19	[1]
Moisture content	%	41,2%	[33]
Bulk density	kg/m^3	222	[1]
Mass density	kg/m^3	673	[3]

Table 17: Characteristics of sawdust

The main input flows to the process are:

- Wood
- Energy and raw materials for the construction and the transport of the machinery for the industrial process
- Energy and materials for the utilisation of the machinery for the industrial process

The main output flows are:

- Sawn timber
- Wood chips
- Sawdust
- Environmental emissions.

Being a process with more than one output it is necessary to associate the total emissions to the environment to each output. To do this, the standards ISO 14040 and ISO 14044 recommend a hierarchy of methods to apply. In this study, it has been chosen to allocate the emissions of the process to the three outputs, comparing the effects of different allocation approaches: by price, by mass and by energy.

Table 18 contains the allocation factors and the values of the parameters used to calculated them.

	Allocation factor by price [-]	**Volume [m³]**	**Density [Kg/m3]**	**Allocation factor by mass**	**LHV [MJ/Kg$_{dry\ matter}$]**	**Allocation factor by energy**
Sawn timber	0,96	1	673	**0,69**	19	**0,69**
Woodchips	0,03	0,841	276	**0,24**	19	**0,24**
Sawdust	0,01	0,3	222	**0,07**	19	**0,07**

Table 18: Characteristics of the output flows and allocation factors

The allocation factors by price and the volume of sawn timber, woodchips and sawdust are taken from the Ecoinvent Database [33]

The densities are calculated following the indication of the *Wood fuels handbook*, by Aebiom [1] for Pine.

Allocation factors by mass and by energy are considered to be the same because the lower heating values of the three outputs are the same. For this reason in the next part of the study, often the considerations are referred just to allocation by mass, implicating that the results for energetic allocation are exactly the same.

5.2.1.4 *Partially dry sawdust from industrial processes*

This pathway analyses the use of a mix of wet and dry sawdust. It is assumed that the wet and the dry sawdust are produced in the proportion of 60% from fresh wood at 50% moisture, and 40% from partially dry wood at 10% moisture [56].

The process of the production of the partially dry sawdust is considered to be comparable with the one of the production of wet sawdust analysed before and the emissions due to the drying of the sawdust in the industrial process can considered to be negligible. In fact, considering the allocation factor (0,01), the emissions due to the additional wood required for drying of the timber in a kiln furnace are considered to be negligible, according to the cut-off rules chosen, The main differences in terms of environmental impact will be in the next processes due to the lower energy density and thus higher transport emissions and the higher request of energy for drying in the pellets manufacturing.

The characteristics of the partially dry sawdust assumed for this study, obtained as a weighted average of the characteristics of the two flows of sawdust are contained in Table 19.

	Unit	Amount	Source
LHV dry	MJ/kg $_{dm}$	19	[1]
Moisture content	%	28,7%	Weighted arithmetic mean
Bulk density	kg/m^3	204	[1]
Mass density	kg/m^3	619	[1]

Table 19: Characteristics of partially dry sawdust

The environmental emissions are allocated to the partially dry sawdust only by price.

5.2.1.5 *Straw*

The characteristics of the straw considered in this study are listed in the Table 20.

	Unit	Amount	Source
LHV dry	MJ/kg$_{dm}$	17,5	[11]
Moisture content	%	14	[63], [11]
Bulk density	kg/m^3 dry basis	130	[17]
Density (wet basis)	Kg/m^3	151	Calculated

Table 20: Characteristics of straw

Straw is a by-product of the production of wheat.

The processes used to quantify the environmental impact of the cultivation of wheat and the production of straw was purchased from PE International. The data sets refer to the processes of wheat straw winter cultivation in five different European countries: Germany, Poland, United Kingdom, the Netherlands and Spain. Data are site specific and strictly related to the region situation.

Emissions are allocated between the two outputs of the process on an economical basis.

The allocation factors by price of straw for each process of the cultivation of wheat straw are reported in Table 21.

	DE	UK	ES	PL	NL
Allocation factor	0,107	0,152	0,122	0,09	0,168

Table 21: Straw allocation factors

The wheat is a yearly crop that is sown in autumn and then harvested in mid summer.
After being harvested, straw can be left in the field to provide nutrients to the next crop or it can be removed for other purposes, as in this case. This causes the necessity to add more fertilisers in order to compensate for the effect of the removal of the straw. This aspect is accounted in the processes of PE international.
The amounts of fertilisers and chemicals assumed to be applied yearly to the crop are shown in Table 22.

	DE	UK	ES	PL	NL
Nitrogen fertiliser [kg_N/ha/y]	165	190	95	65	190
Phosphouros fertiliser [kg_P/ha/y]	30	34	53	10	9
Potassium fertiliser [kg_K/ha/y]	40	42	31	24	10
Fungicides [kg_{AI}/ha]	0.43	0.52	0.03	0.11	0,57
Herbicides [kg_{AI}/ha]	1,43	2,73	0,57	0,69	5,70
Insecticides [kg_{AI}/ha]	0,04	0,05	n.a.	n.a.	0,03

Table 22: Fertilisers applied [Kg_N/ha/y]

5.2.2 Transport

Transport processes include both transport of the raw material to the pellet mill and transport of the pellets to the stores or directly to the boilers in case of combustion in big facilities. If the pellets are used for domestic heating, the transport of pellets from the pellet store to the house is not accounted in this study as its environmental impacts are considered to be negligible.

The choices of the distances and the means of transport for each feedstock and for pellets are based on available information, found in the literature.

For woodchips from European forest residues, wood chips from short rotation coppice, sawdust and straw, it has been considered that are transported by a truck with a payload capacity of 27 t for an average distance of 50 Km between the harvesting place and the pellet mill [57].

The average distance between the pellet plant and the store or the combustion facility has been estimated to be 500 km. This is considered a representative distance for the several flows of pellets common in Europe [60].

The emissions due to the transport are taken from the ELCD database [15].

Concerning forest residues a specific scenario has been analysed: the combustion of wood pellets from Canada. In fact wood pellets from forest residues burned in Europe are sometimes imported from extra-European countries and particularly from Canada.

In the annual statistical report on biomass of Aebiom [2] it is stated that in 2010 the 25% of pellets used in EU27 have been imported from extra-European countries and in particular the 9,4% were from Canada. Considering the constant expansion of bioenergy, this import route is deemed to become even more relevant in the future.

The transport of wood pellets for a long distance implies the combustion of fossil fuels in the means of transport and partly decreases the environmental benefits of using biomass. The choice to consider this scenario allows to weight how much this factor influences the whole environmental impact of wood pellets. It can be considered as a worst case scenario since there are few places in the world farther from Europe than British Columbia.

Data related to the distances and the means of transport for Canadian pellets are taken from the study of Magelli et al [44] that analyses the environmental impact of exported wood pellets from Canada to Europe.

The timbers harvested are supposed to be transported for 110 km by truck from the forest to a centralised plant, where they are chipped and then transported to the pellets plant by truck for 27 km. Afterwards the pellets are carried to the Vancouver port by train for 750 km and then shipped to the Stockholm port. The distance by sea between Vancouver and Stockholm is 15500Km.

It is assumed that, once in Europe, pellets are transported by truck for 100 km to the store or directly to the combustion facility, in case of big plant.

This is not the only route for pellets imported from Canada, in fact other important destination are the harbours of Antwerp and Rotterdam, but in this analysis just this scenarios has been considered, assuming that the differences between these routes in terms of environmental impact of the pellets production chain are small.

Concerning the pellets produced and used in Europe, information about the distances and the means of transport are taken from Sikkema et al. [59].

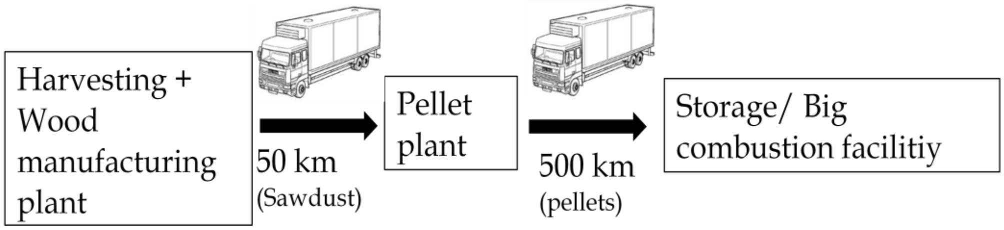

Figure 19 and Figure 20 show a scheme of the transport distances for the pathways considered.

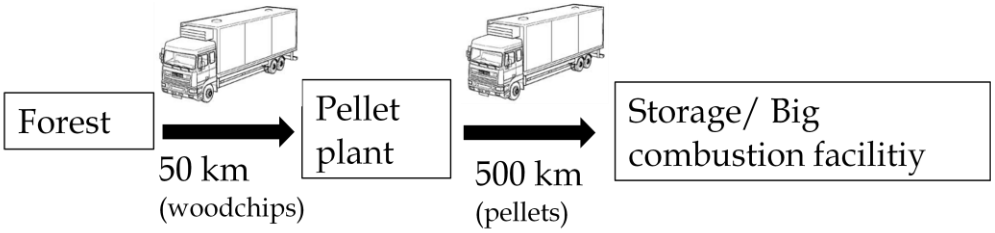

Figure 16: Scheme of the transport of pellets produced from woodchips from forest residues from Europe

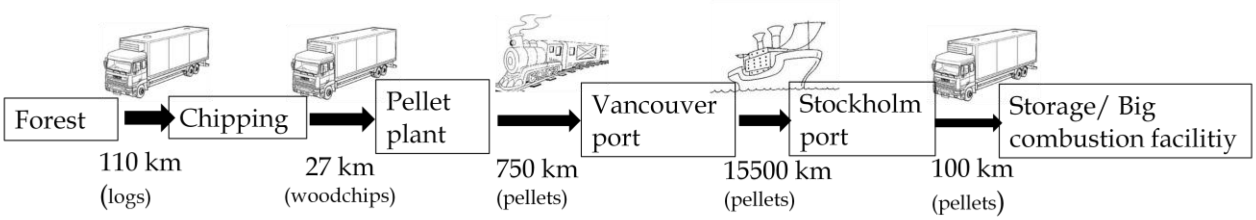

Figure 17: Scheme of the transport of pellets produced from woodchips from forest residues in Canada and exported in Europe

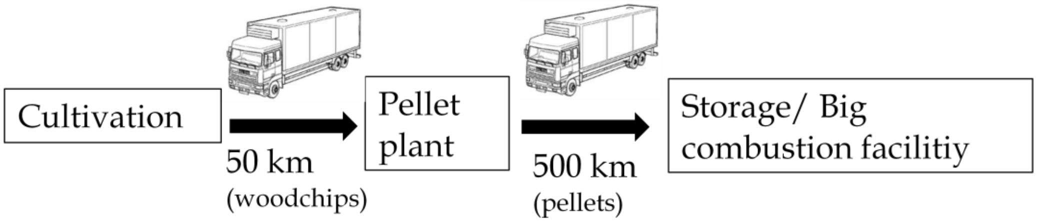

Figure 18: Scheme of the transport of pellets produced from woodchips from poplar

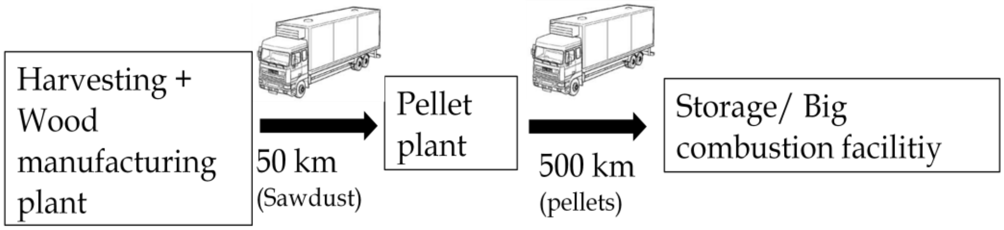

Figure 19: of the transport of pellets produced from sawdust

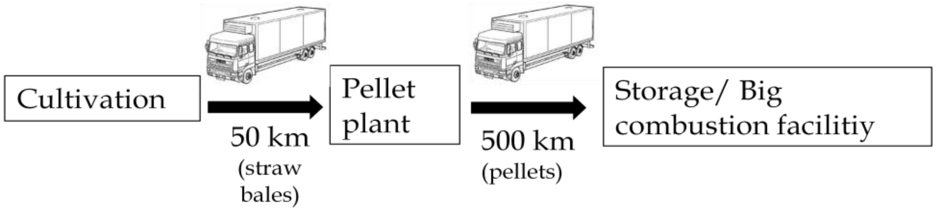

Figure 20: Scheme of the transport of pellets produced from wheat straw

5.2.3 Manufacturing of wood pellets

The process of wood pellet manufacturing consists of a few basic sub-processes: drying, size reduction, pelletizing, cooling, screening and bagging [45].

The processes are considered to be the same for all the feedstocks considered, but there are differences concerning the quantity of energy required for each phase depending on the characteristics of the raw material. For example the pelletisation of straw requires less quantity of energy for the drying phase than the one of wood, due to the lower moisture content of the straw.

The process of pelletisation itself can be preceded by pre-treatments in order to remove inert materials like stones and soil, or metal impurities from the feedstock.

The vast majority of the feedstocks requires to be dried to produce high quality end products within specifications. Just a few raw materials like straw are able to avoid the drying process because it has a moisture content already suitable for the pelletisation. There are different kinds of dryer that can be used; the most common ones are rotary drum dryers.

Inside the dryer, the raw material is in contact with the flue gases from the combustion of natural gas, or biomass (pellet or raw material) in order to decrease the moisture content of the feedstock by evaporation. Generally at the end of the drying phase the feedstock has a moisture content of 8%-10%.

Size reduction is carried out by chipping (if the raw material is not chipped yet) and grinding machineries such as the hammer mill, a machine whose purpose is to shred or crush aggregate material into smaller pieces. The grinding phase aims at increasing the total surface area of the material and the number of contact points inter–particle bonding during the following compaction process, increasing the density of ground biomass. The energy requirement of this phase depends on the physical and chemical properties of the raw material and on the hammer mill characteristics [45].

Afterward, a conditioning phase can follow. Conditioning allows to increase the quality of the final product. In fact, by increasing the temperature of the feedstock, is promoted the activation of natural binders present in the biomass. For wood generally this phase is not necessary because wood contains enough lignin that acts as a binder, where as straw has to be conditioned to provide durable pellets and to minimise fines release during the handling and the combustion of pellets [63].

Conditioning is generally done with steam but also hot water can be used.

The following step is the densification process, during which the previously ground material is fed to a pellet press. In this machinery, thanks to the high temperature and pressure, the density of the feedstock is increased in an order of 2 to 10 folds and pellets are produced, generally via an extrusion process.

The energy requirement of this step depends on the moisture content and the temperature of the feedstock and the die size [45].

Once that pellets come out from the pellet press, they have a temperature of about 70-90°C [45], so, before being stored, pellets have to be cooled at a temperature of 20°C.

Afterwards the cooled pellets can be passed over a screen in order to remove the fines and then they are packed and stored before leaving the pellet plant.

Data for the description of the process have been taken from literature in order to highlight the differences between the of pellets using different raw materials.
Four different processes have been created. One refers to the production of pellets from woodchips both from forest residues or short rotation forestry, two are for sawdust respectively for wet and for the partially dry one and the last one is for straw.

The main inputs to the process for all the feedstocks are:

- Feedstock (Woodchips, sawdust or straw)
- Heat for drying and for the production of the steam for conditioning, in the case of straw
- Electricity to run the machinery
- Raw materials and energy for the construction and the functioning of the machinery
- Diesel for internal transport
- Wood pellet manufacturing infrastructure

The outputs are:

- Pellets
- Emissions to environment

5.2.3.1 *Production of pellets from woodchips*

The quantities of the input flows assumed in this analysis are listed in the Table 23.

	Unit	Amount	Source
Wood chips	$MJ/MJ_{pellets}$	1,04	[59]
Heat	$MJ/MJ_{pellets}$	0,12	[52]
Electricity	$MJ/MJ_{pellets}$	0,05	[67]
Diesel	$MJ/MJ_{pellets}$	0,002	[31], [45]
Infrastructure	No pcs./$MJ_{pellets}$	$9,00 \cdot 10^{-13}$	[65]

Table 23: Input flows to the process of the production of pellets from wood chips

The quantity of woodchips fed to the process has been evaluated considering that about 3% of the dry matter of woodchips are lost during the handling and the storage, before the production of pellets, and that a loss of dry weight of 1% occurs during the pelletization [59].

The quantity of heat necessary to dry the raw material has been calculated considering a requirement of 1100 $kWh_{heat}/t_{water\ evaporated}$ [52].

In this study it has been considered that the wood chips are dried thanks to the contact with the flow gases produced by the combustion of woodchips in a boiler with an efficiency of 60% [45].

The number of pieces of infrastructure for pellets manufacturing has been taken from the Ecoinvent process *Wood pellet, u=10%, at storehouse*.

The loss of weight of feedstock and the number of pieces of infrastructure are considered constant for all the processes.

5.2.3.2 *Production of pellets from wet sawdust*

Table 24 includes all the input flows to the process of production of pellets from wet sawdust.

The main difference between this and the process described previously is that the production of pellets from sawdust requires less electrical energy because sawdust has smaller dimensions than wood chips, that implies that less energy is required to grind sawdust.

The flue gases for the drier are obtained burning sawdust in a boiler with an efficiency of 60% [45].

	Unit	**Amount**	**Source**
Wet sawdust	$MJ/MJ_{pellets}$	1,04	[59]
Heat	$MJ/MJ_{pellets}$	0,12	[52]
Electricity	$MJ/MJ_{pellets}$	0,04	[31], [45]
Diesel	$MJ/MJ_{pellets}$	0,002	[31], [45]
Infrastructure	No pcs./$MJ_{pellets}$	$9{,}00 \cdot 10^{-13}$	[65]

Table 24: Input flows to the process of the production of pellets from dry sawdust

5.2.3.3 *Production of pellets from partially dry sawdust*

In the Table 25 all the input flows to the process of production of pellets from wet sawdust are listed.

	Unit	Amount	Source
Partially wet sawdust	$MJ/MJ_{pellets}$	1,04	[59]
Heat	$MJ/MJ_{pellets}$	0,07	[52]
Electricity	$MJ/MJ_{pellets}$	0,03	[31], [45]
Diesel	$MJ/MJ_{pellets}$	0,0016	[31], [45]
Infrastructure	No pcs./$MJ_{pellets}$	$9,00 * 10^{-13}$	[65]

Table 25: Input flows to the process of the production of pellets from partially dry sawdust

The input values of heat, electricity and diesel for internal transport are obtained as weighted average of the values for wet sawdust and dry one.

As in the previous case, the heat to dry the feedstock is obtained by the combustion of the sawdust in a boiler and the contact of the flue gases with the sawdust. The efficiency of the boiler is 68%, obtained as weighted average value of the efficiency of the boiler fed respectively with the dry and the wet feedstock [45].

5.2.3.4 *Production of pellets from straw*

Table 26 contains all the input flows of the process of pellet production from straw.

	Unit	Amount	Source
Straw	$MJ/MJ_{pellets}$	1,04	[59]
Heat for drying	$MJ/MJ_{pellets}$	0,017	[52]
Heat for conditioning	$MJ/MJ_{pellets}$	0,007	[63]
Electricity	$MJ/MJ_{pellets}$	0,021	Average [63], [17], [26]
Diesel	$MJ/MJ_{pellets}$	0,002	[31], [45]
Infrastructure	No pcs./$MJ_{pellets}$	$9,52 * 10^{-13}$	[65]

Table 26: Input flows to the process of the production of pellets from straw

The amount of heat needed is the sum of two contributes: heat for drying and heat for the production of heat for conditioning.

The first contribution is 0,017 $MJ_{heat}/MJ_{pellets}$, that is the quantity of heat necessary to decrease the moisture content from 14% to 8%[1]. It has been calculated assuming that 1100 kWh of heat are necessary to evaporate 1 ton of water, as in the previous processes [52].

The second contribute, due to the conditioning phase is 0,007 $MJ_{heat}/MJ_{pellets}$ and it has it is the result of a simple thermodynamic calculation, based on data taken from the study of Sultana et al [63].

The heat is produced burning natural gas in a boiler with an efficiency of 90%.

5.2.4 Combustion

Combustion facilities have been classified following the indication of *The Pellet Handbook* [52]:

- Small scale facilities (<100 kW): domestic pellets stoves
- Medium scale facilities (100 – 1000 kW)
- Large scale (>1000 kW): this category includes Combined Heat and Power plants (CHP)

Data for the description of the processes are taken from Ecoinvent database. The main inputs are:

- Pellets
- Furnace
- Electricity
- Disposal of wood ash.

The main output flows are heat and the compounds carried with the flue gases.

5.2.4.1 Combustion in a domestic stove

A domestic stove with a power of 15 kW and an efficiency of 88 % [54] has been considered representative for the category of small scale facilities.

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[1] The final moisture content of pellets will be 10% for the conditioning

Data for the input flows and the environmental emissions due the combustion are taken from the process of Ecoinvent database *Pellets, mixed, burned in furnace 15 kW*, that is described in details in the Ecoinvent report by Dones et al. [12].

The stove is assumed to require equivalent to 1,5% fuel energy.

The emission factors referred to one mega-joule of heat produced assumed for the stoves and for the other combustion facilities considered are taken from the Ecoinvent database and are reported in Table 27.

It has been assumed that only wood pellets are burned in domestic facilities, because straw pellets are rarely burned in domestic stoves. In fact they have a higher content of ash forming matter and higher emissions of dust, SO_x, NO_x and HCl so they are more suitable for bigger facilities that are equipped with emissions abatement devices [23].

5.2.4.2 Combustion in a district heating plant

A district heating plant has been considered representative for the category of medium scale plants. It has been assumed an efficiency of 88%.

Data for the input flows and the environmental emissions are taken from the Ecoinvent process *Wood chips, from forest, burned in furnace 1000 kW*, detailed in the Ecoinvent report by Dones et al. [12]. It has been considered that the emissions of this plant are comparable to the ones of a plant of the same power that burns pellets.

It has been considered that both wood pellets and straw ones can are burned in this kind of plant, because they have an emissions abatement system, thus the environmental emissions can be considered the same for both the types of pellets.

5.2.4.3 Combustion in a Combined Heat and Power (CHP)

For the category of large scale plants, a CHP plant is considered.

The plant generates both electricity and heat but it is optimized for the production of the latest.

Part of the electricity produced is also used for internal consumption of auxiliary systems..

The plant has a capacity of 6400 kW_{th} and 400 kW_{el} and a thermal efficiency of 85% [12].

Data related to the input and output flows are taken from the Ecoinvent process *Wood chips, burned in cogen 6400 kW_{th}*, described in the report by Dones et al. [12].

As in the previous case, there is not a specific process for the combustion of pellets, so in this study the combustion of woodchips and the combustion of pellets are considered comparable in terms of environmental impact. The emissions abatement system anyway provides a maximum threshold of pollutants that will be emitted in the atmosphere; in the likely case that woodchips combustion caused higher emissions than pellets combustion, this effect would be limited by such system and so this assumption seems to be appropriate.

The CHP is assumed to be equipped with a multi-cyclone that abates the emissions of dusts in the atmosphere.

In order to compare this kind of plant with the other one analysed, it is necessary to quantify only the emissions related to the production of heat.

The environmental impact are then allocated to the heat and the electricity produced by the CHP by exergy.

The exergy describes the available energy, which is embodied in heat and power and is available to be used. One-kilowatt-hour power has an exergy content equal to 1. The exergy content of the heat instead depends on its temperature in comparison to the surrounding, thus the amount of exergy is defined as:

$$EX_Q = Q * (1 - \frac{T_e}{T_s})$$

Where: EX_Q = Heat exergy

Q = Heat energy

T_e = Temperature of the environment

T_s = Temperature of the heat source

According to the Ecoinvent process the allocation factor by exergy associate to heat is 0,757 [12].

The processes used to model the emissions of the three combustion devices considered in this study are taken from the Ecoinvent database v 2.2 and the emission factors of the main pollutants are reported in Table 27, expressed in terms of mass of pollutants per mega-joule of heat produced.

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	CO	**Dust (>PM10)**	**Dust (PM2.5)**	**NMVOC**	**NOx**	**SOX**	**CH4**
	mg/MJ$_{heat}$	**mg/MJ$_{heat}$**	**mg/MJ$_{heat}$**	**mg/MJ$_{heat}$**	**mg/MJ$_{heat}$**	**mg/MJ$_{heat}$**	**mg/MJ$_{heat}$**
Domestic stoves	109,09	34,72	29,55	8,95	79,55	2,84	0,45
District heating	46,59	34,72	69,32	7,47	118,19	2,84	0,45
CHP	8,13	35,47	52,13	7,18	102,18	2,89	0,50

Table 27: Emission factors for wood pellets combustion

In general terms, the emissions of pollutants typical of a incomplete combustion, such as carbon monoxide and NMVOC are higher for the use of domestic stoves than in case of use of district heating or CHP because the injection of secondary air within the boiler allows to reach a higher oxidation of the fuel.

The emissions of PM2.5 and NOx are higher for the district heating and the CHP because in the Ecoinvent processes used in this LCA they are assumed to burned woodchips that contain more nitrogen due to the presence of bark. Moreover, since the pellets are more homogeneous than woodchips, they allow a more uniform combustion, that reduces the emissions of particles.

This introduces a factor of uncertainty in the study; however no specific data for the emissions of large-scale plants fuelled with pellets where found and, furthermore, a higher uncertainty is associated with the estimations of the emissions of pellets combustion, that are strongly influenced by several parameters such as the quality of the wood, the appliance type and, most important, the combustion conditions [53], [40]. The uncertainty introduced using the Ecoinvent processes for woodchips to model the emissions of the pellets combustion is considered acceptable.

5.3 Life cycle impact assessment

The *ILCD handbook, Recommendations for life cycle impact Assessment in the European context* [19] recommends the impact categories to be considered in an LCA and the characterisation method to use in order to evaluate each impact at the midpoint and at the endpoint.

In this study the impact categories and the characterisation methods have been chosen following the indications of LCIA methods at midpoint from the ILCD.

The impacts have been evaluated using the software GaBi that allows to calculate them using different characterisation methods.

Table 28 lists the impact categories and the respective characterisation method considered in this study.

Impact category	**LCIA method**	**Unit**
Climate change	CML2001 - Nov. 09, Global Warming Potential (GWP 100 years)	kg_{CO2eq}/MJ_{heat}
Ozone depletion	CML2001 – Nov - 09, Ozone Layer Depletion Potential (ODP, steady state)	kg_{R11eq}/MJ_{heat}
Human toxicity	USETox2008, Human toxicity	$Cases/MJ_{heat}$
Particulate matter/Respiratory inorganics	Respiratory inorganics	$kg_{PM2.5eq}/MJ_{heat}$
Ionising radiation, human health	ReCiPe Midpoint (H) - Ionising radiation	kg_{U235eq}/MJ_{heat}
Photochemical ozone Formation	ReCiPe Midpoint (H) - Photochemical oxidant formation	$kg_{NMVOCeq}/MJ_{heat}$
Acidification	CML2001, Acidification Potential (AP) nov 2009	kg_{SO2}/MJ_{heat}
Eutrophication, Terrestrial	EDIP 2003, Terrestrial eutrophication	m^2_{UES}/MJ_{heat}
Eutrophication, aquatic	ReCiPe Midpoint (H) - Freshwater eutrophication and ReCiPe Midpoint (H) - Marine eutrophication	kg_{Peq}/MJ_{heat} and kg_{Neq}/MJ_{heat}
Ecotoxicity (freshwater)	USETox2008, Ecotoxicity	PAF*m^3*day
Ecotoxicity (terrestrial)	CML2001 - Nov. 09, Terrestric Ecotoxicity Potential (TETP inf.)	kg_{DCBeq}/MJ_{heat}
Resource depletion, mineral, fossil and renewable	CML2001 - Nov. 09, Abiotic Depletion (ADP elements)	kg_{Sbeq}/MJ_{heat}

Table 28: Characterisation methods used in this study

5.4 *Interpretation of the results*

5.4.1 Impact on climate change

The impact of climate change has been evaluated using the characterisation method CML that is based on the global warming potentials (GWP100 years) recommended by the IPCC (2007).
Figure 21 shows the impact on climate change of all the scenarios analysed expressed in term of grams of carbon dioxide equivalent per mega-joule of heat produced (g_{CO2eq}/MJ_{heat}).
These are only the emissions of fossil carbon dioxide equivalent, in fact the quantity of biogenic CO_2 emitted has not been accounted because it is assumed to be equal to the quantity of CO_2 that the trees have taken from the atmosphere during their life. Other issues related to carbon accounting in forestry are currently under evaluation by the scientific community (e.g. "Carbon Debt"), but have not been included in this work since a consensus has not yet been reached [8], [68], and since is more relevant for "roundwood" rather than for residues and do not affect the use of residues or annual crops.

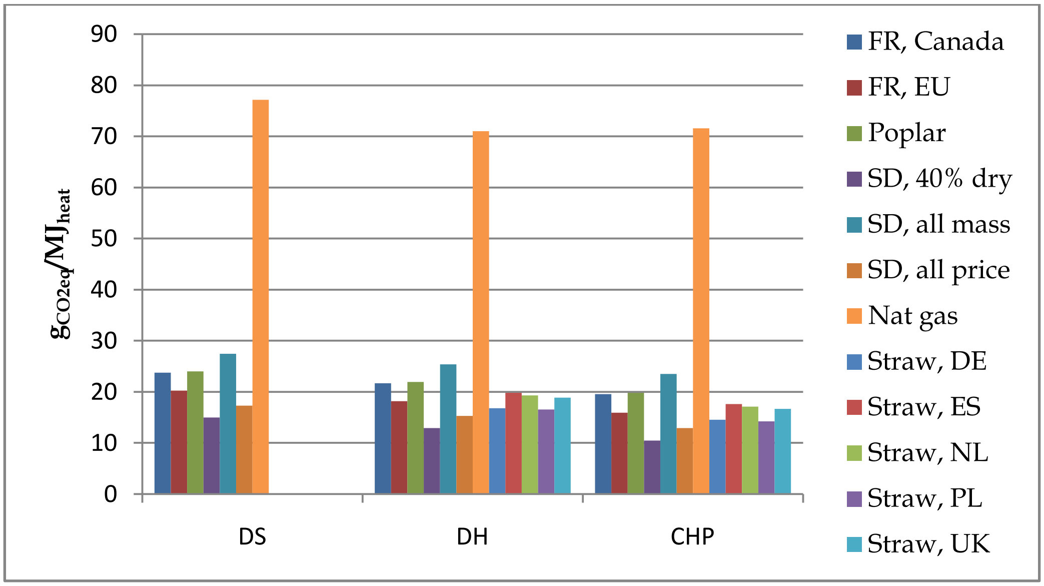

Figure 21: Impact on climate change [g_{CO2eq}/MJ_{heat}]

As mentioned in the previous chapters, one the main advantages of using biomass is the lower emissions of GHGs compared to fossil fuels: Figure 21 shows, in fact, that the environmental impact on climate change due to the use of natural gas is much higher than the one for all the biomass scenarios considered.

Comparing the combustion of pellets in different devices, assuming to burn the same type of pellets, the highest emissions of GHGs are associated with the domestic stove, whereas the lowest are related to the production of heat with a CHP.

Concerning the CHP, the emissions of GHGs related with the production of pellets are slightly higher because we have assumed for the CHP a lower thermal efficiency (85%) than domestic stoves and district heating (88%), as explained in paragraph 5.2.4, but the total emissions of the pathway are lower because the quantity of carbon dioxide equivalent emitted for the facility operations is lower than in the other cases analysed. This is due to the facts that a large-scale plant during its life time produces a higher quantity of mega joules than a small plant, thus the specific emissions of a big plant are divided over a higher quantity of heat and that the electricity for the combustion operations of the CHP is recovered by the CHP itself and it is not taken from the grid, thus the GHG emissions for the production of the electricity are avoided in this scenario.

In order to motivate the different emissions of GHGs, in Table 29 the emissions of fossil carbon dioxide due to the combustion operations of the three combustion devices considered is reported.

	DS	**DH**	**CHP**
g_{CO2eq}/MJ_{heat}	6,6	4,5	1,8

Table 29: GHGs emissions for the combustion operations [g_{CO2eq}/MJ_{heat}]

Comparing the different feedstocks, the production of pellets from partially dry sawdust is the scenario that causes the lowest GHGs emissions thanks to the lower requirement of energy for drying the feedstock and to the lower emissions associated with the transport of the sawdust, that has a higher energy density.

The highest impact instead is associated with the production of pellets from wet sawdust with the allocation by mass.

As explained in paragraph 5.2.1, the allocation factor by mass/energy associated with sawdust is 0,0685, whereas the allocation factor by price is 0,010. This implies that all the emissions of the process of the production of sawdust are almost 7 time higher in the case of allocation by mass, thus increasing the emissions for the pathway.

Table 30 shows the differences in the results in case of allocation by price or by mass/energy in absolute terms and the increase of the emissions due to the allocation by mass.

