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NATIONAL COUNCIL FOR AIR AND STREAM IMPROVEMENT

SCREENING LIFE CYCLE ASSESSMENT OF UNCONVENTIONAL USE PATHWAYS FOR WOODY MILL RESIDUES

SPECIAL REPORT NO. 16-02
AUGUST 2016

by
Chantal Lavigne
NCASI
Montreal, Quebec

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For more information about this research, contact:

Caroline Gaudreault
NCASI
Program Manager – LCA
P.O. Box 1036, Station B
Montreal, QC, H3B 3K5
(514) 286-1182
cgaudreault@ncasi.org

Kirsten Vice
NCASI
Vice President, Sustainable Manufacturing & Canadian Operations
P.O. Box 1036, Station B
Montreal, QC, H3B 3K5
(514) 286-9111
kvice@ncasi.org

To request printed copies of this report, contact NCASI at publications@ncasi.org **or (352) 244-0900.**

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PRESIDENT'S NOTE

Woody mill residues have properties suited to a vast range of unconventional use pathways such as heat production from value-added fuels (pellets, syngas, methane), combined heat and power production from value-added fuels, transport fuel, use in metallurgy, and horticultural growing media. While these uses for woody mill residues are sometimes studied for their potential to reduce anthropogenic greenhouse gas emissions through carbon storage and product substitution, there is little information available regarding other environmental attributes of these use pathways that would allow better understanding of their environmental trade-offs.

Life cycle assessment (LCA) is a methodology used to assess the potential environmental impacts throughout a product's life cycle from raw material acquisition through production, use, and end of life. Potential environmental impacts assessed with LCA include climate change, smog, acidification, eutrophication, fossil fuel depletion, and others. These various impact categories allow the assessment of environmental trade-offs associated with products.

The life cycle assessment study presented in this report provides an overview of potential environmental impacts and benefits of a wide range of management options for woody mill residues through the evaluation of 54 scenarios representing five unconventional use pathways and also, for comparison purposes, a disposal pathway. The results indicate that, for most environmental indicators studied, the impact scores are lower for the unconventional uses than for landfill disposal. In general, scenarios involving the use of value-added fuels in combined heat and power (CHP) systems designed for high electricity output, which displaces fossil fuel-based electricity on the grid, show environmental benefits in more impact categories than other scenarios examined in this study. The environmental trade-offs, however, vary considerably among the pathways and scenarios examined.

Dirk Krouskop

August 2016

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NOTE DU PRÉSIDENT

Les résidus ligneux d'usine ont les propriétés requises pour large éventail d'utilisations non conventionnelles telles que la production indirecte de chaleur à partir de combustibles à valeur ajoutée (granules de bois, gaz de synthèse, méthane), la cogénération à partir de combustibles à valeur ajoutée, la production de carburants pour le transport, l'utilisation en métallurgie et l'utilisation en milieu de culture horticole. L'utilisation des résidus ligneux d'usine est de plus en plus étudiée pour leur potentiel de réduction d'émissions de gaz à effet de serre anthropogénique par le stockage de carbone et par la substitution de produits, mais peu d'information est disponible concernant les autres attributs environnementaux de ces différentes options d'utilisation non conventionnelles qui permettrait d'avoir une meilleur compréhension des compromis environnementaux de ces utilisations.

L'analyse du cycle de vie (ACV) est une méthodologie employée pour évaluer les impacts environnementaux potentiels du cycle de vie d'un produit, c'est-à-dire de l'extraction des matières premières à la fin de vie du produit en passant par sa production et son utilisation. Les impacts environnementaux potentiels évalués avec LCA comprennent les changements climatiques, le smog, l'acidification, l'eutrophisation, l'épuisement des combustibles fossiles, et d'autres. Ces différentes catégories d'impact permettent l'évaluation des compromis environnementaux associés aux produits.

L'étude d'analyse du cycle de vie présentée dans ce rapport donne un aperçu des impacts et bénéfices environnementaux potentiels large éventail d'options de gestion des résidus ligneux d'usine par l'évaluation des cinquante-quatre scénarios représentant cinq voies d'utilisation non conventionnelles et aussi, à des fins de comparaison, à une voie de disposition en fin de vie. Les résultats indiquent que, pour la plupart des indicateurs environnementaux étudiés, les scores d'impact sont plus faibles pour les utilisations non conventionnelles que pour la mise en décharge. En général, les scénarios impliquant l'utilisation de carburants à valeur ajoutée dans les systèmes de cogénération conçus pour maximiser la production d'électricité qui déplace l'électricité à base de combustibles fossiles sur le réseau, montrent des bénéfices environnementaux dans plus de catégories d'impact que les autres scénarios examines dans cette étude. Les compromis environnementaux, cependant, varient considérablement entre les voies et les scénarios examinés.

Dirk Krouskop

Août 2016

SCREENING LIFE CYCLE ASSESSMENT OF UNCONVENTIONAL USE PATHWAYS FOR WOODY MILL RESIDUES

SPECIAL REPORT NO. 16-02
AUGUST 2016

ABSTRACT

In this study, life cycle assessment is used to assess the environmental attributes and trade-offs of different woody mill residue management options in North America. More specifically, this study documents the potential environmental impacts and benefits from disposing of woody mill residues in a landfill, or using them in five unconventional use pathways: heat production from value-added fuels (pellets, syngas, methane), combined heat and power (CHP) generation from these same value-added fuels, transport fuel, use in metallurgy, and use as horticultural growing media. The results indicate that, for most environmental indicators studied, the impact scores are lower for the unconventional uses than for landfill disposal. Scenarios involving the use of syngas in the combined heat and power pathway designed for high electricity output and displacing electricity on the North American electricity grid show the most environmental benefits for most impact categories. Scenarios involving the use of pellets and methane in these CHP systems also yield environmental benefits in a large number of impact categories. Production of heat using syngas is also interesting. In contrast, the scenarios in the transport pathway are among those with the most categories showing the worst relative environmental impact, scenarios in the metallurgy use pathway are relatively neutral (i.e., showing neither significant environmental benefits or impact), and the scenarios under the horticultural growing media pathway are also among those with the greatest number of categories showing a net environmental impact.

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KEYWORDS

electricity, heat, horticultural growing media, LCA, landfill, metallurgy, transport, woody mill residues

RELATED NCASI PUBLICATIONS

Technical Bulletin No. 1016 (October 2013, revised August 2014). *Greenhouse Gas and Fossil Fuel Reduction Benefits of Using Biomass Manufacturing Residues for Energy Production in Forest Products Facilities*.

Technical Bulletin No. 994 (December 2011). *Beneficial Use of Woody Biomass for Energy and Other Purposes*.

ANALYSE DU CYCLE DE VIE PRÉLIMINAIRE DE UTILISATION NON CONVENTIONELLE DES RÉSIDUS LIGNEUX D’USINE

RAPPORT SPECIAL NO. 16-02
AOÛT 2016

RÉSUMÉ

Dans cette étude, l'analyse du cycle de vie est utilisée pour évaluer le profil environnemental et les compromis associés de différentes options de gestion des résidus ligneux d'usine en Amérique du Nord. Plus précisément, cette étude documente les impacts et bénéfices potentiels sur l'environnement et de la mise en décharge des résidus ligneux d'usine, ou de les utiliser dans cinq voies d'utilisation non conventionnelles: la production de chaleur à partir de combustibles à valeur ajoutée (granules, gaz de synthèse, méthane), la cogénération à partir de ces mêmes combustibles à valeur ajoutée, la production de carburants pour le transport, l'utilisation dans la métallurgie, et l'utilisation en milieu de culture horticole. Les résultats indiquent que, pour la plupart des indicateurs environnementaux étudiés, les scores d'impact sont plus faibles pour les utilisations non conventionnelles que pour la mise en décharge. Les scénarios impliquant l'utilisation de gaz de synthèse dans le voie de cogénération maximisant la production d'électricité déplaçant l'électricité du réseau électrique nord-américain montrent le plus de bénéfices environnementaux et ce, pour la plupart des catégories d'impact. Les scénarios impliquant l'utilisation de granules et de méthane dans ces systèmes de cogénération produisent également des avantages environnementaux dans un grand nombre de catégories d'impact. La production de chaleur à partir de gaz de synthèse est aussi intéressante. En revanche, les scénarios de la voie de transport sont parmi ceux qui montrent le plus de catégories d'impacts avec le pire résultats, les scénarios de la voie de l'utilisation en métallurgie sont relativement neutres (i.e, il ne montrent ni bénéfices nets ni impacts nets) et les scénarios de la voie d'utilisation en milieu horticole sont aussi parmi ceux qui ont le plus grand nombre de catégories montrant un impact environnemental net.

Note: Le présent rapport comporte un grand nombre de figures et de tableaux qui s'appuient principalement sur la couleur pour communiquer l'information. Dans le but de conserver des ressources, NCASI a choisi d'imprimer la présente copie en noir et blanc. Les membres peuvent se procurer une version électronique de ce rapport (fichier PDF) pour voir et imprimer ces figures et ces tableaux en couleur en allant sur le site du NCASI réservé aux membres.

MOTS-CLÉS

ACV, chaleur, électricité, métallurgie, milieu de culture horticole, résidus ligneux d’usine, site d’enfouissement, transport

AUTRES PUBLICATION DE NCASI

Bulletin Technique No. 1016 (Octobre 2013, révisé en Août 2014). *Réduction des Émissions de Gaz à Effet de Serre et de la Consommation d’Énergie Fossile due à l’Utilisation de Résidus Manufacturiers de Biomasse pour la Production d’Énergie par les Usines de Produits Forestiers*.

Bulletin Technique No. 994 (Décembre 2011). *Valorisation Énergétique de la Biomasse Ligneuse et Autres Types de Valorisation*.

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TABLES

FIGURES

UNITS

Distance

km: kilometer

Energy

GJ: Gigajoule

kWh: kilowatt hour

MJ: Megajoule

MMBtu: Million British thermal unit

Mass

Bdmt: Bone dry metric tonne

kg: kilogram

lb: pound

st: short ton

t: tonne (metric)

Volume

L: liter

m^3: cubic meter

Nm^3: cubic meter at normal temperature and pressure conditions

SCREENING LIFE CYCLE ASSESSMENT OF UNCONVENTIONAL USE PATHWAYS FOR WOODY MILL RESIDUES

1.0 INTRODUCTION

In recent years, various policies have been proposed and/or implemented to reduce anthropogenic emissions of greenhouse gases, such as the U.S. Clean Power Plan and the United Nations Paris Agreement (United Nations Framework Convention on Climate Change 2015; USEPA 2015). As a result, biomass-derived fuels are increasingly being considered as substitutes for fossil fuels used in the energy and transport sectors. The interest in alternative uses for woody mill residues is also being driven by a desire to maximize the economic value obtained from these materials, resulting in renewed attention to uses such as compost, mulch, and animal bedding. Information on the life cycle environmental attributes of these and other beneficial options could be helpful in identifying potential trade-offs associated with unconventional use pathways for mills and be used as input to life cycle assessment (LCA) studies of broader scope (e.g., if a facility wants to compare its current use of residues with new revenue pathways).

2.0 GOAL OF THE STUDY

The goal of this study is to assess and compare the potential life cycle environmental attributes of several unconventional management options for woody mill residues in North America in a way that accounts for the substitution of alternative materials which are mostly fossil fuel-based. To put these attributes in perspective, they are compared to those of landfill disposal (see Figure 3.1). The assessment is conducted using a screening level LCA, meaning that the LCA makes use of readily available data without additional data collection. This is necessary because some of the unconventional use options reviewed in this study are still at the pilot scale; hence, North American industrial-scale average data are not available. The use of generic data and pilot scale data, while allowing perspective on the environmental trade-offs of the various use options for woody mill residues at an early stage in their development, produces results with a high level of uncertainty; therefore, care should be taken when applying the results of this study.

The study provides an understanding of the environmental attributes of the various management options for woody mill residues using an attributional LCA approach. This allows the attributes of the different options to be compared, but does not reveal the indirect environmental consequences of selecting one course of action over another, a question that would require a consequential LCA approach. Conventional beneficial uses for woody mill residues, such as burning for energy in a mill boiler, are not examined in this study.

3.0 SCOPE OF THE STUDY

3.1 Products under Study

The products under study are woody mill residues from forest products manufacturing facilities consisting primarily of bark and fine residues (e.g., sawdust, planer shavings, sanderdust). Woody mill residues can either be disposed of (e.g., landfilled) or further converted into a final product. As shown in Figure 3.1, one disposal pathway (landfilling) and five unconventional use pathways (heat production from value-added fuels[1] (pellets, syngas, and methane), combined heat and power (CHP) production from residue-derived fuels (pellets, syngas, and methane), transport fuel (via methane, methanol, and ethanol), use in metallurgy (via slow pyrolysis/charcoal), and horticultural growing

[1] The term *value-added fuels* does not include the burning of residues directly, i.e., burning without processing to produce fuels such as pellets, syngas. or methane.

media (via mulch), for a total of six pathways, were studied in this report. The scenarios for each pathway are detailed in Section 3.3.

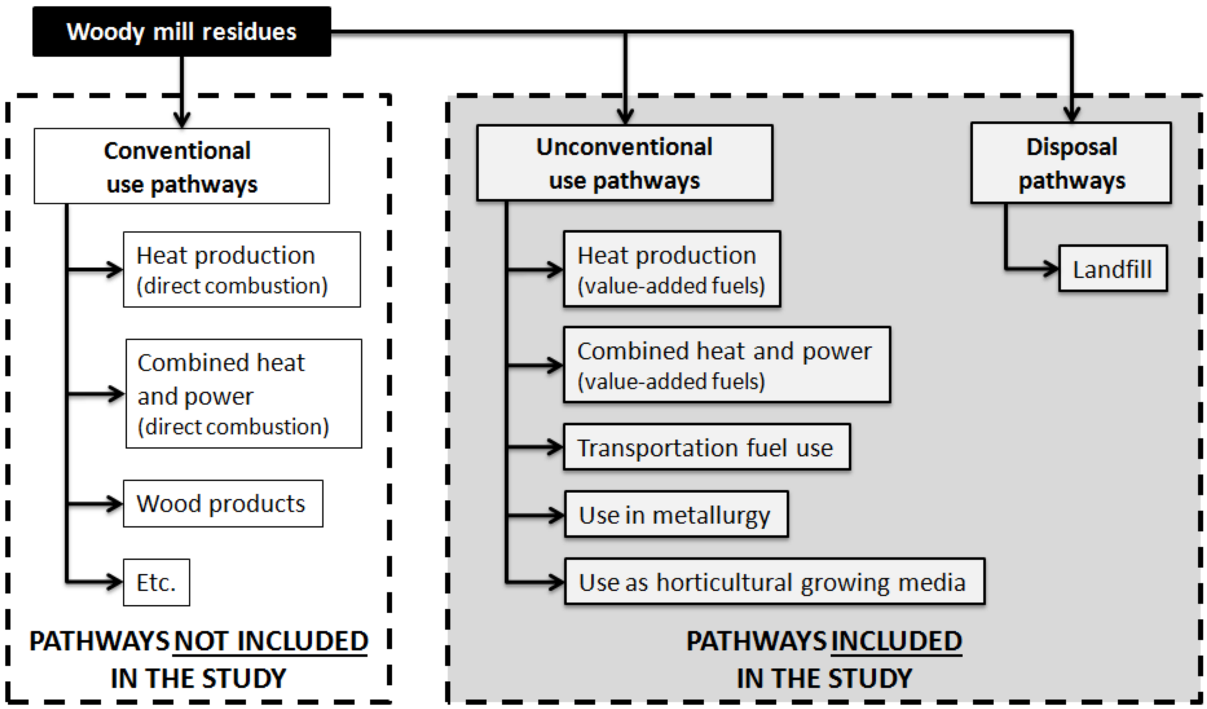


Figure 3.1 Possible Pathways for Woody Mill Residues

3.2 Function, Functional Unit and Reference Flows

The function of the product system under study is the management of woody mill residues.

Typically, the functional unit used to define the system under study in an LCA is expressed as a fixed amount of output product, for example the production of 1 MWh of electricity or the production of 1 tonne of bleach kraft market pulp. This study differs by considering a fixed amount of input, which is the management of 1 tonne of woody mill residues, enabling a comparison of uses independent of the final products[2] or conversion processes.

Functional unit

Management of 1 tonne of woody mill residues in North America

Managing these residues through unconventional use pathways, rather than disposal, implies different product output possibilities such as heat, combined heat and power, transport fuel, and others. The reference flows are thus defined as the different process outputs (e.g., quantity of energy produced, travel distance, volume of growing media) from the management of one tonne of woody residues. Quantitative information on the reference flows is provided in the life cycle inventory presented in Section 4.

[2] In this study, product includes services. Services are tangible and/or intangible elements, such as enabling a car to travel a certain distance.

3.3 Overview of System Boundary and Scenarios

A general overview of the system boundaries applied in this study is shown in Figure 3.2. As shown in this figure, the management of 1 tonne of woody mill residues can be done with unconventional uses of the residues (e.g., heat production from value-added fuels, electricity production from value-added fuels, transport fuel, etc.) or through disposal of the residues (e.g., landfill). Unconventional uses of residues produce products that fulfill additional functions relative to disposal such as providing heat, providing electricity, or enabling the operation of a passenger car. In order to enable the different pathways to be compared on an equal basis, however, their functions need to be made equivalent. The substitution method, one of a number of widely used allocation methods, was selected as the approach for rendering the studied pathways comparable[3]. This was accomplished by dividing the unconventional use pathways in two systems: the biomass system and the alternative system. As shown in Figure 3.2, the biomass system consisted of using the residues in a certain manner or disposing of them and provided both the management of residues function and an additional beneficial function. The alternative system consisted of processes providing the same additional beneficial function as the biomass system, but generally through the use of fossil resources instead of residues. The alternative system was subtracted from the biomass system, enabling the comparison of the different system on the basis of a single management function.

Major sources of manufacturing residues include sawmills, panel plants, and pulp and paper mills. These wood residues consist primarily of bark and fine residues (e.g., sawdust, planer shavings, sanderdust). In this study, all types of woody mill residues were considered as a whole. The manufacturing processes that generate biomass residues occur regardless of whether, or how, the wood residues are beneficially used and are the same for all compared options. Therefore, the environmental aspects associated with these upstream processes were not included in the scope of the study. In other words, all processes equivalent in both systems, such as harvesting and debarking, were excluded from the studied systems, as shown in Figure 3.2.

[3] To learn about methods used to make systems with different functions comparable, refer to NCASI Technical Bulletin No. 1002 (NCASI 2012).

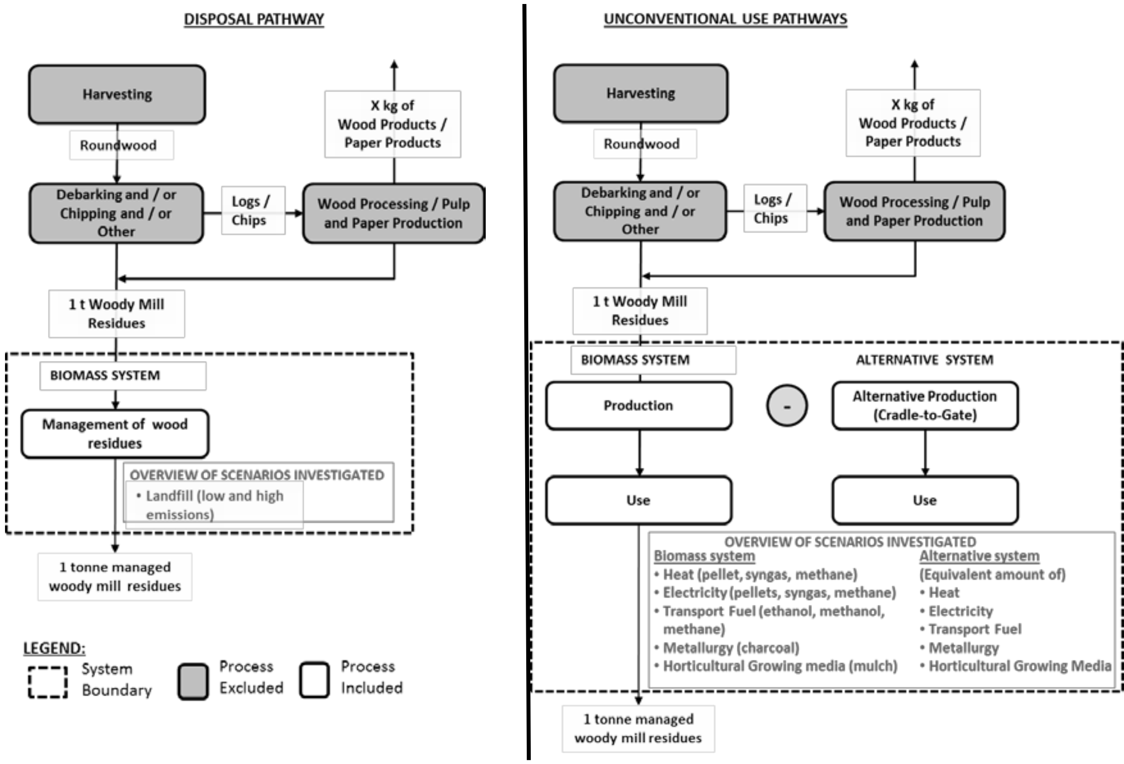


Figure 3.2 General Overview of the System Boundaries Used for the Disposal and Unconventional Use Pathways

For each of the five unconventional use pathways, a number of different scenarios were investigated by selecting different biomass and alternative systems to represent various woody mill residues management options and current product/service replacement possibilities. Scenarios investigated are summarized in Figure 3.2 and further discussed in Sections 3.3.1.1 and 3.3.2. In addition, two sensitivity analyses were performed to assess the effect of modeling choices on the results. The first sensitivity analysis is referred to as "efficiency", where the different biomass system parameters, such as production yield or combustion yield, were varied from their base case scenario values to a low value and high value. The second sensitivity analysis is referred to as "grid mix", where the electricity consumption grid mix, which differs per region or country, was varied to assess the validity of the results if scenarios occur in different regions or countries. More detail regarding the sensitivity analyses is provided in Section 4. Note that parameter values used in the base case scenarios were selected to represent the range of values reported in the literature as detailed in the life cycle inventory section of this report. Selected values represent the mean, the median, or typical value of those reported in the literature. Two scenarios were also applied to the disposal pathway to reflect situations with higher and lower CO_2 emissions.

3.3.1 *Disposal Pathway*

The only disposal pathway considered in this study is landfilling of woody mill residues. While in North America relatively small quantities of woody mill residues are sent to landfills, this pathway was used to put the potential environmental impacts of the unconventional use pathways in perspective. When woody mill residues are sent to landfills in North America, they are sent to industrial rather than municipal waste landfills. Industrial landfills at forest products facilities are typically anaerobic, given the low porosity, high organic content and depth. Anaerobic landfills are known to permanently store part of organic carbon contained in the landfilled product and to emit organic carbon as carbon dioxide as well as methane, a greenhouse gas (GHG) approximately 25 times more potent than carbon dioxide. The scenario definitions and rationale, along with more detail on the various landfill parameters for woody mill residue degradation, are provided in Section 4.

3.3.2 *Unconventional Use Pathways*

3.3.2.1 *Heat Production Pathway*

Woody mill residues can be converted into pellets, syngas, or methane prior to being burned in boilers to produce energy. In some cases, the residues need to be dried and chipped or sorted to obtain acceptable size ranges. Figure 3.3 shows the three alternative biomass systems for the unconventional heat production pathway studied: pellets, syngas, and methane. For each heat production scenario studied, two systems are included within the system boundary: the production of heat from the biomass (biomass system) and the equivalent amount of heat generated using an alternative system. The biomass system includes conversion processes such as pellet production, gasification and/or methanation; the combustion process; and any related upstream production processes (e.g., gasification) as well as related transport between conversion process location and combustion location, except for the syngas biomass system, where the produced syngas is considered burned on site because of its low higher heating value (HHV). The conversion process can include pretreatment of the biomass. For the alternative system, it was assumed that heat could be produced using natural gas, No. 2 fuel oil, No. 6 fuel oil, or coal. The processes included in the alternative system comprise the upstream process units for producing the fossil fuel and the combustion process for heat production at the consumer location. The scenario definitions and rationale, along with more detail on the various unit processes involved in both systems, are provided in Section 4.

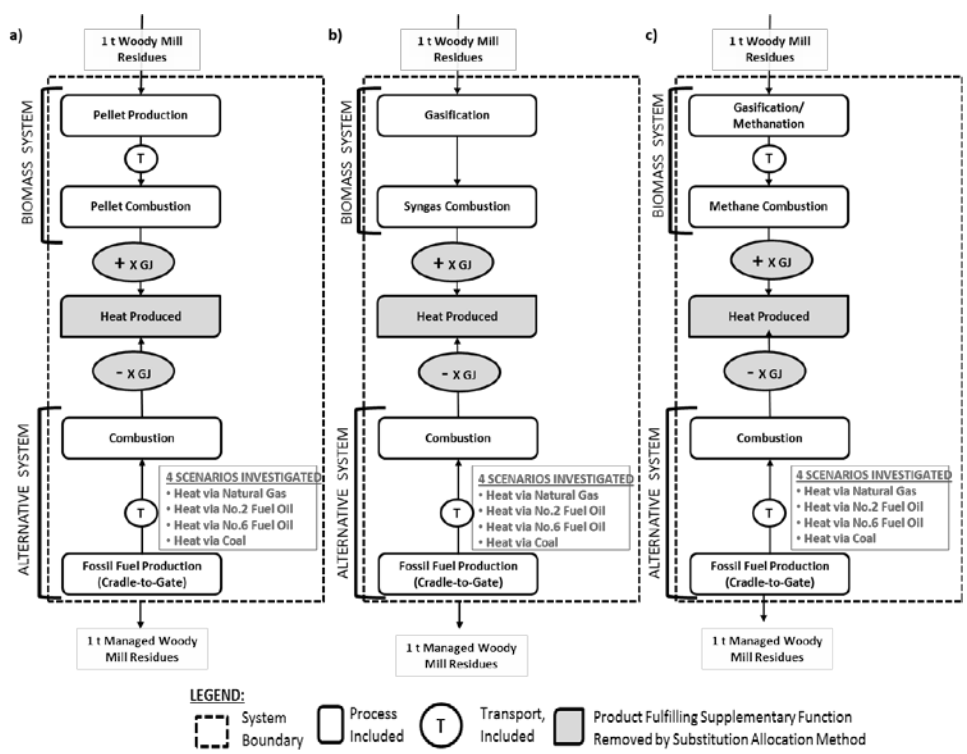


Figure 3.3 Product Systems Studied for Unconventional Heat Production Pathway for the Three Selected Biomass Systems: a) Pellets; b) Syngas; c) Methane

3.3.2.2 *Combined Heat and Power Production Pathway*

Combined heat and power production (CHP) is common in the forest products industry. Heat, as discussed in Section 3.3.2.1, can be produced via residues converted into pellets, syngas, or methane prior to being burned in boilers. Biomass-fired boilers can convert part of this heat into high pressure steam, which can be routed to a back pressure turbine to produce electricity; hence, heat and electricity can be provided in parallel.

Figure 3.4 illustrates the three biomass systems for the scenarios studied for the unconventional combined heat and power production pathway: Pellets, Syngas, and Methane. For each CHP scenario studied, two systems are included within the system boundary: the production of heat and electricity from the biomass (biomass system) and the equivalent amount of heat and electricity generated using the alternative system. The biomass system includes: conversion processes such as pellet manufacturing, gasification and/or methanation; the combustion process; and any related upstream processes (e.g. gasification), as well as transport between the conversion process location and combustion location, except for the syngas biomass system, where the produced syngas is considered burned onsite because of its low HHV. The conversion process can include pretreatment of the biomass. For the alternative system, it was assumed that heat could be produced using natural gas, No. 2 fuel oil, No. 6 fuel oil, or coal, and electricity could be produced using either natural gas or via the North American electricity grid. The processes included in the alternative system comprise the upstream process units for producing the fuels, the combustion process for heat production at the consumer location, the upstream electricity production, and electricity consumption. The scenario definitions and rationale, along with more detail on the various unit processes involved in both systems, are provided in Section 4.

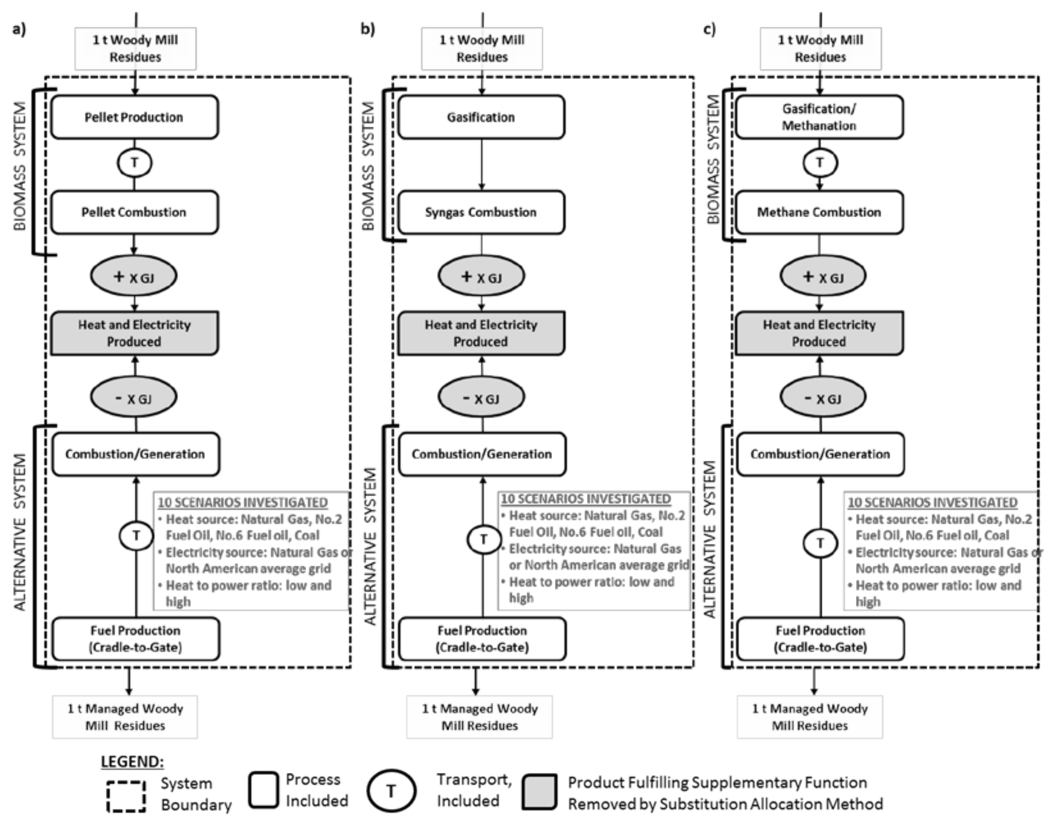


Figure 3.4 Product Systems Studied for Unconventional Combined Heat and Power Production Pathway for the Three Selected Biomass Systems: a) Pellets; b) Syngas; c) Methane.

3.3.2.3 *Transport Fuel Use Pathway*

The use of biofuels in the transport sector is not new; however, research is ongoing regarding the biomass type to be converted, the choice of the conversion process, and improvement of the yield of the conversion process. Transport fuel can enable the operation of a passenger car, hence enabling the user to travel a certain distance. Transport fuel can be produced from woody mill residues through various conversion processes such as gasification followed by syngas conversion to methane or methanol, or via fermentation to produce ethanol.

Figure 3.5 illustrates the three biomass systems for the unconventional use of woody mill residues in the production of automobile fuels studied in this report: methane, methanol, and ethanol. For each transport fuel scenario studied, two systems are included within the system boundary: distance traveled with an average car using a transport fuel made from the biomass (biomass system) and the equivalent distance that would otherwise have been traveled using transport fuel from an alternative system. The biomass system includes conversion processes such as fermentation, gasification followed by methanol production or methanation; operation of a passenger car; and any related upstream processes (e.g., gasification), as well as related transport between the conversion process location and the combustion location. The conversion process can include pretreatment of the biomass. For the alternative system, it was assumed that the transport fuel is diesel, gasoline, or natural gas (the latter in the case of methane). The processes included in the alternative system include the upstream process units for producing the fossil fuel and operation of a passenger car. The scenario definitions and rationale, and more detail on the various unit processes involved in both systems, are provided in Section 4.

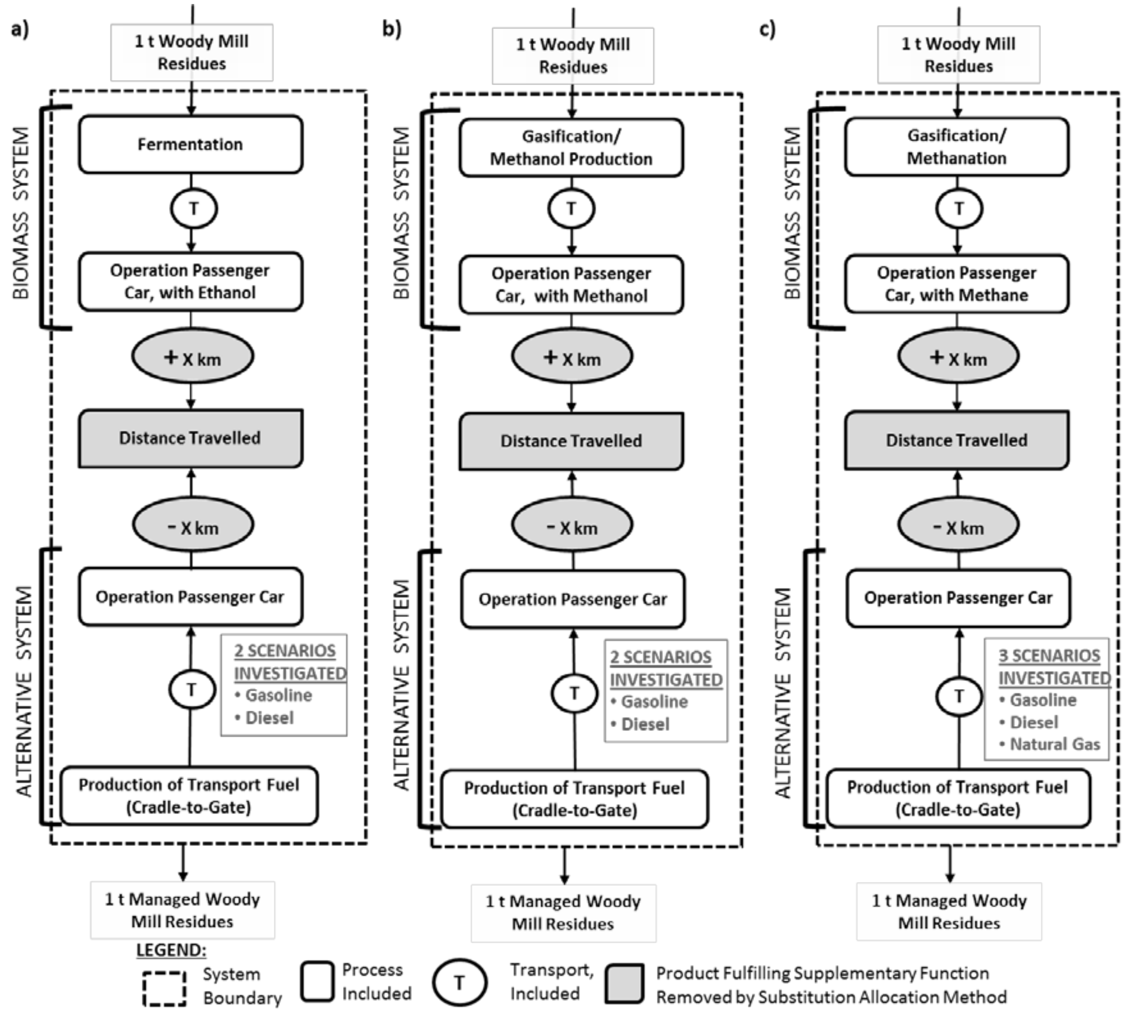


Figure 3.5 Product Systems Studied for the Unconventional Transport Fuel Use Pathway for the Three Selected Biomass Systems: a) Ethanol; b) Methanol; c) Methane

3.3.2.4 *Use in Metallurgy Pathway*

The use of charcoal in the iron industry is an ancient technology and was used throughout Europe before the Industrial Revolution. In parts of Brazil, however, because of foreign exchange policies, the limited low quality coal reserves, and the abundance of wood, the iron industry did not transition to coke (Ackerman and de Almeida 1990). At this time, Brazil produces charcoal by carbonization, also called slow pyrolysis, using mainly traditional “hot-tail” kilns (Bailis et al. 2013). The use of charcoal in the European iron industry is the subject of recent interest as a way to reduce GHG emissions. More precisely, a consortium of 48 European companies called ULCOS (Ultra-Low CO_2 Steelmaking) launched a cooperative research and development initiative in 2004 to reduce carbon dioxide (CO_2) emissions from steel production wherein the use of biomass to replace coke (as a source of carbon, i.e., reducing agent, for pig iron production) was one of the avenues explored for achieving CO_2 emissions reduction (ULCOS, n.d.). In addition, improved charcoal production technologies have been studied with the aim of capitalizing on charcoal by-products such as tars and reducing emissions from the pyrolysis process (Ackerman and de Almeida 1990; Bailis et al. 2013).

Figure 3.6 illustrates the unconventional use of woody mill residues in the production of pig iron used in steel manufacturing, the only use in metallurgy pathway scenario studied in this report. Two systems are included within the system boundary: pig iron production using charcoal produced from a modern technology (biomass system) and the equivalent amount of pig iron that would have otherwise been produced from an alternative system using coke. The biomass system includes conversion processes such as slow pyrolysis; use of the charcoal as a fuel and reducing agent in pig iron production; and any related upstream production processes (e.g., gasification), as well as related transport between the conversion process location and pig iron production location. The conversion process can include pretreatment of the biomass. For the alternative system, it was assumed that the pig iron could be produced using coke. The processes in the alternative system include the upstream process units for producing the fossil fuel and the use of coke in pig iron production. The scenario definition and rationale, along with more detail on the various unit processes involved in both systems, are provided in Section 4.

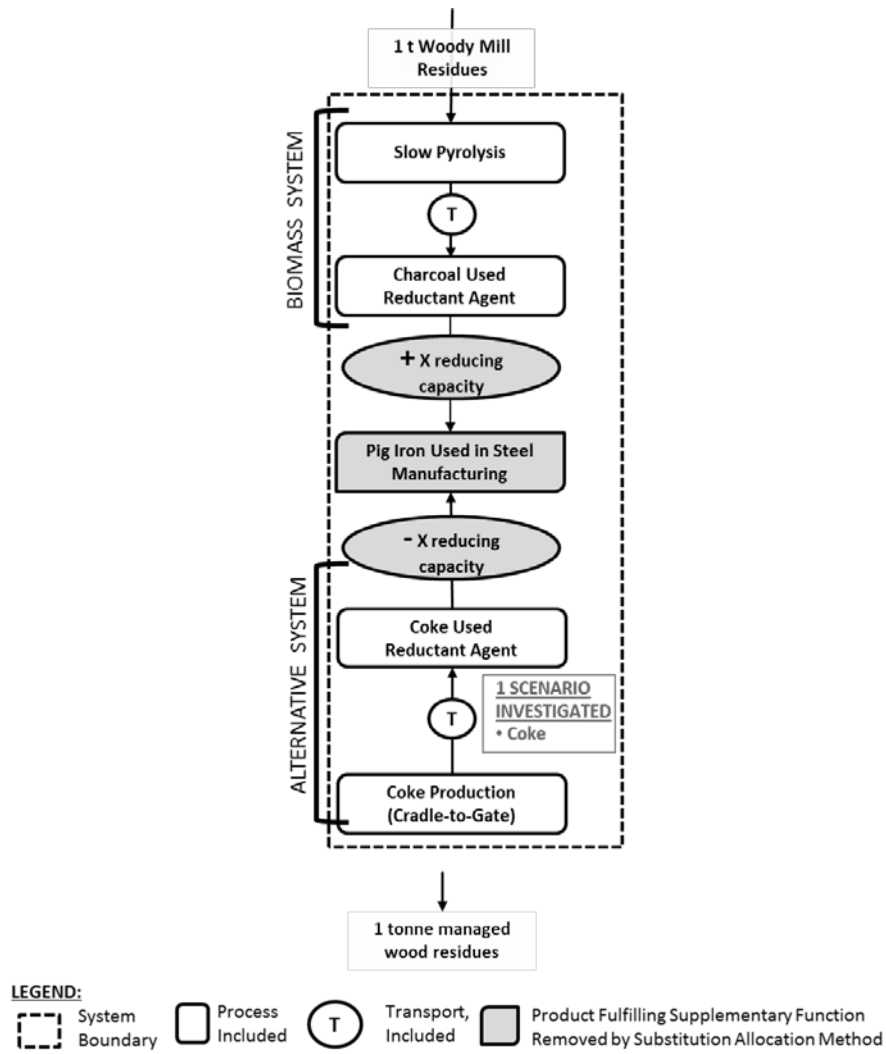


Figure 3.6 Product System Studied for Unconventional Metallurgy Use Pathway for which the Selected Biomass System Is Charcoal

3.3.2.5 *Use as Horticultural Growing Media Pathway*

Mulch can be used as a soil amendment to preserve moisture in soil, moderate soil temperature, and suppress weed growth (NCASI 2011). In this study, mulch is considered as a growing media used by the general consumer market in potting mix (hobby market).

Figure 3.7 illustrates the unconventional use of woody mill residues as a growing media for the system studied in this report. As shown in the figure, only one biomass system is studied for this pathway. Two systems are included within the system boundary of this pathway: growing media produced via mulch (biomass system) and the equivalent amount of growing media that would have been produced from an alternative system. The biomass system includes production of the product (mulching); the use of the mulch as growing media; and any related upstream production processes (e.g. packaging), as well as related transport between the conversion process location and use location. The conversion process can include pretreatment of the biomass. For the alternative system, it was assumed that a growing media mix with peat as primary constituent would be functionally equivalent (Quantis 2012). The processes included in the alternative system include the upstream process units for producing the growing media mix and the use of the growing media. The scenario definitions and rationale, along with more detail on the various unit processes involved in both systems, are provided in Section 4.