	Scenario *SD, all mass*	**Scenario** *SD, all price*	**Increase of the emission due to the allocation by mass**
	g_{CO2eq}/MJ_{heat}		
DS	27,4	17,3	59%
DH	25,4	15,3	66%
CHP	23,5	12,9	82%

Table 30: Differences in the results using the different allocation method

Figure 22, Figure 23 and Figure 24 show the contributions of the processes within each scenario to the total emissions of fossil carbon dioxide.

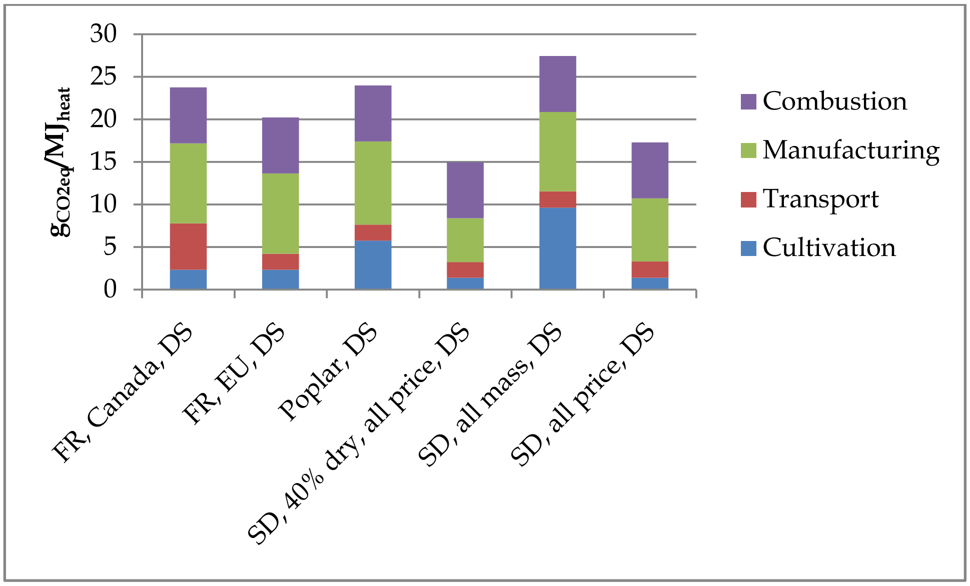

Figure 22: Contributions to the fossil carbon dioxide emissions in case of combustion in a domestic stove [g_{CO2}/MJ_{heat}]

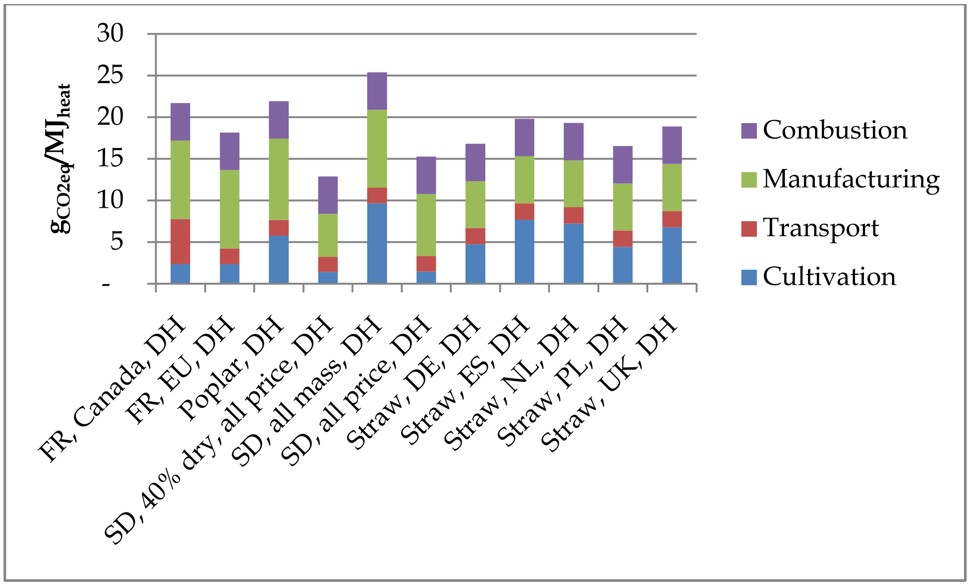

Figure 23: Contributions to the fossil carbon dioxide emissions in case of combustion in a district heating [gCO_{2eq}/MJ_{heat}]

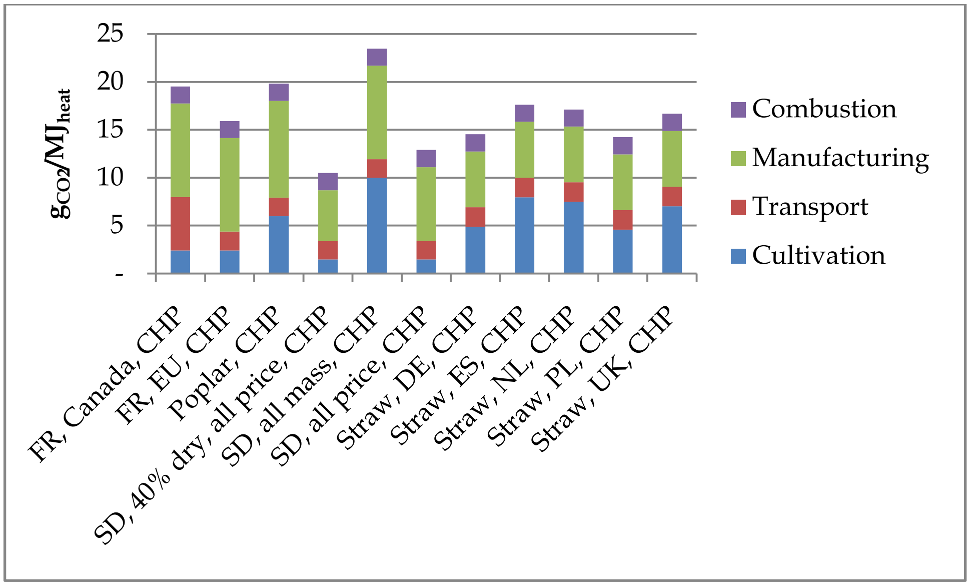

Figure 24: Contributions to the fossil carbon dioxide emissions in case of combustion in a CHP [g_{CO2eq}/MJ_{heat}]

The use of pellets produced from woodchips from forest residues from Canada and woodchips from poplar have a higher impact on the global warming, compared to the pathways of woodchips from forest residues produced in Europe as feedstock. In the first case this is due to the emissions of fossil carbon dioxide during the long range transport, in fact the emissions of

transport, including the production of the means of transport, for woodchips produced in Europe are 1,9 g_{CO2eq}/MJ_{heat}, whereas for woodchips from Canada are 5,4 g_{CO2eq}/MJ_{heat}.
In the second case the higher emissions are due to the higher quantity of field operations and the production of a higher quantity of chemicals necessary for the cultivation phase, compared to the other woody feedstocks analysed. In particular, the use of woodchips from poplar, compared to woodchips from forest residues, causes an increase of GHGs between 18,5% and 24,5%, depending on the scenario. In case of CHP, the emissions of GHGs from poplar have an higher weight on the total emissions of the CHP because the facility operations in the case of CHP produce lower emissions of GHGs than the other combustion devices, as explained before.

Concerning the scenarios of straw, the plots show that the emissions of fossil carbon dioxide due to the cultivation of wheat straw account for a significant percentage on the total emissions. This is due to the use of agrarian machinery, as in the case of poplar cultivation. Actually the emissions of the cultivation of wheat allocated to straw in absolute terms are higher than the ones due to the cultivation of poplar, but the total emissions of the pathways of straw pellets are lower because the emissions of GHGs during straw pellets production are significantly lower, being straw dryer than all the other feedstocks considered.

Anyway, every biomass pathway allows for significant quantity GHGs savings compared to the reference scenario. It has to be remembered that the characterisation method chosen accounts the GHG emissions in a time horizon of 100 years and that, if a shorter time horizon was considered (20 years), the advantage of using pellets instead of fossil fuel would be even higher, thanks to the lower emissions of methane associated with the biomass pathways. In fact, for methane the difference between the GWP20 and the GWP 100 significantly higher than for the main other GHG because it has a shorter half-life time.

The same results that are reported in Figure 21, are reported in Figure 25, expressed in terms of percentage of GHGs savings compared to the reference system,.
The GHGs savings have been calculated as:

$$Savings\ [\%] = \frac{Emissions\ of\ the\ ref\ system - Emission\ of\ the\ scenario}{Emissions\ of\ the\ ref\ system}$$

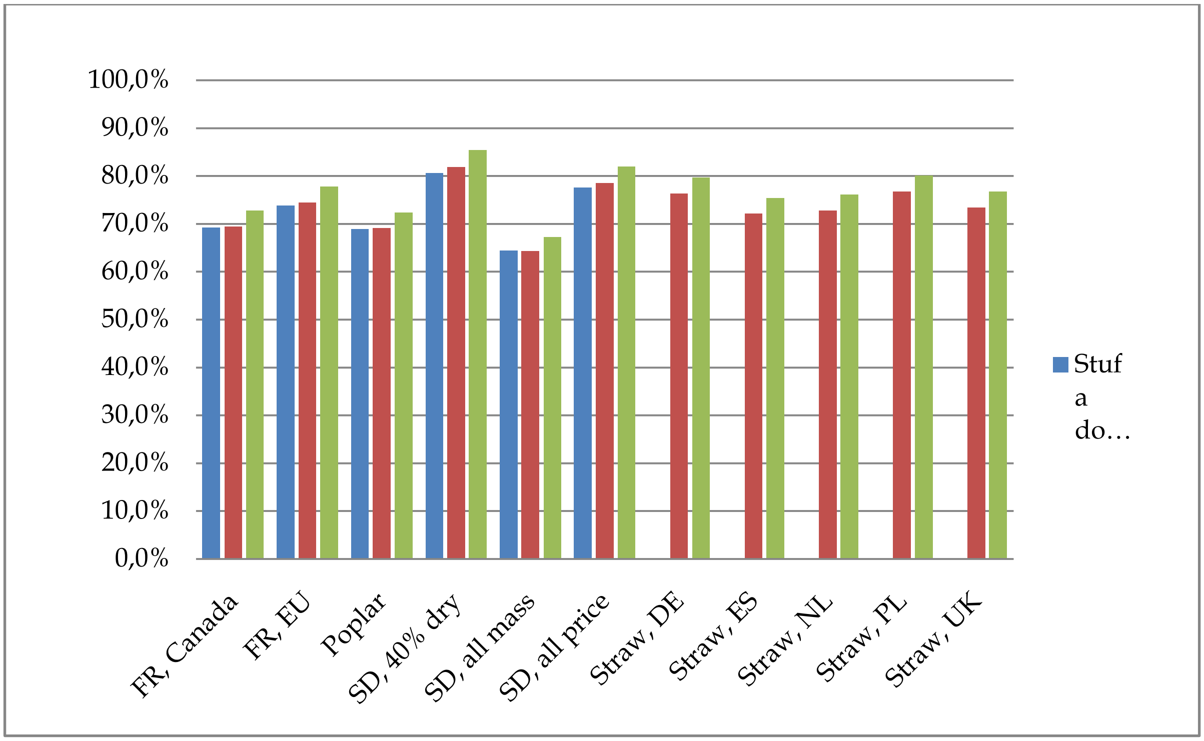

Figure 25: GHG savings

The differences between the various pathways are small, with all the pathways we see savings around or above 70%.

The higher savings are associated with the scenario of CHP for all the feedstocks analysed.

In general terms straw pellets allows higher savings of GHGs than pellets made with woodchips both from poplar and forest residues and wet sawdust. This is an important point to take into account for future utilisations of straw as feedstock, being that most of the other by-products woody feedstocks are going to be totally exploited in the next few years [17].

The savings of GHGs obtained in this work for domestic stove is coherent with the study of Sikkema et al. [60] that made an LCA of pellets production chains using a mix of sawdust and shavings as a feedstock. The results of the two studies, expressed in terms of g_{CO2}/MJ_{heat} are reported expressed in Table 31.

The avoided emissions for the other pathways are not comparable because the reference scenarios are different.

This study						Sikkema et al. [60]
FR, Canada	**FR, EU**	**Poplar**	**SD, 40% dry**	**SD, all mass**	**SD, all price**	**80% Sawdust (mc55%)+20% shavings (mc17%)**
54	57	53	62	49	60	62

Table 31: Comparison between the results [g_{CO2}/MJ_{heat}] of this study and one of the study by Sikkema et al. [60]

The LCA by Caserini et al. [7] estimated a saving of GHGs of 1080 $kg_{CO2eq}/t_{drybiomass}$ for the combustion in a domestic stove equipped with the best available technologies (BAT) In this study the GHGs saving for woodchips from forest residues from Europe, burned in domestic stove is 1082 $kg_{CO2eq}/t_{drybiomass}$.

Thus, the results of the two studies are comparable referring to the combustion of pellets in the domestic stoves,.

Concerning straw pellets, the only available study in scientific literature is the one by Sultana et al. [63] that calculated GHGs emissions of 30,3 g_{CO2eq}/MJ_{pellet}, without considering the combustion of pellets and allocating the emissions of the cultivation of wheat to the straw by energy.

The average result of straw pathways of this study, avoiding the emissions of GHGs due to the combustions operations and considering an economical allocation is 13,6 g_{COeq}/MJ in case of CHP and 16,6 g_{CO2eq}/MJ_{heat}, in case of district heating. The difference between the results is mainly due to a different approach in accounting the emissions of the cultivation phase. In fact, in the study of Sultana et al. [63] the emissions of the cultivation of wheat were allocated to the straw by energy and the emissions of the fertilisers used to replace the nutrients removed with straw were completely allocated to the straw, thus the emissions of the cultivation phase resulted equal to 21$g_{CO2eq}/MJ_{pellets}$. In this study, instead, the emissions of the cultivation of wheat are allocated to straw economically thus the average emissions of GHGs of the cultivation phase calculated are 5,4 $_{gCO2eq}/MJ_{heat}$.

5.4.2 Impact on ozone layer depletion

The impact on ozone depletion is expressed in terms of kg_{R11eq}/MJ_{heat}. The R11 is the Trichlorofluoromethane, a chlorofluorocarbon assumed as the reference compound to evaluate the impact on the ozone depletion.

Figure 26 shows the emissions of $R11_{eq}$ for the scenarios considered.

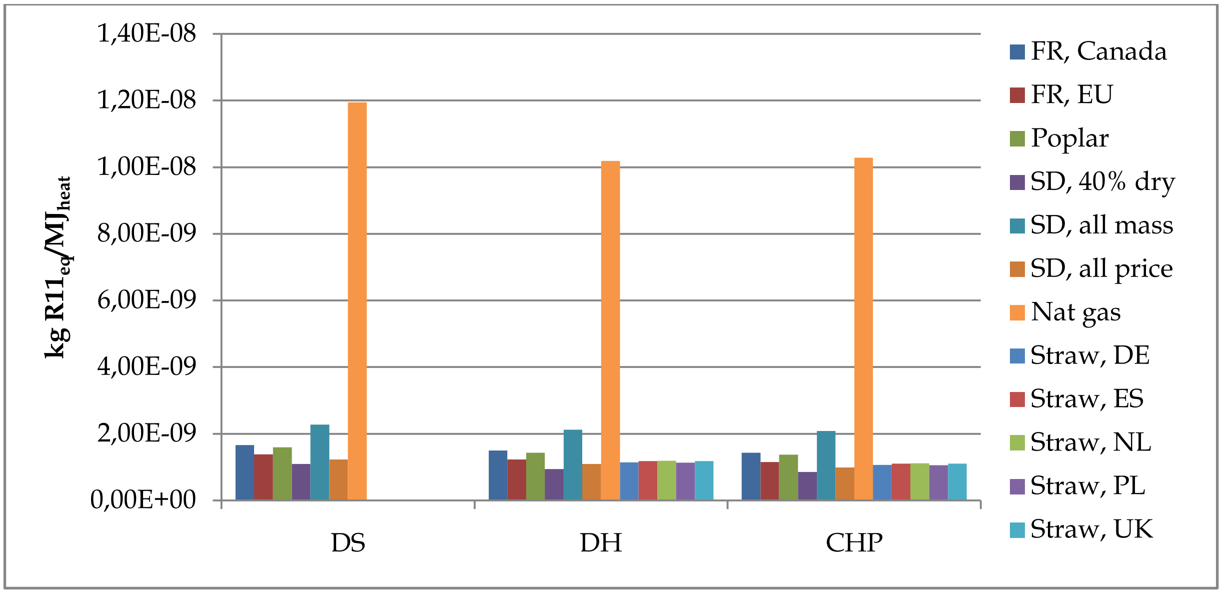

Figure 26: Impact on ozone layer depletion [kgR_{11eq}/MJ_{heat}]

The highest contribution to this impact is related with the halogenated organic compounds emissions, such as Halon.

The use of pellets causes lower emissions of $R11_{eq}$ than the use of natural gas because higher quantities of halogenated organic compounds are released to the atmosphere during the extraction, the handling and the transport of the natural gas. In particular, the use of natural gas instead of pellets causes an increase of the impact on ozone layer depletion comprised between 333% for the pathway *SD, all mass, CHP* and 993% for the pathway *SD, 40% dry, DS.*

Figure 27 show the contribution of each process in the pathways referred to the combustion in a domestic stove. The process with higher variability in the share of total emissions is the cultivation phase.

The sharing of the emissions of $R11_{eq}$ of the other scenarios are reported in Figure 28 and Figure 29.

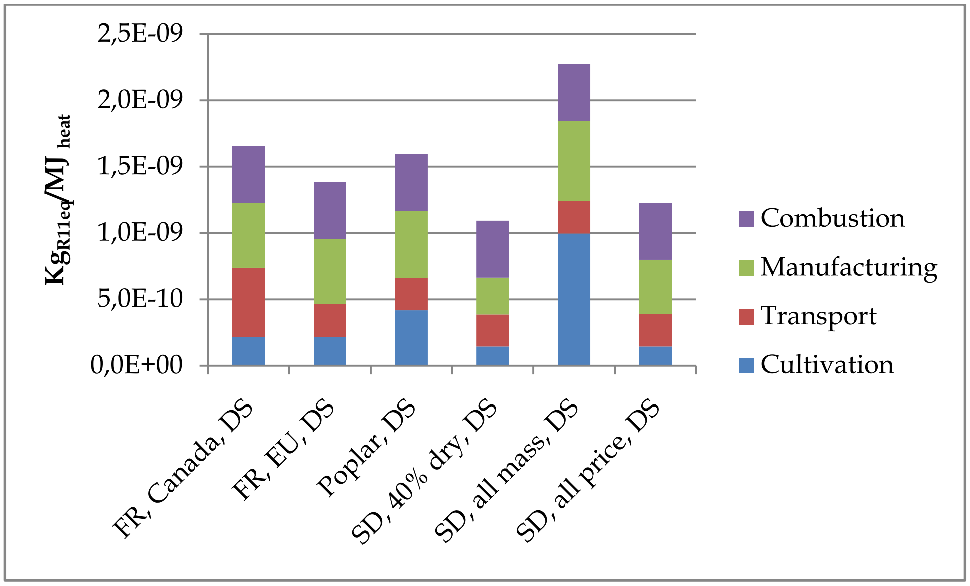

Figure 27: Contribution to the emissions of R11eq in case of combustion in a domestic stove [kg_{R11eq}/MJ_{heat}]

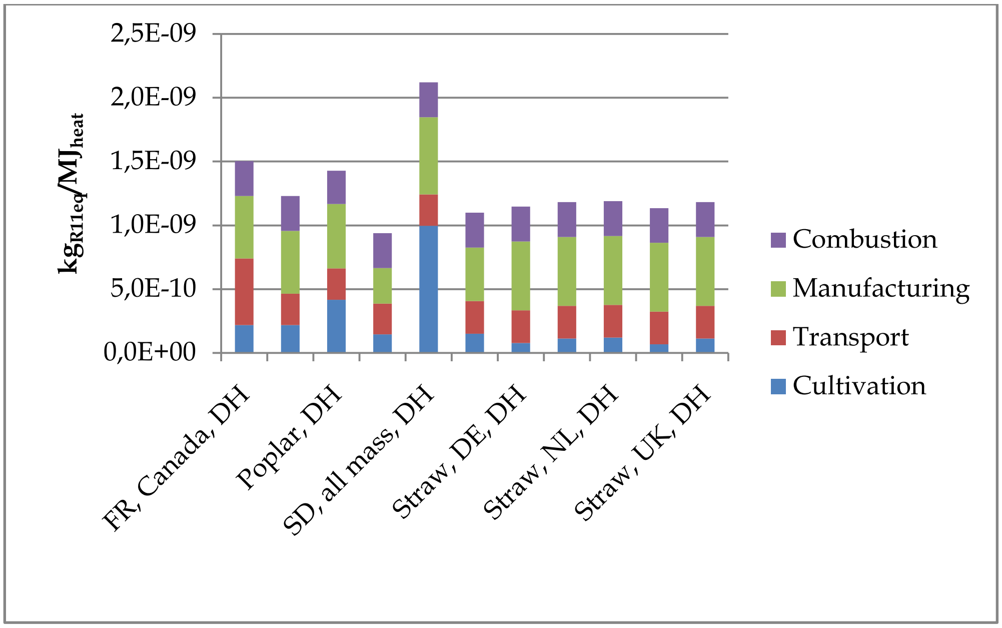

Figure 28: Contribution to the emissions of $R11_{eq}$, in case of combustion in a district heating [kg_{R11eq}/MJ_{heat}]

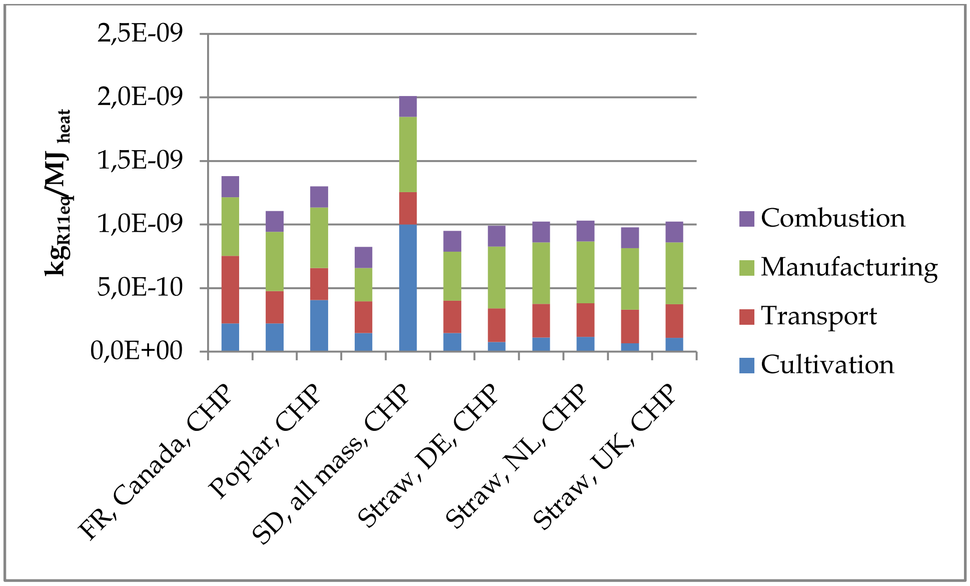

Figure 29: Contribution to the emissions of R11$_{eq}$, in case of combustion in a CHP [kg$_{R11eq}$/MJ$_{heat}$]

5.4.3 Impact on human toxicity

For the impact on human toxicity the USEtox characterisation method has been used. Human effect factors in USEtox relate the quantity taken in by the population via ingestion and inhalation to the probability of adverse effects (or potential risk) of the chemical in humans. It is based on toxicity data for cancer and non-cancer effects derived from laboratory studies [58].

This characterisation method accounts the toxic emissions of the organics and it does not include the contribution to the human toxicity due to emissions of primary particulate, that are accounted in the impact category related with the particulate matter formation (respiratory inorganics).

Usetox2008 expresses the impact in terms of number of cases of disease.

Figure 30 shows the impact on human toxicity of the scenarios analysed.

The emissions of formaldehyde are mainly responsible for the impact on human toxicity considering both the pathways related with the use of pellets and the reference systems fed with natural gas.

The formaldehyde is a volatile organic compound that is formed and emitted during the combustion of woody materials and natural gas, due to the incomplete combustion of the fuel.

In order to show how much the formaldehyde emissions contribute to the impact on human toxicity, Table 32 reports the percentage of formaldehyde referred to the total emissions that cause an impact on human toxicity.

	FR, Canada	FR, EU	Poplar	SD, 40% dry	SD, all mass	SD, all price	Straw, DE	Straw, ES	Straw, NL	Straw, PL	Straw, UK	Nat gas
DS	77,5	79,1	76,9	79,7	78,5	79,5	-	-	-	-	-	98,7
DH	76,7	78,3	75,8	78,9	77,8	78,8	79,2	79,3	79,3	79,2	79,3	89,5
CHP	76,9	78,8	76,2	79,5	78,2	79,3	80,0	80,0	80,0	80,0	80,0	89,5

Table 32: % emissions of formaldehyde on the total emissions accounted for the impact on human toxicity

Considering the biomass scenarios, the formaldehyde accounts from 75% to 80% of the total emissions of toxic compounds and the remaining contributions to the impact on human toxicity are due to the emissions of other compounds such as nitrogen oxides.

For the reference scenario, instead, the emissions of formaldehyde have a higher weight on the total emissions of toxic compounds due to the fact that almost all the VOC released during the combustion of natural gas are formaldehyde and no other significant emissions of toxic element occur in the life cycle of natural gas.

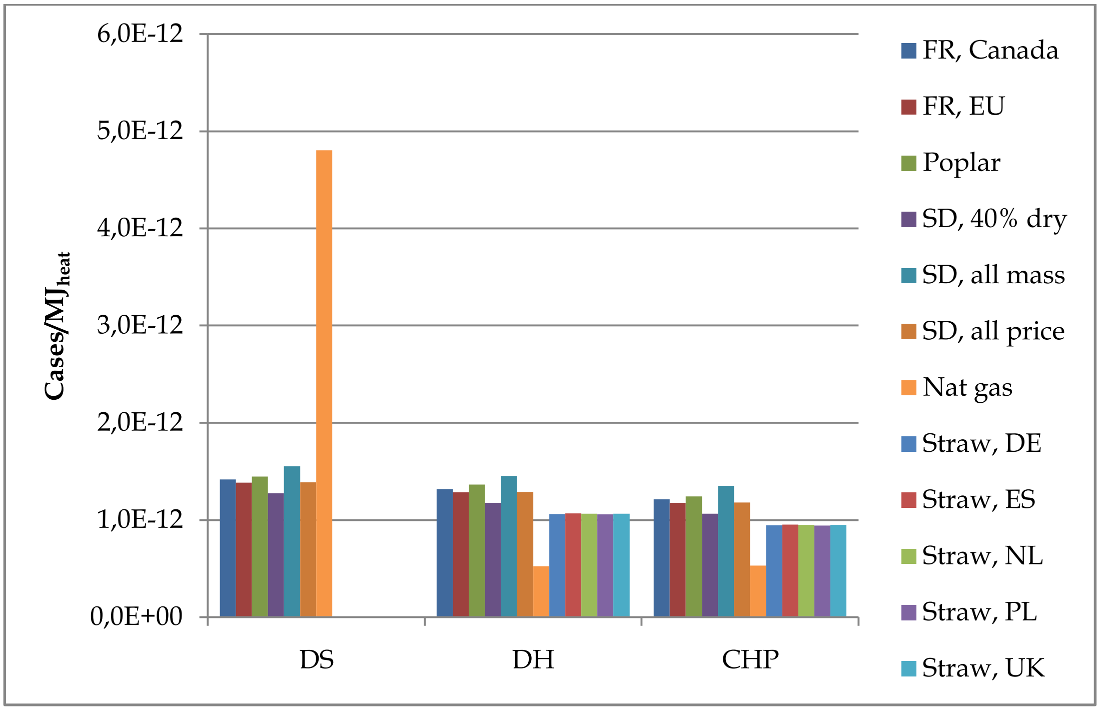

Figure 30: Impact on human toxicity [Cases/MJ$_{heat}$]

Considering the combustion in a domestic stove, the impact on the human toxicity is higher for the reference scenario than for the biomass pathways, whereas is lower in case of combustion in a district heating plant or in a CHP, due to the fact that the combustion of natural gas in a small scale boiler causes higher emissions of formaldehyde than the combustion of natural gas in a large scale plant [12].

In particular, the combustion of pellets in a domestic stove instead of natural gas decreases the impact on human toxicity by 208%, whereas the impact on human toxicity increases by 59% if pellets are burned in a district heating and by 55% in case of CHP.

According to the processes of Ecoinvent database v2.2, the emissions of formaldehyde due to the combustion of natural gas in a domestic stove are ten times higher than in the case of combustion in a large-scale plant, in fact the emission factors of formaldehyde for the domestic stove and the district heating are respectively 1,06 mg/MJ_{heat} and 0,10 mg/MJ_{heat}.

This is explained by the fact that, according to the study by Gordon et al. [30], the formation of formaldehyde during the combustion of natural gas starts when the temperature is to equal about to 400K, it increases until it reaches a peak at about 1300-1500K and then it rapidly decreases. Considering the low temperatures needed in a domestic stove (hot water at 60 – 80°C), combustion of natural gas is achieved in a non-premixed flame with very high ratios of air-to-fuel which has the effect of an overall low flame temperature with consequent higher formation of formaldehyde. In larger plants, instead, combustion is generally done in a pre-mixed flow with much higher flame temperatures and consequently lower amounts of formaldehyde are formed.

Figure 31, Figure 32 and Figure 33 report the contributions to the emissions of toxic elements of each process within the scenarios considered.

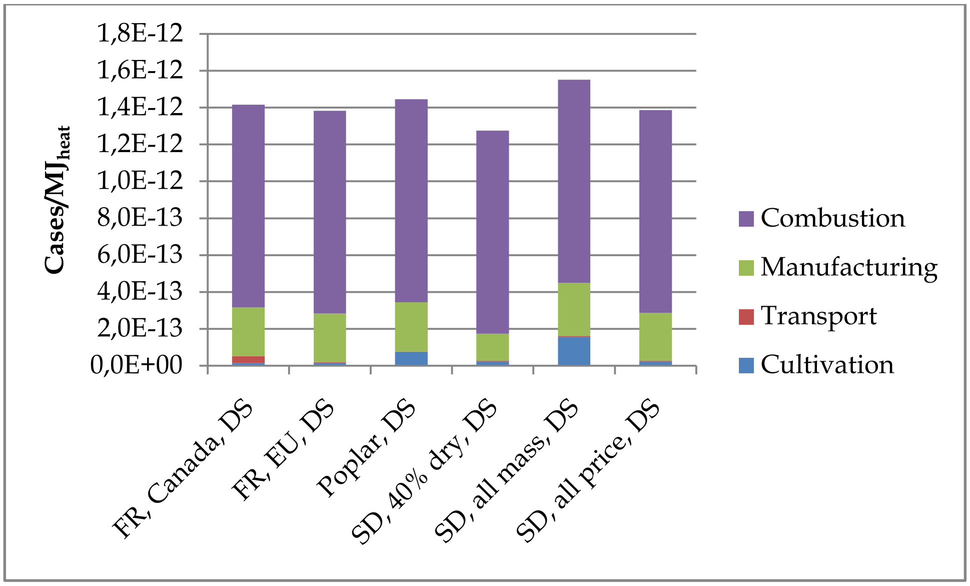

Figure 31: Contribution to human toxicity in case of combustion in a domestic stove [Cases/MJ$_{heat}$]

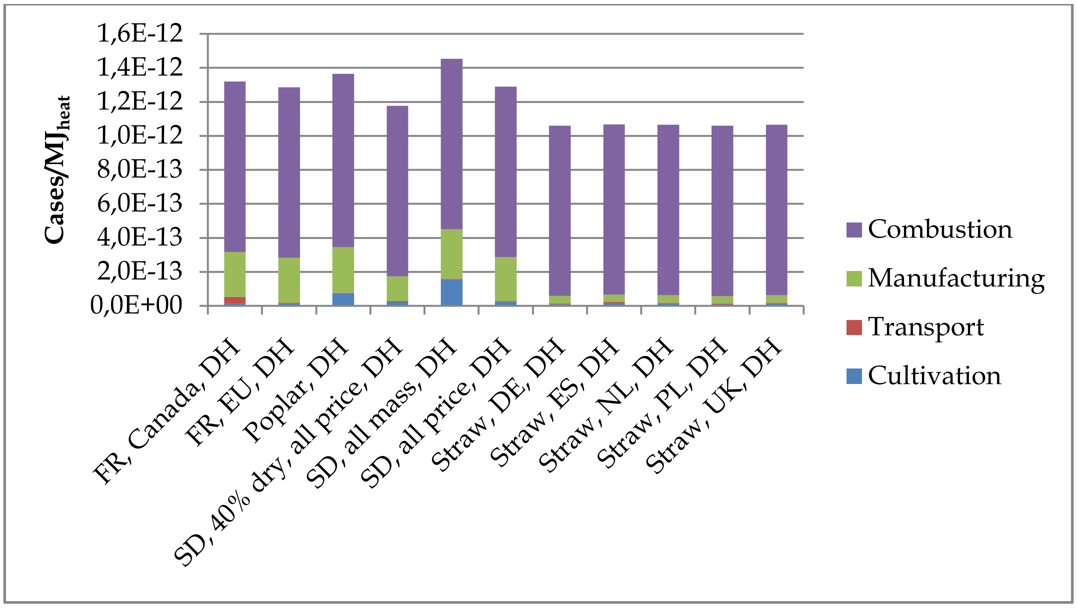

Figure 32: Contribution to human toxicity in case of combustion in a district heating [Cases/MJ$_{heat}$]

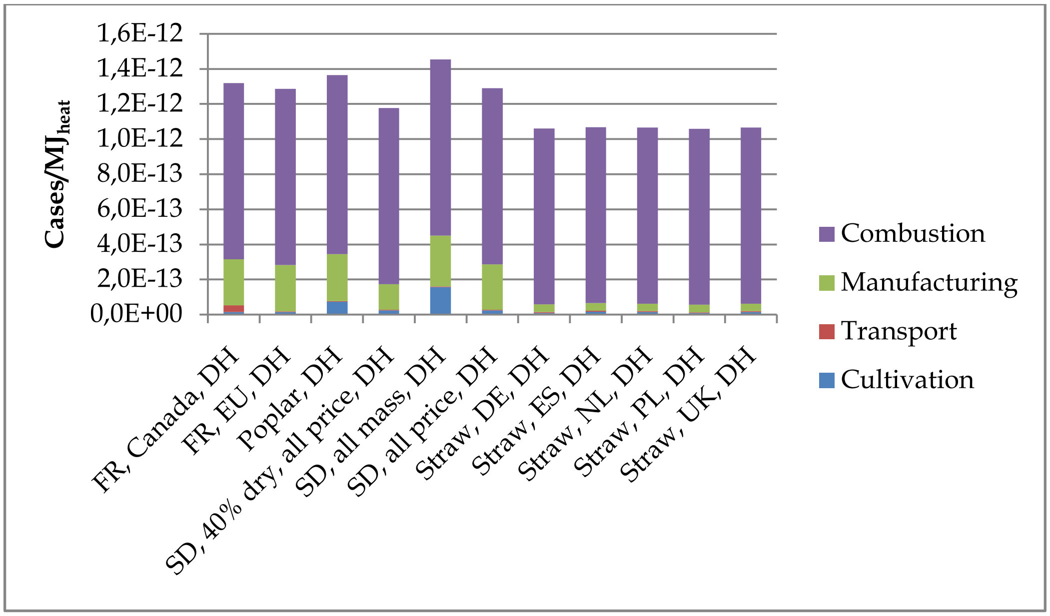

Figure 33: Contribution to human toxicity in case of combustion in a CHP [Cases/MJ$_{heat}$]

5.4.4 Impact on particulate matter/respiratory inorganics

For this impact the ILCD [18] recommends to consider the fraction of particulate matter below 2,5 µm. The method chosen among the available in the Gabi 4.4 software calculates the results in terms of mass of PM2.5 equivalent, considering the emissions of dust and other inorganic species that have potential particulate matter formation.