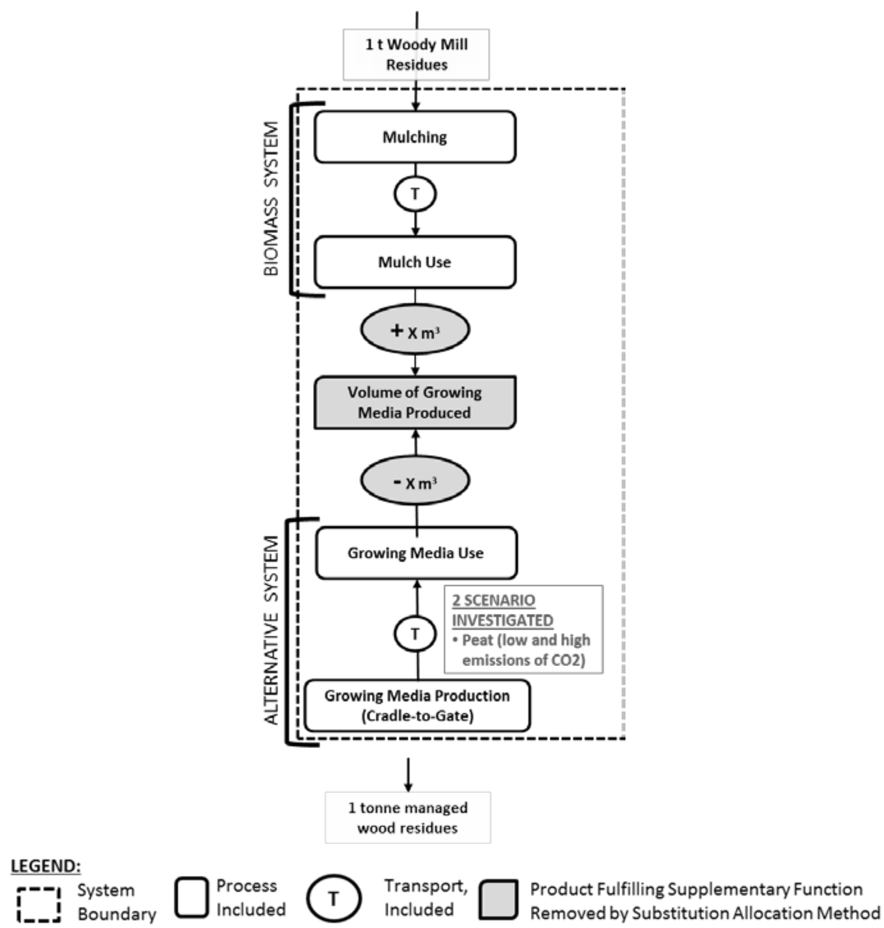


Figure 3.7 Product System Studied for Unconventional Horticultural Growing Media Pathway for which the Selected Biomass System Is Mulch

3.4 Allocation

In order for systems to be compared, they must be functionally equivalent. When a product system fulfills multiple functions (or produces multiple products), allocation methods can be used to attribute the environmental load of the shared processes of the product system to the studied function (or product) and to each of the additional functions (or products) delivered by the shared process (NCASI 2012). In this study, the main allocation situation encountered pertains to the additional function(s) of the product systems described in Section 3.3. According to ISO 14044:2006, the LCA requirements and guidelines standard, allocation shall be avoided by system subdivision or system expansion if possible, otherwise partition shall be performed using an underlying physical relationship where possible, and if not, another relationship (e.g., economic allocation). In this study, the substitution method (a form of system expansion) has been used to deal with the additional function of the unconventional use pathways because it was consistent with the objective of assessing the potential life cycle environmental attributes of unconventional management options for woody mill residues in a way that accounts for the substitution of alternative materials which are mostly fossil fuel-based. The substitution method deals with multifunction systems by subtracting from a multifunction system (e.g., a system providing management of woody mill residues and providing heat) another system that provides the same function as the one needing to be removed (e.g., providing heat), as illustrated in Figure 3.2. In this way, the substitution method allows the user to generate information on the environmental load of the product system and functional unit of interest (e.g., management of 1 tonne of woody mill residues in North America) while including in the framework of analysis the interactions of this system with other product systems (e.g., energy from fossil fuel that is displaced by the use of biomass).

Allocation is also embedded within some of the unit processes modeled in this study. The ecoinvent database (v3.1), which is the main source of data for this study, uses economic allocation as a default method. For unit processes not derived from ecoinvent, a conservative approach was used, i.e., allocating all impacts to the biomass product system investigated. Because many of the processes referenced in this study are only currently in operation at a pilot scale, a conservative approach was deemed appropriate so as not to underestimate the potential environmental impacts of a given beneficial use.

3.5 LCI Database Used

The main data source used was the ecoinvent database (v.3.1, http://www.ecoinvent.org/), a European LCI database. The ecoinvent database contains over 11,000 data sets covering areas such as energy supply, biofuels, and biomaterials. The data sets are based on industrial data and literature reviews, and were compiled by internationally renowned research institutes and LCA consultants.

3.6 Data Quality Goals

The data quality goal of this study was to use readily available data representative of current average technologies in use in North America. Data were most frequently available from the ecoinvent database (v.3.1), a European LCI database, and published literature. The ecoinvent database was adapted to the North American context by modifying the electricity consumption grid mix used in the processes to one representative of North America. Data obtained from these sources are considered adequate for a screening level LCA. The uncertainties of the data were investigated via sensitivity analyses.

3.7 Exclusion and Cut-Off Criteria

For each of the scenarios described above, the following components of each product system were excluded from this study: human activities, such as use of cafeteria appliances and washroom facilities; and unit processes common to the systems compared, such as harvesting and production of woody mill residues. Infrastructures were included in all product systems studied, based on ecoinvent data sets.

Ecoinvent data sets and data from the literature allowed modeling of all process units included in the system boundaries of the studied life cycles; hence, no cut-offs were applied.

3.8 Temporal Boundaries

The temporal boundary of an LCA is the period of time that is included in the assessment. It determines how the processes included within the physical boundaries are modeled. In this study, an infinite temporal boundary was selected, mainly to account for degradation of products in landfills. This means that all life cycle emissions were considered unless carbon would be stored permanently in anaerobic landfills.

3.9 Impact Assessment Methods

3.9.1 *Selected Impact Categories and Life Cycle Impact Assessment (LCIA) Methods*

TRACI 2.1 (v. 1.02) is available within SimaPro™ and was used in this study (Bare 2012). TRACI (Tool for Reduction and Assessment of Chemical and Other Environmental Impacts) is an LCIA methodology developed by the United States Environmental Protection Agency and is representative of US conditions. LUCAS, a Canadian LCIA methodology, has not been updated since its release in 2007 and therefore was not used in this study. TRACI characterizes environmental stressors that have potential effects in ozone depletion, global warming, tropospheric ozone (smog) formation, acidification, eutrophication, human health cancer effects, human health non-cancer effects, human health respiratory effects, ecotoxicity effects and fossil fuel depletion. A description of the TRACI impact categories is presented in Appendix A.

3.9.2 *Selected Impact Categories and Impact Assessment Methods*

In TRACI, the default global warming potentials (GWPs) for carbon removals by trees and for biogenic carbon dioxide emissions are 0 kg CO_2e./kg CO_2. In this study, all of the biomass systems remove the equivalent amount of CO_2 from the atmosphere; however, a few biomass systems do not reemit all of the carbon because it is permanently stored. To account for this difference in carbon stored, a carbon stock approach was used; hence, the default emission factors for carbon uptake and biogenic carbon dioxide emission used by TRACI were kept (i.e., 0 kg CO_2e/kg). However, carbon permanently stored in product was assigned an emission factor of -1.

3.9.3 *Treatment of Biogenic CO_2*

In this study, using TRACI, the results of the potential environmental impacts of the disposal pathway and unconventional use pathways scenarios were assessed using a four-step approach. First, life cycle impact results were assessed. Contribution analyses were then performed for each pathway base case scenario, followed by a semi-quantitative uncertainty assessment. Finally, the disposal pathway and unconventional use pathway life cycle impact results were pulled together for a final comparative assessment in light of the information provided by the previous assessments. The details of the different steps of the approach are presented in Section 5.1.

3.9.4 *LCIA Profile Calculation and Normalization*

For each impact pathway, the environmental impact score was calculated as follows:

$$IS_{P,i} = IS_{P,i,Bio} - IS_{P,i,AS}$$

Where:

$IS_{P,i}$: Impact score of the pathway P for impact category i;

$IS_{P,i,Bio}$: Impact score of the biomass system in pathway P for impact category i; and

$IS_{P,i,AS}$: Impact score of the alternative system in pathway P for impact category i.

For a given pathway, a positive impact score on a given impact category means a net potential environmental impact for that pathway on the studied impact category. In other words, the potential environmental impact from the management processes of the residues is greater than the impacts of the displaced alternative system. In contrast, a negative impact score for a given impact pathway on a specific impact category means that, for this impact category, the pathway results in a net environmental benefit.

To help visualize and interpret the results, a normalization by the maximum was used in this study. More details can be find later in this report.

3.10 Limitations of the Study

The results are valid only for the systems and scenarios studied. Functional equivalence of other combinations of biomass systems and alternative systems not mentioned in this study were not assessed; hence, extrapolating the results to other systems would not be appropriate. The data were sourced or modified to represent a North American context. Applying the results of this study to another geographical location may not be appropriate.

3.11 Software Package

The modeling for this study was performed using SimaPro™ version 8.0.4.

3.12 Critical Review and Public Use of the Results

This study constitutes a comparative assertion of beneficial use and disposal of biomass systems. However, no formal peer review was performed, meaning that the study is not fully compliant with the ISO 14044 Standard.

4.0 LIFE CYCLE INVENTORY

This section describes the life cycle inventory step of the LCA, including the scenarios explored, the unit processes modeled, and the sensitivity analyses undertaken. A unit process is the smallest element considered in the life cycle inventory analysis for which input and output data are quantified. Input and output data consist of flows of energy, product or material entering or leaving the system from or to the environment or another unit process. Because a life cycle inventory is a mix of factual elements and assumptions, sensitivity analyses, i.e., modifying estimated parameter values to examine the effect on the system, help determine the importance of the assumptions with respect to the results.

As previously stated, readily available data from the ecoinvent database were used to model the upstream life cycle inventory information for the unit processes used in the scenarios. Therefore, when describing the unit processes modeled, only the parameters that were modified are detailed in this report. Parameters for which a sensitivity analysis was performed are also presented.

4.1 Scenario Nomenclature

In total, 52 unconventional wood residue management scenarios were studied divided in five pathways, or “uses” for wood residue (see Figures 3.3 through 3.7), along with two scenarios for the disposal pathway. Each has been systematically named in this report according to their use (or “pathway”), biomass system, and alternative system. Table 4.1 summarizes the scenario nomenclature used throughout this report.

Table 4.1 Scenario Nomenclature

Pathway/Use	
LF	Disposal/Landfill
H	Heat Production
CHPh	CHP maximized for heat production
CHPe	CHP maximized for electricity production
TRSP	Transport Fuel use
Metl	Use in Metallurgy
HGM	Use as Horticultural Growing Media

Biomass System	
lowCO_2e[a]	Low emissions of CO_2e
highCO_2e[a]	High emissions of CO_2e
Pellet	Pellets
SG	Syngas
CH4	Methane
MeOH	Methanol
EtOH	Ethanol
Charcoal	Charcoal
Bark	Bark

Alternative System	
NG	Natural Gas
F2	No. 2 fuel oil
F6	No. 6 fuel oil
Coal	Coal
D	Diesel
P	Petrol (gasoline)
Coke	Coke
Peat	Peat
2X	For CHP Scenarios: Same fuel used for electricity and heat generation
E	For CHP Scenarios: Electricity from electricity grid mix

[a] This nomenclature is used to identify a scenario modeled with parameters that results in low CO_2e emissions. It was used in assessing scenarios for two pathways where the uncertainty related to level of GHG emissions is high: disposal pathway and use as horticultural growing media pathway.

4.2 Disposal Pathway

In the event woody mill residues are disposed of, various disposal pathways for non-hazardous solid waste are available in North America. In Canada, non-hazardous solid waste is disposed of in landfills or is incinerated, the former being the most common way to dispose of waste in Canada (Statistics Canada 2005). There are two types of landfills modeled in the Canadian GHG inventory: municipal solid waste (MSW) landfills, and wood waste landfills (Environment Canada 2015). Most wood waste landfills are owned and operated by the forest products industry and are used to dispose of surplus wood residue, such as sawdust, wood shavings, bark, and wastewater treatment plant residuals (Environment Canada 2015). In the United States, two main types of landfills are modeled in the GHG inventory: municipal solid waste (MSW) and industrial landfills (USEPA 2015b). Over 99% of the organic waste placed in industrial landfills is from the food processing (meat, vegetables, fruit) and pulp and paper industries. Methane recovery at industrial landfills is not common practice and is not incorporated in the US GHG Inventory (USEPA 2015b) nor into the Canadian GHG Inventory (Environment Canada, 2015); therefore, it is not accounted for in this study.

Parameters likely to represent degradation in US industrial landfill and wood waste landfills in Canada were investigated. To cover the range of possible scenarios, the combination of parameters resulting in the lowest amount of CO_2e and highest amount of CO_2e were analyzed in this study: managed anaerobic landfills with a low fraction of non-degradable carbon under anaerobic conditions, and managed anaerobic landfills with a high fraction of non-degradable carbon under anaerobic conditions. In both cases, the same fraction of methane was assumed to be oxidized in landfill covers. Table 4.2 summarizes the two scenarios investigated in this study for the woody mill residues disposal pathway. Details of the possible parameters for wood degradation in landfills, modeled scenarios and their justification are described immediately below.

Table 4.2 Scenarios Explored for the Disposal Pathway

Scenario Name*	General Description
LF_lowCO_2e	Managed deep landfills with a high fraction of non-degradable carbon under anaerobic conditions (F_{CCND} = 96.8%), and a fraction of methane oxidized in landfill covers (F_{CH4OX} = 10%)
LF_highCO_2e	Managed deep landfills with a low fraction of non-degradable carbon under anaerobic conditions (F_{CCND} = 50%), and a fraction of methane oxidized in landfill covers (F_{CH4OX} = 10%)

* LF: Landfill
lowCO_2e: combination of parameters resulting in the lowest amount of CO_2e produced from industrial landfill degradation in the US and wood waste landfill degradation in Canada.
highCO_2e: combination of parameters resulting in the highest amount of CO_2e produced from industrial landfill degradation in the US and wood waste landfill degradation in Canada.

4.2.1 *Landfilling of Woody Mill Residues*

In landfills, a fraction of the biogenic carbon in wood-based material decays, primarily into gas. The remaining fraction is non-degradable under anaerobic conditions. The non-degradable fraction varies by type of product, being generally higher in materials with more lignin.

The fraction of material that is non-degradable under anaerobic conditions is needed in order to estimate GHG emissions from landfills receiving wood residues. Values published in the literature for this parameter in the case of woody materials vary widely, from 50% (IPCC 2006b) to over 96.8% (Wang et al. 2011). Moreover, the non-degradable fraction of materials like bark and sawdust that comprise woody mill residues have not been studied, to NCASI's knowledge. For wood waste landfills, Environment Canada uses a fraction of material non-degradable under anaerobic conditions of 64.7%, while the United States GHG National Inventory report (NIR) uses a value of 77% for wood-based discards and branches in landfills and a value of 50% for all waste in MSW landfills (Environment Canada 2015; USEPA 2015b). Environment Canada based its calculation on default values published in IPCC 1996 Guidelines for National Greenhouse Gas Inventories (IPCC 1997), while the USEPA based its calculation for all waste in MSW landfill on IPCC 2006 Guidelines for National Greenhouse Gas Inventories (IPCC 2006a) and on Skog (2008) for branches. There is large uncertainty in this parameter; hence, the lowest reported value (50%) and the highest reporting value (96.8%) are considered in this study by using two scenarios to cover the range of possible values.

Under anaerobic conditions, about half of the degradable carbon is converted to biogenic CO_2 while the other half is converted to CH_4. The decomposition is typically modeled as a first order decay. Under aerobic conditions (e.g., in shallow unmanaged landfills), a much smaller fraction of the gas consists of CH_4. Wood waste landfills in Canada are described as unmanaged deep landfills and as such, a methane correction factor (MCF) of 0.8 is used by Environment Canada to reflect the fraction of material that is degraded under anaerobic conditions (Environment Canada 2015). In the United States, industrial landfills, where woody mill residues could end up, are described as managed landfills; hence, a methane correction factor of 1 is used by EPA (USEPA 2015b).

Another factor influencing the releases of landfill CO_2 and CH_4 to the atmosphere is the presence of systems to collect and destroy methane by burning. In this study it was assumed that manufacturing residues are disposed of in a landfill receiving primarily forest product industry waste and that for these landfills there is no methane capture – assumptions consistent with current practice in the industry and with the approach used by Environment Canada and U.S. EPA to calculate landfill emissions from wood waste and/or industrial landfills for their national inventories (Environment Canada 2015; USEPA 2015b). Therefore, methane released from landfill was not considered to be collected or burned in this study.

Finally, the extent to which CH_4 is oxidized to biogenic CO_2 before exiting the landfill must be considered. It is commonly assumed that about 10% of the methane is oxidized as it moves through the surface layers of a managed landfill covered with CH_4-oxidizing material (IPCC, 2006b). Environment Canada assumes that zero methane is oxidized based on IPCC 1996 Guidelines for National Greenhouse Gas Inventories. IPCC 2006 Guidelines suggest an oxidation factor of 0 (zero) for unmanaged landfills such as the type of wood waste landfills assumed by Environment Canada in its National Inventory Report (NIR) and 10% for managed landfills such as the type of industrial landfills assumed by USEPA in its NIR. In this study, a value of 10% was modeled.

Quantities of carbon dioxide and methane emitted from wood waste and industrial landfills emitted were calculated as follows:

Quantity of Carbon Converted to Gas Under Anaerobic Conditions:

$$Q_{C\rightarrow Gas,ana} = MCF \times Q_R \times CC \times (1 - F_{CCND})$$

Where Q_R is the quantity of residues required to be managed, i.e., 1 dry tonne; CC the carbon content of residues (CC= 50%); and F_{CCND} the fraction of carbon that is non-degradable under anaerobic conditions. In this study, two values for F_{CCND} were assessed: 0.5 and 0.968.

Quantity of Carbon in Gas Converted to Methane ($Q_{C\text{->}CH4}$):

$$Q_{C\rightarrow CH4} = Q_{C\rightarrow Gas,an} \times F$$

Where F is the fraction of gas generated under anaerobic conditions that is methane (F = 0.5 in this study).

Quantity of Methane Not Collected and Burned (Q_{CH4NCB})

$$Q_{CH4NCB} = Q_{C\rightarrow CH4} \times \frac{16}{12}(1 - F_{CH4CB})$$

Where F_{CH4CB} is the fraction of methane collected and burned. In this study, the value used for F_{CH4CB} was: 0.

Quantity of Methane Released to the Environment ($Q_{CH4,Landfill}$):

$$Q_{CH4,Landfill} = Q_{CH4NCB} \times (1 - F_{CH4OX})$$

Where F_{CH4OX} is the fraction of methane oxidized in landfill covers. In this study, two values for F_{CH4OX} were assessed: 0 for unmanaged landfills and 0.1 for managed landfills.

Total Quantity of Carbon in Gas (from aerobic and anaerobic decomposition):

$$Q_{C\rightarrow Gas} = Q_R \times CC \times [1 - MCF * F_{CCND}]$$

Quantity of Carbon Dioxide Released to the Environment ($Q_{CO2,Landfill}$):

$$Q_{CO2,Landfill} = \left(Q_{C\rightarrow Gas} - Q_{CH4,landfill} \times \frac{12}{16}\right) \times \frac{44}{12}$$

To cover the range of possible scenarios, the parameters producing the scenarios emitting the lowest amount of CO_2e and highest amount of CO_2e were used from a total of four combinations of parameters likely to represent industrial landfills in the US and wood waste landfill in Canada. The ranges of parameters considered were: MCF (0.8 or 1), F_{CCND} (50% or 96.8%), and F_{CH4OX} (0% with MCF 0.8 or 10% with MCF 1). The landfill parameter values selected in this study for woody mill residues are summarized in Table 4.3.

Table 4.3 Parameters Values Selected to Represent the Two Base Case Scenarios (Low and High CO2e Emissions) from Landfilling of Wood Mill Residues

Parameter Analyzed	Value Analyzed		Rationale/Source(s)
Biogenic carbon content (CC)	Low CO_2e	50%	IPCC default value for wood residues (IPCC\ 2006b, Table 2.4)
	High CO_2e	50%	
Non-degradable carbon under anaerobic conditions (F_{CCND})	Low CO_2e	96.8%	Average carbon conversion value for oak, spruce and radiata pine from Wang et al. 2011, Table 2
	High CO_2e	50%	IPCC (2006a, p. 3.13) default value for the fraction of carbon that decomposes under anaerobic conditions for all waste.
Methane correction factor (MCF) i.e., fraction of landfill under anaerobic conditions	Low CO_2e	1	IPCC values for managed landfills (IPCC 2006a, Table 3.1). Industrial landfills at forest products facilities are typically anaerobic, given the low porosity, high organic content and depth it is likely these landfills.
	High CO_2e	1	
Fraction of gas converted to methane under anaerobic conditions (F)	Low CO_2e	0.5	IPCC (2006b)
	High CO_2e	0.5	

(Continued on next page.)

Table 4.3 Continued

Parameter Analyzed	Value Analyzed		Rationale/Source(s)
Fraction of methane oxidized in landfill covers (F_{CH4OX})	Low CO_2e	10%	IPCC value for managed landfills(IPCC 2006b)
	High CO_2e	10%	
Fraction of methane burned (F_{CH4CB})	Low CO_2e	0%	Assumption that no landfills into which wood residues are placed are equipped with methane collection systems (Environment Canada 2015; USEPA 2015)
	High CO_2e	0%	

Other environmental loads related to landfilling activities were modeled using the ecoinvent v2.2 data set “Disposal, wood untreated, 20% water, to”, where the foreground electricity consumption grid mix was modified to represent the North American context and where their values were assumed to be constant for both landfill disposal pathway scenarios. The data set from ecoinvent 2.2 was used because it is not available in the newer ecoinvent 3.1 default allocation database.

4.3 Unconventional Use Pathways

Five unconventional use pathways were investigated: heat production from value-added fuels, combined heat and power production from value-added fuels, transport fuel derived from residues, use in metallurgy, and use as horticultural growing media. Various scenarios and sensitivity analyses were explored within each unconventional use pathway. Figure 4.1 is a schematic of the various combinations of each biomass system with each alternative system considered in this study for each unconventional use pathway. Details of the scenarios investigated for each pathway are in the following sections.

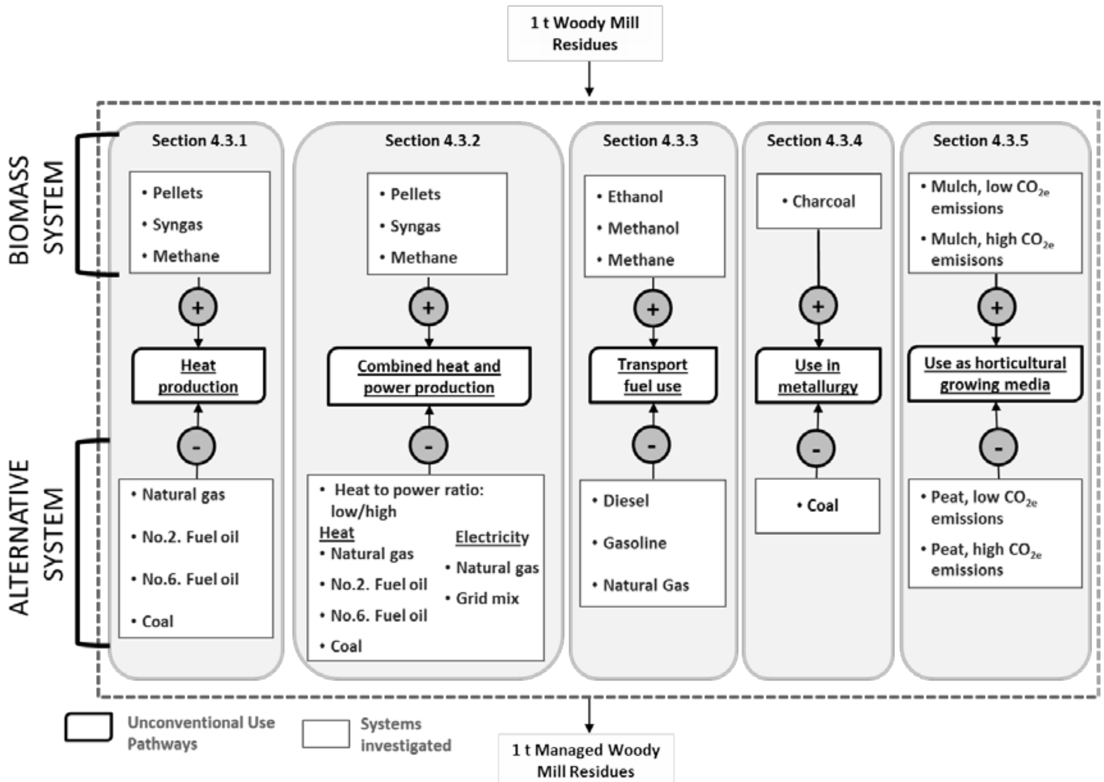


Figure 4.1 Overview of the Studied Scenarios for Unconventional Use Pathways
[Each biomass system is investigated in relation to various alternative systems.]

4.3.1 *Heat Production Pathway*

In this study, 12 scenarios were modeled to explore the heat production pathway. The 12 scenarios investigated can be grouped within three biomass systems representing wood fuels obtained from the conversion of woody mill residues: heat produced via pellet combustion; heat produced via syngas combustion; and heat produced via methane combustion. It was considered that these three biomass systems could replace heat produced by alternative systems burning natural gas, No. 2 fuel oil, No. 6 fuel oil, or coal.

The amount of heat produced by one tonne of converted woody mill residues varies for each biomass system. Table 4.4 summarizes the amount of heat produced by each biomass system, the required quantity and type of converted woody mill residue, and the equivalent quantity of alternative fuels that would be displaced to generate the same heat output. Details on the modeled scenarios and their justification are described below.

Table 4.4 Scenarios Explored for the Production of Heat from Converted Woody Mill Residues

Scenario Name*	General Description				
	Heat Produced	Biomass System		Alternative System	
		Quantity	Fuel Type	Quantity	Fuel Type**
H_Pellet_NG	15 GJ	1,000 kg	Pellet	476 m^3	Natural gas
H_Pellet_F2				442 L	No. 2 fuel oil
H_Pellet_F6				413 L	No. 6 fuel oil
H_Pellet_Coal				583 kg	Coal
H_SG_NG	9.79 GJ	2,144 m^3	Syngas	311 m^3	Natural gas
H_SG_F2				289 L	No. 2 fuel oil
H_SG_F6				269 L	No. 6 fuel oil
H_SG_Coal				381 kg	Coal
H_CH4_NG	8.54 GJ	270 m3	Methane	270 m^3	Natural gas
H_CH4_F2				251 L	No. 2 fuel oil
H_CH4_F6				234 L	No. 6 fuel oil
H_CH4_Coal				332 kg	Coal

*H: Heat, SG: Syngas, CH4: Methane, NG: Natural Gas, F2: No. 2 Fuel oil, F6: No. 6 fuel oil.
** Fuel HHV: Natural gas (0.038 GJ/m3), No. 2 fuel oil (0.039 GJ/L), No. 6 fuel oil (0.0418 GJ/L), Coal (0.0302 GJ/kg).

4.3.1.1 *Biomass Systems*

Three parameters are of importance when modeling the conversion of woody mill residues and their use for heat production: conversion process efficiency, combustion efficiency, and heat content of the fuel [e.g., higher heating value[6] (HHV)]. Table 4.5 summarizes the amount of heat produced by the combustion of the three converted woody mill residues, as well as values for the parameters used in sensitivity analyses (in parentheses). The assumptions made and literature sources used in modeling the biomass systems are presented in greater detail in subsequent sections.

[6] The higher heating value is the amount of heat released by the complete combustion of one unit mass of dry energy source (e.g., bone-dry wood fuel) plus the latent heat of the water vapor formed during combustion and re-condensed to the liquid state.

Table 4.5 Base Case Scenarios and "Efficiency" Sensitivity Analysis Parameter Values for Heat Production Pathway

Parameters of Importance	Biomass Systems*		
	Heat via Pellets	Heat via Syngas	Heat via Methane
Conversion process efficiency (energy basis)**	100% (90 - 100%)	56.8% (46% - 82%)	51.1% (39% - 75%)
Boiler efficiency, HHV Basis (%)***	79% (70 - 90%)	83% (70% - 90%)	83% (70% - 90%)
Feedstock HHV	19 GJ/Bdmt (17 – 21 GJ/Bdmt)	5.5 MJ/Nm^3 (4 – 7 MJ/Nm^3)	38.1 MJ/Nm^3 (34.4 – 38.1 MJ/Nm^3)
Heat produced from 1 tonne woody mill residues (GJ)	15.0 GJ (10.7 – 18.9 GJ)	9.8 GJ (4.7 – 18.8 GJ)	8.5 GJ (4.9 – 13.5 GJ)

*Ranges used in sensitivity analyses are provided in parentheses.
** Conversion process efficiency = (Energy content of the energy carrier at output - Energy from the energy carrier used in the process)/Energy content of 1 tonne of woody mill residues @ 20 GJ/t dry wood. HHV of wood is taken from (NCASI 2014b).
*** Heat recovered / heat input.

4.3.1.1.1 *Pellets*

Pellet production has continued to rise, largely motivated by policies driving increased renewable fuel use. Production and combustion technologies are well established.

4.3.1.1.1.1 *Pellet Production*

For the purposes of this study, it was assumed that a pellet plant processes only woody mill residues. Wood residues are first pretreated (e.g., screened), dried, crushed, and mixed. They are then pelletized, cooled, and bagged for shipping.

The following ecoinvent process data set, for producing 1 kg of pellets from sawmill wood residue and wood chips, was used in this study because it was readily available:

- Wood pellet, measured as dry mass {RoW}| wood pellet production | Alloc Def, U

These ecoinvent data represent modern wood pellet plants operating in Switzerland (2011-2012), the unit processes for which include wood residue pretreatment (e.g., screening), drying, crushing, mixing, pelleting, and pellet bagging. The pellets produced at the modeled wood pellet plants meet the German standard of quality DIN-plus certification (Swiss Centre for Life Cycle Inventories 2015). To represent the North American context, the ecoinvent process data were modified by replacing the electricity consumption mix with the North American grid. Also, the ecoinvent data set only accounted for water emitted to air; however, pellet manufacturing plants also emit substances such as particulate matter, carbon monoxide, nitrogen oxides, and volatile organic compounds (NCASI 2011). These emissions can originate from the combustion gases as well as from the heating of wood itself. Given that data for pellet plant dryer emissions are not available at this time, emission factors for releases from direct-fired particleboard rotary dryers were used as a surrogate, given their use of similar types of wood residues (NCASI, 2013b). Multiclones were selected as being representative of particulate emission control technologies used at pellet plants, according to the information collected by Beauchemin and Tampier (2010) from pellet plant operations in British Columbia, Canada. While other emission control technologies are also used at pellet plants, a sensitivity analysis was not performed on this parameter in this study as this is a screening LCA and not all options were investigated in detail.

In addition, Table 4.6 summarizes energy requirements reported in the literature for pellet production. Various fuels can be used for drying residues when producing wood pellets. In the US, drying is mainly done using wood residues (Katers, Snippen, and Puettmann 2012; Reed et al. 2012). However, because the data for pellet production readily available in the ecoinvent database used pellets to dry pellets, this choice was retained. The quantity of energy required to dry woody mill residues depends on the original moisture content of residues; however, moisture content of residues is not always reported in the literature. The median values of the wood-drying energy requirements reported in the literature for electricity consumption, as well as wood residues (excluding data from Katers et al. because it is incomplete) or the sum of natural gas and diesel consumption, were used in the pellet production model applied in this study, with woody mill residues as the feedstock. The median was used to represent the average of the reported values rather than the mean because the data set incorporates a number of values that are either much higher or much lower compared to the rest of the data, to achieve a more accurate reflection of the central tendency of the distribution. The ecoinvent process mentioned above was modified to reflect this energy consumption.

Table 4.6 Reported Energy Requirements for Pellet Production

Moisture Content of Woody Mill Residues Input	Reported energy requirement				Reference
	Electricity (kWh/t produced pellets)	Wood Residues (MJ/t produced pellets)	Natural Gas (MJ/t produced pellets)	Diesel (MJ/t produced pellets)	
Unknown	112	N/A	245	0	Petersen Raymer, 2006
50-65%	112	N/A	3172	205	Magelli et al. 2009
65%	63	N/A	2.6	443	Fantozzi and Buratti 2010
Low, unspecified	161	539***	N/A	N/A	Reed et al. 2012
Unknown	Unknown	1421	Unknown	N/A	Katers et al. 2012
Unknown	161	N/A	198	0	Porsö and Hansson 2014
Unknown	223	N/A	3370	32	Tsalidis et al. 2014
50%	190 Range (100-239)	N/A	148*	0	UK Department of Energy & Climate Change 2014
Lower than 50%	96**	N/A	276**	0	Swiss Centre for Life Cycle Inventories 2015

* Based on a reported 37 MJ/t produced pellet for wood input moisture content of 25%.
** Energy consumption/t dry pellet.
*** Assuming 20 MJ/kg.

Table 4.7 Base Case Scenario (BC.Sc.) and "Efficiency" Sensitivity Analysis (Low, High) Parameter Values Selected to Model Pellet Production

Product	Parameter Analyzed	Value Analyzed		Comments
Pellet	Conversion process efficiency on an energy content basis, also referred to as pellet yield* (mass pellet produced/mass woody mill used)	BC.Sc.	100% (1t/t)	Pellet production is reported as a no-mass-loss process, i.e., a 100% efficient process regarding the amount of wood residues. Therefore, dry mass entering the process assumed to equal the amount of dry pellets exiting the process (Jungbluth et al. 2007). For sensitivity analysis, a 10% reduction in conversion efficiency was used.
		Low	90% (0.9t/t)	
		High	100% (1t/t)	
	Electricity consumption (kWh/t pellet)	BC.Sc.	112	The average scenario represents the median of the literature values reported in Table 4.6. The range of values investigated in the sensitivity analysis represents the lowest and highest values reported in the literature.
		Low	63	
		High	239	
	Drying fuel consumption (MJ/t pellet)	BC.Sc.	276	The average scenario represents the median of the literature values reported in Table 4.6. The range of values investigated in the sensitivity analysis represents the lowest and highest values reported in the literature.
		Low	148	
		High	3370	

* Conversion process efficiency = (Energy content of the energy carrier at output - Energy from the energy carrier used in the process)/Energy content of 1 tonne of woody mill residues @ 20 GJ/t dry wood.

4.3.1.1.1.2 *Pellet Combustion*

Pellets can be combusted in units of various nominal heat input capacity. In this study, the focus is on large combustion units to limit the number of scenarios investigated and because air emissions data from wood combustion are readily available for large combustion units such as wood-fired boilers. Stoker boilers are the most commonly used combustion units for burning woody biomass at North American forest products manufacturing facilities (NCASI 2008, 2011); hence, in this study, stoker boilers equipped with wet scrubbers were used as a surrogate for pellet combustion in large units.

The amount of usable energy produced from the combustion of one tonne of pellet (E_{DC}) is calculated as follows:

$$E_{DC} = Q_R \times HHV \times Eff$$

Where:

Q_R: Amount of pellets (tonnes, dry wt. basis);
HHV: Higher heating value (GJ HHV/dry tonne); and
Eff: Boiler efficiency (fraction between zero and 1).

Stoker boiler efficiencies are strongly affected by the content of water in the fuel. This is depicted in Figure 4.2. Table 4.8 summarizes data on the HHV, moisture, and ash content of wood pellets, and thermal efficiency of stoker boilers reported in the literature. It can be seen that reported HHV for pellets ranges from 16.9 GJ/t to 21 GJ/t (dry pellets), moisture content from 3.4 to 10%, ash content from 0.3 to 1.9%, and boiler efficiency from 69 to 91%. Using this information, the average value for HHV was calculated as 19 G/t (dry pellets), and the average moisture and ash contents were calculated as 6% and 1.2%, respectively. The average boiler efficiency was calculated as 79% which, incidentally, is the same value reported by Kostiuk and Pfaff (1997) for an industrial stoker boiler fed with wood at 6% moisture.

Table 4.8 Reported Higher Heating Value, Moisture and Ash Content, and Boiler Efficiency for Pellet Combustion

Reported Value				**References**
HHV GJ/t dry pellet	Boiler Efficiency	Moisture Content (%)	Ash Content (%)	
	79%	6%[ɣ]		Kostiuk and Pfaff 1997
16.9	-	-	-	Petersen Raymer 2006
17.1 – 17.8	-	3.4-6.4	0.3 - 1%	Tumuluru et al. 2010
19.4	-	6%	-	Pa, Bi, and Sokhansanj 2011
17-20	-	4 – 10%	-	Melin 2011
18.7 - 19.9	69-75%**	4.6% - 5%	0.3% - 1.9%	Roy, Dutta, and Corscadden 2013
19.5	91%*	-	-	Porsö and Hansson 2014
20.5	-	-	-	Gerssen-Gondelach et al. 2014
18.1	-	10%	0.9%	Tsalidis et al. 2014
19 - 21	-	4.7-7.3%	0.3 - 3.7%	Arranz et al. 2015

[ɣ] Average value calculated from the other cited literature sources reported in the table.
* District heating plant.
** Furnace capacity 7-32 kW.

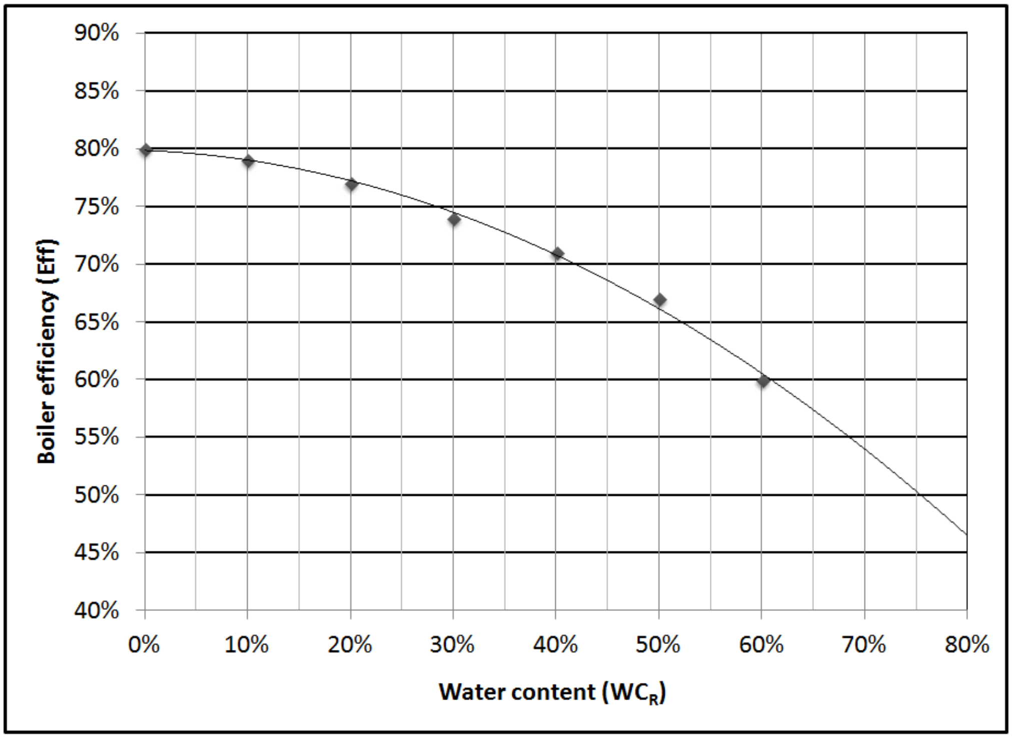


Figure 4.2 Stoker Boiler Efficiency as a Function of Fuel Water Content (WC_R)[7]
[Based on Kostiuk and Pfaff (1997)]

The parameters used in the model and sensitivity analyses to represent the combustion of pellets are summarized in Table 4.9.

[7] "Relationship of heat losses expressed as percent of available heat and efficiency to moisture content (a higher heating value of 19.7 MJ/kg stack gas temperature of 260°C and 40% excess air is assumed)" Kostiuk and Pfaff 1997.

Table 4.9 Base Case Scenario (BC.Sc.) and "Efficiency" Sensitivity Analysis (Low, High) Parameter Values Selected to Model Heat Production from Pellets Combusted in Stoker Boilers

Product	Parameter Analyzed	Value Analyzed		Comments
Pellet	Boiler efficiency	BC. Sc.	79%	The boiler efficiency for the average scenario is for pellets with 6% moisture content. Lowest and highest values are taken from Table 4.8.
		Low	70%	
		High	90%	
	Higher heating value (HHV)	BC. Sc.	19 GJ/BDmt	The average value and the range of heating values are based on a literature review presented in Table 4.8.
		Low	17 GJ/BDmt	
		High	21 GJ/BDmt	
	Emission control technology	BC. Sc. Sc., Low and High	Wet scrubber	Emission factors applicable to pellet combustion are unavailable; hence, values used are those for wood residue combustion. Emissions reflect the use of wet scrubber technology given its broad use on wood-fired combustion units (NCASI 2008, 2011)
	Heat Production (E_{DC})	BC. Sc.	15 GJ/t dry wood	Using the quantity of pellets produced from 1 t of woody mill residues and the parameter values for pellet combustion (Avg, Low, High), the range of values investigated are calculated according to the following equation $E_{DC}=Q_R \times HHV \times Eff.$. Where: E_{DC}: energy produced from boiler; Q_R: quantity of pellets; HHV: higher heating value; Eff: boiler efficiency
		Low	10.7 GJ/t dry wood	
		High	18.9 GJ/t dry wood	

Emissions from pellet combustion were modeled using emission factors for wood-fired boilers equipped with wet scrubbers derived from US Boiler MACT data and/or company data made available to NCASI as published in the NCASI NPRI Handbook (NCASI 2014a). Emissions factors for CO_2, CH_4 and N_2O were taken from U.S. EPA AP-42 (USEPA 1995e).