In fact, there are two main classes of particulate matter:

- Primary particulate that is emitted directly in particle form or in form of a gas that rapidly condenses to form particles
- Secondary particulate that is mainly formed by chemical reactions that occur in the atmosphere and that involves the emissions of volatile organic compounds, ammonia and sulphur and nitrogen oxides.

The impact of the scenarios analysed are reported in Figure 34.

Being methane a gaseous fuel it generates very small emissions of primary particulate and the impact on respiratory inorganics is mainly due to the emissions of the precursors of secondary particulate: sulphur and nitrogen dioxides and even those are in a small quantity in the natural gas.

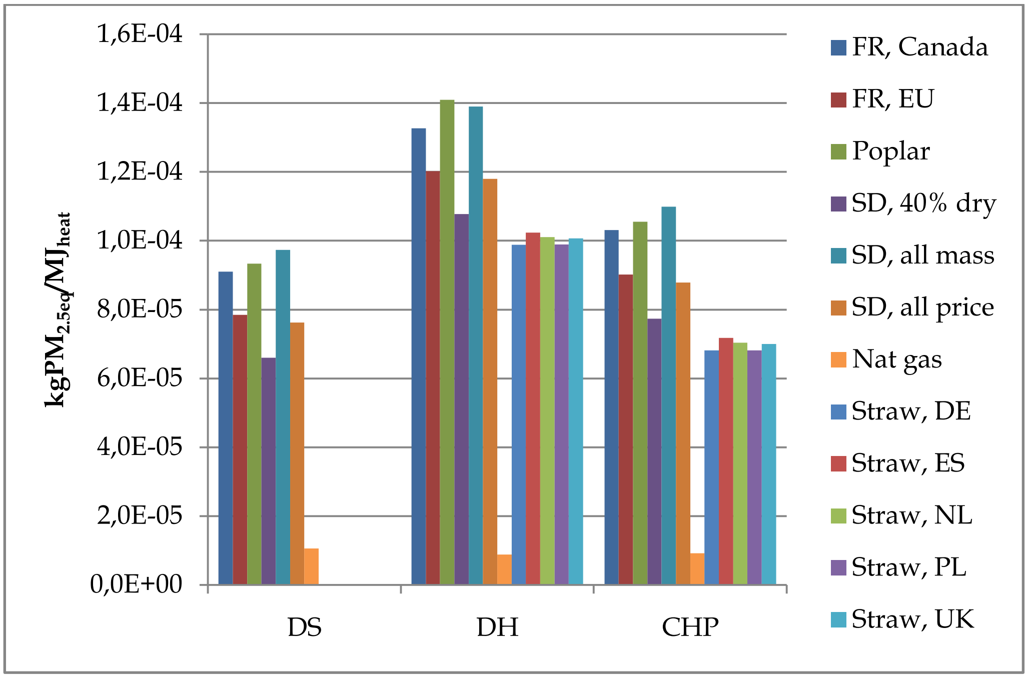

Figure 34: Impact on respiratory inorganics [$kg_{PM2.5e}q/MJ_{heat}$]

The impact on respiratory inorganics of the biomass scenarios, on the contrary, is mostly due to emission of primary particulate.

Table 33 shows the sharing of the emissions of primary particulate on the total emissions of PM2.5 equivalent for the scenarios analysed.

	FR, Canada	FR, EU	Poplar	SD, 40% dry	SD, all mass	SD, all price	Straw, DE	Straw, ES	Straw, NL	Straw, PL	Straw, UK	Nat gas
DS	58%	66%	56%	66%	63%	67%	-	-	-	-	-	19%
DH	68%	75%	66%	76%	72%	76%	73%	71%	72%	73%	72%	15%
CHP	64%	72%	62%	73%	68%	73%	68%	65%	66%	68%	67%	16%

Table 33: Sharing of the emissions of primary particulate [%]

Figure 35, Figure 36 and Figure 37 show the contributions to the total impact on respiratory inorganics of each process within the scenario analysed.

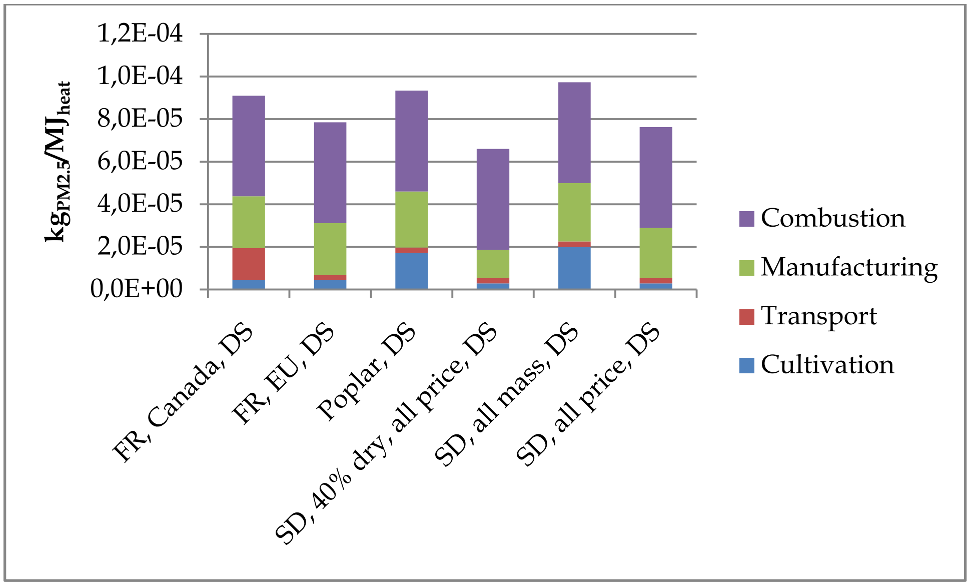

Figure 35: Contribution to respiratory inorganics in case of combustion in a domestic stove [$kg_{PM2.5}/MJ_{heat}$]

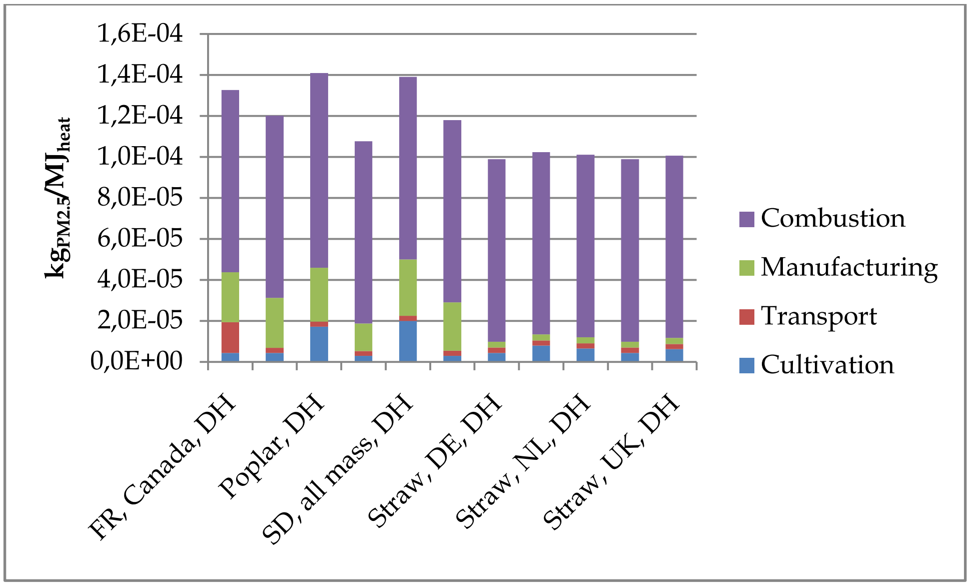

Figure 36: Contribution to respiratory inorganics in case of combustion in a district heating [$kg_{PM2.5}/MJ_{heat}$]

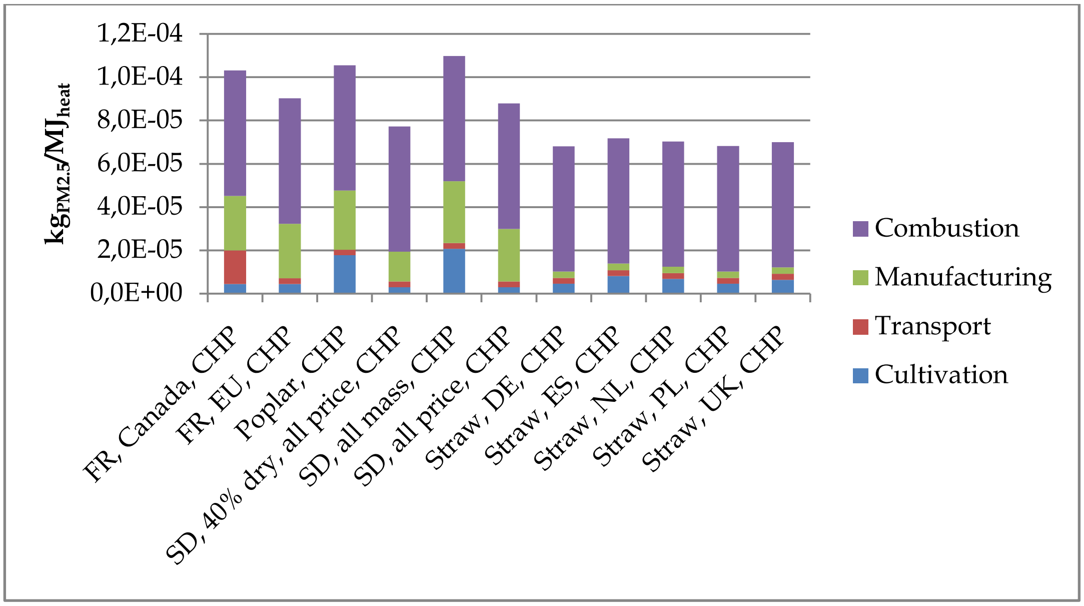

Figure 37: Contribution to respiratory inorganics in case of combustion in a CHP [$kg_{PM2.5}/MJ_{heat}$]

In general terms, the impact on respiratory inorganics category of the cultivation phase and the transport are mainly due to the emissions of precursors of the secondary particulate, due to the combustion of diesel, whereas the impact of the manufacturing and the combustion phases are mainly associated with the direct emissions of dust in the atmosphere. The emissions caused by the pellets production are mainly due to the combustion of the raw material used for drying.
For all the straw scenarios the impact on respiratory inorganics category due to the production of pellets is lower than in all the other scenarios because the straw is assumed to be dried with the flue gases coming from the combustion of natural gas, thus all the emissions of dusts for drying accounted in the other scenarios are, in this case, avoided.

The impact on respiratory inorganics was evaluated also in the study by Ghafghazi et al. [27] that evaluated an impact of 0,08 $g_{PM2,5}/MJ_{heat}$ for pellets made by sawdust, to which emissions are allocated on a mass basis, burned in a district heating. This study, instead, for the similar scenario *SD, all mass, DH* calculated emissions of 0,14 $g_{PM2.5eq}/MJ_{heat}$. The differences between the results are partly justified by the fact that the transport of pellets is not accounted in the study of Ghafghazi et al..

5.4.5 Impact on ionising radiation

The impact on ionising radiation has been evaluated using the characterisation method *ReCiPe Midpoint (H) - Ionising radiation* and it is expressed in terms of kg_{U235eq}/MJ_{heat}.
The emissions of uranium-235 equivalent per mega-joule of heat produced for each pathway analysed are reported in Figure 38.

This impact is mainly caused by the emissions in the atmosphere of Carbon-14.
Carbon-14 is a naturally occurring radioactive isotope of carbon, that has a half-life time of 5700 years. Fossil fuels do not contain Carbon-14 because the Carbon-14 stored by the biomass during its life millions of years ago is already decayed.

In the biomass scenario analysed almost all the contribution of ionising radiation is, however, due to the production of electricity, used both for the production of pellets and the combustion operations.
This is mainly due to the fact that in this study the electricity is assumed to be produced by the energetic mix of Europe. Being that some European country produces electricity from nuclear, the quantity of uranium-235 equivalent emitted associated with the production of electricity is significant. Thus the higher requirement of electricity of wood pellet production chain compared to the natural gas one explains the fact that the emissions of uranium-235 equivalent are much lower in the reference scenarios than in the bio-heat pathways. But this has little to do with the nature of the feedstock and much more with the processes associated.

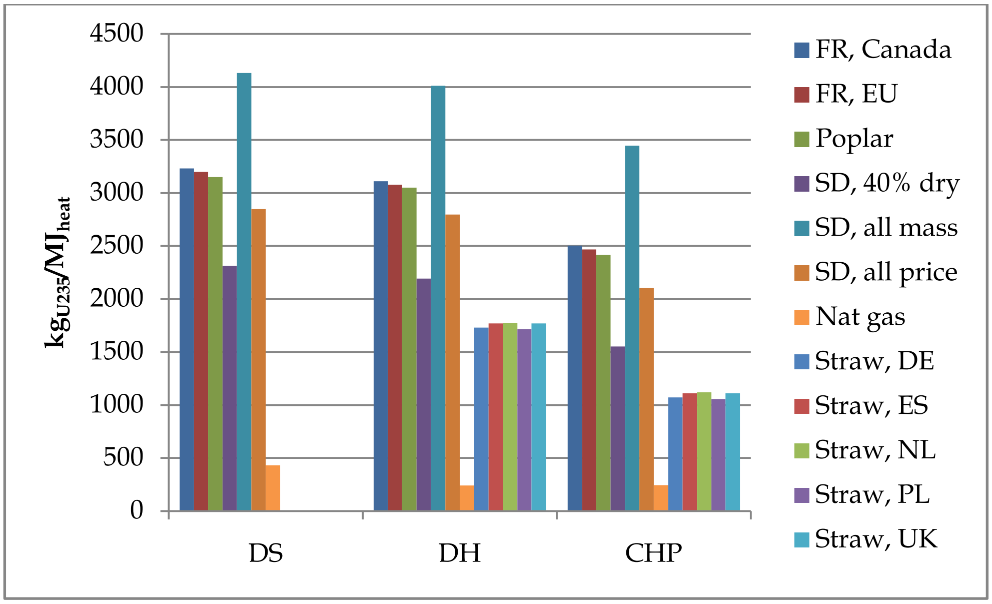

Figure 38: Impact on ionizing radiation [kg$_{U235}$/MJ$_{heat}$]

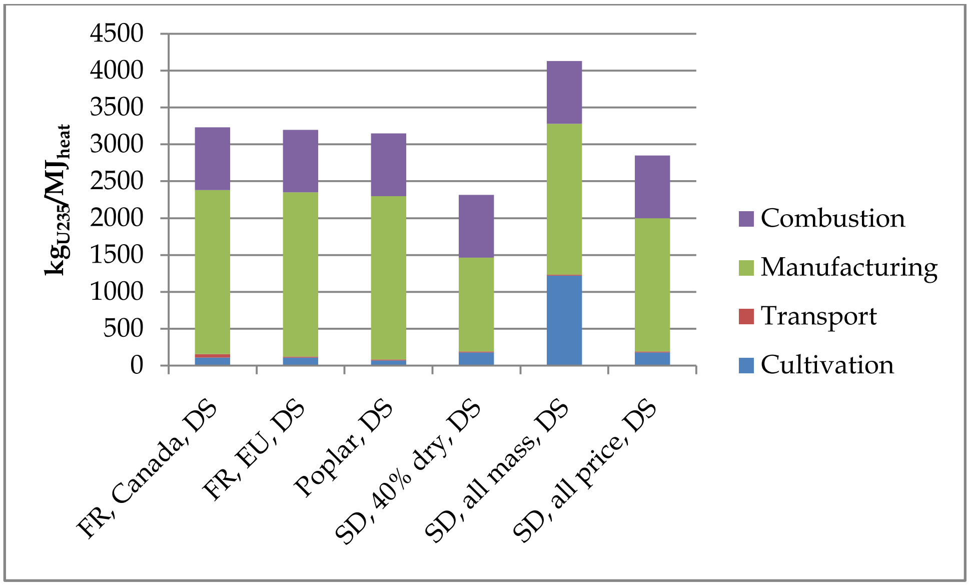

Figure 39: Contribution to ionising radiation in case of combustion in a domestic stove [kgU$_{235eq}$/MJ$_{heat}$]

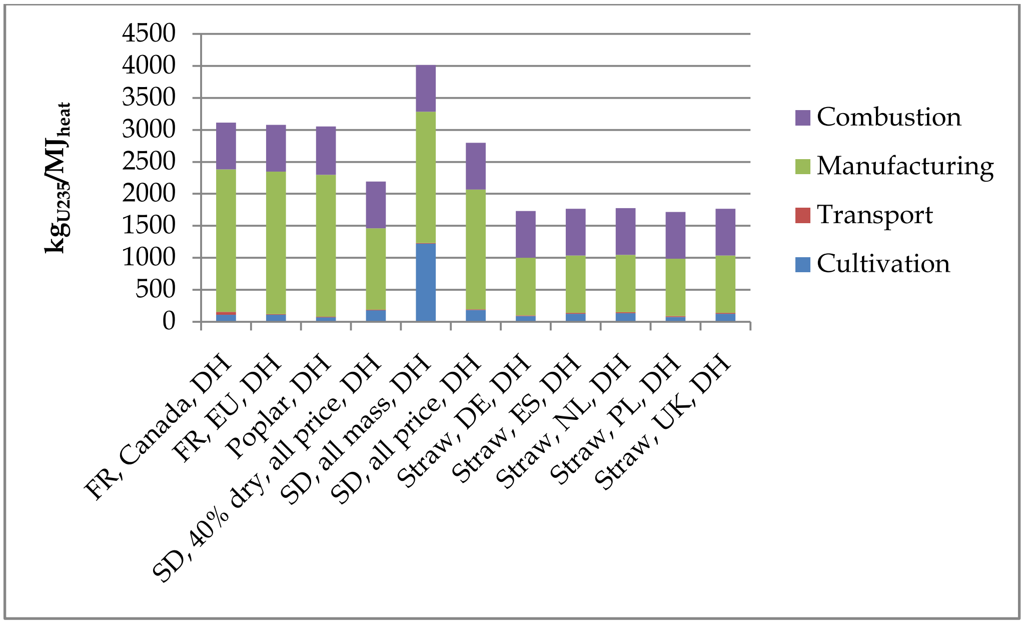

Figure 40: Contribution to ionising radiation in case of combustion in a district heating [kgU_{235eq}/MJ_{heat}]

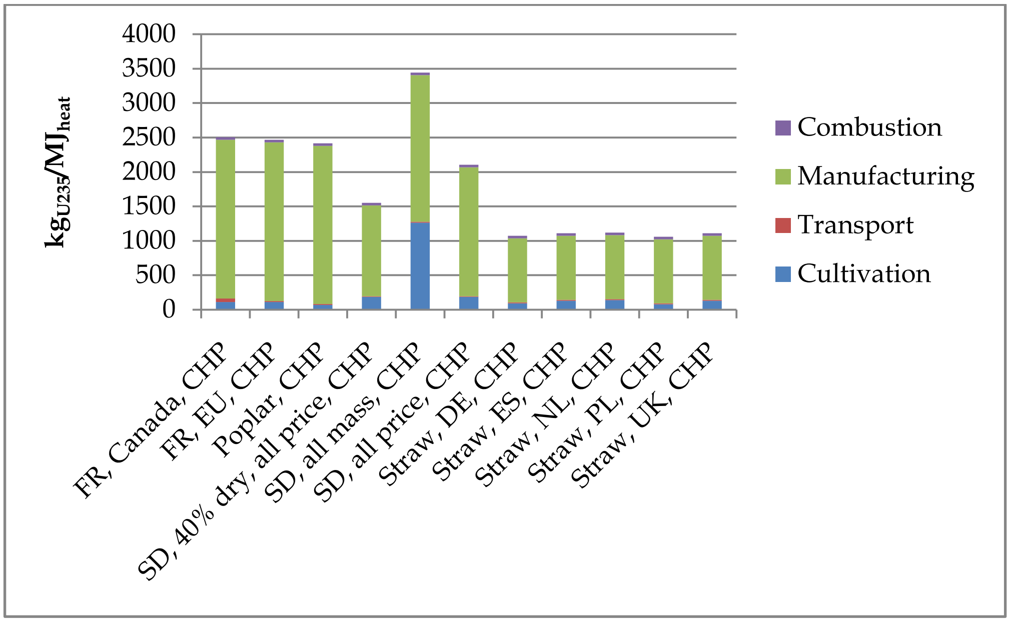

Figure 41: Contribution to ionising radiation in case of combustion in a CHP [kgU_{235eq}/MJ_{heat}]

The sharings of the ionising emissions from the processes are coherent with what stated before: the manufacturing of pellets, being the process with the highest requirement of electricity, is the one with the highest emissions of uranium-235 equivalent.

The emissions of the combustion phase are associated with the production of electricity for boiler operations. In the Ecoinvent process of CHP, the consumption of electricity from the grid is not accounted because it is produced by the CHP itself that is the main reason why the emissions of ionising radiation in CHP scenarios are much lower than in all the other processes.

The emissions of ionising radiation associated with straw pathways are the lowest among the scenarios analysed because the production of straw pellets requires less energy than all the other feedstocks considered in this study.

The significant impact of the production of sawdust, allocation by mass, is due, to the consumption of electrical energy during the industrial process. As explained in the case of the impact on climate change, the allocation by mass emphasises all the emissions due to the production of sawdust and particularly, in this case, the emissions associated with production of electricity.

The considerations about this impact are strongly dependent on the energetic mix of the country: the higher is the sharing of the nuclear in the energetic mix of a country, the more significant are the emissions of ionising radiation.

This aspect is not considered in more detail in this study because it is not coherent with the goal of the work, that is to assess the environmental impact of an averaged European pellets production chain, but this issue has to be taken into account in the case of referring to a specific country or region.

5.4.6 Impact on photochemical ozone formation

The impact on the photochemical ozone formation is expressed in $kg_{NMVOCeq}/MJ_{heat}$.

The formation of tropospheric ozone is due to the photolysis of nitrogen dioxide (NO_2) to nitric oxide (NO) which then reacts with molecular oxygen to form ozone. The ozone is removed by the atmosphere thanks to its reaction with nitric oxide. This cycle includes both reactions of production and removal of ozone so that it is possible to keep a constant concentration of O_3 in the troposphere. The reactions that take part in this cycle are:

$NO_2 + h\upsilon \rightarrow NO + O$

$O + O_2 \rightarrow O_3$

$O_3 + NO \rightarrow NO_2 + O_2$

Anthropic emissions of nitrogen dioxide cause an increase of the ozone in the troposphere.

Also the organic volatile compounds in the atmosphere interfere with this cycle, reacting with the radicals OH and the nitrogen oxides present in the atmosphere to form nitrogen dioxide and other products without actually removing ozone from the troposphere. Therefore, this phenomenon increases the concentration of the tropospheric ozone which has a negative impact on the health of humans and vegetation caused by its strong oxidant power that causes irritations to the human airways and limits the growth of the vegetation.

This is why the nitrogen oxides and the volatile organic compounds are precursors of the tropospheric ozone formation.

In all the pathways analysed the highest contribution to this impact is due to the emissions of nitrogen oxides and just a small contribution comes from direct emissions of volatile organic compounds.

Figure 42 shows the emissions of $NMVOC_{eq}$ caused by each scenario.

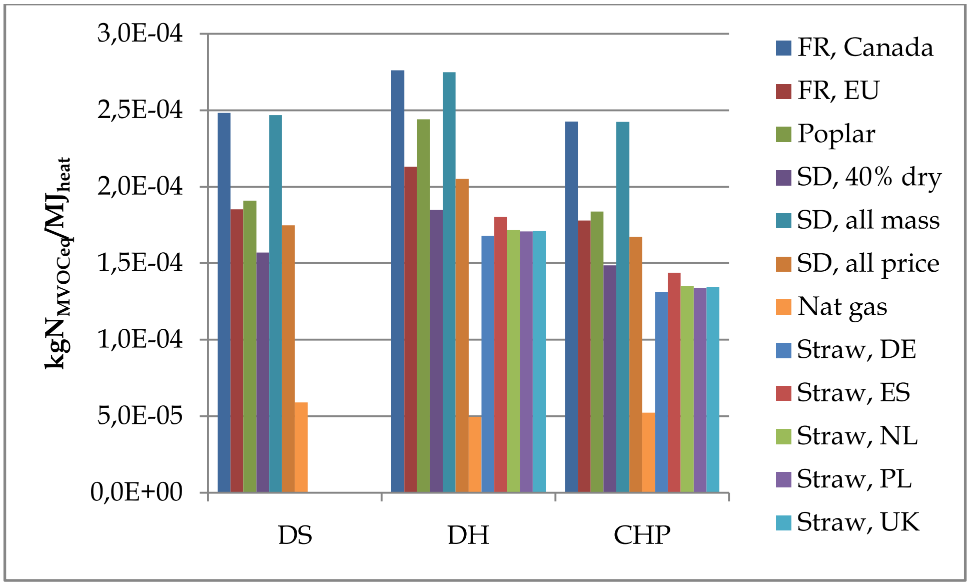

Figure 42: Impact on photochemical ozone formation [$kg_{NMVOCeq}/MJ_{heat}$]

In Figure 43 the sharing of the compounds that contribute to the formation of the tropospheric ozone are reported.

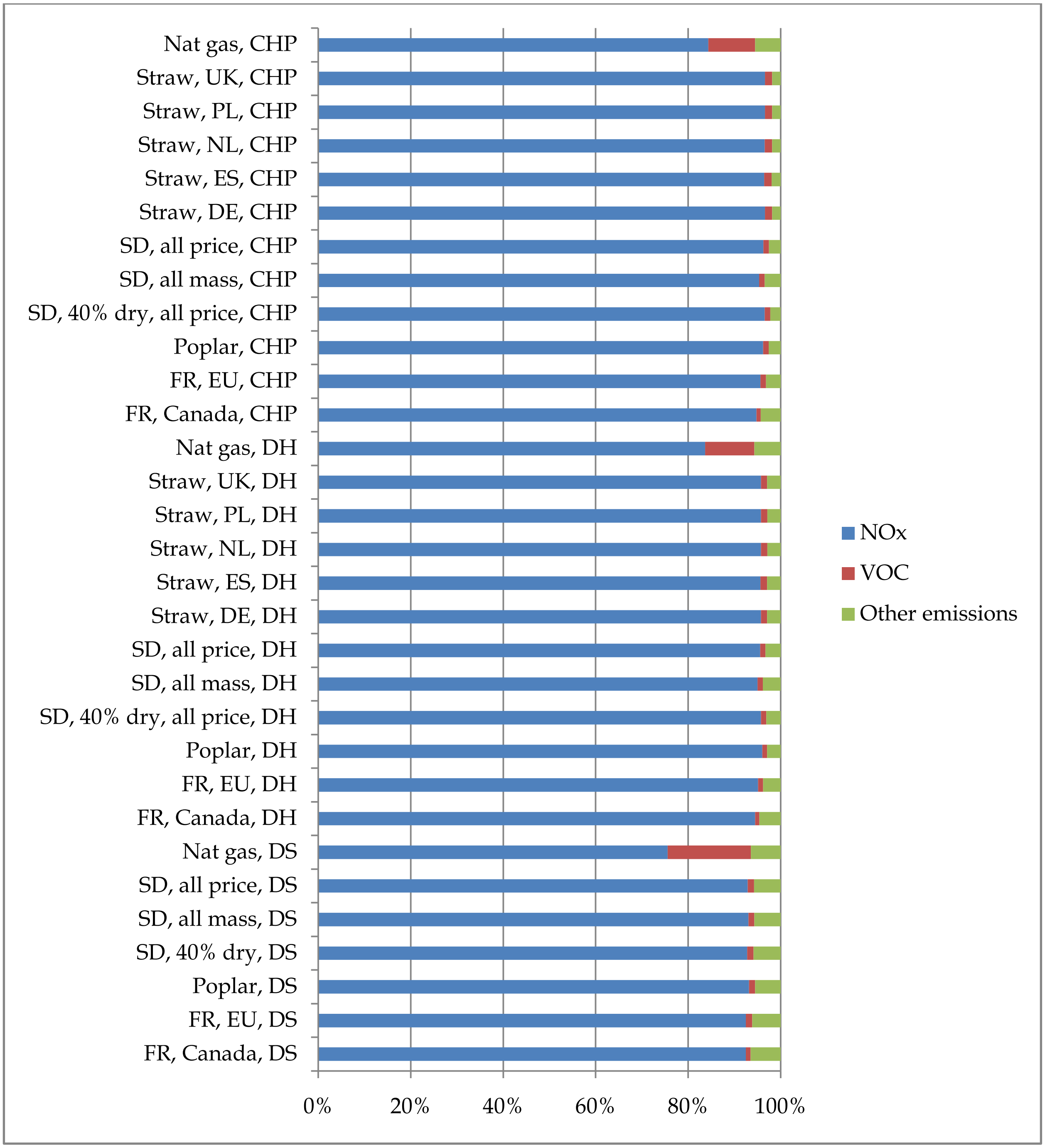

Figure 43: Sharing of the compounds that contribute to the photochemical ozone formation [%]

Note that, referring to the biomass pathways, almost all of the impact is caused by the emissions of nitrogen dioxide, where as in the case of natural gas there is a higher contribution of volatile organic compounds that occurs mainly during the operations of the extraction and handling of the fossil fuel, that cause direct emissions of VOCs in the atmosphere.

In Figure 44, Figure 45 and Figure 46 the contributions of the processes within each pathway are reported.

In all the scenarios analysed the highest contribution is caused by the process of combustion and in particular is mainly due to the emissions of NO_x due to the presence of nitrogen in the fuel.

Generally, there are two main mechanisms for the formation of nitrogen oxides during combustion: thermal-NO_x and fuel-NO_x. Without going too deep into this topic which is common knowledge [10], [28], thermal-NO_x derive from the oxidation of the nitrogen in the combustion air, whereas the formation of fuel-NO_x is due to the presence of nitrogen in the fuel.

The formation of thermal-NO_x does not become important until combustion temperatures reach about 1800 K. This is never achieved in biomass combustion, thus the main mechanism of NO_x formation is the simple oxidation of the fuel-bound nitrogen.

For methane combustion, instead, several techniques are nowadays available to reduce the emissions of NO_x (low-NO_x burners, high air-fuel ratio to keep flame temperature low etc) so that NO_x release from natural gas combustion can be easily minimised

The emissions factors of nitrogen oxides for the reference scenarios are reported in Table 10 whereas the emissions factor for pellets combustion are reported in Table 27.