GHG emissions due to biomass residue combustion were modeled using emission factors for CO_2, CH_4 and N_2O for wood boilers from USEPA AP-42 (USEPA 1995e: AP42, Section 1.6 updated in 2003)

CO_2: 83.8 kg CO_2/GJ (195 lb/MMBtu input)

CH_4: 0.009 kg CH_4 / GJ (0.021 lb/MMBtu input)

N_2O: 0.0056 kg N_2O/GJ (0.013 lb/MMBtu input)

Ash (1.2 wt.% of total mass of residues, average value as calculated based on values from Table 4.8) was assumed to be disposed of in facility landfills. Landfilling of wood ash was modeled using data from the ecoinvent database (from "Wood ash mixture, pure (waste treatment) {CH}/ treatment of, sanitary landfill") and adjusted to reflect the North American context by selecting a North American electricity consumption grid mix.

As for transport distances for pellets from production location to combustion location, while most pellets travel long distances to Europe (Gerssen-Gondelach et al. 2014; Pa, Bi, and Sokhansanj 2011), the scenario investigated in this study was focused on more local applications. Transport modes and distances were estimated using transport data for wood products published in the U.S. 2012 Commodity Flow Survey (U.S. Department of Transportation and U.S. Department of Commerce 2015). The mass-weighted average distances by mode of transport that were modeled are

- Truck: 279.7 km*weight, and
- Train: 99.8 km*weight.

4.3.1.1.2 *Syngas*

Syngas can be used to substitute for fossil fuels in heat and/or power generation applications or be further converted to liquid fuels, such as ethanol and methanol, for use in the transportation sector (Brown 2015; Jungbluth et al. 2007). The production of syngas is a technology arriving at the commercial stage of its development. At this time, low quality syngas is known to be produced and combusted at wood products manufacturing operations sites, for example.

4.3.1.1.2.1 *Syngas Production*

Gasification is a process that maximizes fuel gas production by heating biomass at high temperature in the presence of a limited quantity of oxygen (NCASI 2011). The biomass is thermally decomposed into a gaseous mixture of carbon monoxide (CO), hydrogen (H_2), methane (CH_4), carbon dioxide (CO_2), and small amounts of light hydrocarbons (Brown, 2015). The process includes pretreatment (e.g., grinding, drying), gasification, and syngas cleaning (e.g., removals of tars, dust, alkali, halogens) (Jungbluth et al. 2007). Cleaning enables use of the produced syngas for methanol synthesis. Using syngas for heat or power generation does not require the same properties (i.e., heating value, composition, purity, etc.) of syngas intended for methanol production. Therefore, the degree to which the syngas must be cleaned, if at all, will depend on its intended ultimate use. Given the lack of readily available data on the effect of cleaning on syngas properties, for this study it was assumed that syngas is cleaned using the same processing sequence irrespective of the ultimate use.

Two different technologies are used for gasification: fixed-bed gasification and fluidized bed gasification. Gasification can be pressurized or atmospheric. Pressurized gasifiers are well suited for application where the syngas is used in CHP systems or gas turbines, while atmospheric gasifiers can produce syngas for methanol production or direct heat recovery applications. The gasifiers modeled in this study are of the atmospheric type, given the availability of relevant data for this technology. The values used to model the fluidized bed gasifier and the fixed-bed gasifier were taken from an extensive literature survey performed by ecoinvent (Jungbluth et al. 2007).

Syngas production efficiency, on an energy basis, ranges between 46% and 82% (Jungbluth et al. 2007). Higher values, albeit optimistic (Felder and Dones 2007), were also included in the range of values to be investigated via sensitivity analysis, as summarized in Table 4.10. In this study, an overall production efficiency, on an energy basis, of 56.8% was used as average value (Jungbluth et al. 2007).

Table 4.10 Base Case Scenario (BC. Sc.) and "Efficiency" Sensitivity Analysis (Low, High) Parameter Values Selected to Model Syngas Production

Product	Parameter Analyzed	Value Analyzed		Comments
Syngas	Production efficiency on an energy basis (syngas yield)*	BC. Sc.	56.8% (2144 Nm^3/t)[8]	Syngas production efficiency, on an energy basis, ranges between 46% and 82% (Jungbluth et al. 2007). Higher values are also included in the range of values to be investigated via sensitivity analysis. A production efficiency of 56% is used in the analysis (Jungbluth et al. 2007).
		Low	46% (1673 Nm^3/t)	
		High	82% (2982 Nm^3/t)	

* Production efficiency = (Energy content of the energy carrier at output - Energy from the energy carrier used in the process)/Energy content of 1 tonne of dry woody mill residues @ 20 GJ/t dry wood.

An equal quantity of the two following ecoinvent process data sets, for producing syngas from wood chips, were used to represent the conversion of woody mill residues:

- Synthetic gas {CA}| production, from wood, at fixed bed gasifier | Alloc Def, U; and
- Synthetic gas {CA}| production, from wood, at fluidized bed gasifier | Alloc Def, U.

4.3.1.1.2.2 *Combustion of Syngas*

According to ecoinvent documentation, the higher heating value of syngas is 5.6 MJ/Nm^3[9], the thermal efficiency of syngas is 90% when combusted on-site, and the emissions resulting from syngas combustion depend on syngas composition (Jungbluth et al. 2007). The higher heating value of syngas can range from 4 to 18 MJ/Nm^3. Lower HHVs (4 – 7 MJ/Nm^3) are typical of syngas produced by air gasification, while syngas with higher HHVs (10 – 14 MJ/Nm^3) are more common when gasification is carried out using oxygen or steam (Holmgren et al. 2012). Higher HHV-syngas has not been frequently reported in the literature, but the expected median value of lower HHV syngas is closer to 5.5 MJ/Nm^3, which is the average value selected in this study (NCASI 2011). Also, it was assumed that the efficiency of a boiler burning syngas is the same as that of natural gas-fired boilers.

Heat production from syngas can range from 4.7 to 18.8 GJ/t dry wood, based on the range of syngas yield (see Table 4.10), HHV (4-7 MJ/Nm3), and boiler efficiency (70-90%), as summarized in Table 4.11.

Emissions from syngas combustion were modeled according to the composition of syngas as described in the ecoinvent documentation (Jungbluth et al. 2007) and reported here:

- CO (17,1% wt. or 0.197 kg/Nm3) converted completely to CO_2;
- CO_2 (15.7% wt or 0.181 kg/Nm3) emitted as such;
- CH_4 and C_nH_m altogether (2.4% wt. or 0.028 kg/Nm3) are considered as natural gas and the following ecoinvent data set, "Heat, district or industrial, NGAS {RoW}| heat production, natural gas, at industrial furnace >100kW | Alloc Def", emissions only, was used to account for the emissions;
- H_2 is converted to water; however, additional NO_x emissions relating to the combustion of H_2 were considered to be 0.213 mg NO_x per kg H_2.

[8] Nm^3:cubic meter at normal temperature and pressure conditions.
[9] Nm^3:cubic meter at normal temperature and pressure conditions.

Table 4.11 Base Case Scenario (BC. Sc.) and "Efficiency" Sensitivity Analysis (Low, High) Parameter Values Selected to Model Syngas Heat Production from Gas-Fired Boilers

Product	Parameter Analyzed	Value Analyzed		Comments
Syngas	Higher heating value (HHV)	BC. Sc.	5.5 MJ Nm^3	The higher heating value of syngas can range from 4 to 18 MJ/Nm3. Lower HHVs (4 – 7 MJ/Nm3) are associated with air gasification, while higher HHVs (10 – 14 MJ/Nm3) are reported from oxygen or steam gasification (Holmgren et al. 2012). Higher HHVs have not been frequently reported in the literature and the median value is closer to 5.5 MJ/Nm3 for lower HHV syngas (NCASI 2011).
		Low	4 MJ Nm^3	
		High	7 MJ Nm^3	
	Boiler efficiency	BC. Sc.	83%	Assuming efficiency for natural gas boilers of 83%. To assess the importance of this parameter, boiler efficiency is varied from 70% to 90%.
		Low	70%	
		High	90%	
	Heat Production	BC. Sc.	9.8 GJ/t dry wood	Calculated from the production efficiency, HHVs and boiler efficiency.
		Low	4.7 GJ/t dry wood	
		High	18.8 GJ/t dry wood	

4.3.1.1.3 *Methane*

Methane production is a technology arriving at the pilot and demonstration plant stage of its development. Once methane production reaches broad commercial deployment, the product could use the existing natural gas supply infrastructure for its distribution and be used in many applications (Steubing, Zah, and Ludwig 2011).

4.3.1.1.3.1 Methane Production from Syngas

Gasification and methanation are intimately integrated, and therefore they are considered as a whole. Wood chips are dried and chipped prior to the gasification step. This is followed by syngas cleaning and methanation. In the methanation stage, the carbon-containing substances are transformed into methane and CO_2 (van der Meijden, Veringa, and Rabou 2010). The methane yield is increased by increasing the pressure of the gas and lowering its temperature. Lastly, H_2O is removed as well as CO_2, leaving the methane ready for injection into the natural gas grid (Felder and Dones 2007; (van der Meijden, Veringa, and Rabou 2010).

Production process efficiency (%), i.e., the amount of methane in HHV available for external use per HHV of one tonne of dry wood, depends on the level of integration of the different processing steps, the type of gasifier, and the gas cleaning method. Production process efficiency can range between 52 and 75% (van der Meijden et al. 2010). However, production process efficiency as low as 39% have been reported (Steubing, Zah, and Ludwig 2011). Hence, the methane production process efficiency could range from 39% to 75%.

According to ecoinvent data, the gross methane production yield[10] is 56%, with a gasification efficiency of 73% and a methanation efficiency of 76.5% (Felder and Dones 2007; Jungbluth et al. 2007). When using part of the generated methane to produce heat for the process, the net yield results in 0.270 Nm^3[11] of methane per kg of dry wood and a production process efficiency of 51.1%. The resulting gas is composed of 97.3% (% mol.) CH_4, 2.6% CO_2 and 0.1% H_2O and its HHV is 38.1 MJ/Nm^3 (Jungbluth et al. 2007).

Table 4.12 summarizes the average methane production efficiency and values selected to perform a sensitivity analysis.

Table 4.12 Base Case Scenario (BC. Sc.) and "Efficiency" Sensitivity Analysis (Low, High) Parameter Values Selected to Model Methane Production

Product	Parameter Analyzed	Value Analyzed		Comments
Methane	Production process efficiency on an energy basis (methane yield)*	BC. Sc.	51.1% (270 Nm^3/t dry wood)	Production process efficiency value can range between 39% (Steubing et al., 2011) and 75% (van der Meijden et al. 2010). According to ecoinvent, the production process efficiency of the methane production process equals 51.1%, which is close to the midpoint value of the production process efficiency range (57%); hence, it was considered an acceptable choice for the average value.
		Low	39% (205 Nm^3/t dry wood)	
		High	75% (394 Nm^3/t dry wood)	

* Production process efficiency = (Energy content of the energy carrier at output - Energy from the energy carrier used in the process)/Energy content of 1 tonne of dry woody mill residues @ 20 GJ/t dry wood

The following ecoinvent process data set, for producing 1 m^3 of methane, was used:

- Methane, 96% by volume {RER}| methane production, 96% by volume, from synthetic gas, wood | Alloc Def, U

The process was adjusted to reflect the North American context by selecting a North American electricity consumption grid mix.

4.3.1.1.3.2 *Combustion of Methane*

To model the combustion of methane for heat production, one needs to know the transport mode and distance between the location where methane is produced and the location where it is used; boiler efficiency; higher heating value of methane (HHV); and boiler emissions.

Transport mode and distances from production location to combustion location were estimated using transport data for fuel oils (including diesel, bunker C, and biodiesel). These data were published in the U.S. 2012 Commodity Flow Survey (U.S. Department of Transportation and U.S. Department of Commerce 2015). The mass weighted average distances by mode of transport[12] that were modeled are

- Truck: 47 km*weight; and
- Train: 24.6 km*weight.

[10] Gross methane production yield = Energy content of the energy carrier at output/ Energy content of 1 tonne of dry woody mill residues @ 20 GJ/t dry wood (excludes the energy used in the process from the energy carrier)
[11] Nm^3:cubic meter at normal temperature and pressure conditions.
[12] Although methane might be moved by pipeline, the analysis indicates that transport-related emissions have a small effect on the results, even assuming truck and train transport.

Combustion of methane can be approximated as that of natural gas; hence, boiler efficiency when burning methane was assumed to be an average of 83% (AGRA Simons Limited 2000). A similar assumption was made for non-GHG boiler emissions, and thus emissions from the combustion of methane were modeled using emission factors applicable to natural gas-fired boilers derived from US Boiler MACT data, when available, and AP-42 data otherwise, as published in the NCASI NPRI Handbook (NCASI 2014a). This assumption is not applicable to CO_2 and CH_4 emissions, which in the case of methane fuel from woody biomass, are biogenic.

The higher heating value of methane used in this study was 38.1 MJ/Nm^3 to be consistent with that of the production chain as modeled by ecoinvent (Jungbluth et al. 2007). Lower values of HHVs for methane have been reported to vary between 34.4 and 37.2 MJ/m^3 (Steubing, Zah, and Ludwig 2011; van der Meijden et al. 2010), and thus, the lower value of the range has been used as a sensitivity analysis. The highest reported HHV of methane in the reviewed literature is 38.1 MJ/NM^3 (Jungbluth et al. 2007); hence, that value was selected as the highest HHV investigated in the sensitivity analysis.

Using the available ranges for methane production yield (50-75%) (see Table 4.12), HHV (34.4-38.1 MJ/Nm3), and boiler efficiency (70-90%), it was estimated that the heat production from methane can range from 6.3 to 13.5 GJ/t dry wood, as summarized in Table 4.13.

Table 4.13 Base Case Scenario (BC. Sc.) and "Efficiency" Sensitivity Analysis (Low, High) Parameter Values Selected to Model Methane Heat Production from Gas-Fired Boilers

Product	Parameter Analyzed	Value Analyzed		Comments
Methane	Higher heating value (HHV)	BC. Sc.	38.1 MJ/ Nm^3	The higher heating value of methane used in this study is 38.1 MJ/Nm3 to be consistent with the production chain as modeled by ecoinvent (Jungbluth et al. 2007). Lower values of HHVs have been reported to range from 34.4 MJ/Nm^3 to 37.2 MJ/Nm^3 (Steubing et al. 2011; van der Meijden et al. 2010). The lower end of the reported range is used in the sensitivity analysis. The highest reported HHV for methane in the reviewed literature is 38.1 MJ/Nm^3 (Jungbluth et al. 2007); hence, that value is used to represent the higher value for HHV in the sensitivity analysis.
		Low	34.4 MJ/ Nm^3	
		High	38.1 MJ/ Nm^3	
	Boiler efficiency	BC. Sc.	83%	It can be assumed that natural gas boilers have an efficiency of 83% (AGRA Simons Limited 2000). Boilers with efficiencies of 96% have been reported (Steubing et al., 2011; van der Meijden et al. 2010), but there is no reason to believe the efficiency is higher when burning methane; hence, a conservative approach is taken and boiler efficiency is varied by about ±10%.
		Low	70%	
		High	90%	
	Heat production	BC. Sc.	8.54 GJ/t dry wood	Calculated from the production process efficiency, the HHV and boiler efficiency.
		Low	4.93GJ/t dry wood	
		High	13.5 GJ/t dry wood	

4.3.1.2 *Alternative System Producing Heat*

4.3.1.2.1 *Combustion of Natural Gas*

Emissions resulting from the combustion of natural gas in an industrial boiler were calculated using emission factors derived from US Boiler MACT data when available, and AP-42 data otherwise, as published in the NCASI NPRI Handbook (NCASI 2014a). Emissions factors for carbon monoxide and nitrogen oxide are specified for seven different combustion technologies in the Handbook, and the average of these values was used in this study. Emissions factors for CO_2, CH_4 and N_2O were taken from USEPA AP-42, as described in the text box below (USEPA 1995d).

Emission Factors for CO_2, CH_4 and N_2O from Natural Gas combustion were taken from U.S. EPA's AP-42 (USEPA 1995d: AP-42, Section 1.4 updated in 1998)

CO_2: 50.7 kg CO_2/GJ (118 lb/MMBtu input)

CH_4: 0.000967 kg CH_4 / GJ (0.00225 lb/MMBtu input)

N_2O: 0.00089 kg N_2O/GJ (0.00208 lb/MMBtu input), considering 10% of N_2O emissions are from controlled low-NO_x burners and 90% from uncontrolled burners (SGA Energy Limited 2000).

The following ecoinvent data set was used for the production, transport and distribution of natural gas:

- **Production, transport and distribution of natural gas** "Natural gas, high pressure {CA-AB}/market for", "Natural gas, high pressure {CA-QC}/market for", and "Natural gas, high pressure {US}/market for" with ratios representing their production volume.

This data set is expressed in terms of the quantity of natural gas produced. To calculate the energy produced, the following was assumed:

- **Natural gas:** boiler efficiency of 83% and HHV of 1,020E Btu per cubic feet (0.038 GJ/m^3) (AGRA Simons Limited 2000; USEPA 1995a).

Transport modes and distances were already accounted for in the ecoinvent data sets used for this study.

4.3.1.2.2 *Combustion of Fuel Oil*

Emission factors associated with the combustion of No. 2 fuel oil and No. 6 fuel oil in boilers equipped with mechanical collectors were derived from US Boiler MACT data when available, and AP-42 data otherwise, as published in the NCASI NPRI Handbook (NCASI 2014a). Emission factors for CO_2, CH_4 and N_2O were taken from USEPA AP-42, as described in the text box below (USEPA 1995c).

Emission Factors for CO_2, CH_4 and N_2O from No. 2 Fuel oil combustion were taken from USEPA AP-42 (USEPA 1995c: AP-42, Section 1.3 updated in 2010):

CO_2: 68.4 kg CO_2/GJ (159 lb/MMBtu)

CH_4: 0.000160 kg CH_4 / GJ (0.000371 lb/MMBtu)

N_2O: 0.0008 kg N_2O/GJ (0.00186 lb/MMBtu)

Emission Factors for CO_2, CH_4 and N_2O from No. 6 Fuel oil combustion were taken from U.S. EPA AP-42 (USEPA 1995c: AP-42, Section 1.3, updated in 2010):

CO_2: 70.7 kg CO_2/GJ (165 lb/MMBtu), average value of emission factors for low and high sulfur No. 6 Fuel oil

CH_4: 0.00287 kg CH_4 / GJ (0.00667 lb/MMBtu)

N_2O: 0.00152 kg N_2O/GJ (0.00353 lb/MMBtu)

The following ecoinvent data set was used for the production, transport, and distribution of fuel oil[13]:

- **Production, transport and distribution of No. 2 fuel oil** "Light fuel oil {RoW}/market for"; and
- **Production, transport and distribution of No. 6 fuel oil** "Heavy fuel oil {RoW}/market for".

The data set is expressed in terms of the quantity of fuel oil produced. To calculate the energy produced, the following was assumed:

- **No. 2 Fuel oil and No. 6 fuel oil:** boiler efficiency of 87%, HHV of 140,000 Btu per gallon (39 GJ/m^3) for No. 2 fuel oil and HHV of 150,000 Btu per gallon for No. 6 fuel oil (41.8 GJ/m^3). (AGRA Simons Limited 2000; USEPA 1995a).

The ash content of residual oils is typically between 0.05 and 0.1% , while distillate oil has negligible ash content (NCASI 2008). In this project, an ash content of 0.05% was assumed for distillate oil and 0.1% for residual oil. Ash treatment was modeled using the ecoinvent data set "Lignite ash {}| treatment of, sanitary landfill", modified to represent the North American context by using the North American electricity consumption grid mix. Transport modes and distances were already accounted for in the ecoinvent data sets used for this study.

4.3.1.2.3 *Combustion of Coal*

Pulverized coal boilers are commonly used at US pulp and paper mills (NCASI 2013a; USEPA 2012). These boilers are typically equipped with electrostatic precipitator (ESP) emission control technology (USEPA 2012). Emissions from combusting pulverized coal in boilers equipped with ESP control technology were calculated using emission factors derived from US Boiler MACT data when available, and AP-42 data otherwise, as published in the NCASI NPRI Handbook (NCASI 2014a). Emission factors for CO_2, CH_4 and N_2O were taken from USEPA AP-42, as described in the text box below (USEPA 1995b).

[13] The production process is expressed in mass units. Therefore, a density of 7 lb/gal and 8 lb/gal were used for No. 2 fuel oil and No. 6 fuel oil, respectively.

Emission Factors for CO_2, CH_4 and N_2O from Coal combustion were taken from USEPA AP-42 (USEPA 1995b: AP-42, Section 1.3 updated in 1998):

CO_2: 99.8 kg CO_2/GJ (232 lb/MMBtu) , value for medium-volatile bituminous coal

CH_4: 0.000716 kg CH_4 / GJ (0.00167 lb/MMBtu), average value from three PC-fired configuration

N_2O: 0.00105 kg N_2O/GJ (0.00244 lb/MMBtu), average value from three PC-fired configuration

The following ecoinvent data set was used for the production, transport, and distribution of coal:

- **Production, transport and distribution of coal** "Hard coal {RNA}/market for".

The data set is expressed in terms of the quantity of coal produced. To calculate the energy produced, the following was assumed:

- **Coal :** boiler efficiency of 85%, HHV of 13,000 Btu per pound (Council of Industrial Boiler Owners 2003).

The ash content of coal is typically between 3 and 30%, with an average of about 7.5% for coal burned in industrial boilers (NCASI 2013a). In this study, an ash content of 7.5% was assumed for pulverized coal boilers. Ash treatment was modeled using the ecoinvent data set "Lignite ash {}| treatment of, sanitary landfill", adjusted to reflect the North American context by using the North American electricity consumption grid mix. Transport modes and distances were already accounted for in the default model.

4.3.2 *Combined Heat and Power Production Pathway*

Combined heat and power (CHP) systems are typically composed of a boiler that generates pressurized steam which can then be used to spin a steam turbine to power an electric generator (NCASI 2011), thereby producing both heat and electricity. Direct combustion of wood or fossil fuels in CHP or cogeneration systems is common, whereas combustion of value-added fuel is not. Cogeneration systems are typically operated in regions with high electricity prices, limited access to the electricity grid, and within industries with high simultaneous demand for electricity and thermal energy (NCASI 2011). In 2012, 96.4% of the electricity produced by the US forest products industry was produced by cogeneration systems (American Forest & Paper Association 2014).

In this study, combustion of residue-derived pellets, methane and syngas in CHP units was analyzed as an unconventional biomass use. Fifteen scenarios were modeled for each of (a) CHP units that predominately produce heat, and (b) CHP units that predominately produce electricity, resulting in a total of 30 scenarios for this pathway. For the biomass system, the same scenarios described in Section 4.3.1 (Heat Production) were used: energy produced with pellet combustion; energy produced with syngas combustion; and energy produced with methane combustion. All these biomass systems could be used to replace heat produced from the combustion of natural gas, No. 2 fuel oil, No. 6 fuel oil, or coal, and to replace electricity either produced from natural gas or taken from the North American grid. The heat produced by the alternative system was modeled as described in Section 4.3.1.2. Table 4.14 summarizes the different scenarios investigated in this study, including the amount of energy produced by each biomass system, the required quantity and type of converted woody mill residue, and the equivalent quantity of alternative fuels that would be displaced to generate the same energy output. Details on the modeled scenarios and their justification are described below.

Table 4.14 Scenarios Explored for the Production of Combined Heat and Power from Converted Woody Mill Residues

Scenario name*	General Description								
	Scenarios Where CHP Generates Mainly Heat								
	Biomass System			Heat Alternative System			Power Alternative System		
	Energy Produced (heat + energy)	Quantity	Fuel Type	Energy Produced	Quantity	Fuel Type	Energy Produced	Quantity	Energy Source Type
CHPh_Pellet_NG_2X	14.29 GJ	1 000 kg	Pellet	11.7 GJ	371 m^3	Natural gas	2.56 GJ	212 m^3	Natural gas
CHPh_ Pellet _NG_E								711 kWh	North American electricity consumption grid mix
CHPh_ Pellet _F2_E					345 L	No. 2 fuel oil			
CHPh_ Pellet _F6_E					322 L	No. 6 fuel oil			
CHPh_Pellet_Coal_E					455 kg	Coal			
CHPh_SG_NG_2X	9.32 GJ	2 144 m^3	Syngas	7.65 GJ	242 m^3	Natural gas	1.67 GJ	138 m^3	Natural gas
CHPh_SG_NG_E								464 kWh	North American electricity consumption grid mix
CHPh_SG_F2_E					225 L	No. 2 fuel oil			
CHPh_SG_F6_E					210 L	No. 6 fuel oil			
CHPh_SG_Coal_E					297 kg	Coal			
CHPh_CH4_NG_2X	8.13 GJ	270 m3	Methane	6.67 GJ	211 m^3	Natural gas	1.46 GJ	124 m^3	Natural gas
CHPh_CH4_NG_E								405 kWh	North American electricity consumption grid mix
CHPh_CH4_F2_E					196 L	No. 2 fuel oil			
CHPh_CH4_F6_E					183 L	No. 6 fuel oil			
CHPh_CH4_Coal_E					259 kg	Coal			

(Continued on next page. See notes at end of table.)

Table 4.14 Continued

Scenario Name	Scenarios where CHP generates mainly electricity								
	Biomass System			Heat Alternative System			Power Alternative System		
	Energy Produced (heat + energy)	Quantity	Fuel Type	Energy Produced	Quantity	Fuel Type	Energy Produced	Quantity	Energy Source Type
CHPe_Pellet_NG_2X	14.29 GJ	1 000 kg	Pellet	0.750 GJ	24 m^3	Natural gas	13.5 GJ	1 128 m^3	Natural gas
CHPe_Pellet _NG_E								3 750 kWh	North American electricity consumption grid mix
CHPe_Pellet _F2_E					22 L	No. 2 fuel oil			
CHPe_Pellet _F6_E					21 L	No. 6 fuel oil			
CHPe_Pellet_Coal_E					29 kg	Coal			
CHPe_SG_NG_2X	9.32 GJ	2 144 m^3	Syngas	0.490 GJ	15 m^3	Natural gas	8.84 GJ	729 m^3	Natural gas
CHPe_SG_NG_E								2 447 kWh	North American electricity consumption grid mix
CHPe_SG_F2_E					14 L	No. 2 fuel oil			
CHPe_SG_F6_E					13 L	No. 6 fuel oil			
CHPe_SG_Coal_E					19 kg	Coal			
CHPe_CH4_NG_2X	8.13 GJ	270 m3	Methane	0.427 GJ	14 m^3	Natural gas	7.71 GJ	653 m^3	Natural gas
CHPe_CH4_NG_E								2 136 kWh	North American electricity consumption grid mix
CHPe_CH4_F2_E					13 L	No. 2 fuel oil			
CHPe_CH4_F6_E					12 L	No. 6 fuel oil			
CHPe_CH4_Coal_E					17 kg	Coal			

*CHPh: CHP maximized for Heat production, CHPe: CHP maximized for Electricity production, SG: Syngas, CH4: Methane, NG: Natural gas, F2: No. 2 fuel oil, F6: No. 6 fuel oil, 2X: Same fuel used to produce heat and electricity, E: Electricity supplied from the grid.

4.3.2.1 *Biomass System*

In this study, a hypothetical combined heat and power configuration (CHP) representative of those commonly used in the forest products industry was modeled. This system, depicted in Figure 4.3, consists of a boiler generating high pressure steam which is then routed to a back pressure steam turbine.

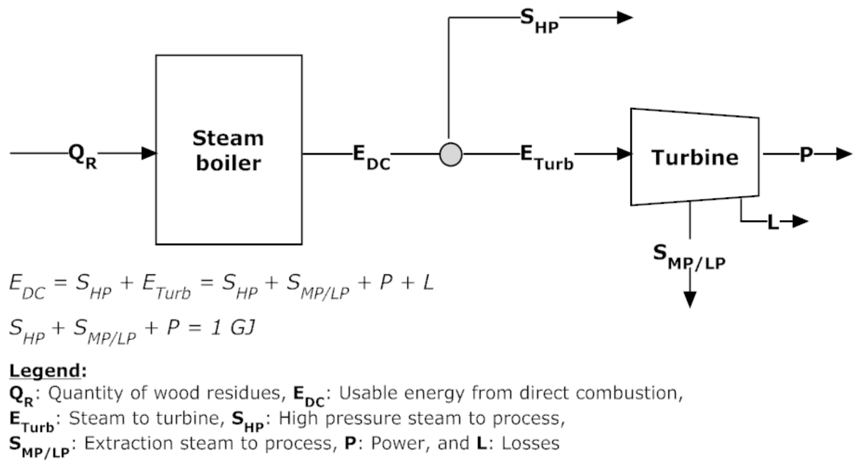


Figure 4.3 Hypothetical CHP Configuration Considered in This Study

The relationship between Q_R and E_{DC} is described in Section 4.3.1.1.1.2. Two groups of scenarios were considered to represent the range of CHP operations: (a) one representing CHP units that predominately produce heat (CHPh), and (b) one representing CHP units that predominately produce electricity (CHPe) through use of a condensing turbine (NCASI 2014b). This latter group of scenarios could be considered representative of cases where very little steam is required by the process. The two groups of CHP configuration scenarios are presented in Table 4.15.

Table 4.15 CHP Scenario Configuration Groups

Scenario Configuration Group	E_{DC}	E_{Turb}	S_{HP}*	P	$S_{MP/LP}$	$S_{HP}+S_{MP/LP}$	L
	(GJ)						
CHPh	1.0499	0.9974	0.05 E_{DC} = 0.0525	0.18 E_{Turb} = 0.1795	0.77 E_{Turb} = 0.7680	0.8205	0.05 E_{Turb} = 0.0499
CHPe	1.0499	0.9974	0.05 E_{DC} = 0.0525	0.95 E_{Turb} = 0.9475	0	0.0525	0.05 E_{Turb} = 0.0499

* Used for sootblowing.

Based on the amount of usable energy produced by combusting pellets, syngas or methane from one tonne of woody mill residues, and the CHPh and CHPe configuration, the amounts of heat and electricity produced by the different studied biomass systems and CHP range of operations are summarized in Table 4.16.

Table 4.16 Summary of Heat and Power Produced from 1 Tonne of Converted Woody Mill Residues

		Biomass Systems Producing Heat and Electricity		
		Pellets	**Syngas**	**Methane**
CHPh	**Heat**	11.72 GJ	7.65 GJ	6.67 GJ
	Power	2.56 GJ	1.67 GJ	1.46 GJ
	Total usable energy produced	14.29 GJ	9.32 GJ	8.13 GJ
CHPe	**Heat**	0.75 GJ	0.49 GJ	0.43 GJ
	Power	13.54 GJ	8.84 GJ	7.71 GJ
	Total usable energy produced	14.29 GJ	9.32 GJ	8.13 GJ

4.3.2.2 *Alternative System*

4.3.2.2.1 *Energy Production from Natural Gas*

The following ecoinvent data set was used to estimate electricity production at utility plants:

- Electricity, high voltage {CH}| electricity production, natural gas, 10MW | Alloc Def, U.

The parameters representing the origin of the natural gas supply were adjusted to reflect the North American context by selecting a natural gas supply representative of North America.

4.3.2.2.2 *North American Electricity Consumption Grid Mix*

The North American electricity consumption grid mix was modeled using the Canadian and American electricity production mix as available in the ecoinvent database, as well as the calculated contribution of each country to the consumed North American electricity grid mix based on their total electricity production for 2012 as reported in the electricity production statistics published by the International Energy Agency (http://www.iea.org/statistics/statisticssearch/):

- 13% Electricity, high voltage {CA}| production mix | Alloc Def, U (634 449 GWh produced in 2012); and
- 87% Electricity, high voltage {US}| production mix | Alloc Def, U (4 290 547 GWh produced in 2012).

The American electricity production mix has been changing rapidly. In 2015, the US average was 33% coal and 33% natural gas (U.S. Energy Information Administration (EIA) 2016). To account for production mix variation over time and space, a sensitivity analyses is performed where electricity consumption grid mixes produced mainly by hydroelectricity and coal were used, namely the Quebec electricity consumption grid mix in Canada and the MRO (Midwest Reliability Organization) electricity grid in the US. The two following data sets from the ecoinvent database were used to model the electricity consumption mixes:

- Electricity, high voltage {CA-QC}| market for; and
- Electricity, high voltage {MRO}| market for.

Both regions, Quebec and MRO, are host to forest products facilities; hence, they represent realistic alternative scenarios.

Table 4.17 Electricity Production Mix Used in the Model, in Base Case Scenarios, and in “Grid Mix” Sensitivity Analyses

Production from:	Electricity Production Mix Used in the Model		Electricity Production Mix Used in Base Case Scenarios	Electricity Production Mix Used in “Grid Mix” Sensitivity Analyses	
	Canada (2012)	United States (2012)	North America (NA)	Quebec, Province of Canada	MRO – US Only, Central United States Region
Coal	16%	45%	41%	0%	72%
Oil	1%	1%	1%	0%	0%
Gas	6%	23%	21%	0%	3%
Wood	1%	1%	1%	0%	2%
Nuclear	14%	20%	19%	2%	11%
Hydro	60%	7%	14%	96%*	4%
Wind	1%	2%	2%	1%	7%

* Includes hydro imports from Labrador.

4.3.3 *Transport Fuel Use Pathway*

Biofuels are currently being produced and used in the transport sector. Corn- and sugarcane-based bioethanol produced in the US and Brazil account for 89% of current global bioethanol production (Limayem and Ricke 2012) and represent 1.5% vol. of the world motor gasoline production (U.S. Energy Information Administration (EIA) 2015). The use of land to grow corn, soybeans, and sugarcane to produce biofuel feedstocks is sometimes perceived to be in direct competition with using land to grow food crops. This perception has motivated, at least in part, the development of biofuels from lignocellulosic biomass, such as crop residues, wood, paper waste, and others (Morales et al. 2015). Forest and agricultural residues are more abundant than food crops and their harvest has a lower environmental burden than food crops (Zhang 2010). However, lignocellulosic conversion technologies such as gasification and hydrolysis followed by fermentation to produce biofuels are still emerging technologies needing optimization with few existing large-scale production plants (Karlsson et al. 2014; Littlewood et al. 2014; Morales et al. 2015; Savaliya, Dhorajiya, and Dholakiya 2013; Wiloso, Heijungs, and De Snoo 2012; Zhang 2010).

Transportation biofuels must be compared on a per km basis in order to account for engine efficiency, fuel energy content, and combustion emissions (Borrion, McManus, and Hammond, 2012). Engine efficiency varies with fuel (Cherubini et al. 2009). Also, specific engine types can accommodate only a limited number of biofuel types. Ethanol can be used in gasoline-engine vehicles (as part of the E10 blend with gasoline = up to 10% v/v) and in flexible-fuel engine vehicles (as part of the E85 blend with gasoline = up to 85% v/v) (Bergthorson and Thomson 2014). Methanol can also be used in flex-fuel engines when blended with gasoline up to 85% v/v (M85 blend) (Bergthorson and Thomson 2014), while methane is used in replacement of natural gas in compressed natural gas vehicle systems (Truong and Gustavsson 2013).

Operation of a light duty passenger vehicle, as modeled by ecoinvent, results in the environmental impacts associated with exhaust emissions as well as non-exhaust emissions due to vehicle motion (e.g., tire abrasion) and pre-combustion (Jungbluth et al. 2007). According to the ecoinvent documentation, tail pipe emissions were measured using the New European Driving Cycle test. This test is performed on a chassis dynamometer and comprises cold start, urban driving, and extra-urban driving emission testing. The carbon content of the measured tail pipe emissions of CO_2, CO, and CH_4 is used to calculate fuel consumption derived from the carbon mass balance. Fuel consumption and emissions associated with the combustion of biofuel, gasoline, and diesel in passenger car engines are derived using the same measurement and calculation methods, and thus they are directly comparable. This information is summarized in Table 4.18.

Table 4.18 Fuel Consumption and Tail Pipe Emissions of CO_2, CO and CH_4 for Selected Fuels

Fuel	**Fuel Consumption**	**CO_2§**	**CO§**	**CH_4§**
	kg/km			
Gasoline, low sulfur	6.25E-02	1.97E-01	9.84E-04	5.42E-06
Diesel, low sulfur	5.51E-02	1.73E-01	6.10E-04	3.28E-06
Natural Gas	6.41E-02	1.72 E-01	4.46E-04	4.51E-05
Methane, 96 vol-% from biogas	6.73E-02	1.72E-01	4.46E-04	4.51E-05
Ethanol*	8.05E-02	1.53E-01	7.09E-04	3.87E-06
Methanol	1.30E-01	9.31E-04	1.77E-01	1.44E-06

* In the ecoinvent database, a 5% ethanol blend is used with gasoline. In this study, data are extrapolated to 100% ethanol.
§ Biogenic emissions are associated with methane, ethanol and methanol combustion, while fossil emissions are associated with gasoline and diesel combustion.

In this study, seven scenarios were modeled to represent the unconventional use pathway of wood-derived biofuel for transportation. The seven scenarios investigated can be subdivided into three biomass systems: the use of ethanol as transport fuel; the use of methanol as transport fuel; and the use of methane as transport fuel. All three biomass systems could replace diesel and/or gasoline as transport fuels and, in the case of methane, could also replace natural gas. Table 4.19 summarizes the different scenarios investigated in this study, based on the distance a vehicle was able to travel; the required quantity and type of residue-derived fuel; and the equivalent quantity of alternative fuels that would be displaced to enable a vehicle to travel the same distance. Details on the modeled scenarios and their justifications are described below.

Table 4.19 Scenarios Explored for the Use of Converted Woody Mill Residues as Transport Fuels

Scenario name*	**General description**				
	Distance compared	**Biomass system**		**Alternative system**	
		Quantity	**Fuel Type**	**Quantity**	**Fuel Type**
TRSP_EtOH_D	2942 km	263 kg	Ethanol	162 kg	Diesel
TRSP_EtOH_P				184 kg	Gasoline
TRSP_MeOH_D	2320 km	301 kg	Methanol	128 kg	Diesel
TRSP_MeOH_P				145 kg	Gasoline
TRSP_CH4_D	3017 km	203 kg	Methane	166 kg	Diesel
TRSP_CH4_P				189 kg	Gasoline
TRSP_CH4_NG				193 kg	Natural Gas

*TRSP: Transport Application, CH4: Methane, D: Diesel, P: Gasoline (synonym: petrol), NG: Natural Gas.

4.3.3.1 *Biomass System*

4.3.3.1.1 *Ethanol*

4.3.3.1.1.1 *Ethanol Production from Fermentation*

Ethanol from lignocellulosic feedstock, such as wood, can be produced via biochemical conversion (hydrolysis followed by fermentation), or using a thermochemical pathway involving gasification and catalytic synthesis (Mu et al. 2010; NCASI 2011). Woody mill residues are suitable feedstock for ethanol production (Mabee and Saddler 2010; Singh et al. 2010), and some pilot scale facilities for bioconversion of lignocellulosic material are already in operation (Borrion, McManus, and Hammond 2012; Mabee and Saddler 2010). The production of ethanol via the biochemical pathway was the process modeled in this study because of the availability of relevant data in the ecoinvent database.

The production of ethanol via the biochemical process involves four steps: pretreatment, hydrolysis, fermentation, and distillation (Limayem and Ricke, 2012). The model developed by ecoinvent to describe this process is largely based on the National Renewable Energy Laboratory (NREL) study[14] of the biomass-to-ethanol process which involves co-current dilute acid prehydrolysis (i.e., pretreatment), simultaneous enzymatic saccharification (i.e., hydrolysis) and co-fermentation prior to distillation (Jungbluth et al. 2007). Pretreatment and hydrolysis are necessary steps to separate the lignin from the cellulose and hemicellulose, and to allow for the enzymatic transformation of cellulose into sugars (Borrion, McManus, and Hammond 2012; Morales et al. 2015). The sugar is then fermented into ethanol, which is further separated by distillation (Littlewood et al., 2014). Lignin and waste from the process can be recovered and utilized as fuel to provide process heat and electricity to the ethanol production facility (Savaliya, Dhorajiya, and Dholakiya 2013).

Reported ethanol production yield for woody or agriculture lignocellulosic biomass varies between 94.8 to 378 kg ethanol/t dry biomass, with an average rounded value of 260 kg ethanol/t dry biomass, as can be seen in Table 4.20 (Jungbluth et al. 2007; Mabee and Saddler, 2010; Mu et al. 2010; Singh et al., 2010; Spatari, Bagley, and MacLean 2010; Swiss Centre for Life Cycle Inventories 2015). The values used in this study, as summarized in Table 4.21, are somewhat different from the reported literature values. The average value for ethanol production yield used in this study was the one model by the ecoinvent database, which is slightly higher than the average values cited by the reported literature. The lowest reported minimum ethanol production yield of 94.8 kg ethanol/t dry biomass appears to be an exception in comparison to other reported yield values; hence, in this study, a minimum ethanol production yield of 157 kg ethanol/t dry biomass was used in the sensitivity analysis. Ethanol production yields depend on, among other parameters, cellulose and hemicellulose content of the biomass, which varies from one biomass type to another. For wood, the maximum calculated theoretical yield of ethanol production is estimated as 320 kg ethanol/kg dry wood by Singh et al. (2010), who assume full conversion of cellulose and hemicellulose to sugars and subsequent conversion of sugars to ethanol at the theoretical yield of 0.51kg ethanol/kg sugar. However, the maximum reported ethanol yield is for non-wood lignocellulosic biomass. In addition, practical production yields are normally lower than the maximum theoretical production yield. For these reasons, this latter value (320 kg ethanol/kg dry wood) was used in this study as the highest ethanol production yield for the sensitivity analysis.

[14] (Wooley et al. 1999).