The transport accounts for the highest percentage in the scenarios of pellets produced from woodchips imported from Canada, compared to all the other scenarios. Also this contribution is due to NOx emissions, particularly due to the transport by ship, fed with heavy fuel oil that emits a significant quantity of nitrogen dioxide.

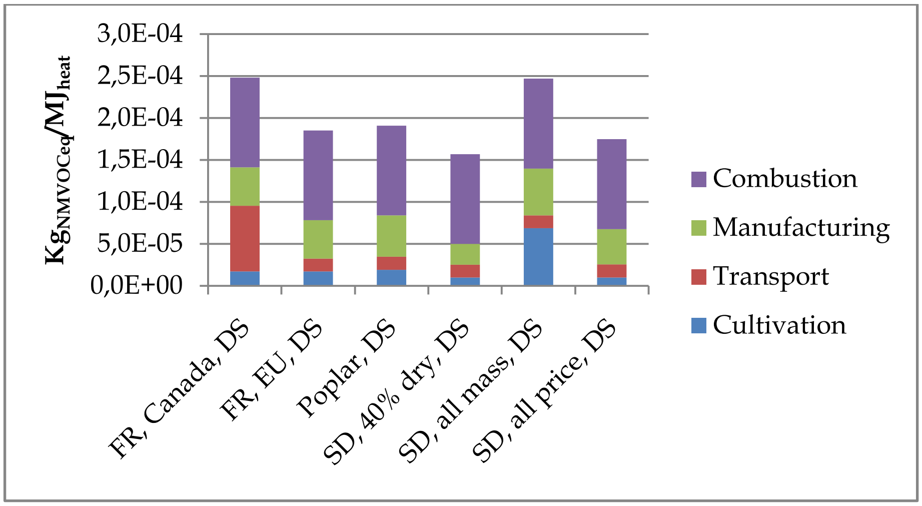

Figure 44: Contribution to the photochemical ozone formation in case of combustion in a domestic stove [Kg_{NMVOC}/MJ_{heat}]

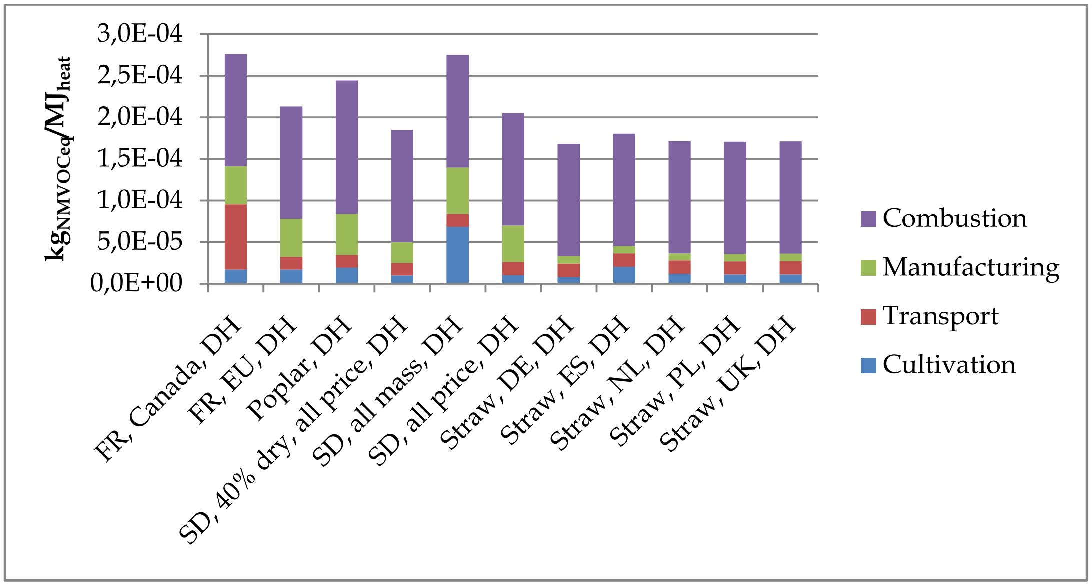

Figure 45: Contribution to the photochemical ozone formation in case of combustion in a CHP [Kg_{NMVOC}/MJ_{heat}]

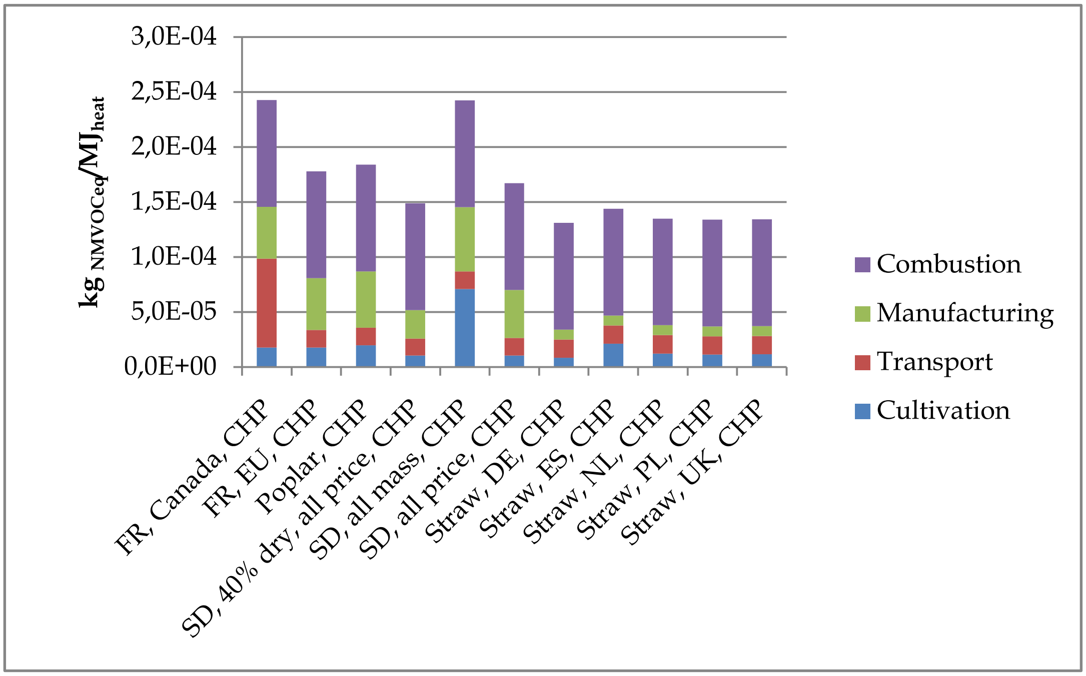

Figure 46: Contribution to the photochemical ozone formation in case of combustion in a district heating [Kg_{NMVOC}/MJ_{heat}]

5.4.7 Impact on air acidification

The impact on air acidification has been evaluated using the characterisation method *CML2001, Acidification Potential (AP)* and it is expressed in terms of kg_{SO2eq}/MJ_{heat}.

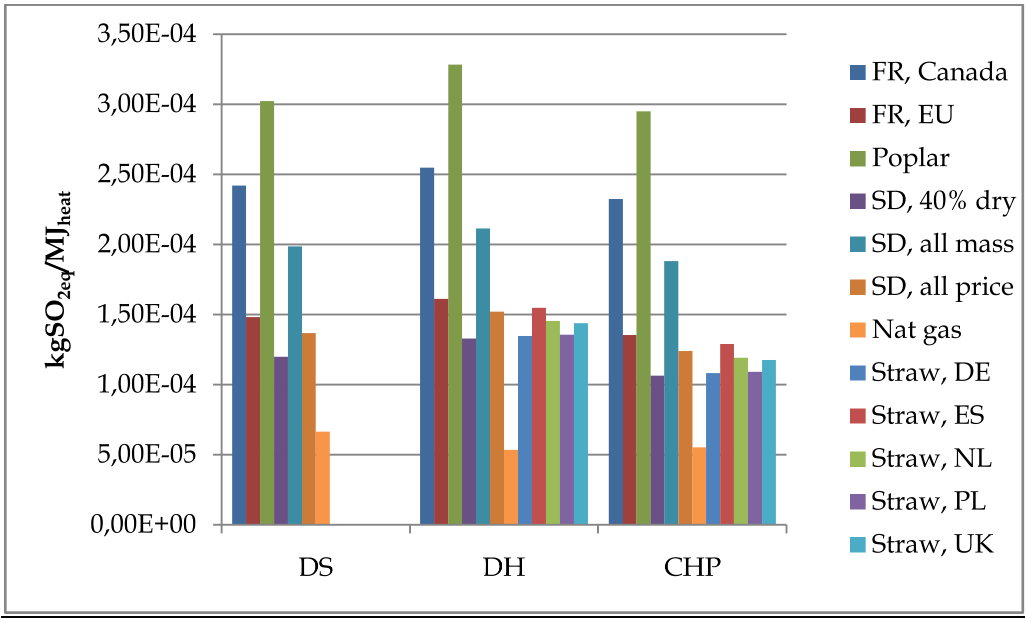

Figure 47: Impact on air acidification [$kgSO_{2eq}/MJ_{heat}$]

The main contribution to this impact is from the emissions of nitrogen compounds in the atmosphere: mainly ammonia, ammonium ions and nitrogen oxides.

The impact on acidification due to natural gas is much lower than the impact of all the bio-heat pathways and that is due to the fact that the combustion of pellets causes significant emissions of NO_x, compared to natural gas, due to the presence of nitrogen in the wood, as reported in the previous paragraph about the photochemical ozone formation.

The pathway with the production of woodchips from poplar has the highest emissions of sulphur dioxide equivalent among all the pathways analysed: this feedstock is the only cultivated one, and presents thus important contribution due to emissions of ammonia in the cultivation phase, due to the use of urea as nitrogen fertiliser. The difference between the pathways of forest residues from Europe and the use of poplar woodchips is comprised between 0,15 and 0,16 g_{SO2eq}/MJ_{heat} and the emissions associated with the poplar scenario are about double of the ones of forest woodchips scenario.

Figure 48, Figure 49, Figure 50 shows the contribution of each process to the total emissions of SO_{2eq} for the scenarios considered.

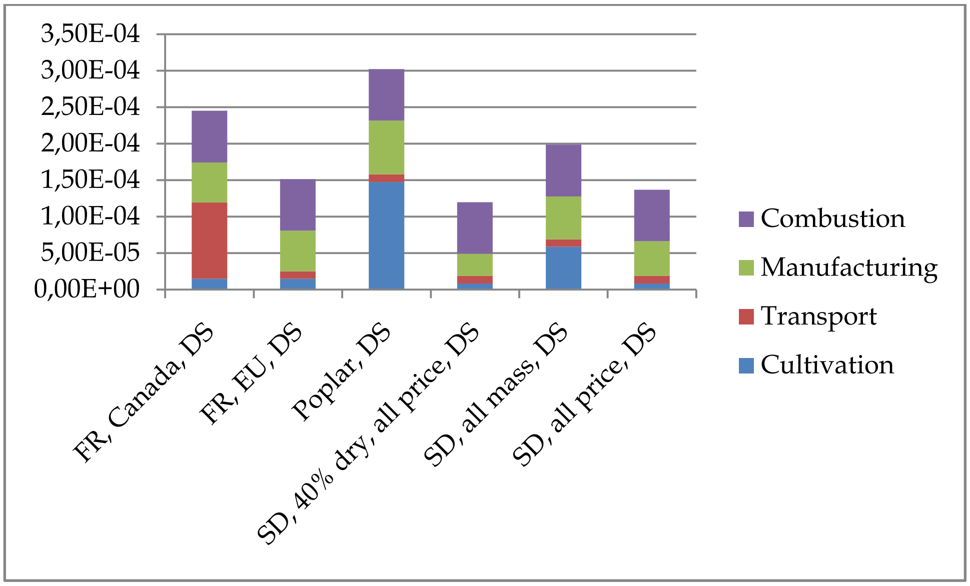

Figure 48: Contribution to the air acidification in case of combustion in a domestic stove [kg_{SOeq}/MJ_{heat}]

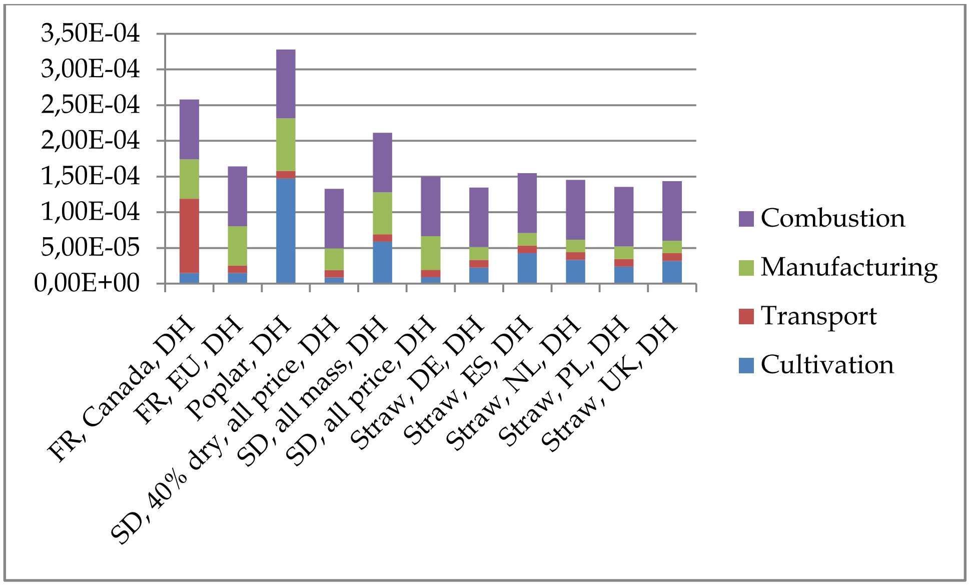

Figure 49: Contribution to the air acidification in case of combustion in a district heating [kg_{SOeq}/MJ_{heat}]

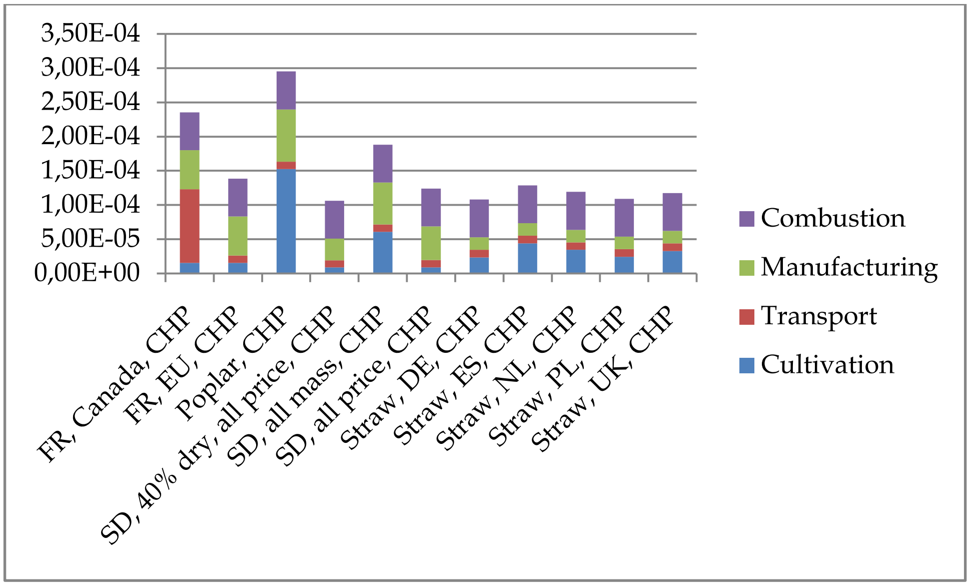

Figure 50: Contribution to the air acidification in case of combustion in a CHP [$kg_{SO_{eq}}/MJ_{heat}$]

In the CHP pathways the combustion gives a lower contribution to the total impact on air acidification than in all the other pathways, due the fact that it does not take electricity from the grid, that causes emissions of NO_x and SO_2 for the combustion of fossil fuels.

Cultivation in general is an important contribution to the acidification potential.

The impact of the cultivation phase strongly depends on the quantity of nitrogen fertilisers volatilised in the atmosphere in the form of ammonia and ammonium ion. In fact the highest contributions to the whole emissions of SO_{2eq} are associated with the pathways of pellets from poplar woodchips and straw pellets, because these are the only ones that include the use of a nitrogen fertiliser in the cultivation phase.

Emissions from transport give the lowest contribution in each scenario except for the one of pellets produced from raw material imported from Canada. In this case, the transport phase contributes for the higher emissions of SO_2 and NO_x from the combustion of heavy fuel oil in the transatlantic ships. In particular, the transport accounts from 6% to 8% in case of pellets from woodchips from Europe, whereas it accounts from 40% to 46% in case of woodchips from Canada and the emissions associated to the long-range transport scenarios increase the total emissions of the pathway with woodchips from Europe from 57% to 60%.

The impact on air acidification was evaluated also in the study of Caserini et al. [7] in case of pellets burned in a domestic stove. This study estimated that the use of wood pellets causes an increase of 1,63 $kg_{SO2eq}/t_{drybiomass}$. The results is coherent with the one of this study which is equal to 1,55 $kg_{SO2eq}/t_{drybiomass}$ in case of the scenario of woodchips from Europe, combusted in a domestic stove.

5.4.8 Impact on terrestrial eutrophication

The characterisation method used to evaluate the impact on terrestrial eutrophication is *EDIP 2003, Terrestrial eutrophication* and the results are expressed in terms of m^2_{UES}/MJ_{heat}.

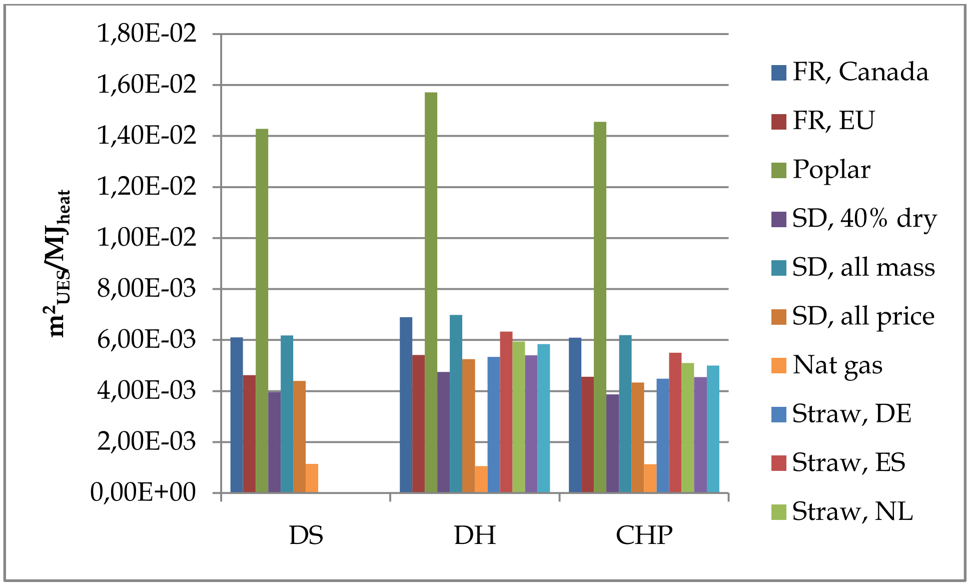

Figure 51: Impact on terrestrial eutrophication [m^2_{UES}/MJ_{heat}]

The impact on terrestrial eutrophication is caused by the emissions of two nitrogen compounds in the atmosphere: nitrogen oxides and ammonia.

The combustion of pellets is the process that highly contributes to the emissions of nitrogen oxides, caused by the presence of nitrogen in the wood.

The lowest impact on the terrestrial eutrophication of the reference scenarios is principally justified by the fact that the combustion of natural gas causes lower emissions of nitrogen oxides, as explained previously.

Figure 52, Figure 53 and Figure 54 report the contributions of the processes within each pathways to the terrestrial eutrophication.

The pathways of poplar are the only one in which the emissions of the cultivation phase are the higher among all the processes of the pathway and are mainly caused by the emissions of ammonia in the atmosphere, due to the use of nitrogen fertilisers for the cultivation of poplar. In particular the emissions of the cultivation phase are more than 4 (431%) times higher than the ones of the cultivation of wheat associated to straw.

In the pathways of straw pellets the cultivation phase generates a higher impact on terrestrial eutrophication compared with the woodchips and sawdust scenarios, due to the use of nitrogen fertilisers. This is due to the fact that the raw materials of the woodchips and sawdust scenarios do not require the use of fertilisers.

A significant contribution to the impact on terrestrial eutrophication is from the phase of transport in the cases of woodchips imported from Canada caused by emission of nitrogen oxides mostly due to the use of the ship and the truck.

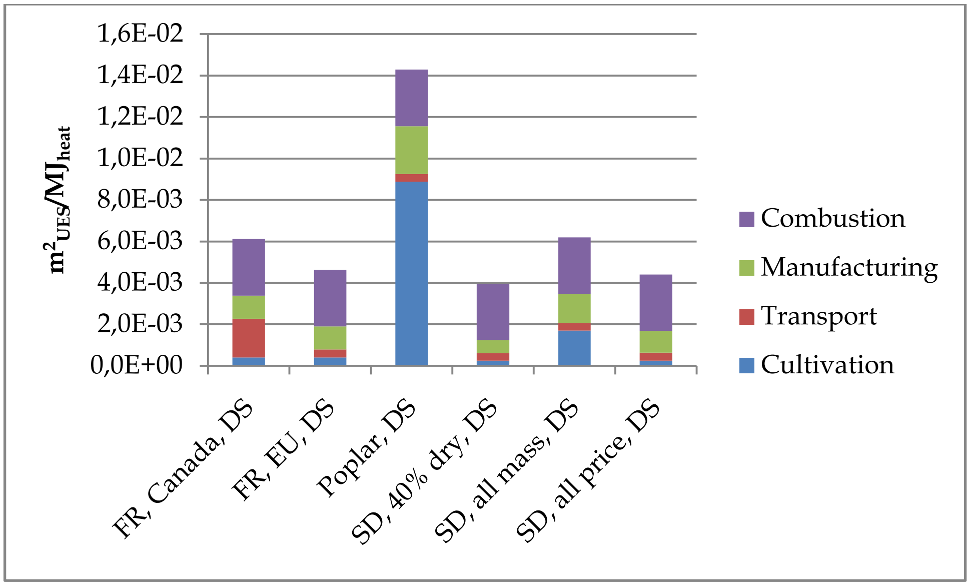

Figure 52: Contribution to terrestrial eutrophication in case of combustion in a domestic stove [m^2_{UES}/MJ_{heat}]

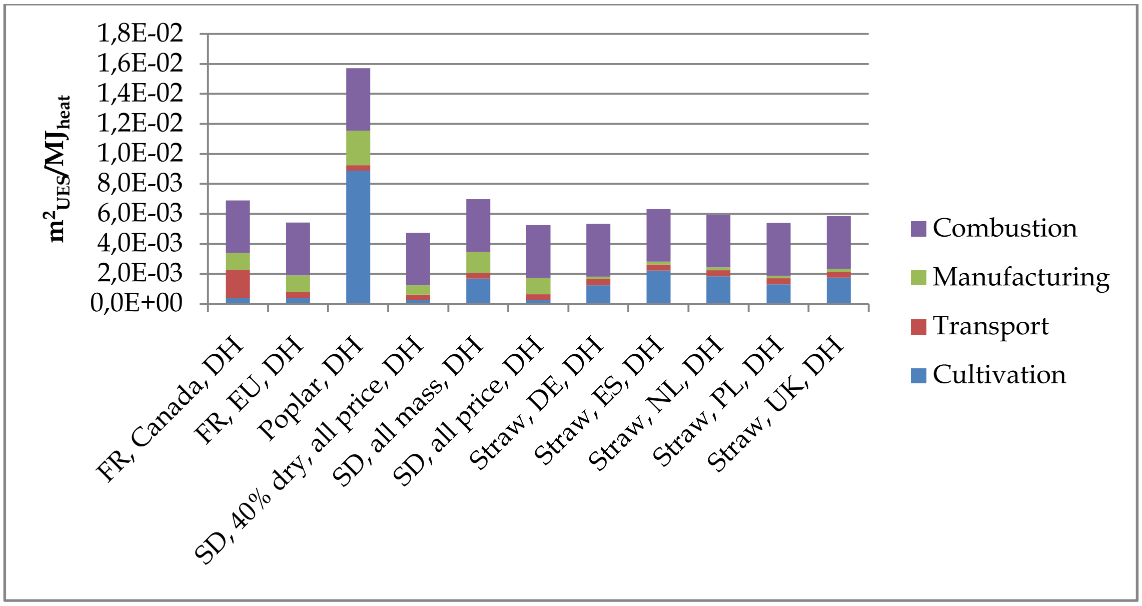

Figure 53: Contribution to terrestrial eutrophication in case of combustion in a district heating [m^2_{UES}/MJ_{heat}]

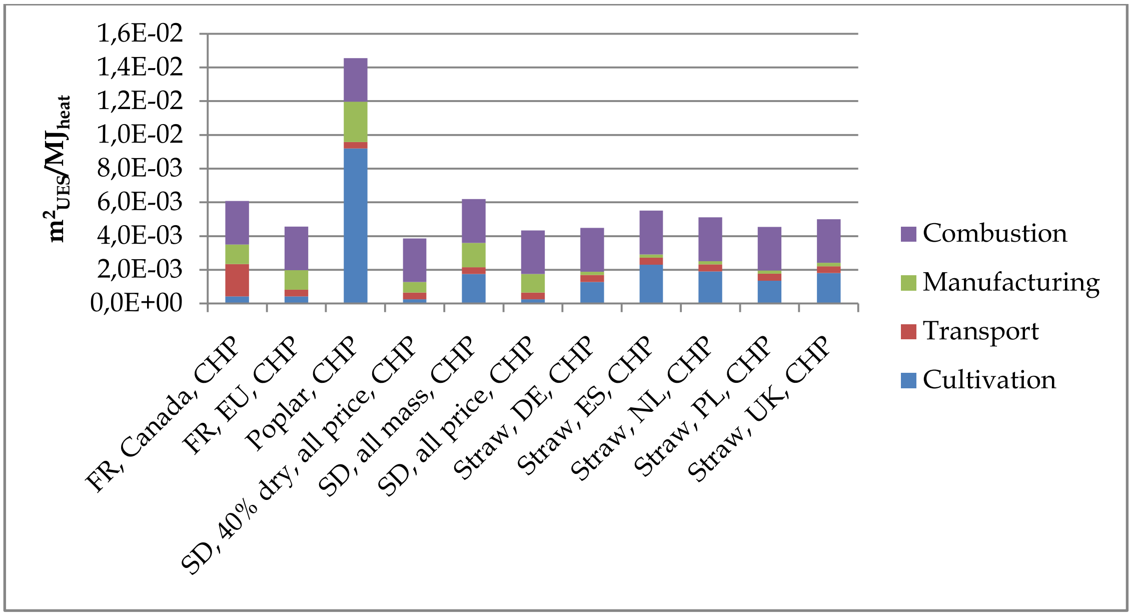

Figure 54: Contribution to terrestrial eutrophication in case of combustion in a CHP [m^2_{UES}/MJ_{heat}]

5.4.9 Impact on aquatic eutrophication

The impact on aquatic eutrophication was evaluated using the method Recipe Midpoint as recommended by the ILCD [19]. This method makes a difference between freshwater systems and marine systems.

The impact on freshwater is defined in terms of kg_{Peq}/MJ_{heat}, and it accounts for the emissions of phosphorous in different forms, while the impact on the marine environment is measured in kg_{Neq}/MJ_{heat} and it includes all the emissions of nitrogen in different forms.

Figure 55 shows the impact on freshwater eutrophication, while the contribution of each process to the total impact are reported in Figure 56, Figure 57 and Figure 58.

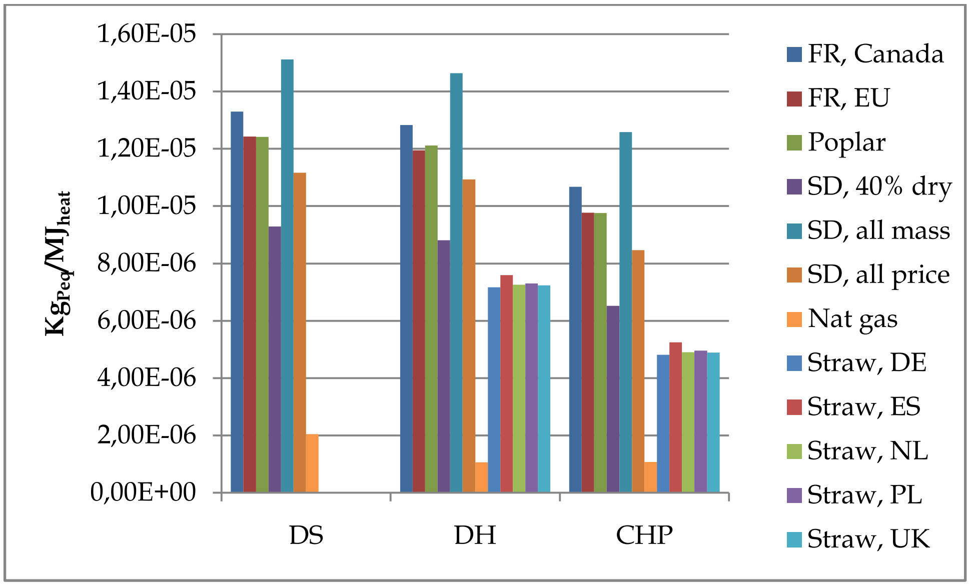

Figure 55: Impact on freshwater eutrophication [kg_{Peq}/MJ_{heat}]

Figure 56, Figure 57 and Figure 58 shows the contribution of the processes to the total impact on freshwater eutrophication.

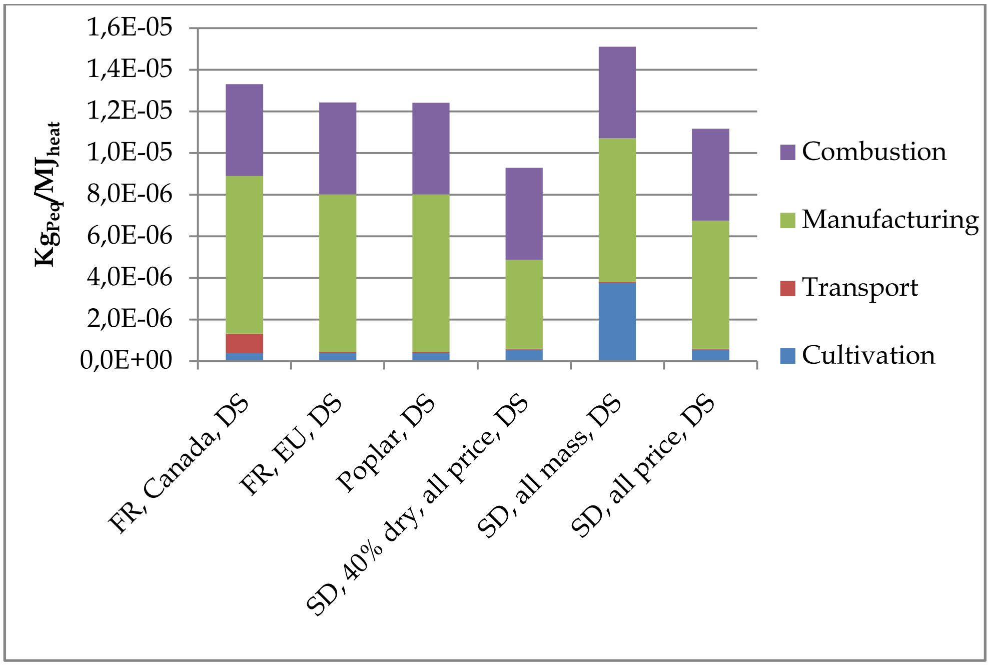

Figure 56: Contribution to the freshwater eutrophication in case of combustion in a domestic stove [kg$_{Peq}$/MJ$_{heat}$]

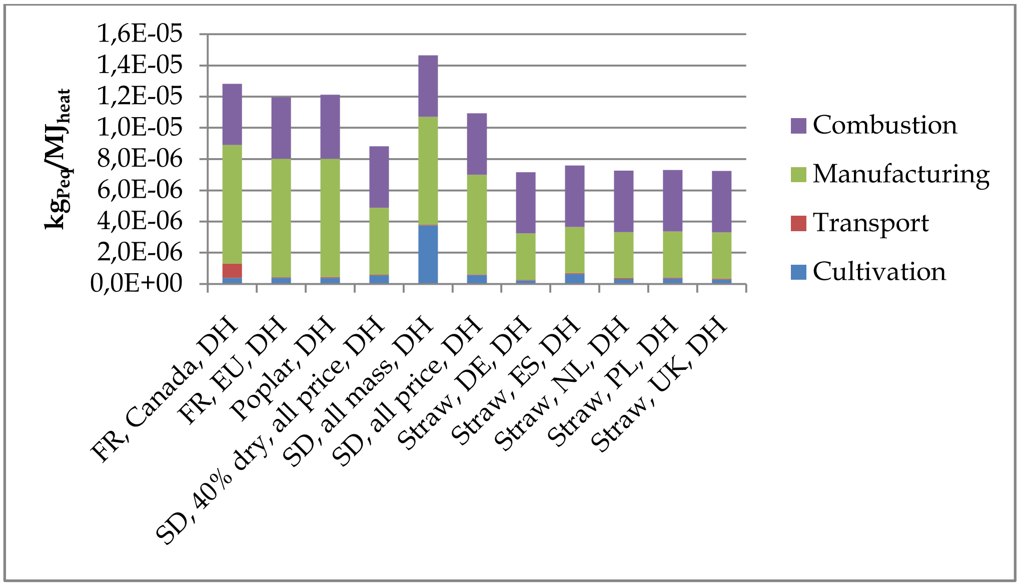

Figure 57: Contribution to the freshwater eutrophication in case of combustion in a district heating [kg$_{Peq}$/MJ$_{heat}$]

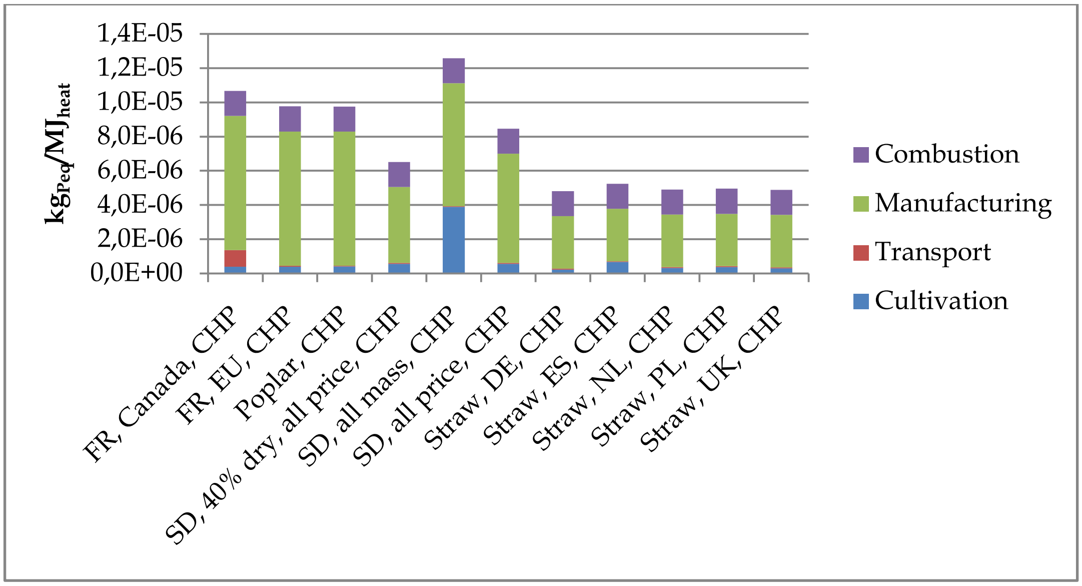

Figure 58: Contribution to the freshwater eutrophication in case of combustion in a CHP [kg$_{Peq}$/MJ$_{heat}$]

Note that this is only the contribution to eutrophication caused by phosphorous and phosphoric compounds and that the plots do not represent the total impact on eutrophication that is also caused by the emissions of nitrogen compounds.

The production of electricity causes significant emissions of phosphate in the freshwater, this explains the fact that the highest emissions are associated with the scenarios with a high requirement of electricity for the production of pellets and, vice versa, the scenarios of straw are the ones with the lowest impact on freshwater eutrophication among the biomass pathways because they have the lowest consumption of electricity.

SD, all mass, DS is the scenario with the highest emissions of phosphorous equivalent. As explained in Section 5.4.1, these significant emissions are due to the different allocation methodologies.

The production of pellets from woodchips both from poplar and from forest residues is responsible for a higher impact due to the high amount of electricity needed to produce pellets, compared to the straw and sawdust, 40% dry, pathways.

Figure 59 shows the impact on marine eutrophication in terms of kg$_N$/MJ$_{heat}$.

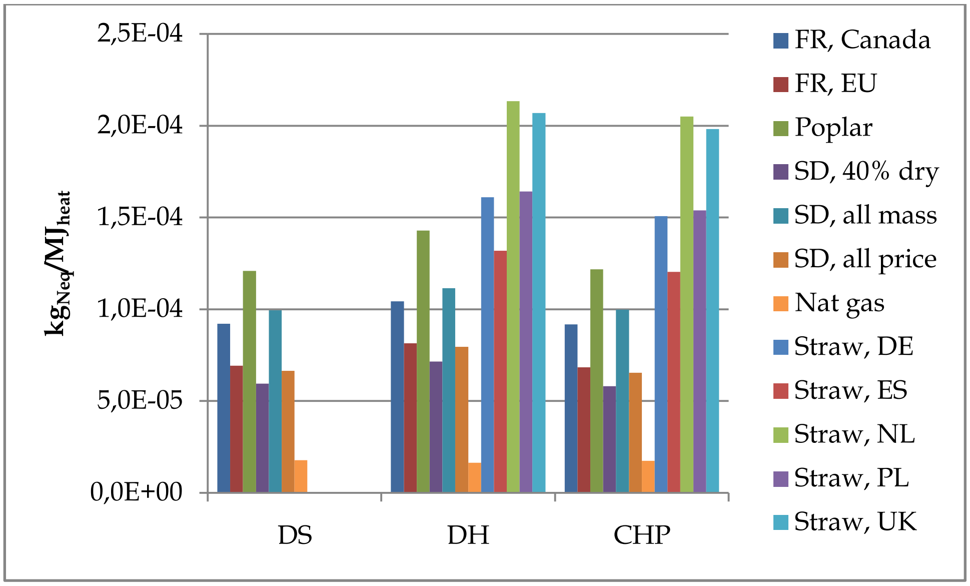

Figure 59: Impact on marine eutrophication [kg_{Neq}/MJ_{heat}]

In this case the highest emissions of nitrogen equivalent are associated with the pathways of straw pellets.

The contribution of each process to the total impact associated with the scenarios is reported in Figure 60, Figure 61 and Figure 62.

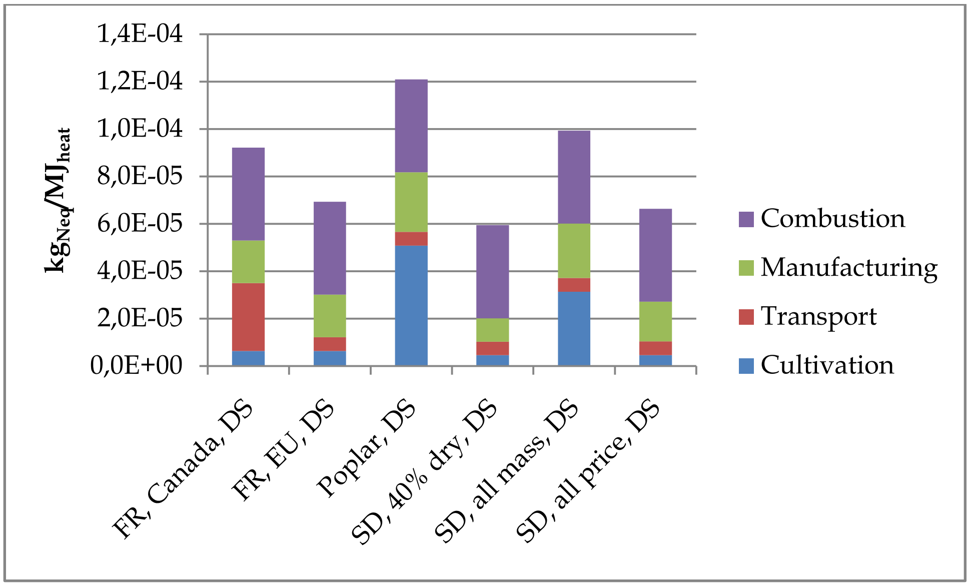

Figure 60: Contribution to the marine eutrophication in case of combustion in a domestic stove [Kg_{Neq}/MJ_{heat}]

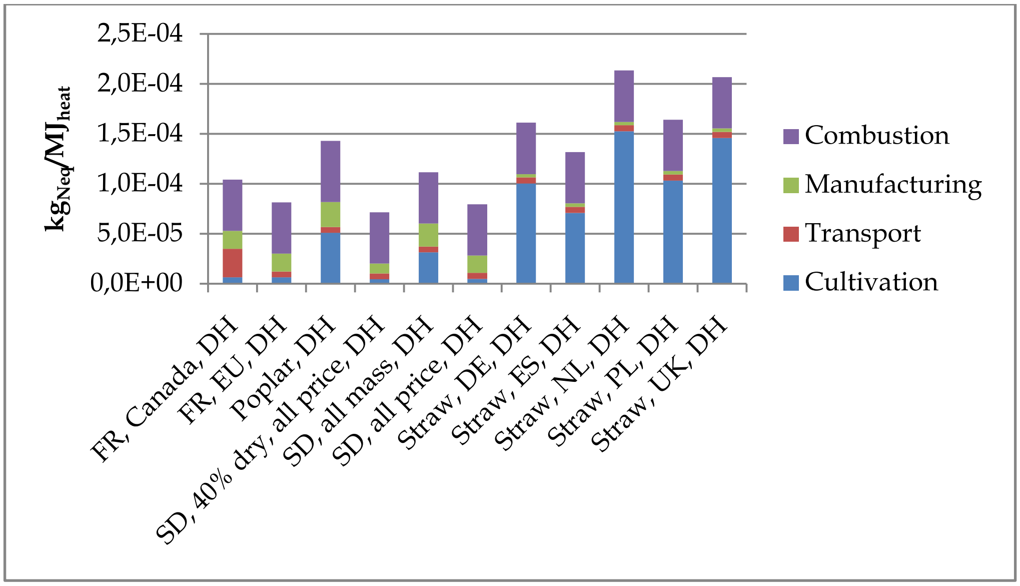

Figure 61: Contribution to the marine eutrophication in case of combustion in a district heating [Kg_{Neq}/MJ_{heat}]

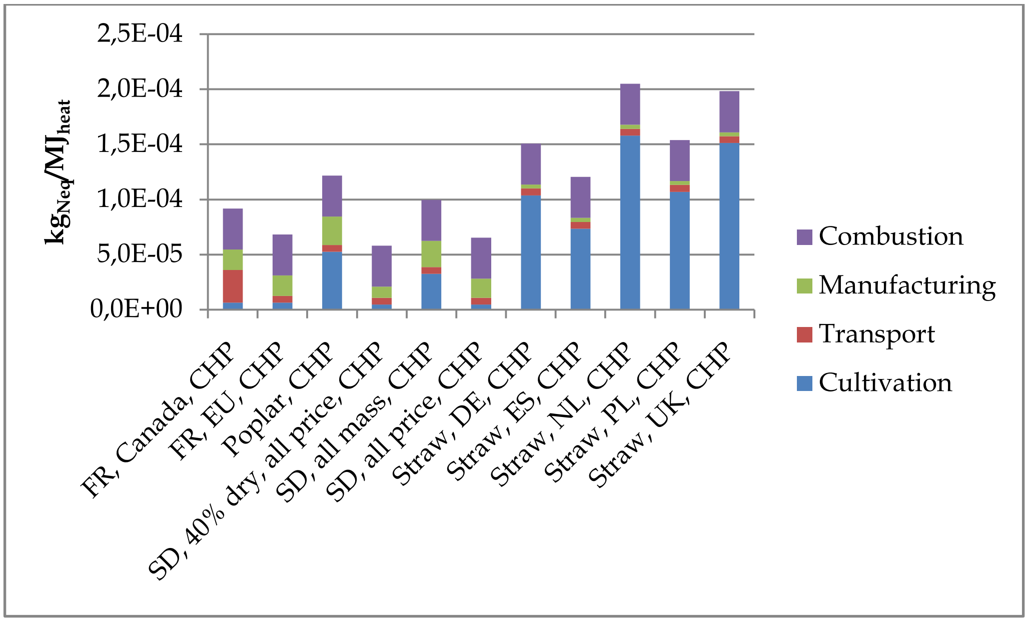

Figure 62: Contribution to the marine eutrophication in case of combustion in a CHP [Kg_{Neq}/MJ_{heat}]

The processes that give the highest contribution are the combustion and the cultivation, depending on the scenarios.

The emissions of nitrogen during the cultivation phase are mainly due to the use of nitrogen fertilisers that are partially released in the environment after their application, whereas the emissions from the combustion are mostly related to the emissions of nitrogen oxides in the atmosphere, due to the presence of the nitrogen in the feedstock.

In particular in the pathways of straw, the cultivation phase causes the highest quantity of emissions of nitrogen equivalent: in all the pathways of straw the impact of the cultivation accounts for more than 60% of the total emissions.

The relevance of the impact of the cultivation phase on eutrophication is mainly due to release of the nitrogen in form of emissions of nitrates (NO_3^-) in fresh water and emissions of nitrogen oxides (NO_x) in the atmosphere.

Considering the other impact categories influenced by the emissions of nitrogen compounds, such as terrestrial eutrophication, air acidification, this is the only impact category for which the straw pellets pathway has a higher impact compared to poplar one.

This is due to fact that in these two scenarios the fate of nitrogen fertilisers has been modelled in two different ways.

In particular, the emissions of nitrogen compounds in the environment referred to the production of 1MJ of heat by a district heating plant are reported in Table 34 (the emissions for 1MJ produced by a CHP are slightly higher, due to the lower thermal efficiency of the CHP, but the proportions are the same, thus here the case of CHP is not reported).

		Poplar, DH	**Straw, DE, DH**	**Straw, ES, DH**	**Straw, NL, DH**	**Straw, PL, DH**	**Straw, UK, DH**
NH_3 in the atm	**Kg_{NH3}/MJ_{heat}**	8,3E-05	9,4E-06	1,6E-05	1,4E-05	9,5E-06	1,3E-05
NO_x in the atm	**Kg_{NOx}/MJ_{heat}**	1,8E-05	7,8E-06	1,9E-05	1,1E-05	1,1E-05	1,1E-05
NO_3^- in the water	**kg_{NO3-}/MJ_{heat}**	1,6E-04	4,1E-04	2,4E-04	6,3E-04	4,1E-04	6,0E-04

Table 34: Distribution of nitrogen in the environmental compartments

It is important to underline that the emissions of nitrogen compounds in the atmosphere for poplar cultivation are higher than the one of wheat cultivation allocated to straw, which, on the contrary, causes higher emissions of nitrate in the deep water. This results in a higher impact on terrestrial eutrophication and air acidification, for poplar cultivation mainly influenced by the emissions in the atmosphere, and, vice versa, in a higher impact on marine eutrophication for the cultivation of wheat straw.

In the pathways of the poplar the sharing of the emissions of the cultivation phase are comparable with the ones of the combustion phase. In particular the percentage of the sharing for each scenario are reported in Table 35.

	DS	**DH**	**CHP**
Cultivation	42,0%	35,6%	43,2%
Combustion	32,4%	42,8%	30,5%

Table 35: Sharing of the emissions of nitrogen equivalent for poplar pathway [%]

In all the pathways referred to woodchips and sawdust the combustion phase emits more nitrogen equivalent than all the other phases. The cultivation phase has a lower importance because the raw material (wood from forests) is assumed to not require the application of fertilisers. Actually, in some cases, Urea is used even on natural forest to stimulate growth, but it is not a common practice in Europe and it has therefore not been considered in this work.

In the case of woodchips from Canada, the transport gives a significant contribution due to the emissions of NO_x principally caused by the use of the ship and the trucks.

It is complex to evaluate the impact on eutrophication only caused by phosphorous or nitrogen emissions because both give their contribution to the same phenomenon. The two Recipe impact methods tend to highlight only different aspects of the same impact, but they do not give a complete evaluation of the eutrophication.

For this reason it has been evaluated the impact of the method choice in the sensitivity analysis in Paragraph 5.4.13.

5.4.10 Impact on ecotoxicity

The impact on ecotoxicity is evaluated with two different methods: the USEtox 2008, referred to the impact on freshwater and the CML 2001 that is for the terrestrial ecotoxicity.

The first one is suggested by the ILCD [19], while the ILCD does not report any suggestions about the characterisation method to use to evaluate the impact on terrestrial ecotoxicity. The CML characterisation method has been used in this study in order to evaluate the impact on terrestrial ecotoxicity, with the awareness that the ILCD considers this method still immature to be recommended.

The method Usetox 2008 provides an estimate of the potentially affected fraction of species (PAF) integrated over time and volume per unit mass of a chemical emitted (PAF*m^{3}* day/kg) [58].

Figure 63 shows the impact of each scenario in terms of PAF*m^{3}*d/MJ_{heat}.

The emissions due to the pathways of poplar are one order of magnitude higher than the ones associated with all the other scenarios and this is mainly due to the use of herbicides.

In particular the main contribute to the whole impact is associated with the quantity of Glyphosate that migrates in the soil.

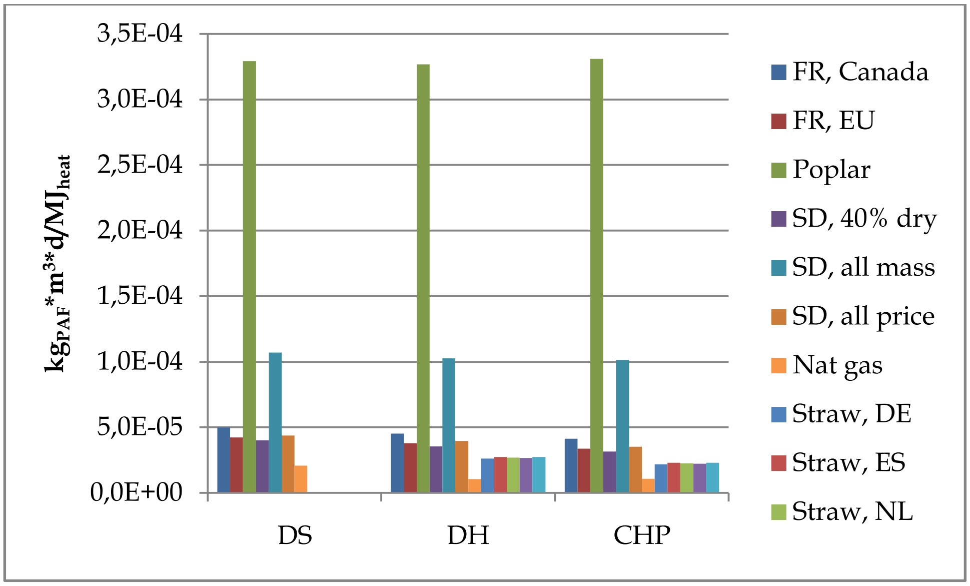

Figure 63: Impact on freshwater ecotoxicity [kg_{PAF}*m^{3}*d/MJ_{heat}]

The transport of pellets from Canada to Europe increases by 15% to 22% the impact of the pathway of pellets made with woodchips from Europe. The impact caused by the transport is mainly associated with nitrogen dioxides emitted by the trans-oceanic ships.

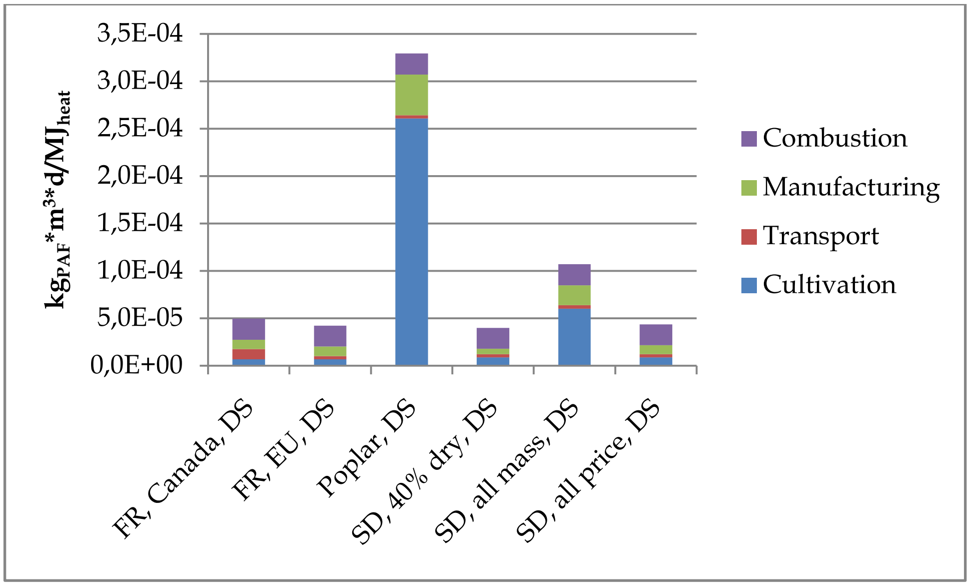

Figure 64: Contribution to the freshwater ecotoxicity in case of combustion in a domestic stove [$kg_{PAF}*m^{3}*d/MJ_{heat}$]

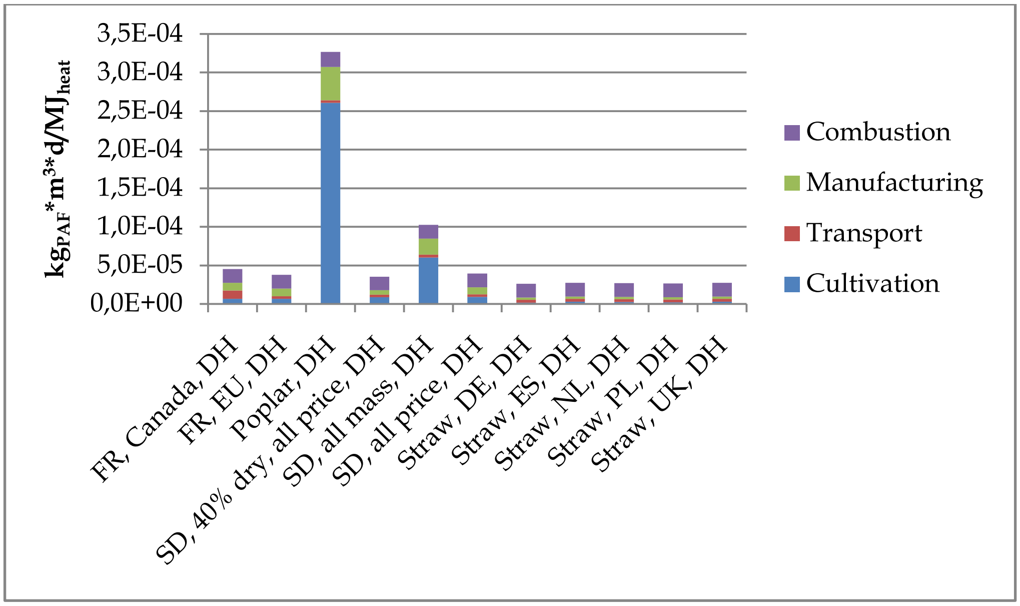

Figure 65: Contribution to the freshwater ecotoxicity in case of combustion in a district heating [$kg_{PAF}*m^{3}*d/MJ_{heat}$]

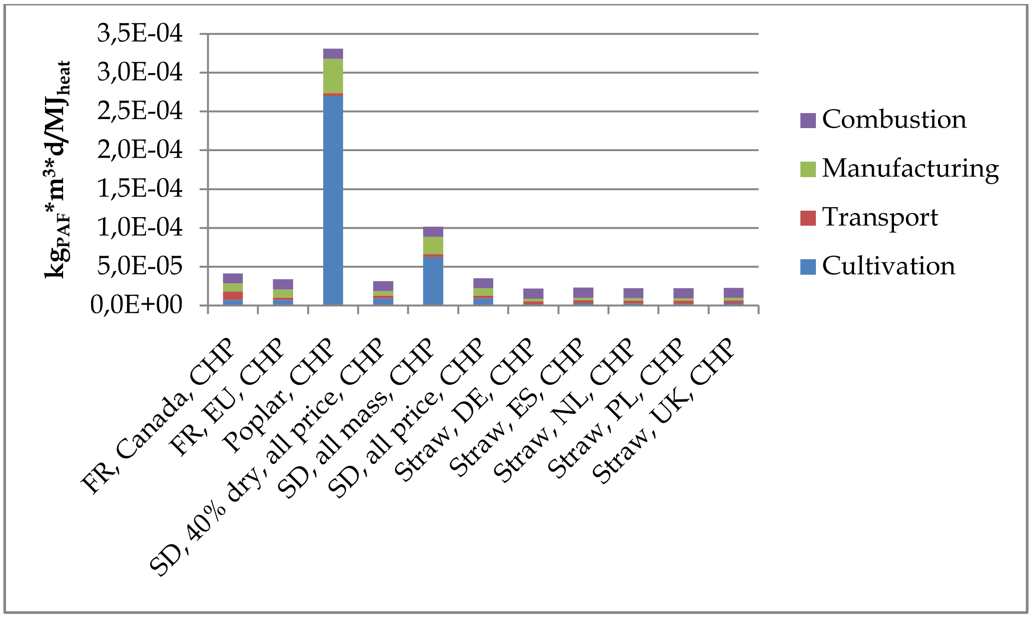

Figure 66: Contribution to the freshwater ecotoxicity in case of combustion in a CHP [$kg_{PAF}*m^3*d/MJ_{heat}$]

The characterisation method CML 2001, Terrestrial ecotoxicity potential expresses the impact on ecotoxicity in terms of kg_{DCBeq}/MJ_{heat}.

The dichlorobenzene is a lipophilic, organic compound that tends to be accumulated in the fatty tissues and has a toxic impact on human health.

The impact on terrestrial ecotoxicity of the scenarios considered is reported in Figure 67.

The reference scenario has a lower impact on human toxicity compared to all the other biomass pathways.

The impact on terrestrial toxicity is mainly due to the emissions of heavy metals, in particular chromium, due to the disposal of the wood ashes to landfarming, after the combustion. The heavy metals emitted are the ones that have been absorbed by the trees during their lives.

There is a growing interest in the possible emissions of heavy metals from different biomass types within the scientific community and preliminary research shows that this could be a potentially environmentally harmful, as shown in this work [64].

The natural gas does not contains heavy metals. This explains the fact the burning pellets causes a higher impact on terrestrial ecotoxicity than burning natural gas.

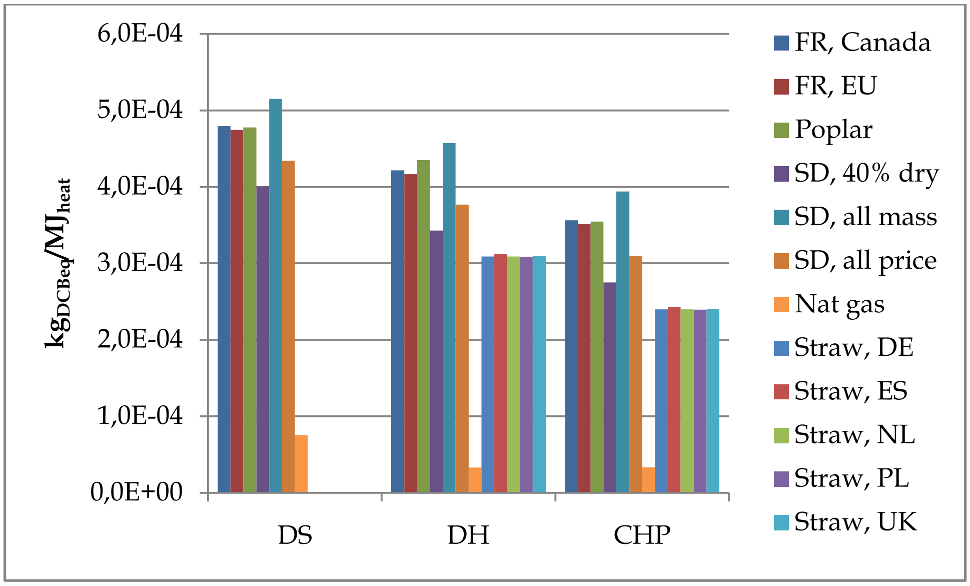

Figure 67: Impact on terrestrial ecotoxicity [kg_{DCBeq}/MJ_{heat}]

Figure 68, Figure 69 and Figure 70 show the contributions of the processes to the terrestrial ecotoxicity in each scenario analysed.

The combustion phase (that includes also the disposal of the wood ashes to landfarming) has the highest influence on terrestrial ecotoxicity in each scenario.

The impact on terrestrial toxicity is almost the same for the scenarios of woodchips from poplar and forest both from Europe and Canada. This is due the fact that the cultivation and the transport phases, that are the processes that mainly differs in these pathways, give just a small contribution to the total impact on terrestrial ecotoxicity.

The scenarios referred to the straw have the lowest impact among all the scenarios thanks to a very low impact of the cultivation phase and a lower contribution given by the process of pellets production compared to all the other pathways, due to the fact that straw is assumed to be dried with natural gas whereas in the other scenarios the raw materials are assumed to be dried with woody biomass that contain heavy metals.

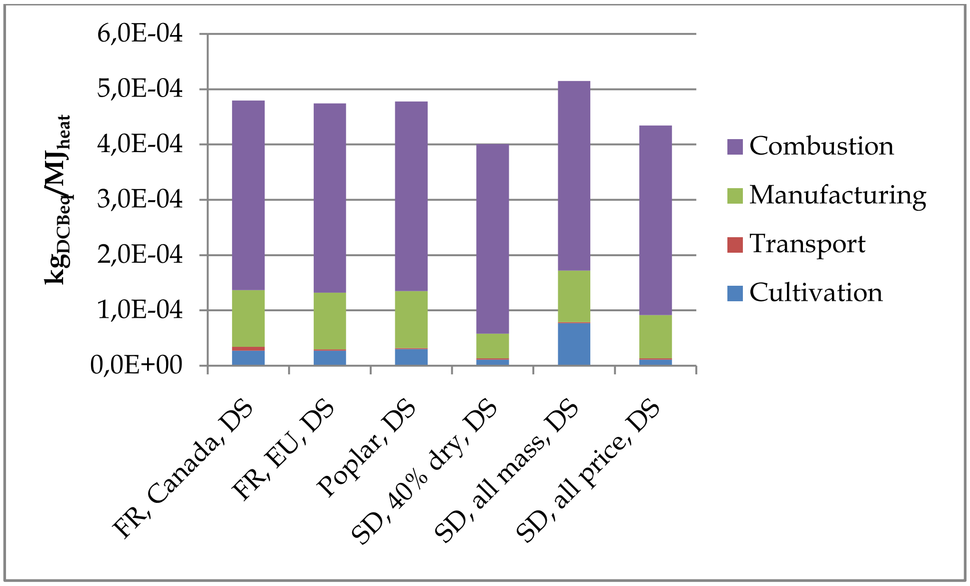

Figure 68: Contribution to the terrestrial ecotoxicity in case of combustion in a domestic stove [kg_{DCBeq}/MJ_{heat}]

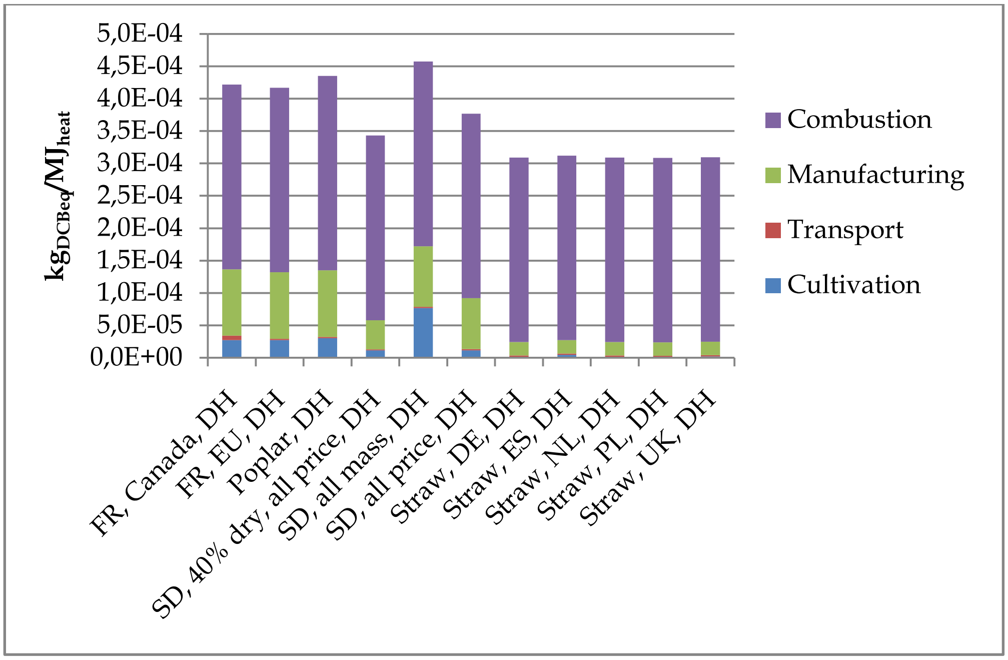

Figure 69: Contribution to the terrestrial ecotoxicity in case of combustion in a district heating [kg_{DCBeq}/MJ_{heat}]

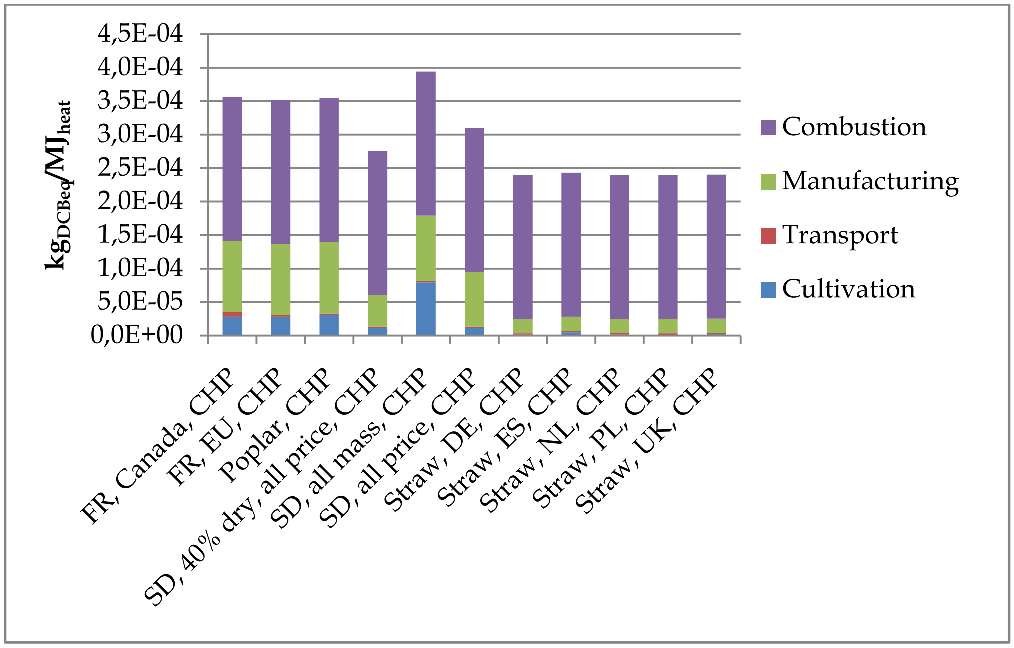

Figure 70: Contribution to the terrestrial ecotoxicity in case of combustion in a CHP [kg_{DCBeq}/MJ_{heat}]

5.4.11 Impact on resource depletion

The impact on resources depletion has been evaluated using the method by the CML2001. This method includes the consumption of non renewable resources material and elements during the life cycle. It does not include the non renewable energy resources, such as natural gas.