Table 4.20 Ethanol Production Yields Associated with the Biochemical Conversion Process Reported in the Literature

Average Yield	Minimum Yield	Maximum yield	Study
Calculated average value of 259 kg/t dry lignocellulosic biomass	162 kg /t dry lignocellulosic biomass	378 kg /t dry lignocellulosic biomass[*]	Literature review reported in ecoinvent report (Jungbluth et al. 2007)[**]
Selected average value of 263 kg ethanol 95%wt.dry basis/t dry wood			Ecoinvent database (Swiss Centre for Life Cycle Inventories 2015)
		320 kg /kg dry wood	(Singh et al. 2010)
	94.8 kg/t dry wood[§] 86.9 kg/t dry corn stover	237 kg/t dry wood[§] 213.3 kg/t dry corn stover	(Mabee and Saddler, 2010)
Calculated average value of 257 kg/dry ton wood chips for near term technology targets	207 kg/dry ton wood chips for current technology	271 kg/dry ton for long term technology targets	(Mu et al. 2010)
	157 kg/dry t corn stover and switch grass	237 kg/dry t corn stover and switch grass	(Spatari et al. 2010)

* This value is for non-wood lignocellulosic biomass and is well above the calculated theoretical maximum yield for woody lignocellulosic biomass of 320 kg/t dry wood; hence was not considered as the highest ethanol production yield in this study.

**Ethanol yields are converted from a wet basis to a dry basis assuming a dry matter content of 55.6% (Jungbluth et al., 2007).

§ The author reports that wood residues could deliver bioethanol yields between 0.12 and 0.30 m3/t wood on a dry basis, while agricultural residues (corn stover) could deliver between 0.11 and 0.27 m^3/dry t. The values reported in the above table were calculated using the density of 100% ethanol, i.e., 790 kg/ m3.

Table 4.21 Base Case Scenario (BC. Sc.) and "Efficiency" Sensitivity Analysis (Low, High) Parameter Values Selected to Model Ethanol Production

Product	Parameter Analyzed	Value Analyzed		Comments
Ethanol	Ethanol production yield (kg ethanol/t dry wood)	BC. Sc.	263	The average value represents the ethanol production yield used in the ecoinvent database and corresponds to average of the reported ethanol production yields. The maximum value used for sensitivity analysis is the calculated theoretical maximum yield. The minimum value used is not the minimum yield reported because that value appears to be an exception in comparison to other reported minimum values. Considering 157 kg ethanol/t dry wood is half of the theoretical maximum production yield, the selected minimum value is deemed acceptable for the purpose of this study.
		Low	157	
		High	320	

Electricity produced at the bioconversion site can vary between 1 and 2.5 kWh/L (Spatari, Bagley, and MacLean 2010). This energy is generated from the combustion of process waste, such as lignin, biogas from the anaerobic digester used for treating process wastewater, undigested solids (hemicellulose/cellulose fibres), and unfermented sugars. Burning waste can provide heat and electricity to the process, making it self-sufficient and, in some cases, generating a surplus that can be sold to the grid (Littlewood et al. 2014; Savaliya, Dhorajiya, and Dholakiya 2013). The ecoinvent data set accounts for an electricity surplus sold to the grid of 6.5 kWh/t dry wood (0.035 kWh/L ethanol). An economic allocation approach was used to partition the bioconversion inputs and emissions between the produced ethanol (99.7%) and sold electricity (0.3%). Considering that almost all of the inputs and emissions are allocated to ethanol, the ethanol production model used is conservative. The emissions from the combustion of unconverted solids modeled in the described ecoinvent data set are adapted from the data set “wood chips, in cogen 6400kWh, wood emissions control”.

In summary, the following ecoinvent process data set, for producing 1 kg of ethanol from 3.8 kg of dry wood chips was used:

- Ethanol, without water, in 95% solution state, from fermentation {SE}| ethanol production from wood | Alloc Def, U.

4.3.3.1.1.2 *Ethanol Combustion in a Passenger Car*

Depending on the amount of fuel-grade ethanol blended with gasoline, the mixed fuel can be used either in conventional gasoline-type engines (5-20% ethanol v/v) or in modified engines such as the flexi-fuel engine (85-100% ethanol v/v) (Bergthorson and Thomson, 2014; González-García, Moreira, and Feijoo 2010; Savaliya, Dhorajiya, and Dholakiya 2013; Spatari, Bagley, and MacLean 2010).

In has been reported that a flexi-fuel vehicle using 100% gasoline, ethanol blended with gasoline in 10% v/v (E10), and ethanol blended with gasoline in 85% v/v (E85) have, respectively, average fuel consumptions of 0.066 kg/km, 0.069 kg/km, and 0.092 kg/km (González-García, Moreira, and Feijoo 2010). In other words, these data suggest that the flexi-fuel vehicle needs about 3.5% more energy to travel a kilometer when fueled with E85 than a vehicle fueled by 100% gasoline flexi-fueled vehicle. However, it has also been reported that energy consumption for an E85-fueled vehicle can be reduced to 0.0873 kg/km (Gnansounou et al. 2009) and even to 0.0842 kg/km using pure ethanol (Borrion, McManus, and Hammond 2012). Ethanol contains less energy than pure gasoline; however, it has a higher octane rating, which can increase the efficiency of the vehicle engine. As shown in Table 4.22, it is unclear what the average fuel consumption of a flexi-fuel vehicle using E100 will be.

The ecoinvent process “Operation, passenger car, ethanol 5%/CH U” and information provided in the ecoinvent report for “operation, passenger car, [gasoline], low sulfur”, were used to calculate and model the hypothetical emissions from a vehicle using 100% ethanol. For this study, it was assumed for ease of calculation that the engine efficiencies of a gasoline fuel vehicle and an ethanol fuel vehicle are the same; hence, the ethanol fuel consumption for a vehicle fueled by 100% ethanol is estimated at 0.0894 kg/km[15]. This ethanol fuel consumption value used in this study is within the range reported in the literature as show in Table 4.22. However, given the importance of fuel consumption, its influence on the results was assessed with a sensitivity analysis specified in Table 4.23.

[15] The HHVs of low-sulfur gasoline and ethanol are 42.5 and 29.7MJ/kg, respectively (Jungbluth et al. 2007).

Table 4.22 Ethanol Fuel Consumption

Fuel Consumption (kg/km)	Fuel	Study
0.0920	E85	(González-García et al., 2010)
0.0873	E85	(Gnansounou et al., 2009)
0.0842	E100	(Borrion et al., 2012)

Table 4.23 Base Case Scenario (BC. Sc.) and "Efficiency" Sensitivity Analysis (Low, High) Parameter Values Selected to Model Ethanol Fuel Consumption

Product	Parameter Analyzed	Value Analyzed		Comments
Ethanol	Fuel consumption (kg ethanol/km)	BC. Sc.	0.0894	The average scenario value is calculated based on ecoinvent data. The minimum and maximum values used are the minimum and maximum value reported from the literature review.
		Low	0.0842	
		High	0.0920	
	Distance traveled (km/t dry wood)	BC. Sc.	2942	Calculated based on ethanol production yield and ethanol fuel consumption
		Low	1707	
		High	3800	

Ethanol supply, which includes transport and distribution of ethanol, was modeled using "Ethanol without water, in 99.7% solution state, from fermentation, at service station {CH}/market for" adjusted to reflect a North American electricity consumption grid mix and ethanol production data as provided in Section 4.3.3.1.1.1. From the selected average ethanol production yield of 263 kg per 1 tonne of woody mill residues, and average fuel consumption of 0.0894 kg ethanol/km, it can be calculated that 1 tonne of woody mill residues enables an average Euro 3[16] car to travel 2,942 km. The sensitivity analyses (see Table 4.23), including the range of production yields and the range of fuel consumption, suggest that this type of vehicle would be able to travel a distance between 1707 to 3800 km/t dry wood.

4.3.3.1.2 *Methanol*

4.3.3.1.2.1 *Methanol Production from Syngas*

They are a variety of technology alternatives for producing methanol via biomass gasification; however, only the methanol production process described by ecoinvent is investigated in this report. A sensitivity analysis was performed on the methanol production yield to investigate the influence of this parameter on the results.

The process model describing the synthesis of methanol from syngas is largely based on data pertaining to the production of methanol from natural gas because of lack of data. According to ecoinvent, this is because the production of methanol from syngas is not yet a mature technology, and the process aspects related to the integration of biomass gasification with methanol production are

[16] European emission limits for newly registered road vehicles that came into force in January 2001. In this study, however, the average fuel consumption for a vehicle purchased in 2005 is used (Jungbluth et al. 2007).

still being researched and developed. However, the ecoinvent documentation also states that the production processes for methanol from natural gas and methanol from syngas are very similar, and therefore, they have considered some of the process stages as identical. It is worth noting, however, that preliminary research suggests that the integration of the syngas and methanol production processes would potentially result in significant energy savings with resulting biomass-to-methanol efficiencies as high as 55% (Zhang 2010). In order to produce methanol, the carbon oxides contained in the syngas are hydrogenated over a suitable catalyst to achieve a H_2/CO ratio suitable for the production of methanol. The methanol yield used in the ecoinvent database is based on four literature sources reporting values from 42.3 to 50.8% on a mass basis. Assuming part of the syngas is combusted to supply heat to the process, and an HHV for methanol of 22.7 MJ/kg, it is estimated that 7.126 Nm^3 of syngas will be consumed to produce 1 kg of methanol (Jungbluth et al., 2007). The methanol production yield ranges from 252 to 337 kg methanol/t dry wood when considering the combustion of part of the syngas to supply heat to the process as summarized in Table 4.24.

Table 4.24 Base Case Scenario (BC. Sc.) and "Efficiency" Sensitivity Analysis (Low, High) Parameter Values Selected to Model Methanol Production

Product	**Parameter Analyzed**	**Value Analyzed**		**Comments**
Methanol	Production yield (kg methanol/t dry wood)	BC. Sc.	301	The average scenario represents the value used in the ecoinvent database, which is based on a limited set of published data. The maximum and minimum values used are based on four literature sources as compiled in the ecoinvent report (Jungbluth et al. 2007).
		Low	252	
		High	337	

The following ecoinvent process data set, for producing 1 kg of methanol from 7.1255 m3 of syngas, was used:

- Methanol, from biomass {CH}| methanol production, from synthetic gas | Alloc Def, U.

This process model was adjusted to reflect the North American electricity consumption grid mix.

4.3.3.1.2.2 *Methanol Combustion in a Passenger Car*

As with ethanol combustion in a passenger car, methanol can be blended with gasoline and used in a gasoline-fueled engine when methanol content is low. In the case of flexi-fuel vehicles, higher methanol contents in the fuel blend have been reported (e.g., 85% v/v or M85) (Bergthorson and Thomson 2014; Jungbluth et al. 2007).

The ecoinvent process data set "Operation, passenger car, methanol/CH U" was used to model the fuel consumption of methanol in a passenger car (0.12965 kg/km). This information is based on a data set pertaining to Euro 2[17] vehicles using methanol. This data set was adjusted by ecoinvent to reflect a Euro 3[18] vehicle (Jungbluth et al. 2007).

The production of methanol is modeled as described in Section 4.3.3.1.2. Using this model, it was estimated that 301 kg of methanol would be produced from 1 tonne of woody mill residues. Assuming the fuel consumption range for methanol is proportional to that of ethanol, the distance

[17] European emission limits for newly registered road vehicles that came into force in January 1996.
[18] European emission limits for newly registered road vehicles that came into force in January 2001. In this study, however, the average fuel consumption for a vehicle purchased in 2005 was used (Jungbluth et al. 2007).

traveled using methanol fueled vehicle was estimated to vary between 1,883 and 2,751 kg methanol/km, which were the values used in a sensitivity analysis (see Table 4.25).

Table 4.25 Base Case Scenario (BC. Sc.) and "Efficiency" Sensitivity Analysis (Low, High) Parameter Values Selected to Model Methanol Fuel Consumption

Product	Parameter Analyzed	Value Analyzed		Comments
Methanol	Fuel consumption (kg methanol/km)	BC. Sc.	0.130	The average scenario uses the value from ecoinvent. The minimum and maximum values are estimated in proportion to the fuel consumption range for ethanol.
		Low	0.122	
		High	0.134	
	Distance traveled (km/t dry wood)	BC. Sc.	2,314	Calculated based on methanol production yield and methanol fuel consumption
		Low	1,883	
		High	2,751	

Transport and distribution of methanol were model according to the default ecoinvent data set "Methanol, from biomass {CH}| market for | Alloc Def, U", which is based on the US commodity Flow Surveys of 1993, 1997, 2002, and 2007.

4.3.3.1.3 *Methane*

4.3.3.1.3.1 *Methane Production from Syngas*

The details related to methane production were presented in Section 4.3.1.1.3.1 and the corresponding summary table is reproduced here (see Table 4.26). As a reminder, the following ecoinvent process data set, for producing 1 m^3 of methane from 3.7 kg of dry wood chips, was used:

- Methane, 96% by volume {CH}| methane production, 96% by volume, from synthetic gas, wood | Alloc Def, U.

This process model was adjusted to reflect the North American electricity consumption grid mix.

Table 4.26 Base Case Scenario (BC. Sc.) and "Efficiency" Sensitivity Analysis (Low, High) Parameters Values Selected to Model Methane Production

Product	Parameter Analyzed	Value Analyzed		Comments
Methane	Production yield (m^3 methane/t dry wood)	BC. Sc.	270	The average scenario represents the value used in the ecoinvent database, which is based on a limited set of published data. The maximum and minimum values used are based on four literature sources as compiled in the ecoinvent report (Jungbluth et al. 2007).
		Low	205	
		High	394	

4.3.3.1.3.2 *Methane Combustion in a Passenger Car*

Methane can be used in vehicles with adapted internal combustion engines (Felder and Dones 2007) or in gas engines (Power and Murphy 2009). When used in an adapted internal combustion engine, the fuel efficiency of the vehicle running on methane is similar to that of a vehicle using low sulfur gasoline; however, when methane is used in an engine designed to use gaseous fuels, the fuel efficiency would improve by almost 20% to 5.1E-2 kg/km (Power and Murphy 2009). Research has shown that an average gas-fuel consumption of 4.26E-2 kg/km[19] is possible when methane was used in an engine designed to use gaseous fuels (Uusitalo et al. 2014).

The ecoinvent process “Operation, passenger car, methane, 96 vol-%, from biogas/CH U” was used to model the fuel consumption of methane per km of traveled distance by a passenger car. The methane supply chain was modeled with the ecoinvent process data set “Methane, 96% by volume, from biogas, from high pressure network, at service station {CH}/market for”, adjusted to reflect the North American electricity consumption grid mix.

Section 4.3.1.1.3.1 on methane production noted that 1 tonne of woody mill residues (i.e., wood chips, dry mass) produces 270 Nm^3 of methane. Using a methane density of 0.752 kg/Nm^3 and a fuel consumption of 6.73E-2 kg/km (Jungbluth et al. 2007), it has been calculated that 1 tonne of woody mill residues would enable a vehicle to travel 3,017 km. The type of engine used in the analysis is an adapted internal combustion engine; hence, the fuel efficiency would be similar to that of an engine using low sulfur gasoline. The impact of fuel efficiency on the results was assessed with a sensitivity analysis specified in Table 4.27.

Table 4.27 Base Case Scenario (BC. Sc.) and “Efficiency” Sensitivity Analysis (Low, High) Parameter Values Selected to Model Methane Fuel Consumption

Product	Parameter Analyzed	Value Analyzed		Comments
Methane	Fuel consumption (kg methane/km)	BC. Sc.	0.0673	The average scenario uses the value from ecoinvent. The minimum value is from Power and Murphy (2009) and the maximum value represents a similar fuel efficiency as that of an engine using low sulfur gasoline
		Low	0.051	
		High	0.0693	
	Distance traveled (km/t dry wood)	BC. Sc.	3,017	Calculated based on methane production yield and methane fuel consumption
		Low	2,222	
		High	5,805	

Transport and distribution of methane were assumed to be by pipeline, as modeled in the ecoinvent data set: “Methane, 96% by volume, from biogas, high pressure, at user {CH}| production | Alloc Def, U”.

4.3.3.2 Alternative System

4.3.3.2.1 Gasoline, Low Sulfur

The ecoinvent process data set “Operation, passenger car, [gasoline], low [sulfur]” was used to model the fuel consumption of low sulfur gasoline per kilometer of distance traveled by a passenger car.

[19] Original fuel consumption value was 2.16 MJ/km. Unit conversions based on an HHV of 38.1 MJ/Nm^3 and a density of 0.752 kg/Nm^3.

According to ecoinvent documentation, 0.0625 kg of gasoline is necessary to enable a car to travel 1 kilometer (Jungbluth et al. 2007). Gasoline supply at the service station was modeled according to ecoinvent process data set “[Gasoline], low-sulfur {RoW}/market for”.

4.3.3.2.2 *Diesel, Low Sulfur*

The ecoinvent process data set “Operation, passenger car, diesel, low [sulfur]” was used to model the fuel consumption of diesel per kilometer of traveled distance by a passenger car. According to ecoinvent documentation, 0.0551 kg of diesel is necessary to enable a car to travel 1 kilometer (Jungbluth et al. 2007). Diesel supply at the service station was modeled according to the ecoinvent process data set “Diesel, low-sulfur {RoW}/market for”.

4.3.3.2.3 *Natural Gas*

The ecoinvent process data set “Operation, passenger car, natural gas” was used to model the fuel consumption of natural gas per kilometer of distance traveled by a passenger car. According to ecoinvent documentation, 0.0641 kg of natural gas is necessary to enable a car to travel 1 kilometer (Jungbluth et al., 2007). The origin of natural gas supply at the service station was modeled according to the ratios of natural gas consumption for the United States, Alberta and Quebec, the only three regions for which data are available in ecoinvent, over the total production of these three regions. Ecoinvent process data sets “Natural gas, high pressure {CA-AB}/market for”, “Natural gas, high pressure {CA-QC}/market for”, and “Natural gas, high pressure {US}/market for” were used. Default ecoinvent transport distance by pipeline for natural gas from production location to user location was used.

4.3.4 *Use in Metallurgy Pathway*

In 2012, Canada produced 7.7 million metric tonnes of pig iron[20] and 13.5 million metric tonnes of steel, while the United States produced 32.1 million metric tonnes of pig iron and 88.7 million metric tonnes of steel (United States Geological Survey 2014). One way of reducing environmental impacts of “virgin” steel production is to use charcoal instead of coke, to reduce CO_2 emissions (Norgate et al. 2012). The production of charcoal for use in steel production is an unconventional use of woody mill residues in North America.

Most steel is produced via an integrated blast furnace followed by a basic oxygen furnace. The blast furnace process is used to reduce the iron oxides (pig iron) into molten hot iron, which is then refined into steel in the basic oxygen furnace process. The most energy-consuming process in integrated steel plants is the blast furnace, which can use coke, coal, oil, and natural gas as reducing agents. Charcoal can be used instead of coke in the blast furnace; however, it is unlikely that coke can be entirely substituted by charcoal because charcoal has a much lower crushing strength compared to coke (Norgate et al. 2012). In this study, it was assumed that 20% of coke can be replaced with charcoal, a feasible and practical proportion according to Norgate et al. (2012).

In this study, only one scenario was modeled to represent the unconventional use pathway of biomass in metallurgy: the use of charcoal as a reducing agent in pig iron production as a substitute for coke. Table 4.28 summarizes the scenario investigated in this study, where the quantity and type of biomass and that of the alternative system are expressed in terms of the materials (charcoal and coke) entering the pig iron process. Details on the modeled scenario and its justification are described below.

[20] Pig iron is the intermediate product of smelting iron ore. It is the molten iron from the blast furnace, which is a large and cylinder-shaped furnace charged with iron ore, coke, and limestone.

Table 4.28 Scenario Explored for the Use of Converted Woody Mill Residues in Metallurgy

Scenario Name*	General Description§				
	Pig Iron Produced	Biomass System		Alternative System	
		Quantity	Type	Quantity	Type
Metl_Charcoal_Coke	4820 kg	300 kg	Charcoal	429 kg	Coke

*Metl: Metallurgy Application.
§ The table only highlights the differences in the system; hence, both systems have an additional 1814 kg of coke.

4.3.4.1 *Biomass System*

4.3.4.1.1 *Charcoal*

The production of charcoal from woody mill residues, its use in steel-making, and the assumptions used to model these processes are described in the following material.

4.3.4.1.1.1 *Charcoal Production*

Charcoal is produced by slow pyrolysis of wood, also called carbonization. Tarry vapors (i.e., tar-laden vapors), CO_2, CO, and H_2O are emitted from the production of charcoal from wood (Antal and Grønli 2003). Condensable wood gases can be recuperated to produce by-products or burned to produce process heat [Food and Agriculture Organization of the United Nations (FAO) 1985]. Modern charcoal process technologies can be classified into three types, in terms of how they initiate the carbonization of wood and provide heat during the process: internal heating (e.g., Missouri kiln), external heating (e.g., a VMR retort), and heating with recirculated gas (e.g., the Degussa process) (Antal and Grønli 2003). In some countries (e.g., Brazil), charcoal produced in kilns is used in iron works, while in others (e.g., Norway), charcoal is used for the production of silicon (Werner et al. 2007).

Emissions from retort systems are much lower than those from kiln systems because the former combust the pyrolysis gases in-situ (Reumerman and Frederiks 2002). Because air emissions are regulated in the US, kilns not able to comply with the regulations, such as many Missouri kilns, have ceased to operate (Antal and Grønli 2003); hence, charcoal production using an external heat source (e.g., retort system) was the model selected for this study.

In the modeled process, it was assumed that the vapors from the retort are burned to waste or passed through boilers to recover heat for the retort (FAO 1985). Wood charcoal yield production in atmospheric pressure retorts can vary between 28.8 and 33.0%, with an average of 30%. The carbon content of the resulting charcoal can vary between 69.1 and 86.6%, with an average of 76% (Antal and Grønli 2003). These data are summarized in Table 4.29. Charcoal produced with softwood or hardwood bark is in the form of powder rather than lump, which constrains the possibilities for its use in industrial processes (FAO 1985). While it is believed that the process value chain modeled in this study is plausible, i.e., using charcoal produced from woody mill residues as a reducing agent in pig iron production, using the modeled charcoal production process in a process value chain with another end use might not represent a technically feasible pathway.