The characterisation factors are named *abiotic depletion potentials* (ADP) and it is expressed in kg of antimony equivalent (Sb), which is the adopted reference element [19]. It is calculated for elements and, in the case of economic reserves and reserve base, several mineral compounds [19].

Figure 71 reports the impacts of all the scenarios analysed is expressed in terms of Sb equivalent per one mega-joule of heat produced.

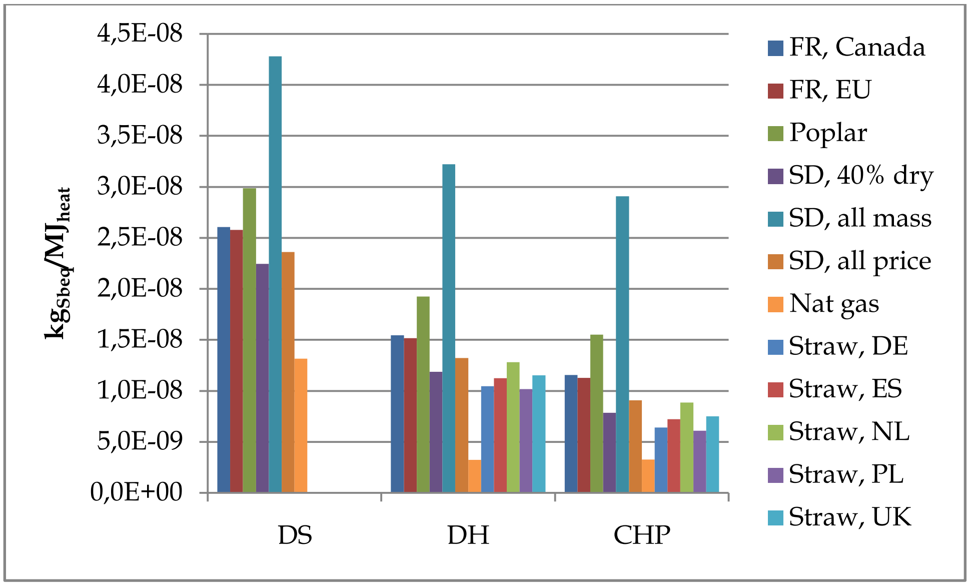

Figure 71: Impact on resources depletion [kg$_{Sbeq}$/MJ$_{heat}$]

The reference scenario has a lower impact on the resources depletion than the biomass pathways, that require a higher quantity of resources compared to the reference scenarios due to the largest amount of infrastructure needed.

Figure 72, Figure 73 and Figure 74 show that the main differences between the scenarios are related to the combustion phase that strongly influences the sharing of the impact on resources depletion, which is higher for domestic stoves and lowest in case of CHPs. This is due to the fact that the mega joules of heat produced by a big plant during its life are much higher than the ones produced by a small plant and, although the big plant causes the depletion of a higher quantity of resources than a small one, the ratio between resources depleted and heat produced is favourable for the bigger plants.

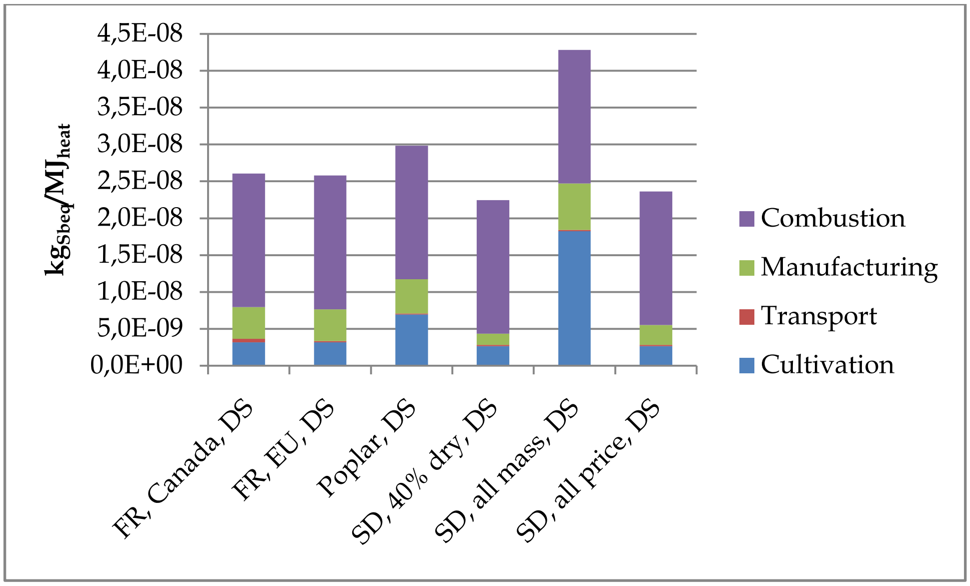

Figure 72: Contribution to resources depletion in case of combustion in a domestic stove [kg_{Sbeq}/MJ_{heat}]

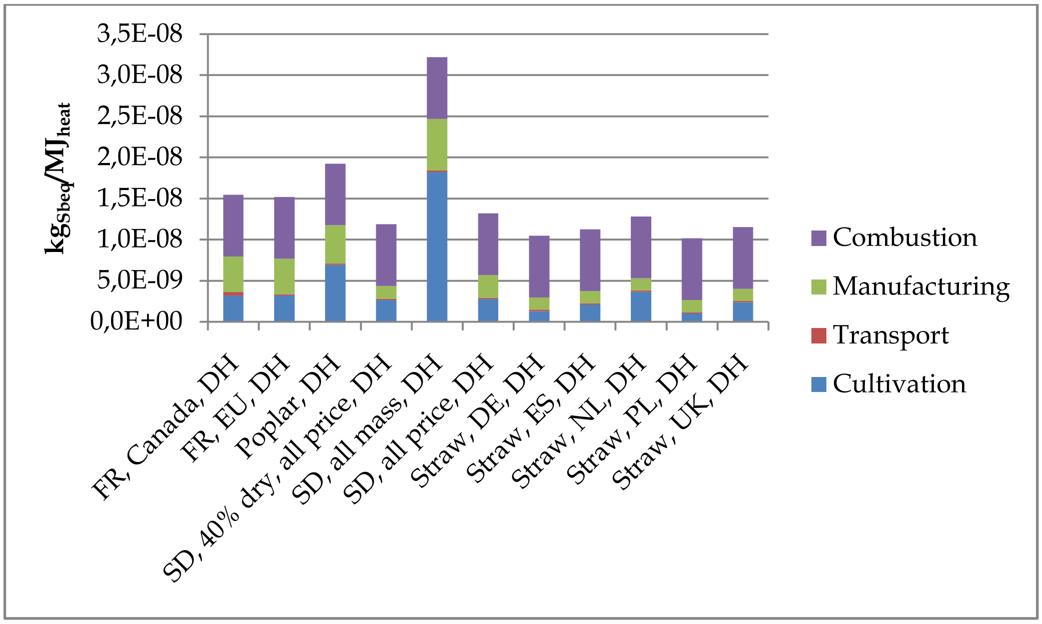

Figure 73: Contribution to resources depletion in case of combustion in a district heating [kg_{Sbeq}/MJ_{heat}]

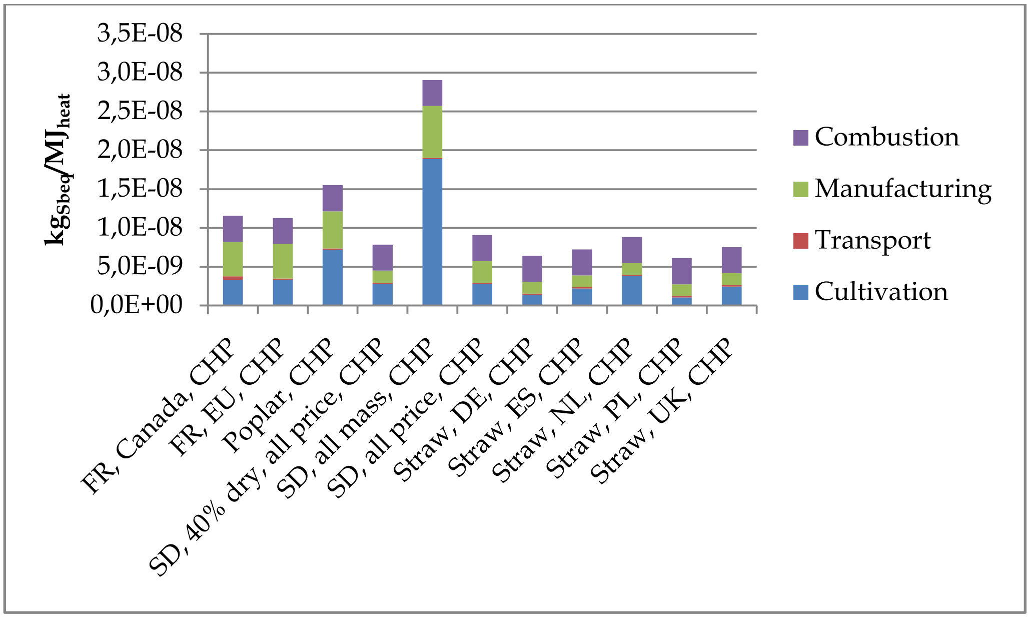

Figure 74: Contribution to resources depletion in case of combustion in a CHP [kg_{Sbeq}/MJ_{heat}]

The resources depletion for the cultivation phase is mainly related to the production of Urea, that accounts for the 79% of the impact of the cultivation phase.

The use of agrarian machineries, in particular of the mobile chopper, accounts for 19% of the impact for the cultivation phase, due to the fact that they have a high turnover. Heavy duty machineries need to be almost yearly maintained and their lifetime rarely exceeds 5-7 years.

5.4.12 General considerations

5.4.12.1 Considerations on the choice of the allocation method

As stated before, the allocation of the emissions from sawmill to the sawdust does not represent a physical process, but it is a methodology that associates the emissions of the industrial multi-outputs processes to only one of the products (e.g. the sawdust).

The choice of the allocation method is dependent on the goal of the study; actually it is recommended by the ISO standards to avoid allocation when possible and rather apply a system expansion, but that is not always possible, as for this study.

In general terms, the allocation of the emissions to the sawdust tends to increase/decrease the weight of the impact of the process of the production of sawdust on the total impact evaluation.

The process of the production of the sawdust is also included in the process of the production of wood pellets, in fact the wet sawdust is assumed to be dried burning sawdust itself. Thus both the impacts associated with the cultivation phase (intended as the production of sawdust) and the manufacturing of pellets are influenced by the choice of the allocation method.

The results obtained with the two allocation methods are significantly different, as seen for the impact categories analysed.

The allocation factor by price and the one by mass/energy are respectively assumed to be equal to 0,010 and 0,0685: it means that the emissions related to the production of sawdust are considered almost 7 times higher if allocated by mass/energy than by price.

If an impact is strongly influenced by one flow that has a relevant importance in the production of the sawdust, the resulting total impact is very different, comparing the two allocation methodologies.

For example, the industrial process that delivers sawdust, sawn timber and woodchips requires a significant quantity of electrical energy. That implies that in all the cases in which the production of electricity gives a significant contribution to the impact category considered, the differences between the environmental impacts of the pathways of sawdust allocated by price and by mass/energy are higher than in the ones in which the production of electricity does not give a significant contribution.

For example, the production of electrical energy causes significant emissions of ionising radiations, so the difference on this impact in the case of allocation by mass and by price is high. The plot in Figure 75 shows the influence of the allocation for the impact on ionising radiation. Using the mass/energy allocation increases the impact on ionising radiation by 45% in case of combustion in domestic stove, by 43% in case of combustion in a district heating plant and by 64% in case of combustion in a CHP.

The transport and the combustion are completely not influenced by the allocation method.

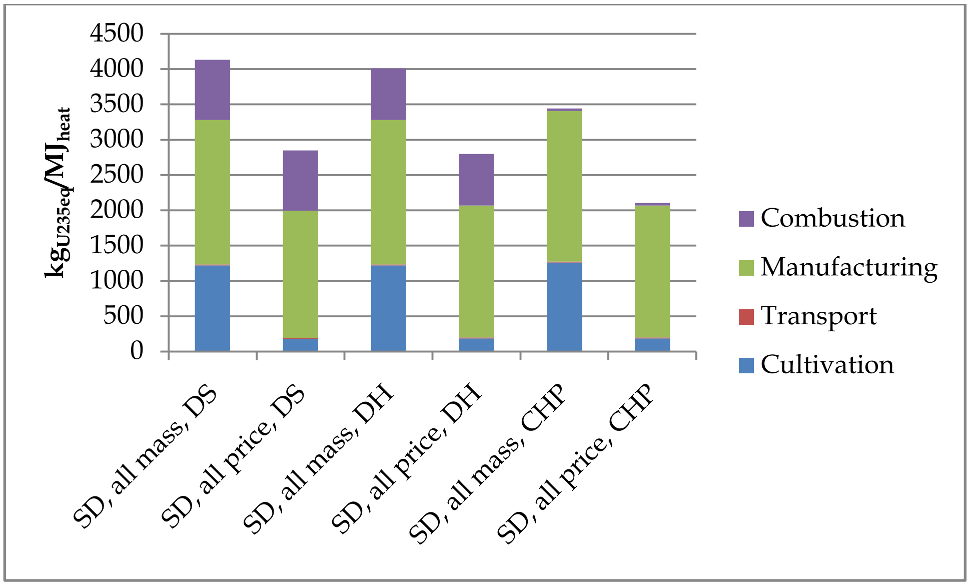

Figure 75: Impact on ionising radiation for the pathways *SD, all mass* and *SD, all price* [kg_{U235eq}/MJ_{heat}]

The allocation by price follows an economic principle and assigns to the sawdust a low value because it is a by-product of the process, whereas following the allocation by mass/energy all the products are supposed to have the same value because they all have the same energy content and the emissions are associated to each products considering the mass of it produced.

In our opinion the allocation by price is the one that better fits the goal of this study.

The sawdust has not to be considered to have the same value of the sawn timber, that is the main output of the process, just because they have the same LHV. Actually sawdust is assumed to have a lower value because it is just a by-product of the process and it would be produced even if not used for the production of pellets.

Thus, the production of pellets is a process that valorises this by-product and this aspect is not taken into account by an allocation by mass/energy: it would be a paradox to "penalize" the performance associated with the exploitation of an industrial residue compared to the use of an apposite energy crop (e.g. poplar).

This explains the fact that in all the other pathways in which emissions have to be allocated to one products (straw and sawdust partially dry), only the economical allocation method has been considered.

The only issue that has to be considered when using allocation by price, is that the economical allocation factors can change in relation to the prices of the products. For example, the growing requirement of sawdust to produce pellets, could cause an increase of the price of the sawdust in the near future, thus increasing the allocation factor by price and consequently the emissions allocated to the production of the sawdust.

This issue has been analysed also by the regulators (EU commission) and their decisions will be discussed in Paragraph 5.5.

5.4.12.2 Consideration on the transport

The long-range transport of the pellets imported from Canada has a higher importance on the impacts that are influenced by the compounds typically emitted by the combustion of fossil fuel for the use of the means of transport: truck, train and ships.

The trans-oceanic trip covered by ship fuelled with heavy oil whose combustion causes significant emissions of nitrogen and sulphur dioxides.

This fact mainly influences the impacts on air acidification, photochemical ozone formation and aquatic and terrestrial eutrophication, as already underlined in the study by Magelli et al. [44].

Another impact that is influenced by the long-range transport is the climate change mainly because of the emissions of fossil carbon dioxide due to the combustion of the fossil fuels in the means of transport. However, the increase of GHG emissions due to the long-range transport of pellets is not significant if the saving of GHGs is considered, in fact it always allows higher emissions of GHGs compared to the reference scenario.

Table 36 shows the increases of the impacts abovementioned due to the long-range transport, compared to the pathways of pellets produced from woodchips from Europe.

	Climate change	Air acidification	Photochemical ozone formation	Aquatic eutrophication	Terrestrial Eutrophication
FR, DS	17,5%	62,0%	34,0%	7,1%	32,0%
FR, DH	19,5%	57,2%	29,5%	7,4%	27,4%
FR, CHP	22,7%	69,9%	36,4%	9,3%	33,4%

Table 36: Increase of the impacts due to the long-range transport [%]

5.4.12.3 Novel feedstocks

In general terms the use of sawdust partially dry, with allocation methodology by price has the lowest impact on almost all the impact categories considered. The problem related with the use of sawdust is that its availability on the market is becoming lower due to the fact that the production of pellets is increasing.

In this study poplar woodchips and straw bales are assumed to be the potential feedstocks for the production of pellets in the near future.

Both these raw materials need a proper cultivation phase, which implies the use of agrarian machinery and the use of fertilisers and chemicals.

Being wheat an annual crop, it generally needs even higher quantity of fertilisers per year than poplar.

However, straw has a lower impact on most of the impact categories considered, but also in this case the allocation choice has an important role, since emissions for the cultivation of wheat are very high, but only a small part is allocated to the straw on economical basis.

Other significant differences are that the production of straw pellets needs less electrical energy than the one of wood pellets and that the straw has a lower moisture content, thus it requires the production of less heat to be dried.

In particular only the impact on marine eutrophication is higher for the straw pathways than for the poplar ones, due both to the fact that straw needs a higher quantity of nitrogen fertiliser that causes higher emissions of NO_3^- in the water and that the two scenarios are modelled in different ways, as explained in Paragraph 5.4.9.

The main disadvantage of the use of straw pellets is that they do not burn like woody ones: straw pellets produce roughly double the amount of ash because of the higher content of ash-forming matter and moreover straw contains high amounts of problematic elements such as silicon, chlorine, potassium and nitrogen, due to the uptake from the soil during its growth [63]. The use of straw pellets in domestic stoves is not recommended (or even possible) as they have too high emissions and would surely create problems for the stove.

However, straw fired plants are increasing and technological solutions are available or are being designed in order to have efficient and problem-free operations. For example, straw pellets can substitute coal or be co-fired in coal dust fired power plants because, in principle, the injection of the fuel in the boiler takes place in the same way and just small modifications have to be done to the structure of the plant [35].

Another possibility is to use straw to make pellets using a mix of straw and wood as feedstock [52]. This could produce cheaper pellets and the criticalities of straw would be only limited.

5.4.12.4 Geographic effect on biomass sustainability

A further analysis on the differences between the impact of the straw cultivation in 5 European countries (Germany, Spain, The Netherlands, Poland and United Kingdom) have been investigated.

The impact categories resulted to be significantly influenced by the cultivation, which have been analysed are:

- Global warming
- Human toxicity
- Photochemical ozone formation
- Air acidification
- Terrestrial eutrophication
- Marine eutrophication
- Ecotoxicity
- Resources depletion

Figure 76 shows the results of the environmental impacts of the pathways analysed. In order to visualise the differences between the pathways, data are normalised on the average result of each impact and then the impacts are expressed as difference by the mean value in term of percentage.

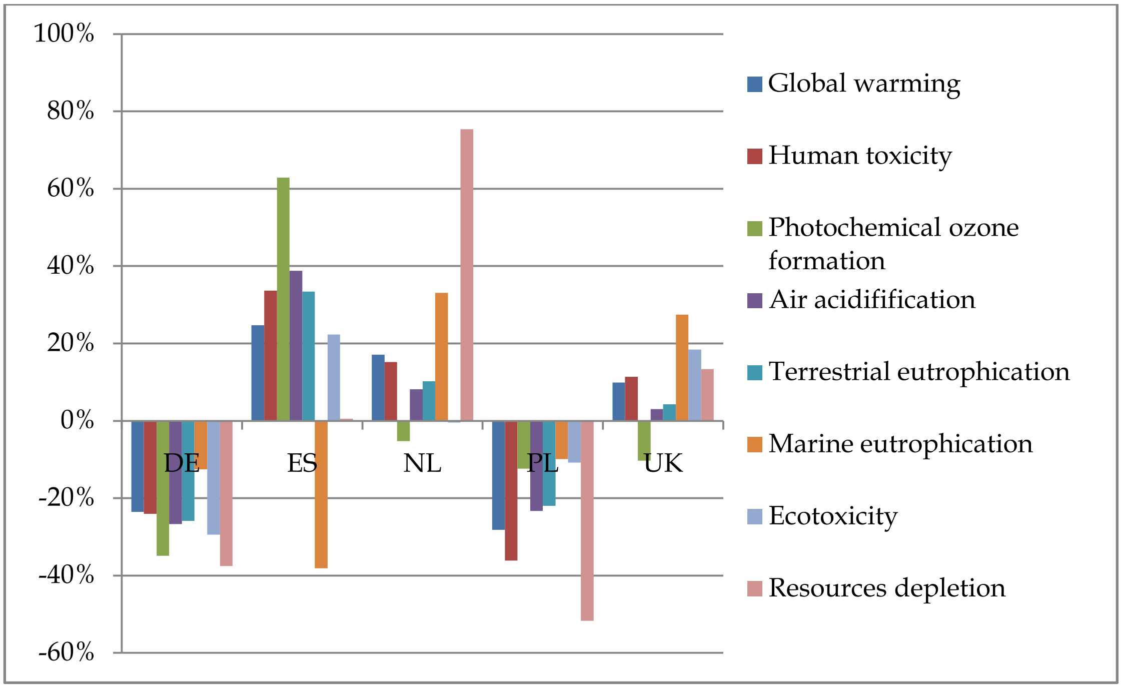

Figure 76: Impacts of the emissions allocated to wheat straw for the European countries considered

In general terms, the cultivation of wheat straw in Germany and in Poland causes a lower environmental impact than in the other countries considered, whereas the performances of the wheat straw cultivation in Spain, the Netherland and the United Kingdom are mostly over the average.

The cultivation of wheat straw in Spain causes the highest impact on all the impact categories analysed, except for the resources depletion and the marine eutrophication.

The emissions of the cultivation of wheat are allocated to straw following the economical principle. Being that the ratio between the price of wheat grains and the price of the straw is not constant in all the Europe, the allocation factor changes from country to country, as shown in Table 37, thus the share of the total emissions of the cultivations allocated to straw is changeable.

The lower emissions for the pathways of Germany and Poland can be justified by the lower allocation factor and, on the contrary, the significant impact of the cultivation of straw in Spain and the United Kingdom can be associated with the higher relative price of straw than in the other countries and consequently to a higher allocation factor.

In order to better understand the effect of the allocation, the impact for the wheat cultivation are reported in Figure 77

	DE	ES	NL	PL	UK
Allocation factor of straw [%]	10,7%	15,2%	12,2%	9,0%	16,8%

Table 37: Straw allocations factors.

The performances of the cultivation of wheat (without any allocation), are different from the ones allocated to straw overall in the case of the United Kingdom and Poland: for the former all the environmental impacts analysed resulted to be lower than the mean of the other countries, whereas in the second case resulted to be higher.

For the other countries, instead, the trend of the environmental performance for wheat cultivation is similar to the one of the performance allocated to sawdust.

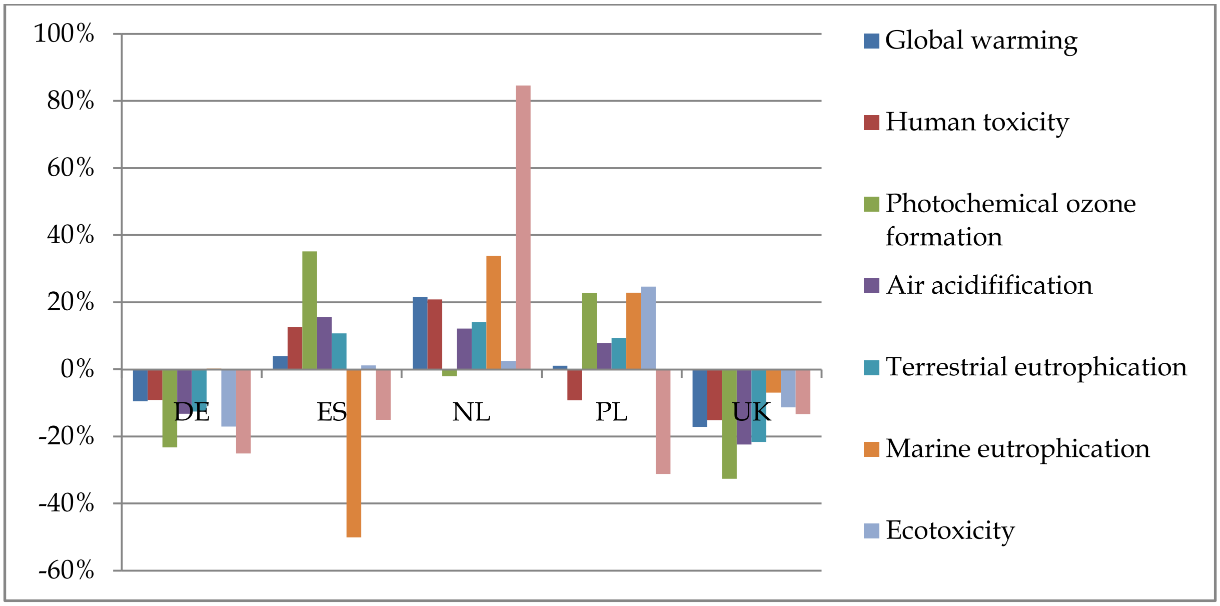

Figure 77: Impacts of the wheat cultivation for the European countries considered

5.4.13 Sensitivity analysis

In this Paragraph the environmental impacts of some alternative pathways than the base scenario are described and analysed. In particular, the sensitivity analysis is focused on:

- The impacts of using natural gas instead of biomass for drying
- The variation of the impact on ecotoxicity due the reduction/increase of the amount of the herbicides used in the cultivation of poplar
- The impact on eutrophication, using a characterisation method that is not recommended by the ILCD, but that accounts together the effect of the emissions of nitrogen and phosphorous compounds.

Use of natural gas burned for drying the feedstock

In this analysis the possibility to use natural gas instead of biomass for drying the feedstock is investigated.

The choice of the impact categories to consider is based on the previous considerations about the differences between burning woody biomass and natural gas. In particular, the impact categories supposed to be mostly influenced by the use of the natural gas for drying that are considered in this sensitivity analysis are:

- Global warming
- Ozone layer depletion
- Human toxicity
- Respiratory inorganics
- Air acidification
- Marine eutrophication

It is assumed that the natural gas is burned in a boiler with a thermal efficiency of 90% [45].

In general terms, the higher differences between the two process alternatives analysed are associated with the poplar pathway. This is due to the facts that using natural gas for drying means also avoid all the emissions related with cultivation phase of the raw material used for drying and the poplar cultivation phase is the one with the higher environmental impacts compared to the others.

In fact, according to our scenarios, the quantity of raw material needed to produce the pellets is the sum of the contribution of the raw material that is actually pelletised and the raw material that has to be burned for drying. To both this contributions the emissions of the cultivation phase/production of the feedstock are associated.

In Table 38 the emissions of GHGs of the manufacturing phase of the scenarios analysed are reported. In the base case scenario, the emissions associated with the production/cultivation of the feedstock for drying are accounted in the manufacturing phase and not in the cultivation one. The straw pathways are not included in this sensitivity analysis because straw has been already supposed to be dried with natural gas in the base case scenario.

In order to compare the results with the ones obtained previously, the emissions of GHGs are always referred to the production of 1 MJ of heat produced.

Being that the thermal efficiency of the domestic stove and the district heating are the same (see Paragraph 5.2.4), the emissions associated with the production of pellets burned in one of them to produce 1 MJ of heat are the same. The CHP, instead, has a lower thermal efficiency, thus it needs a higher mass of pellets to produce 1 MJ of heat, that causes higher emissions in the manufacturing phase.

		Biomass for drying	**Natural gas for drying**	**Increase of the emissions of the production phase[%]**
		Woodchips		
DS/DH	**g_{CO2eq}/MJ_{heat}**	9,4	19,5	106%
CHP	**g_{CO2eq}/MJ_{heat}**	9,8	20,1	106%
		Sawdust, wet, mass allocation		
DS/DH	**g_{CO2eq}/MJ_{heat}**	9,3	18,4	97%
CHP	**g_{CO2eq}/MJ_{heat}**	9,8	17,8	82%
		Sawdust, wet, price allocation		
DS/DH	**g_{CO2eq}/MJ_{heat}**	7,4	18,4	148%
CHP	**g_{CO2eq}/MJ_{heat}**	7,7	17,8	131%
		Sawdust, partially dry		
DS/DH	**g_{CO2eq}/MJ_{heat}**	5,1	11,5	123%
CHP	**g_{CO2eq}/MJ_{heat}**	5,3	11,9	123%

Table 38: Emissions of GHGs during the manufacturing phase [g_{CO2eq}/MJ_{heat}]

The use of natural gas in substitution of the biomass for drying causes a significant increase of the impact on global warming of the pellets production phase (from 82% to 148%).

Being that the production of pellets is the process that in almost all the pathways considered causes the highest impact on climate change, the influence of the use of natural gas for drying, instead of the biomass has been evaluated also referred to the total emissions. Results are reported in Table 39.

		FR, Canada	***FR, EU***	***Poplar***	***SD, 40% dry***	***SD, all mass***	***SD, all price***
		Domestic stove					
Biomass	**g_{CO2eq}/MJ_{heat}**	23,8	20,2	24,0	15,0	27,4	17,3
Nat gas	**g_{CO2eq}/MJ_{heat}**	33,8	30,3	33,7	21,3	36,5	28,3
Increase	%	**42%**	**50%**	**40%**	**42%**	**33%**	**64%**
		District heating					
Biomass	**g_{CO2eq}/MJ_{heat}**	21,7	18,2	21,9	12,9	25,4	15,3
Nat gas	**g_{CO2eq}/MJ_{heat}**	31,7	28,2	31,6	19,2	34,5	26,3
Increase	%	**46%**	**55%**	**44%**	**49%**	**36%**	**72%**
		CHP					
Biomass	**g_{CO2eq}/MJ_{heat}**	19,5	15,9	19,8	10,5	23,5	12,9
Nat gas	**g_{CO2eq}/MJ_{heat}**	29,9	26,3	29,8	17,0	31,5	23,0
Increase	%	**53%**	**65%**	**51%**	**62%**	**34%**	**78%**

Table 39: Emissions of GHGs of the pathways analysed [g_{CO2eq}/MJ_{heat}]

In all the pathways the use of natural gas for drying causes a significant increase of the emissions of GHGs, but, in any case a GHG saving is still achieved compared to the use of natural gas (reference scenario).

The comparison between the base case scenarios, the pathways with drying with natural gas and the reference scenario are reported in Figure 78, Figure 79 and Figure 80.

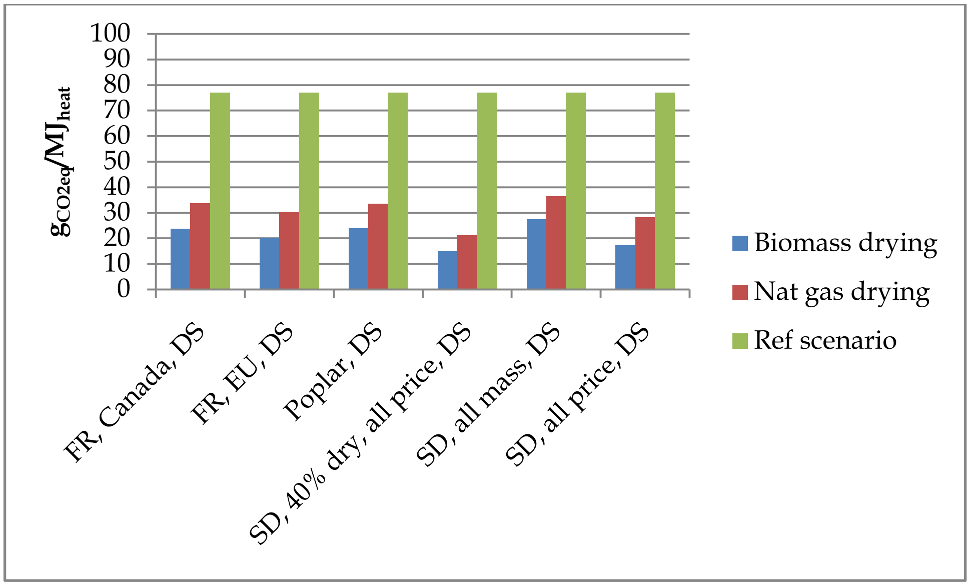

Figure 78: Impact on global warming in case of combustion in a domestic stove [g_{CO2}/MJ_{heat}]

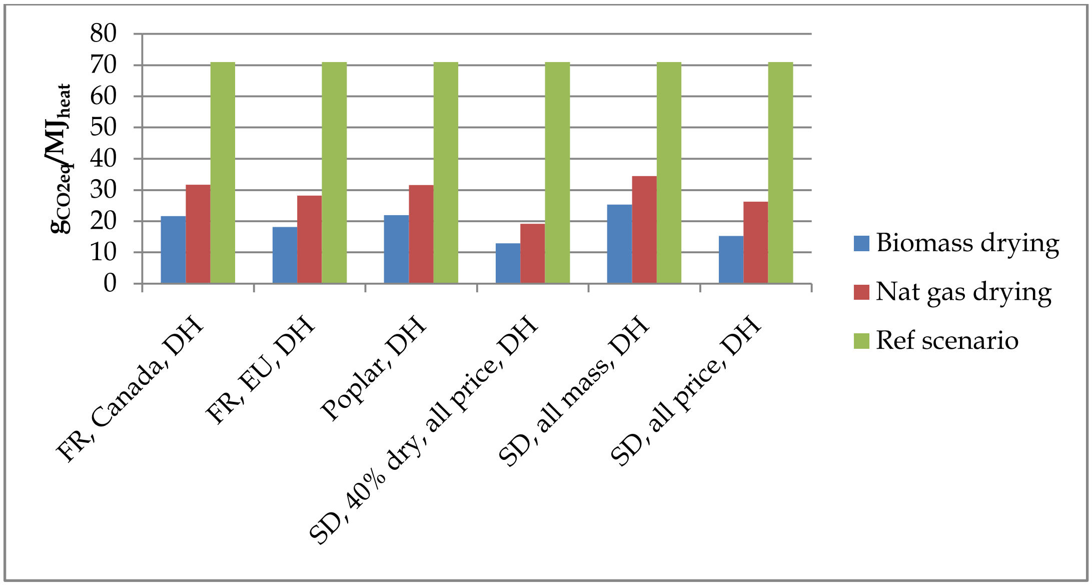

Figure 79: Impact on global warming in case of combustion in a district heating [g_{CO2}/MJ_{heat}]

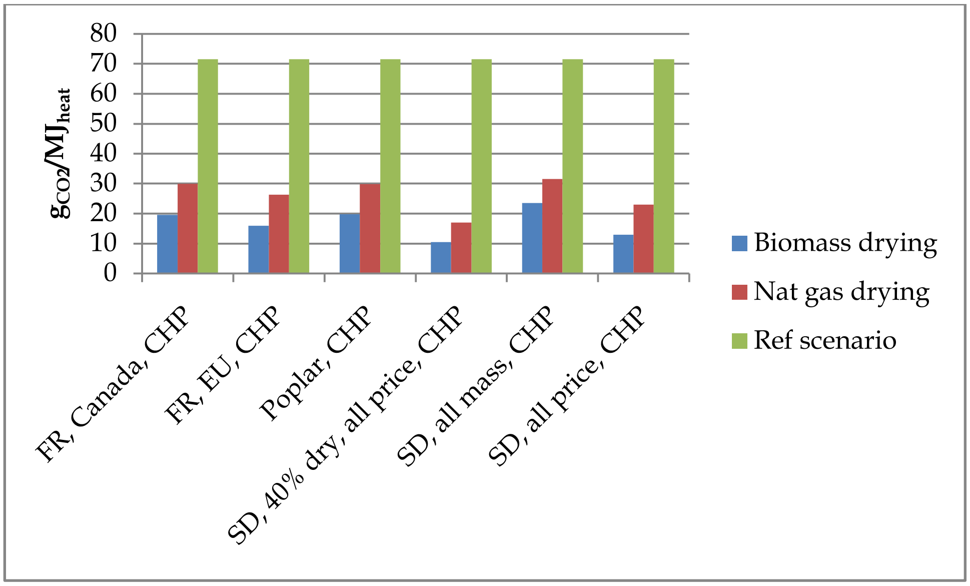

Figure 80: Impact on global warming in case of combustion in a CHP [g_{CO2}/MJ_{heat}]

The use of natural gas for drying has also a significant impact on the **ozone layer depletion**, in fact it causes an increase of emissions of $R11_{eq}$ by 65% to 186%.

This is due to the fact that emissions of VOCs for the cultivation/production of the woody feedstock used for drying are much lower compared to the ones due to the extraction, the handling and the transport of natural gas.

The emissions of R11 equivalent are reported in the plot in Figure 81.

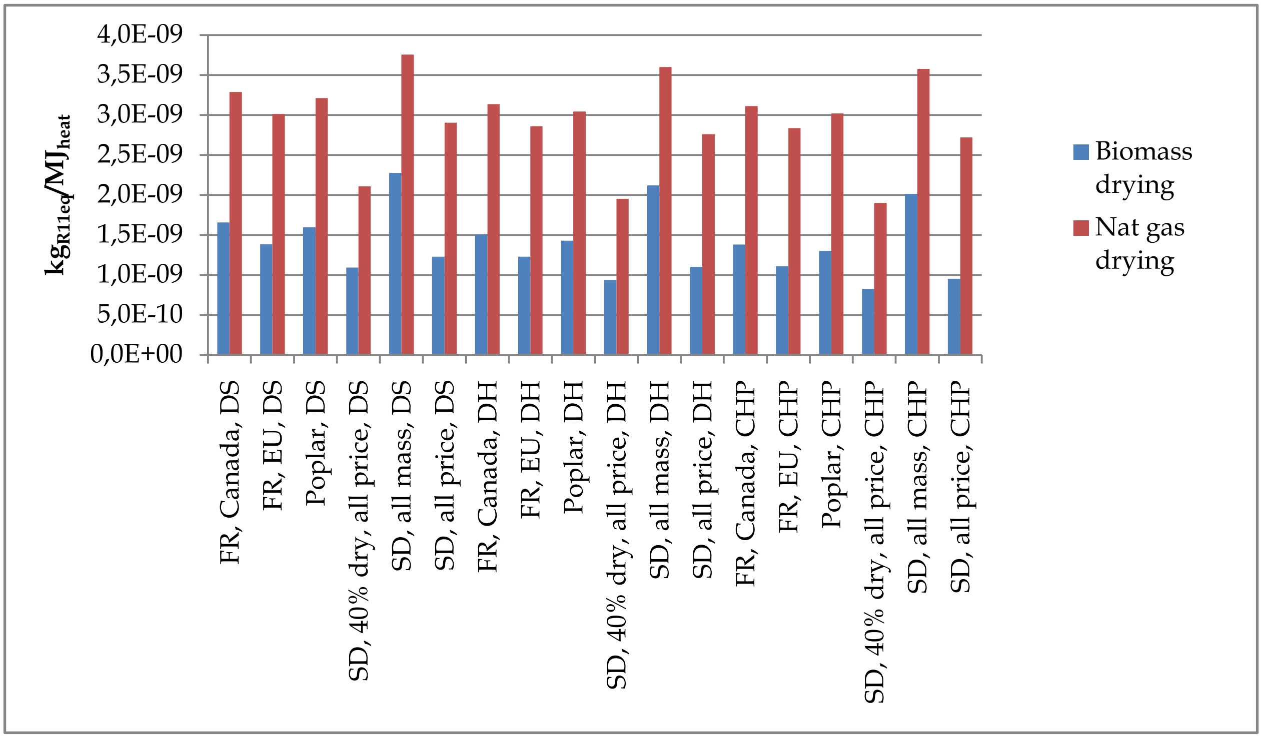

Figure 81: Impact on ozone layer depletion [kg$_{R11eq}$/MJ$_{heat}$]

The impact on **human toxicity**, as underlined before, is mainly due to the emissions of formaldehyde that is created in a higher quantity during the combustion of natural gas than in the combustion of biomass.

However, the total impact on human toxicity for the scenario with the use of natural gas results to be lower than the one of the base case scenario. While natural gas combustion causes higher emissions of formaldehyde, the combustion of woodchips causes significant emissions of other VOCs that accounted for the total impact on human toxicity.

The reduction of the impact on human toxicity associated with the use of natural gas is comprised between 5% and 12%. The lower increase on the impact is associated with *sawdust, 40% dry* pathway, thanks to the fact that it requires a lower quantity of heat for drying, thus its impact is less influenced by the kind of fuel used for drying.

Figure 82 shows the differences between the scenarios analysed.

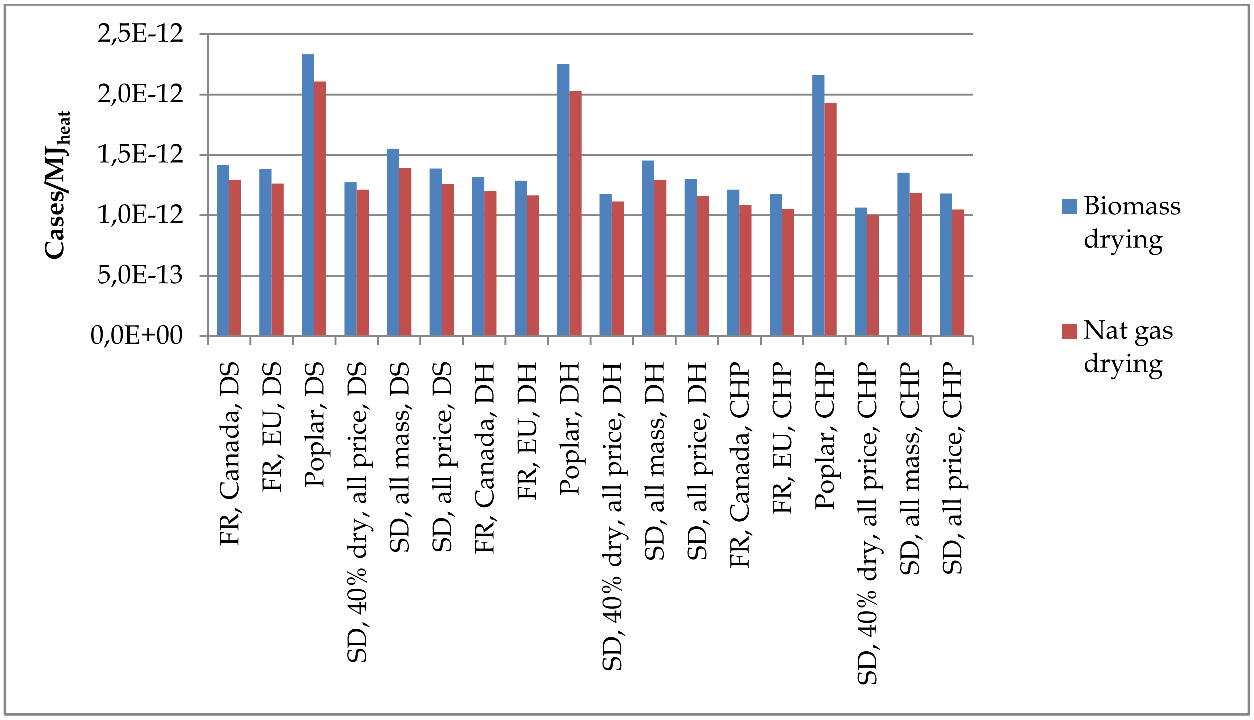

Figure 82: Impact on human toxicity [Cases/MJ$_{heat}$]

The results of this study underline also that the combustion of woody biomass causes a significant impact on the respiratory inorganics category.

The use of natural gas for drying allows to reduce the impact on **respiratory inorganics** from 8% to 22% compared with the base case scenario.

Being that almost all the impact on respiratory inorganics of the production of pellets is due to the combustion of the fuel for drying, in absolute terms the differences between the scenarios are more or less the same for the sawdust and woodchips scenarios (about $1,7*10^{-5}$ kg$_{PM2.5}$/MJ$_{heat}$) because the feedstocks are assumed to have about the same moisture content and the boilers for the sawdust and the woodchips for drying have been assumed to cause the same emissions. In the case of partially dry sawdust, the advantage of using natural gas is lower because the sawdust partially dry has already a lower moisture content than the other feedstocks, thus it needs less heat for drying.

The plot in Figure 83 shows the difference between the scenarios.

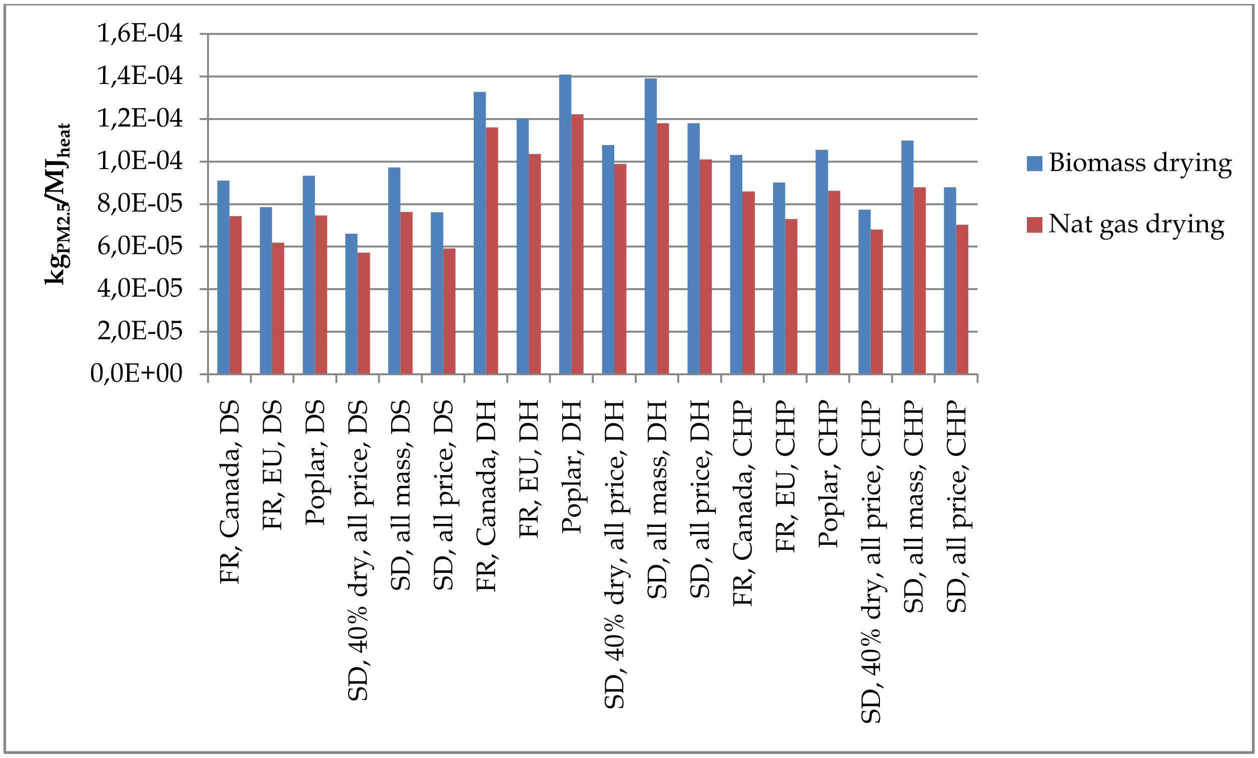

Figure 83: Impact on respiratory inorganics [kg$_{PM2.5}$/MJ$_{heat}$]

The use of natural gas for drying decreases slightly also the impact on **air acidification**: the emissions of sulphur dioxide equivalent are reduced by 2% to 11%, depending on the pathway. The higher differences between the two scenarios, in particular, are associated with the pathway of polar due to the fact the cultivation of poplar causes significant emissions of nitrogen compounds that increase the acidification of the air. Using natural gas for drying means also cancel this contribution.

The results are reported in Figure 84.

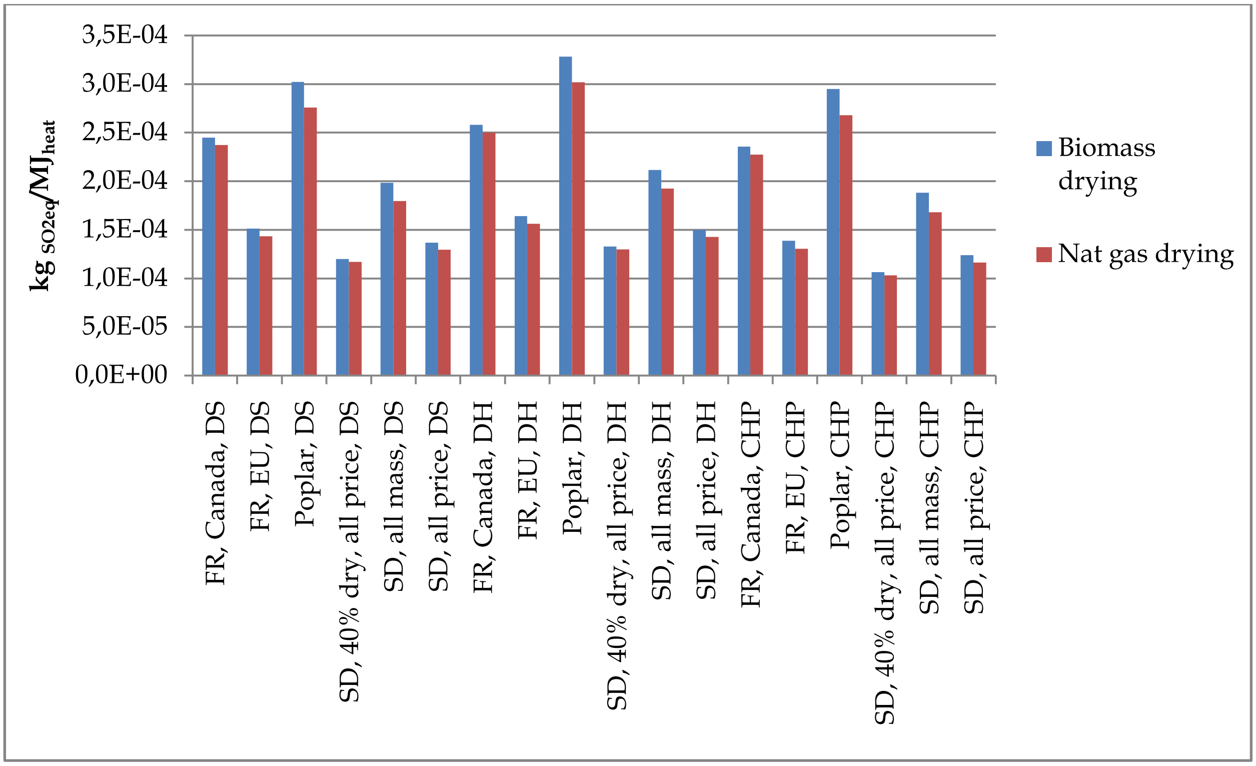

Figure 84: Impact on air acidification [kg_{SO2eq}/MJ_{heat}]

Also the impact on **marine eutrophication**, due to the emissions of N compounds is favourable for the use natural gas for drying compared to the base case scenario.

As for the impact on air acidification, the differences between pathways with natural gas for drying and the base case scenario, expressed in absolute term are higher for poplar than for all the other feedstock.

The results for the impact on marine eutrophication are reported in Figure 85.

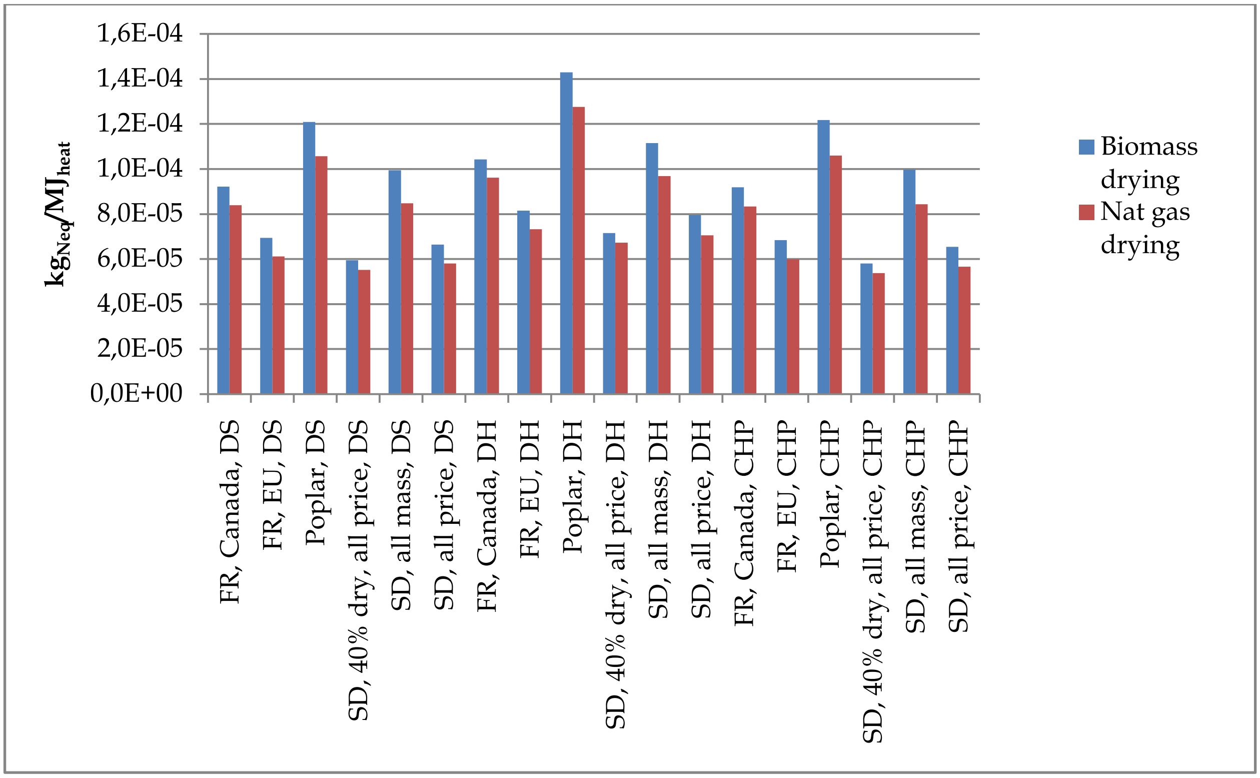

Figure 85: Impact on marine eutrophication [kg$_{Neq}$/MJ$_{heat}$]

Impact on ecotoxicity for the use of herbicides in the poplar cultivation

This analysis aims at underlining the impact on human toxicity and ecotoxicity due to the use of herbicides in the poplar cultivation.

The scenario of pellets burned in domestic stove was considered as representative.

Two more scenarios were investigated:

- *Poplar+20:* in which the use of herbicides was increase by 20% compared to the base case scenario
- *Poplar -20:* in which the use of herbicides was decreased by 20% compared to the base case scenario.

The increase in the use of herbicides (scenario *Poplar+20*) has an higher impact on ecotoxicity than on human toxicity, in fact, compared to the base case scenario the total impact on ecotoxicity is increased by 17%, whereas the impact on human toxicity is increased only by 1%.

This is due to the fact that the impact on ecotoxicity is mainly associated with the use of herbicides, whereas the impact on human toxicity is more influenced by the emissions of other substances (e.g. formaldehyde).

Focusing the attention on the impact on ecotoxicity, all the impacts due to the emissions in the agricultural soil are caused by the use of pesticides, whereas the impact on freshwater and the atmosphere are due also to the emissions of other substances, as shown in Table 40.

	Poplar+20	***Poplar-20***
Emission to air	1%	-1%
Emission to fresh water	11%	-13%
Emissions to sea water	0%	0%
Emission to agricultural soil	20%	-20%
Emission to industrial soil	0%	0%

Table 40: Percentage of change of the total impact on ecotoxicity

In conclusion, the use of herbicides has a significant impact on ecotoxicity, overall for the fractions of herbicides that migrate to the soil and to the freshwater, whereas the impact on human toxicity is slightly influenced by the use of herbicides, but it mostly depends on the emissions of other substances, as already highlighted in Paragraph 5.4.3.

Impact on eutrophication

As underlined discussing the results of this study, the two characterisation method suggested by the ILCD Handbook [19] to assess the impact on eutrophication account separately the contribution of nitrogen and phosphorous compounds emitted in the environment. Thus, in order to give an overview of the impact on aquatic eutrophication of the pathways analysed, the characterisation method *CML2001 -Nov 2009, Eutrophication potential (EP)* that accounts both for the contribution of the emissions of nitrogen and phosphorous compounds, has been used.

The results, in terms of $kg_{PO3\text{-}eq}/MJ_{heat}$ are reported in Figure 86.

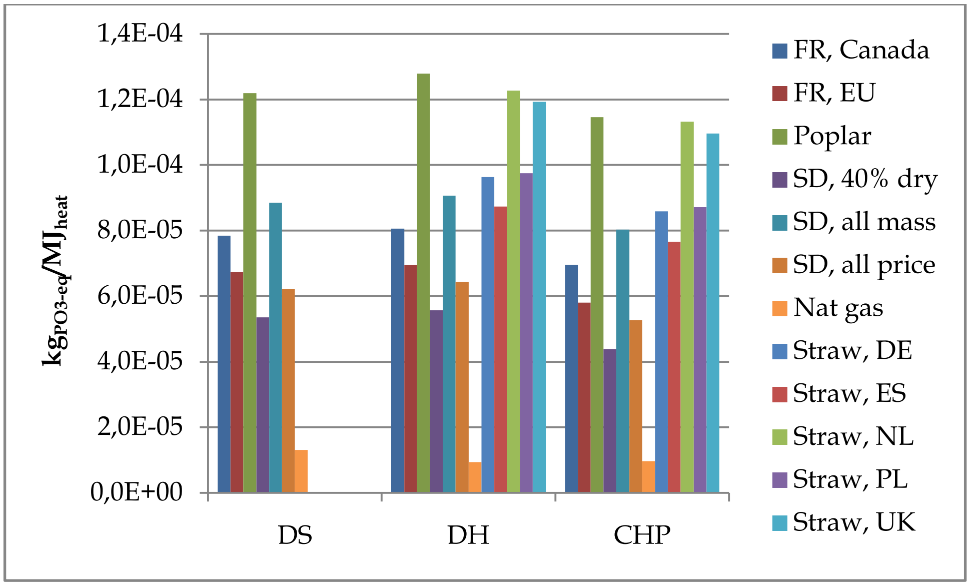

Figure 86: Impact on eutrophication [$kg_{PO3\text{-}eq}/MJ_{heat}$]

According to this characterisation method, the poplar scenario has the highest impact among all the pathways analysed. This result is the combination of the effects of the higher emission of phosphate due to a higher requirement of electricity of the pathway of poplar compared to straw scenario and the higher emissions of nitrogen due to the cultivation phase, compared to woodchips and sawdust scenario.

In fact Figure 87, Figure 88 and Figure 89 shows that the cultivation phase of poplar causes more emissions of phosphate equivalent than the woodchips and sawdust ones, whereas the emissions allocated to wheat straw cultivation phase have the highest impact on eutrophication. Anyway, the emissions of straw cultivation are partly compensated by lower emissions of phosphate, due to lower requirements of electricity and heat to produce straw pellets than wood ones, thus the total impact on eutrophication is lower for straw than for poplar.

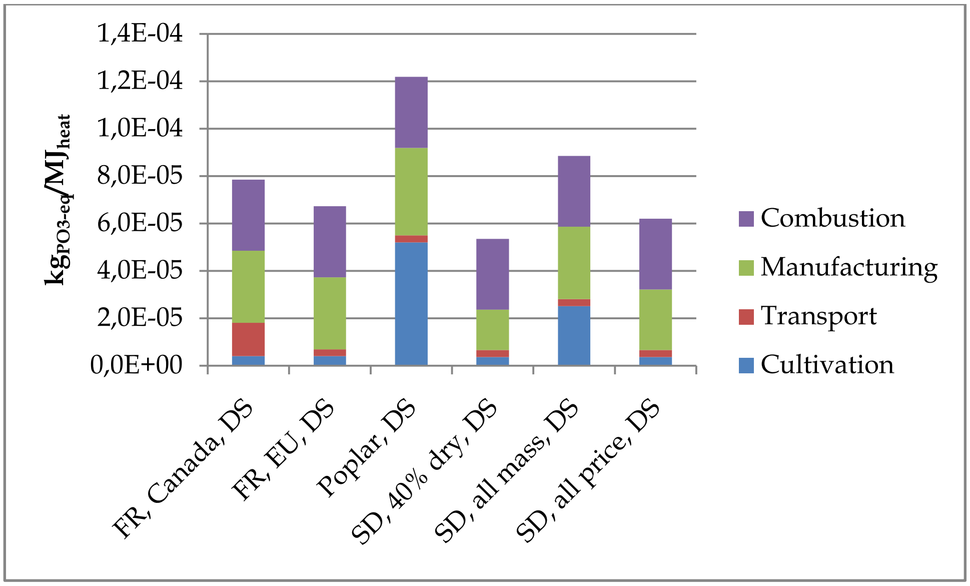

Figure 87: Contribution to the aquatic eutrophication in the case of combustion in a domestic stove [$kg_{PO3\text{-}eq}/MJ_{heat}$]

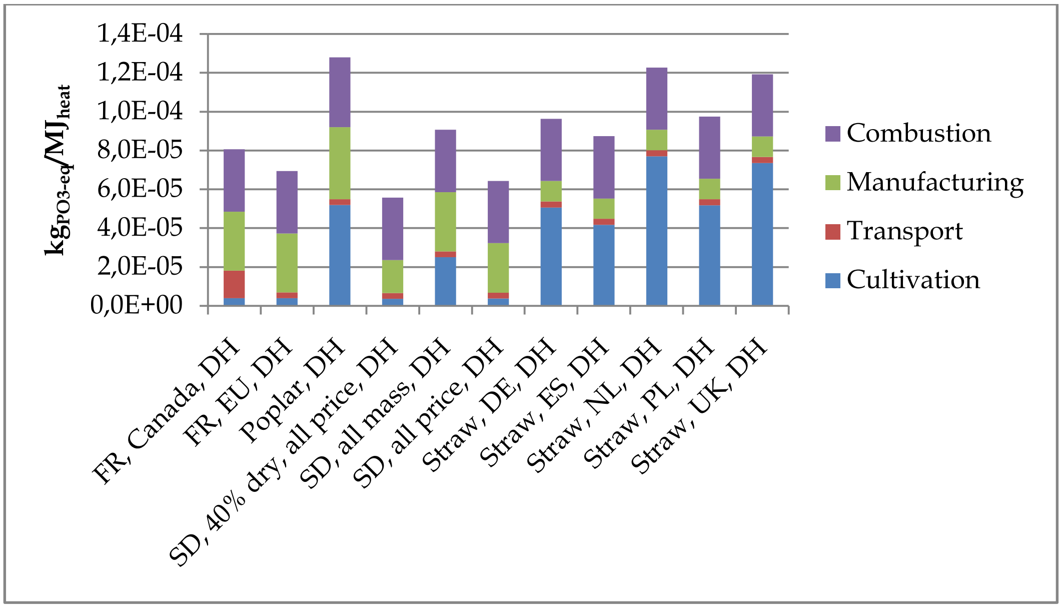

Figure 88: Contribution to the aquatic eutrophication in the case of combustion in a district heating [$kg_{PO3\text{-}eq}/MJ_{heat}$]

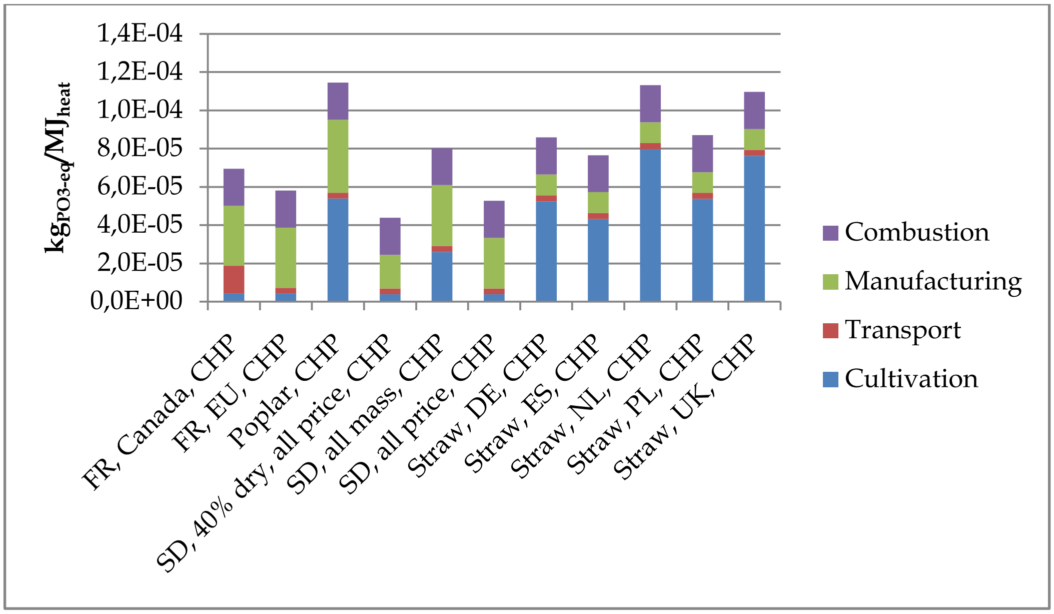

Figure 89: Contribution to the aquatic eutrophication in the case of combustion in a CHP [kg_{PO3-eq}/MJ_{heat}]

In conclusion the use of the CML method allows evaluating together the influence of the nitrogen and phosphorous emissions on the eutrophication: it can be considered the "sum" of the results obtained with two Recipe characterisation methods analysed in Paragraph 5.4.9.

5.5 Comparison with the results of the RED methodology

As explained in the Paragraph 2.3, the *Report from the Commission to the Council and the European Parliament on sustainability requirements for the use of solid and gaseous biomass sources in electricity, heating and cooling* is accompanied by an impact assessment that provides recommendations how to evaluate the GHG emissions of solid and gaseous biofuels.

According to the scenarios illustrated in the Report, pellets from forest residues from Europe and from SRF are transported for 50 km and pellets from Brazil are transported for about 11000km.

In this paragraph a comparison between three different scenarios is attempted.

In order to evaluate the influence of the transport distance, three scenarios are analysed:

- The Typical values
- The results of this study
- A scenario in which the transport distances of this study were changed to be the same in the EC Report (*mixed scenario*).

The scenario of forest residues from Europe and Canada have been compared respectively with the scenarios *Wood briquettes or pellets from forest residues (EU forest) – wood as process fuel* and *Wood briquettes or pellets from forest residues (Brazilian forest) -wood as process fuel,* whereas the scenario of polar has been compared with the pathway *Wood briquettes or pellets from short rotation forestry (EU) – wood as process fuel.*

In order to allow the comparison, all the values reported in this Paragraph are referred to one mega-joule of feedstock.

Table 41 reports the results obtained with the two methodologies.

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	g_{CO2eq}/MJ_{heat}		
	Typical values	**This study**	**Mixed scenario**
FR EU	2	12	11
FR Canada	15	15	14
Poplar	4	15	14

Table 41: Results of the three methodologies [g_{CO2eq}/MJ_{heat}]

The results are considerably different for the scenarios of forest residues from Europe and polar, whereas they are comparable in the case of forest residues from Canada.

The differences in the results reflect the differences between the evaluation methodologies applied. In fact, although the pathway of forest residues from Canada seems to have comparable emissions of GHGs comparing the two methodologies, the contribution of each process within the pathways is very different, as shown in Table 42.

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		Typical values	**This study**	**Mixed scenario**
		gCO_{2eq}/MJ		
FR EU	Cultivation	0,0	2,1	2,1
	Processing	0,5	8,3	8,3
	Transport and distribution	0,7	1,7	0,4
	TOT	**2**	**12,0**	**10,7**
FR Canada	Cultivation	0,0	2,1	2,1
	Processing	0,5	8,3	8,3
	Transport and distribution	13,7	4,8	3,2
	TOT	**15**	**15,1**	**13,6**
Poplar	Cultivation	2,1	5,1	5,1
	Processing	0,5	8,6	8,6
	Transport and distribution	0,7	1,7	0,4
	TOT	**4**	**15,3**	**14,0**

Table 42: Comparison between the emissions of the processes [g_{CO2eq}/MJ]

According to this study, the emissions due to the transport do not play a significant role in the total impact on climate change, in fact the difference between the results of this study and the mixed scenario are not very significant.

According to the Report of the European Commission, all the GHG emissions associated with the production of a residue have to be neglected, thus all the emissions related with the harvesting of the trees and the consequent production and collection of forest residues are not accounted in the calculation of the Typical values. These contributions, instead, are included in the results of this study and this explains the differences in the category "cultivation" for the pathways of forest residues.

The results of this study show that the emissions of GHGs for the harvesting and chipping of the forest residues from Europe are significant and they are even comparable with the typical values that represent the emissions for the whole pathway.

The emissions calculated in this study due to the production of pellets are always higher than the typical values. This can be partly motivated by the fact that, according to the Report, the pellets are supposed to be produced using the electricity and the heat delivered by a CHP fuelled with woodchips. In this case all the emissions related with the production of heat and electricity are not accounted because biogenic, but an higher amount of feedstock is needed to produce pellets, thus higher emissions should results from the cultivation of the feedstock. But, as indicated before, this was not included in the methodology of the Report and thus this effect is completely lost in the values of the Commission.

In this study the use of a CHP that delivers heat and electricity for the production of pellets is not considered because it is not yet a common practice in Europe.

Another fact that emphasises the differences in the results for the two methodologies is that the typical values do not account the emissions due to the production of the machineries and the infrastructures for the production of pellets.

Additionally, comparing the Typical values and the scenario with the same distances (*mixed scenario*), the emissions calculated for the transport are always higher in the case of the Typical values and in particular the difference is very significant in the case of long-range transport in which the value of the normative is more than 4 times higher than the one of the mixed scenario. This is due to the fact that, according to the Report, an amount of 0,115 $MJ_{HFO}/MJ_{pellets}$ is needed to fuel the ship across the ocean, while in this study, the consumption of heavy fuel oil of a bulk carrier is assumed to be 0,025 $MJ_{HFO}/MJ_{pellets}$ [15].

Another difference between the two methodologies is that the Report of the Commission includes only three GHG: CO_2, CH_4 and N_2O, whereas, in this study, using an LCA approach, a higher number of GHGs has been considered in the evaluation of the impact on the global warming.

Moreover the GWP100 assumed for the calculation of the typical values for the Directive are lower than the ones used in the complete LCA and appear to be outdated, as shown in Table 43.

Finally, another difference between the Report and this study is the choice of allocation method to use. This issue actually does not influence the comparison between the results, because in the scenario analysed there is not any case of multi-outputs process.

However, in general terms, the choice of the allocation methodology strongly influences the final results.

The Report establishes that, when necessary, the energetic allocation has to be used.

In this study, instead, it is demonstrated that this allocation method is not appropriate for the evaluation of the environmental impacts of a by-product that has the same energy content of the main product delivered by the process (e.g. sawdust), because the emissions allocated to the by-product could result in the paradox that, under an environmental point of view, its use is considered worst than the use of a raw material.

In this respect, the choice of the Commission to consider some by-products as residues and thus assign them zero emissions up to collection seems more appropriate than an energy allocation.

	This study (IPCC, 2007)	**Report of the Commission (IPCC, 2001)**
CH_4	25	23
N_2O	298	296

Table 43: Comparison between the GWPs used in this study and for the calculation of the typical values

In conclusions, the evaluation methodology of the EC Report does not account many of contributions to the total emissions of GHGs of the pellets production chains that have to be included in a traditional LCA, such as the emissions related with the construction of the infrastructures and the machineries. According to this study, these emissions result to significantly influence the impact on the climate change of the pellets production chain.

The only issue for which the European Commission has been very "strict" is the evaluation of the amount of the heavy fuel oil used for the transport of the pellets by ships that, according the ELCD database [15] is almost five times lower.

6 Conclusions

In this study the environmental impact of different pathways of pellets production and combustion have been analysed using an LCA approach.
Hereunder the **main points of interest** of the study are highlighted.

- The study confirms the high **reduction of GHG emissions** due to the use of pellets in substitution of fossil fuels, as already investigated by other studies: the emissions of GHGs related to all the operations that occur within the pathways analysed to produce pellets are always much lower than the ones of the reference scenario. The GHGs emissions of the pathways analysed are comprised between 12 g_{CO2eq}/MJ_{heat} (*SD, 40% dry, all price, CHP*) and 27,4 g_{CO2eq}/MJ_{heat} (*SD, all mass, DS*), while the GHGs savings range from 64,3% (*SD, all mass, DH*), to 85,4% (*SD, 40% dry, all price, CHP*), compared to natural gas fuelled plants equipments.

- In general terms, the **main criticisms related with the use of pellets are associated with the combustion phase.** In particular, it causes **higher emission of dusts, heavy metals and nitrogen compounds** that might cause a negative impact on several of the impact categories analysed, compared to the reference scenario.
  It has to be stated that the choice of the reference scenario, in the case of district heating and CHP, can be considered a 'conservative' one, in fact the use of pellets was compared with the use of natural gas, but the use of other 'dirtier' fossil fuels in big plants is still quite common in Europe [21], [59], above all for large-scale plants. If the combustion of pellets in a district heating and CHP were compared with other reference scenario (e.g. coal), as in the study of Sikkema et al. [60] and Caserini et al.[7], the differences would probably be lower.

- Table 44, Table 45 and Table 46 report the total impacts of all the pathways and impact categories analysed. The red cells are the ones in which the biomass scenario scores worse than the one of the reference system and, vice versa, the cases in which the biomass has a lower impact are highlighted in green.

In particular, **the use of pellets is favourable for the impact on climate change and ozone layer depletion**, whereas **it is worse than the use of natural gas for the impacts on human toxicity, respiratory inorganics, ionising radiation, photochemical ozone formation, air acidification, terrestrial and aquatic eutrophication, terrestrial and aquatic ecotoxicity and resource depletion.**

In particular, the results for the main impact categories considered, compared with the impact on natural gas, are reported in Figure 90.

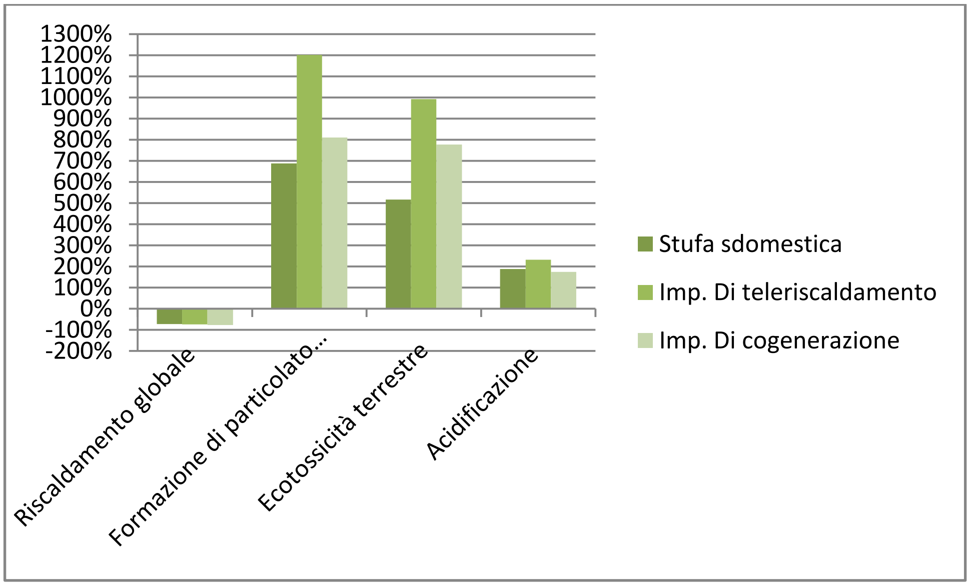

Figure 90: Results of the study compared to the reference scenario

- **Some of the impact categories considered are influenced by the emissions of the same compounds**: for example, the emissions of nitrogen compounds influence the aquatic and the terrestrial eutrophication, the air acidification and the formation of tropospheric ozone.

  In particular, the emissions of nitrogen compounds within the biomass pathways analysed are mainly due to:

  - Emissions of NO_x in the atmosphere from the combustion of pellets (fuel-NO_x and thermal NO_x)

- Emissions of NO_x, NH_3 and N_2O in the atmosphere from the use of nitrogen fertilisers for the cultivated crops
- Emissions of NO_3^- in the deep water from the use of nitrogen fertilisers for the cultivated crops
- Emissions of NO_x in the atmosphere from the combustion of fossil fuels in the means of transport

The cultivated crops, such as straw and poplar, **have a significant** contribution to the above mentioned impacts due to **the use nitrogen fertilisers**.

- Comparing the three combustion devices analysed, the **lowest emissions of GHGs are associated with the combustion of pellets in a CHP** that allows also the highest savings of GHGs among the pathways analysed, thanks to the allocation of the emissions to heat and electricity. Additionally the electricity needed for the combustion operations is recovered from the production of heat and the bigger dimensions of the plant contribute to lower the specific emissions of GHGs for the combustion operations. On the contrary, the use of a small scale domestic stove causes the highest emissions of GHGs.

- Comparing the different feedstocks, the pathway of **sawdust with mass/energy allocation scores the worst result for its impact on global warming** for the effects of the allocation that are underlined at the next point.

  The use of an already partially dried feedstock (sawdust, 40%), instead, decreases significantly the emissions of GHG, thanks to a lower requirement of electricity and heat to produce the pellets. Thus, if a dried by-product of an industrial process is available, its use for the pellets production is an interesting scenario to investigate.

- The **different allocation methodologies of the emissions to the sawdust have a significant influence on the final results**; in fact the impacts for the pathways with allocation by mass/energy are always significantly higher than the ones with the allocation by price.

  In our opinion allocation by mass/energy does not give a coherent representation of the real situation; in fact, according to this approach, the sawdust has the same value of the main product, thus the emissions are allocated to the products proportionally to the mass delivered by the industrial process. Following this approach, a higher impact is assigned to the use of a by-product than the use of an apposite energy crops (poplar), which could create a paradox for which it is favoured the plantation of the energy crops rather than the use of the residue.

Thus, the allocation of the emissions to sawdust by price has to be considered in making comparison with other scenarios. In this case, the use of sawdust as a feedstock has a positive impact on global warming and the advantage to valorise a by-product of an industrial process.

One of the main disadvantages of using an economic allocation approach is that the allocation factor is not constant in the time, but it changes in relation with the market dynamics.

- The long-range transport of the feedstock, compared to the European scenario of forest residues, causes an increase of the emissions of GHGs between 15%, in the case of pellets combustion in a domestic stove, and 19% in the case of combustion in a CHP. However, **the imported pellets still guarantee a 70% GHGs savings**.

  The long-range transport has a significant effect on the impact categories that account the emissions of nitrogen and sulphur compounds in the atmosphere (air acidification, terrestrial eutrophication, marine eutrophication and tropospheric ozone formation), due to the emissions of nitrogen oxides from the combustion of fossil fuels in the mean of transport and particularly caused by the use of heavy oil in maritime transport.

  Figure 91 shows the results for these impact categories for the scenario of woodchips from Canada and from Europe, compared to the reference scenario.

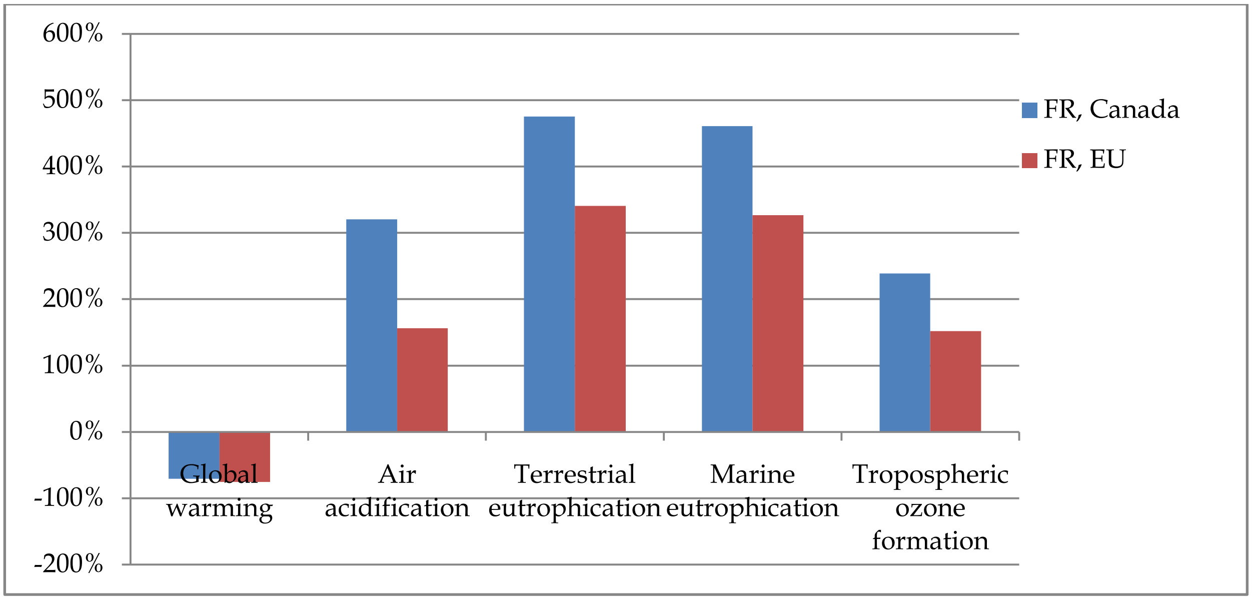

Figure 91: Influence of the transport

- **The impact on climate change for the wheat straw scenario is mainly caused by the cultivation phase**, that accounts from 26% to 45% on the total emissions. Due to the fact that wheat is a yearly crop, it requires an intensive cultivation. These emissions are allocated to straw on an economical basis.

  The main advantages of using straw are that it is a by-product and it is harvested at relatively low moisture.

  The main issues of using straw are **related to the combustion** that causes high quantity of ashes and other compounds (Cl, N, K and Si) present in the straw itself.

  Moreover, the removal of straw from the field would cause a loss of nutrients (N, P, K and SOC) which need to be replaced with synthetic and organic fertilisers. Ash disposal could mitigate this effect, but it has not been investigated in this work.

  All these aspects have not been directly evaluated in this study, but they should be considered in future works.

- The use of an energy crop, p**oplar in SRF, causes the highest impact on global warming.** This is due to the higher amount of GHG emissions during the cultivation phase, which account for about the 25% of the total emissions of the pathway.

- The choice of drying the raw material using natural gas rather than the raw materials itself, results a significant increase in the total emissions of GHGs for each pathways from 26% to 39%. However, **the pellets appear to guarantee a GHGs savings even with the use of natural gas for drying,** in fact it allows savings between 51% to 76%.

  The use of natural gas for drying instead of the biomass **causes also a significant worsening for the impact of ozone depletion**, due to the higher emissions of VOC associated with the extraction and the transport of natural gas than the ones due to the use of a woody biomass.

  The use of natural gas would have, instead, a **positive influence for the impacts on human toxicity, respiratory inorganics, air acidification and marine eutrophication**.

- **The choice of the characterisation method influences the final results**, as shown in the sensitivity analysis. This study is the first one that follows the recommendations of the ILCD Handbook [19] that should be a useful point of reference also for future studies in order to obtain comparable results.

- **The use of herbicides** and their consequent migration to the environmental compartments **have a significant impact on the ecotoxicity**, mostly in the case of poplar.

  The impact categories related with the toxicities, **human toxicity, respiratory inorganics and terrestrial ecotoxicity**, instead, **are mainly associated with the emissions of toxic compounds during the combustion of pellets**, such as formaldehyde, fine particles and heavy metals.

- **The comparison between the results of this study and the Typical values** of the Report of the European Commission [9] **shows significant differences** mainly due to the use of different methodologies, to the fact that for the calculations of the typical values the emissions are associated to the residues only up to the collection and to different emissions factors assumed for the transport.

  The values of the Commission seem to underestimate the energy consumption for forest residues collection and for pellets production.

6.1 Other important open issues

This study is an assessment of the main environmental impacts related to the use of pellets. However some simplifications in the system modelling have been made, some issues have not been analysed and, therefore, some questions remain open.

Hereunder some **suggestions for future research** are reported, on the basis of the current experience:

- **Evaluation of the impact of the land use change**, both direct and indirect; e.g. planting a poplar SRF on a cropland previously used for annual crops, would have direct beneficial effects in terms of carbon stock, but if the annual crop needed to be grown on another land that would cause indirect land use change and associated emissions
- **Evaluation of the actual timing of carbon release**; e.g. if residues were left on the forest floor, they would decompose and release slowly their carbon dioxide, but if they were burned they release everything in one time and this might have a negative impact on atmospheric CO_2 that would be mitigated only in time (carbon debt)
- **Evaluation of the effect of varying emission factors for the combustion of pellets,** being that a certain uncertainty is associated with the estimations of these emissions factors**.** Moreover**, evaluation of the environmental impact due to the combustion of wood pellets in large-scale plants (**that in this study are considered to burn as woodchips) **and due to the combustion of actual straw pellets** (in this study the emissions of the combustion of the straw pellets are considered to be equal to the ones caused by the combustion of woodchips).
- **Evaluation of the effects** on the results due to the use **of different reference scenarios** (e.g. the European thermal energy mix, the use of woodlogs in a fireplace)
- **Analysis of** pathways with other **feedstocks that can be potentially pelletised in the future** such as miscanthus, switch grass, grain hull wastes, sugar beet wastes, fruit stones etc [17].
- **Evaluation of the environmental impact due of the use of pellets at European level** in order to quantify the absolute impact that the use of pellets in substitution to other fuels can have.

DS		*FR, Canada, DS*	*FR, EU, DS*	*Poplar, DS*	*SD, 40% dry, DS*	*SD, all mass, DS*	*SD, all price, DS*	*Nat gas*
Climate change	g_{CO2eq}/MJ_{heat}	23,8	20,2	24,0	15,0	27,4	17,3	77,2
Ozone depletion	kg_{R11eq}/MJ_{heat}	2,2E+01	1,8E+01	2,2E+01	1,3E+01	2,5E+01	1,5E+01	7,1E+01
Human toxicity	$Cases/MJ_{heat}$	1,4E-12	1,4E-12	2,3E-12	1,3E-12	1,6E-12	1,4E-12	4,8E-12
Particulate matter/ respiratory inorganics	$kg_{PM2.5eq}/MJ_{heat}$	9,1E-05	7,9E-05	9,3E-05	6,6E-05	9,7E-05	7,6E-05	1,1E-05
Ionising radiation	kg_{U235eq}/MJ_{heat}	3,2E+03	3,2E+03	3,1E+03	2,3E+03	4,1E+03	2,8E+03	4,3E+02
Photochemical ozone formation	kg_{NMVOC}/MJ_{heat}	2,5E-04	1,9E-04	1,9E-04	1,6E-04	2,5E-04	1,7E-04	5,9E-05
Air acidification	kg_{SO2}/MJ_{heat}	2,4E-04	1,5E-04	3,0E-04	1,2E-04	2,0E-04	1,4E-04	6,7E-05
Terrestrial eutrophication	m^{2}_{UES}/MJ_{heat}	6,1E-03	4,6E-03	1,4E-02	4,0E-03	6,2E-03	4,4E-03	1,1E-03
Freshwater eutrophication	kg_{Peq}/MJ_{heat}	1,3E-05	1,2E-05	1,2E-05	9,3E-06	1,5E-05	1,1E-05	2,0E-06
Marine eutrophication	kg_{Neq}/MJ_{heat}	9,2E-05	6,9E-05	1,2E-04	5,9E-05	9,9E-05	6,6E-05	1,8E-05
Freshwater ecotoxicity	$PAF*m^{3}*d/MJ_{heat}$	5,0E-05	4,2E-05	3,3E-04	4,0E-05	1,1E-04	4,4E-05	2,1E-05
Terrestrial ecotoxicity	kg_{DCBeq}/MJ_{heat}	4,8E-04	4,7E-04	4,8E-04	4,0E-04	5,1E-04	4,3E-04	7,5E-05
Resource depletion	$kg\ _{Sbeq}/MJ_{heat}$	2,6E-08	2,6E-08	3,0E-08	2,2E-08	4,3E-08	2,4E-08	1,3E-08

Table 44: Result for the pathways of domestic stove. Red cells indicate a worst impact for biomass pathways than for the reference scenario, green cells indicate a worst impact for the reference scenario than for biomass pathways

		FR, Canada, DH	FR, EU, DH	Poplar, DH	SD, 40% dry, all price, DH	SD, all mass, DH	SD, all price, DH	Straw, DE, DH	Straw, ES, DH	Straw, NL, DH	Straw, PL, DH	Straw, UK, DH	Nat gas
Climate change	g_{CO2eq}/MJ_{heat}	21,7	18,2	21,9	12,9	25,4	15,3	16,8	19,8	19,3	16,5	18,9	71,0
Ozone depletion	kg_{R11eq}/MJ_{heat}	1,5E-09	1,2E-09	1,4E-09	9,4E-10	2,1E-09	1,1E-09	1,1E-09	1,2E-09	1,2E-09	1,1E-09	1,2E-09	1,0E-08
Human toxicity	$Cases/MJ_{heat}$	1,3E-12	1,3E-12	2,3E-12	1,2E-12	1,5E-12	1,3E-12	1,1E-12	1,1E-12	1,1E-12	1,1E-12	1,1E-12	5,3E-13
Particulate matter/ respiratory inorganics	$kg_{PM2.5eq}/MJ_{heat}$	1,3E-04	1,2E-04	1,4E-04	1,1E-04	1,4E-04	1,2E-04	9,9E-05	1,0E-04	1,0E-04	9,9E-05	1,0E-04	8,8E-06
Ionising radiation	kg_{U235eq}/MJ_{heat}	3,1E+03	3,1E+03	3,1E+03	2,2E+03	4,0E+03	2,8E+03	1,7E+03	1,8E+03	1,8E+03	1,7E+03	1,8E+03	2,4E+02
Photochemical ozone formation	kg_{NMVOC}/MJ_{heat}	2,8E-04	2,1E-04	2,4E-04	1,8E-04	2,7E-04	2,1E-04	1,7E-04	1,8E-04	1,7E-04	1,7E-04	1,7E-04	5,0E-05
Acidification	kg_{SO2}/MJ_{heat}	2,5E-04	1,6E-04	3,3E-04	1,3E-04	2,1E-04	1,5E-04	1,3E-04	1,5E-04	1,5E-04	1,4E-04	1,4E-04	5,4E-05
Terrestrial eutrophication	m^2_{UES}/MJ_{heat}	6,9E-03	5,4E-03	1,6E-02	4,7E-03	7,0E-03	5,3E-03	5,3E-03	6,3E-03	5,9E-03	5,4E-03	5,8E-03	1,1E-03
Freshwater eutrophication	kg_{Peq}/MJ_{heat}	1,3E-05	1,2E-05	1,2E-05	8,8E-06	1,5E-05	1,1E-05	7,2E-06	7,6E-06	7,3E-06	7,3E-06	7,2E-06	1,1E-06
Marine eutrophication	kg_{Neq}/MJ_{heat}	1,0E-04	8,1E-05	1,4E-04	7,2E-05	1,1E-04	8,0E-05	1,6E-04	1,3E-04	2,1E-04	1,6E-04	2,1E-04	1,6E-05
Freshwater ecotoxicity	$PAF*m^3*d/MJ_{heat}$	4,5E-05	3,8E-05	3,3E-04	3,5E-05	1,0E-04	3,9E-05	2,6E-05	2,7E-05	2,7E-05	2,7E-05	2,7E-05	1,0E-05
Terrestrial ecotoxicity	kg_{DCBeq}/MJ_{heat}	4,2E-04	4,2E-04	4,4E-04	3,4E-04	4,6E-04	3,8E-04	3,1E-04	3,1E-04	3,1E-04	3,1E-04	3,1E-04	3,3E-05
Resource depletion	kg_{Sbeq}/MJ_{heat}	1,5E-08	1,5E-08	1,9E-08	1,2E-08	3,2E-08	1,3E-08	1,0E-08	1,1E-08	1,3E-08	1,0E-08	1,2E-08	3,2E-09

Table 45: Result for the pathways of district heating. Red cells indicate a worst impact for biomass pathways than for the reference scenario, green cells indicate a worst impact for the reference scenario than for biomass pathways

		FR, Canada, CHP	FR, EU, CHP	Poplar, CHP	SD, 40% dry, all price, CHP	SD, all mass, CHP	SD, all price, CHP	Straw, DE, CHP	Straw, ES, CHP	Straw, NL, CHP	Straw, PL, CHP	Straw, UK, CHP	Nat gas
Climate change	g_{CO2eq}/MJ_{heat}	19,5	15,9	19,8	10,5	23,5	12,9	14,5	17,6	17,1	14,2	16,7	71,6
Ozone depletion	kg_{R11eq}/MJ_{heat}	1,4E-09	1,2E-09	1,4E-09	8,5E-10	2,1E-09	9,9E-10	1,1E-09	1,1E-09	1,1E-09	1,1E-09	1,1E-09	1,0E-08
Human toxicity	$Cases/MJ_{heat}$	1,2E-12	1,2E-12	2,2E-12	1,1E-12	1,4E-12	1,2E-12	9,4E-13	9,5E-13	9,5E-13	9,4E-13	9,5E-13	5,3E-13
Particulate matter/ respiratory inorganics	$kg_{PM2.5eq}/MJ_{heat}$	1,0E-04	9,0E-05	1,1E-04	7,7E-05	1,1E-04	8,8E-05	6,8E-05	7,2E-05	7,0E-05	6,8E-05	7,0E-05	9,2E-06
Ionising radiation	kg_{U235eq}/MJ_{heat}	2,5E+03	2,5E+03	2,4E+03	1,6E+03	3,4E+03	2,1E+03	1,1E+03	1,1E+03	1,1E+03	1,1E+03	1,1E+03	2,5E+02
Photochemical ozone formation	kg_{NMVOC}/MJ_{heat}	2,4E-04	1,8E-04	1,8E-04	1,5E-04	2,4E-04	1,7E-04	1,3E-04	1,4E-04	1,4E-04	1,3E-04	1,3E-04	5,2E-05
Air acidification	kg_{SO2}/MJ_{heat}	2,3E-04	1,4E-04	3,0E-04	1,1E-04	1,9E-04	1,2E-04	1,1E-04	1,3E-04	1,2E-04	1,1E-04	1,2E-04	5,5E-05
Terrestrial eutrophication	m^2_{UES}/MJ_{heat}	6,1E-03	4,6E-03	1,5E-02	3,9E-03	6,2E-03	4,3E-03	4,5E-03	5,5E-03	5,1E-03	4,5E-03	5,0E-03	1,1E-03
Freshwater eutrophication	kg_{Peq}/MJ_{heat}	1,1E-05	9,8E-06	9,8E-06	6,5E-06	1,3E-05	8,5E-06	4,8E-06	5,2E-06	4,9E-06	5,0E-06	4,9E-06	1,1E-06
Marine eutrophication	kg_{Neq}/MJ_{heat}	9,2E-05	6,8E-05	1,2E-04	5,8E-05	1,0E-04	6,5E-05	1,5E-04	1,2E-04	2,0E-04	1,5E-04	2,0E-04	1,7E-05
Freshwater ecotoxicity	$PAF*m^3*d/MJ_{heat}$	4,1E-05	3,4E-05	3,3E-04	3,1E-05	1,0E-04	3,5E-05	2,2E-05	2,3E-05	2,2E-05	2,2E-05	2,3E-05	1,1E-05
Terrestrial ecotoxicity	kg_{DCBeq}/MJ_{heat}	3,6E-04	3,5E-04	3,5E-04	2,8E-04	3,9E-04	3,1E-04	2,4E-04	2,4E-04	2,4E-04	2,4E-04	2,4E-04	3,4E-05
Resource depletion	kg_{Sbeq}/MJ_{heat}	1,2E-08	1,1E-08	1,6E-08	7,9E-09	2,9E-08	9,1E-09	6,4E-09	7,2E-09	8,8E-09	6,1E-09	7,5E-09	3,3E-09

Table 46: Result for the pathways of CHP. Red cells indicate a worst impact for biomass pathways than for the reference scenario, green cells indicate a worst impact for the reference scenario than for biomass pathways

Nomenclature

AI: Active ingredient
CHP: Combined heat and power
DCB: Dichlorobenzene
DH: District heating
dm: dry matter
DS: Domestic stove
EC: European Commission
ELCD: European Reference Life Cycle Database
FR: Forest Residues
GHG: Greenhouse gas
GWP: Global Warming Potential
HFO: Heavy fuel oil
ILCD: International Reference Life Cycle Data System
IPCC: Intergovernmental Panel on Climate Change
LCA: Life cycle assessment
LCI: Life cycle inventory
LCIA: Life cycle inventory assessment
LHV: Lower heating value
NMVOC: Non-metahne volatile organic compound
PAF: Potentially affected of species
RED: Renewable Energy Directive
SD: Sawdust
SOC: Soil organic carbon
SRF: Short Rotation Forestry
UES: Unprotected ecosystem
VOC: Volatile organic compound

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