Emission factors for CH_4, NO_x, CO, ethene, ethane, N_2O, SO_2, and particles from a twin-retort system were taken from Reumerman and Frederiks (2002). The size and amount of particulate matter (i.e., $PM_{2.5}$, particles > $PM_{2.5}$ and <PM_{10}, particles > PM_{10}) were calculated according to the proportion of the specific size of particulates emitted relative to the total emissions of particulates of all sizes as presented in ecoinvent report No. 9 (Werner et al. 2007). The same calculation method as for particulates emissions was used to differentiate the amount of non-methane volatile organic compounds (NMVOC) types.

Table 4.29 Base Case Scenario (BC. Sc.) and "Efficiency" Sensitivity Analysis (Low, High) Parameter Values Selected to Model Charcoal Production

Product	Parameter Analyzed	Value Analyzed		Comments
Charcoal	Charcoal yield a mass basis (wt %)	BC. Sc.	30%	The average scenario represents the average value for yield associated with the production of charcoal in atmospheric pressure retorts (Antal and Grønli 2003).
		Low	28.8%	
		High	33%	
	Fraction of carbon content (wt %)	BC. Sc.	76%	The average scenario represents the average value for carbon content associated with the production of wood charcoal in atmospheric pressure retorts (Antal and Grønli 2003).
		Low	69.1%	
		High	86.6%	
	Charcoal produced per tonne of woody mill residues / Carbon content (kg and kg C)	BC. Sc.	300 kg (228 kg C)	Calculated based on charcoal yield values.
		Low	288 kg (199 kg C)	
		High	333 kg (288 kg C)	

4.3.4.1.1.2 *Charcoal as a Reducing Agent*

A reducing agent is a carbon-rich source that removes oxides and sulfides from metallic ores when heated with them, and thus produces purer forms of metals (FAO 1985). Typically, reducing agents used in the reduction of iron oxides in blast furnaces for the production of steel include coke and tuyère-injected oil, pulverized coal and/or natural gas. Charcoal could replace pulverized coal injection in a large blast furnace (Suopajärvi, Pongrácz, and Fabritius 2013). Charcoal is already being used in mini blast furnaces in Brazil (Suopajärvi, Pongrácz, and Fabritius 2014). A minimum amount of coke needs to be present in the blast furnace because of its physical properties, namely, its porosity and mechanical characteristics. Specifically, because of the lower crushing strength of charcoal, a minimum coke rate to the blast furnace of 250 kg/t pig iron is reported in the literature (Suopajärvi, Pongrácz, and Fabritius 2014). Also, reducing agents such as oil, natural gas, and charcoal have different coke replacement ratios based on their chemical properties and heat content values. The coke replacement ratio for charcoal (i.e., the amount of coke replaced by injecting charcoal) is approximately 0.8 – 1.11 (Suopajärvi, Pongrácz, and Fabritius 2014). Characteristics of interest for charcoal used in the blast furnace include a carbon content ranging from 60 to 80% and a higher heating value ranging from 28 to 33 MJ/kg (Antal and Grønli 2003; FAO 1985). It is reasonable to assume that pulverized coke can be replaced by charcoal on an equivalent energy basis (Norgate et al. 2012). Because the HHVs of charcoal and pulverized coke are similar (de Castro et al. 2013), a coke replacement ratio of 0.95, as reported by Suopajärvi, Pongrácz, and Fabritius (2014), is considered realistic and was used in this study. The carbon content of charcoal used in this study was 76%, as detailed in the previous section.

The parameters considered in the modeling of pig iron production are summarized in Table 4.30. The ecoinvent process data set "Pig iron {GLO}| market for | Alloc Def, U" was used in this study. This model was adjusted to reflect the North American electricity consumption grid mix. Other adjustments made to the data set included modifying the coke supply from 8.84 to 7.15MJ/kg pig iron, adjusting the fossil CO_2 emission from 0.772 to 0.671 kg/kg pig iron, and adding a charcoal supply of 0.0622 kg/kg pig iron as well as biogenic CO_2 emissions of 0.090 kg/kg pig iron (Swiss Centre for Life Cycle Inventories 2015). The use of an injection rate of 0.0622 in this study falls within the range the reported charcoal injection rates of 0.05 to 0.22 kg/kg pig iron (Feliciano-Bruzual, 2014). The biogenic CO_2 emission of 0.090 kg CO_2/kg pig iron was calculated using a carbon mass balance as presented in Classen et al. (2009). The biogenic carbon emitted as CO_2 from the use of charcoal is assumed to be emitted in the same proportion as the carbon emitted as fossil CO_2 from the use of coke and coal in the blast furnace process for pig iron production. Feliciano-Bruzual (2014) reported that 1 kg of coke generates 1.18 kg of CO_2, while 1 kg of charcoal would generate 1.128 kg CO_2. Using this approximation, 0.07kg of biogenic CO_2 would be emitted, indicating that the approximation used in this study was conservative.

Transport mode and distances for charcoal transportation from production location to use location were estimated from transport data for wood products published in the US 2012 Commodity Flow Survey (U.S. Department of Transportation and U.S. Department of Commerce 2015). The mass-weighted average distances by mode of transport that were modeled are

- Truck: 279.7 km*weight; and
- Train: 99.8 km*weight.

Charcoal produced from wood is known to have a low sulfur content and produce a small amount of high pH ash. The basic nature of charcoal ash can act to reduce the requirements for lime or limestone addition to slag for removal of unwanted elements from the hot metal, thus reducing the amount of slag in the blast furnace process and increasing productivity. The low sulfur content results in lower sulfur emissions (Feliciano-Bruzual 2014; Suopajärvi, Pongrácz, and Fabritius 2013). These aspects have not been accounted for in this study.

Table 4.30 Base Case Scenario (BC. Sc.) and "Efficiency" Sensitivity Analysis (Low, High) Parameter Values Selected to Model Pig Iron Production

Product	Parameter Analyzed	Value Analyzed		Comments
Charcoal	Coke replacement ratio (amount of coke replaced by charcoal)	BC. Sc.	0.95	Charcoal's coke replacement ratio is based on its chemical properties and heating value (Suopajärvi et al. 2014).
		Low	0.8	
		High	1.11	
	Charcoal injection rate (kg/kg pig iron)	BC. Sc.	0.0622	A minimum amount of coke, 250 kg/t pig iron, needs to be present in the blast furnace because of its desirable physical properties, namely as a porous and mechanically strong supporting material (Suopajärvi et al. 2014). Considering the minimum amount of coke and the coke replacement ratio, the charcoal injection rates calculated fall within the reported to range from 0.05 to 0.22 kg/kg pig iron (Feliciano-Bruzual, 2014).
		Low	0.0739*	
		High	0.0532	
	Pig iron produce (kg pig iron/t dry wood	BC. Sc.	4820	Calculated from the amount of charcoal produced per tonne of dry wood and the charcoal injection rate.
		Low	3897	
		High	6195	

* More charcoal is needed to replace the same amount of coke.

4.3.4.2 *Alternative System*

4.3.4.2.1 *Coke*

The following data set from ecoinvent was used for producing, transporting, and distributing coke:

- Production, transport and distribution of coke "Coke {GLO}/market for"

This process is expressed on an energy basis. A higher heating value of 28.6 MJ/kg was used to convert units from an energy basis to a mass basis.

4.3.5 *Use as Horticultural Growing Media Pathway*

According to an LCA study of horticultural growing media by Quantis (2012), the following volumes of growing media for a hobby market (potting mix) are functionally equivalent:

- 1 m^3 of bark based growing media: 20% v/v Bark, 80% v/v Black peat and adding 5.3 kg/m3 lime and 1.3 kg/m^3 fertilizer mix; and
- 1 m^3 of peat based growing media: 40% v/v White peat, 60% v/v Black peat and adding 5.7 kg/m^3 lime and 1.3 kg/m^3 fertilizer mix.

For the purpose of this study, because the alternative system (peat) is subtracted from the functionally equivalent biomass system, it was assumed that white and black peat were functionally equivalent and the following comparison, summarized in Table 4.31, was used: 1 m^3 of bark mulch can replace 1 m^3 of peat moss mixed with 2 kg lime.

Emissions from degrading peat and bark mulch are not well documented. For the purposes of this study, greenhouse gas emissions and carbon storage are approximated with emissions reported for composting, an aerobic process. To represent the range of greenhouse gas emissions and carbon storage that might occur when peat or bark mulch degrades, two base case scenarios were modeled in this study:

- low emissions from bark mulch combined with high emissions from peat (HGM_Bark_lowCO_2e_Peat); and
- high emissions from bark mulch combined with low emissions from peat (HGM_Bark_highCO_2e_ Peat).

Table 4.31 summarize the two scenarios investigated in this study. Details on the modeled scenarios and their justification are described in the following section.

Table 4.31 Scenario Explored for Use of Converted Woody Mill Residues as Horticultural Growing Media

Scenario Name*	General Description						
	Growing Medium	Biomass System			Alternative System		
		Quantity	Type	Degradation	Quantity	Type	Degradation
HGM_Bark_low CO_2e_Peat	5.67 m^3	1000 kg	Wood	**Low CO_2e**: 80 %wt. of the carbon is emitted as CO_2, 0.012 %wt. as CH_4 while the remaining carbon is stored in the soil, and 0.2 g of N_2O/kg dry bark mulch	567 kg	Peat	**High CO_2e**: 97.27 %wt. of the carbon is emitted as CO_2, 2.73 %wt. as CH_4 while no carbon is stored in the soil, and 1.6g of N_2O/kg dry peat
		0 kg	Lime		11.3 kg	Lime	
HGM_Bark_high CO_2e_Peat	4.6 m^3	1000 kg	Wood	**High CO_2e**: 97 %wt. of the carbon is emitted as CO_2, 3 %wt. as CH_4 while no carbon is stored in the soil, and 1.6g of N_2O/kg dry bark mulch	464 kg	Peat	**Low CO_2e** :80 %wt. of the carbon is emitted as CO_2, 0.011 %wt. as CH_4 while the remaining carbon is stored in the soil, and 0.2 g of N_2O/kg dry peat
		0 kg	Lime		9.2 kg	Lime	

*GM: growing media.

4.3.5.1 *Biomass System*

4.3.5.1.1 *Bark Mulch*

4.3.5.1.1.1 *Bark Mulch Preparation*

It this study, it was assumed that woody mill residues are shipped to a bark mulch manufacturing plant where the woody mill residues are chipped to a uniform size and bagged for distribution to customers. The following modified ecoinvent process data set, i.e., adjusted to reflect the North American electricity consumption grid mix, was used to model the production of 1 kg of bark mulch ready for distribution:

- Wood chipping, industrial residual wood, stationary electric chipper {RER}| processing | Alloc Def, U".

It was assumed that 1 tonne of woody mill residues (i.e., wood chips, dry mass) produces 1 tonne of mulch. For packaging, the same process and amount of packaging, on a volume basis, as for pellet packaging was used, i.e., 0.0075 kg of "Packaging film, low density polyethylene {GLO}| market for |" per kg of bark mulch.

Transport modes and distances for mulch transportation from production location to use location were estimated based on wood products transport data published in the 2012 US Commodity Flow Survey. The mass-weighted average distances by mode of transport that were modeled are

- Truck: 280 km*weight; and
- Train: 100 km*weight.

4.3.5.1.1.2 *Bark Mulch as Growing Medium*

Greenhouse gas emissions and carbon storage are approximated with emissions reported for composting according to IPCC 2006 Guidelines for National Greenhouse Gas Inventories (Pipatti et al. 2006), which are for methane, 0.08 to 20 g CH_4/kg dry waste, and for nitrous oxide, 0.2 to 1.6 g N_2O/kg dry waste. Considering bark mulch has a density of 196 kg/m^3 (Quantis 2012), and accounting for uncertainty using a 10% variation from that value, this translates into 0.014 to 4.320 kg CH_4/m^3 of bark mulch and 0.035 to 0.346 kg N_2O/m^3 bark mulch, as summarized in Table 4.32.

Assuming a carbon content of 50% wt., 0.5 kg of biogenic carbon/kg bark mulch could be emitted to the atmosphere. IPPC states that for an aerobic process such as composting, a large fraction of the degradable organic carbon in the waste material is converted into carbon dioxide but does not quantify it (Pipatti et al. 2006). USEPA, through its WARM model documentation on compost, says that approximately 80% of the initial organic matter in compost is emitted as CO_2. Considering the wide range of possible biogenic CO_2 emissions from degrading mulch, it was arbitrarily assumed that either all carbon, except the fraction emitted as methane, would be emitted as CO_2 (HGM_High CO2e), or only 80% of the carbon contained in the initial product (HGM_Low CO_2e).

Table 4.32 Parameter Values Selected to Represent the Two Base Case Scenarios (Low and High CO2e Emissions) from Bark Mulch

Product	Parameter Analyzed	Value Analyzed		Comments
Bark mulch	Bark mulch density (kg/m^3)	HGM_Low CO_2e	176	From the average bark mulch density value of 196 kg/m^3), a variation of 10% is used to include uncertainty relative to this parameter and assess its influence on the results.
		HGM_High CO_2e	216	
	Biogenic CO_2 emissions (kg/m^3)	HGM_Low CO_2e	258	80% of the carbon contained in the low density bark mulch is emitted as CO_2.
		HGM_High CO_2e	384	Carbon not emitted as CH_4 from the high density mulch is emitted as CO_2.
	CH_4 emissions (kg/m^3)	HGM_Low CO_2e	0.014	Using the lower range of the IPCC's default emission factor (0.08 g CH_4/kg waste) and the low value for bark mulch density.
		HGM_High CO_2e	4.320	Using the upper range of the IPCC's default emission factor (20g CH_4/kg waste) and the high value for bark mulch density.
	N_2O emissions (kg/m^3)	HGM_Low CO_2e	0.035	Using the lower range of the IPCC's default emission factor (0.20 g N_4O/kg waste) and the low value for bark mulch density.
		HGM_High CO_2e	0.346	Using the upper range of the IPCC's default emission factor (1.6 g N_4O/kg waste) and the high value for bark mulch density.

4.3.5.2 *Alternative System*

4.3.5.2.1 *Peat*

Peat is used in many types of growing media. The ecoinvent process data set "Peat moss {CA-QC}| peat moss production, horticultural use" was used to represent its production. To adapt the process to a North American context, the electricity consumption grid mix was modified from the Quebec electricity consumption grid mix to the North American electricity consumption grid mix. A density of 100 kg dry/m^3 was used for dry peat moss in loose form according to the ecoinvent database.

For packaging, according to the ecoinvent documentation, 0.556 kg/m3 of peat of "Packaging film, low density polyethylene {GLO}| market for |" is needed and was included in the production process for peat moss.

Transport modes and distances for peat transportation from production location to use location were estimated based on fertilizer transport data published in the 2012 U.S. Commodity Flow Survey. The mass-weighted average distances by mode of transport that were modeled are

- Truck: 97 km*weight;
- Train: 310 km*weight; and
- Barge (Inland Water): 77 km*weight.

As with bark mulch, biogenic carbon dioxide, methane, and nitrous oxide were assumed to be emitted from the use of peat moss. Considering a density of 100 kg/m^3 for dry peat moss in loose form and that the peat moss and bark mulch are functionally equivalent on a volume basis, the mass of peat moss needed was calculated according to the volumes of bark mulch used in the two base case scenarios for bark mulch. To link the biomass system to the alternative system, the parameters for peat moss (Table 4.33) were framed in reference to the bark mulch system, i.e., HGH_low CO_2e or HGM_high CO_2e (Table 4.32). Note that in the low bark mulch scenario, GHG emissions for bark mulch are minimized, while they are maximized for peat moss.

The assumed carbon content of peat moss was 55%, which is equivalent to 55 kg of carbon/m^3 of peat (Quantis 2012). For bark mulch, it was assumed that either all carbon in peat moss, except for the fraction emitted as methane, would be emitted as CO_2, or only 80% of the carbon contained in the initial product.

Table 4.33 Parameter Values Selected to Represent the Two Base Case Scenarios (Low and High CO2e Emissions) from Peat Mulch

Product	Parameter Analyzed	Value Analyzed		Comments
Peat Mulch	Peat mulch quantity (kg)	HGM_Low CO_2e	568	Considering a peat moss density of 100 kg/m^3, the quantity of peat moss is calculated to fill the same volume as 1000 kg bark mulch, using to the densities used in the two base case scenarios.
		HGM_High CO_2e	463	
	Biogenic CO_2 emissions (kg/m3)	HGM_Low CO_2e	196	Carbon not emitted as CH_4 is emitted as CO_2.
		HGM_High CO_2e	161	80% of the carbon contained in peat moss is emitted as CO_2.
	CH_4 emissions (kg/m3)	HGM_Low CO_2e	2	Using the upper range of the IPCC's default emission factor (20 g CH_4/kg dry waste).
		HGM_High CO_2e	0.008	Using the lower range of the IPCC's default emission factor (0.08 g CH_4/kg dry waste).
	N_2O emissions (kg/m3)	HGM_Low CO_2e	0.16	Using the upper range of the IPCC's default emission factor (1.6 g N_2O/kg dry waste).
		HGM_High CO_2e	0.02	Using the lower range of the IPCC's default emission factor (0.20 g N_2O/kg dry waste).

4.3.5.2.2 *Fertilizer*

Lime production was modeled with the ecoinvent process data set "Lime {QC-CA}| lime production, milled, loose", adjusted to reflect the North American context by replacing the Quebec electricity consumption grid mix with the North American one.

The use of lime leads to CO_2 emissions as the carbonate lime dissolves. According to IPCC, the default emission factors for the use of limestone is 0.12 kg C/kg lime with an uncertainty of -50% (IPCC, 2006a). Hence, CO_2 emissions from the use of lime with peat were added to the peat scenarios, as shown in Table 4.34.

Table 4.34 Parameter Values Selected to Represent the Two Base Case Scenarios (Low and High CO2e Emissions) from Lime use with Peat Mulch

Product	Parameter Analyzed	Value Analyzed		Comments
Peat Mulch	CO_2 emissions from lime use (kg/m3)	HGM_Low CO_2e	0.88	Based on IPCC default emission factor of 0.12 kg C/kg lime and uncertainty of -50%.
		HGM_High CO_2e	0.44	

5.0 RESULTS AND INTERPRETATION

5.1 Approach Used for Presentation and Interpretation of Results

In this study, the TRACI impact assessment method was used to assess 54 base case scenarios, which led to 54 results for each of the 10 impact categories. In addition, two sensitivity analyses were performed to assess the robustness of the conclusions for the unconventional use pathways. These sensitivity analyses were not applied to the disposal pathway. The first sensitivity analysis is referred to as “efficiency” because the different biomass system model parameters, such as production yield or combustion yield, were varied from their base case scenario value to a low value (low efficiency), and high value (high efficiency). The second sensitivity analysis is referred to as “grid mix” because the grid mix modeled in the biomass system was varied from a North American grid mix base case to a Quebec grid mix (QC) and a Midwest Reliability Organization electricity grid mix (MRO). For the horticultural growing media pathway, the effects of “efficiency” were included in the two base case scenarios investigated, representing the two extreme scenario possibilities. Hence, “efficiency” sensitivity analyses were applied to 50 of the 54 unconventional pathway scenarios. No sensitivity analysis was performed on the alternative systems because it was hypothesized that their uncertainties are much smaller than for the biomass system, as they consist of well-established technologies. In the case of the “Combined Heat and Power” scenarios, a grid mix sensitivity analysis was applied only on the unit process providing the end-product electricity, given that it was hypothesized that the supply of the alternative system is generalized to North America; hence, locations of major suppliers to broad regions are known and accounted for in the ecoinvent data sets, as opposed to the biomass system, where wood production is regionalized, i.e., woody mill residues will be converted near to their production site because of their energy density.

Given that the approach used for this LCA involved excluding the life cycle stages upstream of the biomass production (e.g., upstream of pellet production), the results do not indicate whether the additional function fulfilled by the biomass system in isolation is better environmentally than producing that same function with the alternative system, e.g., it does not allow to directly compare the production of 1 GJ of energy using woody mill residuals to the production of 1 GJ of energy using fossil fuels. Instead, the results indicate whether the function of managing woody mill residue via a given unconventional use pathway in substitution for an alternative system is estimated to result in larger or smaller potential impacts or benefit than other pathways examined in this analysis. Also, the indirect consequences of replacing a current practice of disposal or use in a conventional pathway with a new practice using the woody mill residues in an unconventional use pathway are not assessed. For instance, the effect of diverting woody mill residues from direct combustion at a forest products manufacturing facility to use in producing ethanol for use as transport fuel cannot be assessed using the results provided below. A consequential LCA would be required.

The results of the assessment of potential environmental impacts for the disposal pathway and unconventional use pathways scenarios are assessed using a four-step interpretation approach, including review of life cycle impact results, contribution analyses to identify key contributing processes, semi-quantitative uncertainty assessment of the life cycle impact results, and overall comparative assessment of the disposal pathway and unconventional use pathway life cycle impact results. The different steps of the approach are detailed below and illustrated in Figure 5.1.

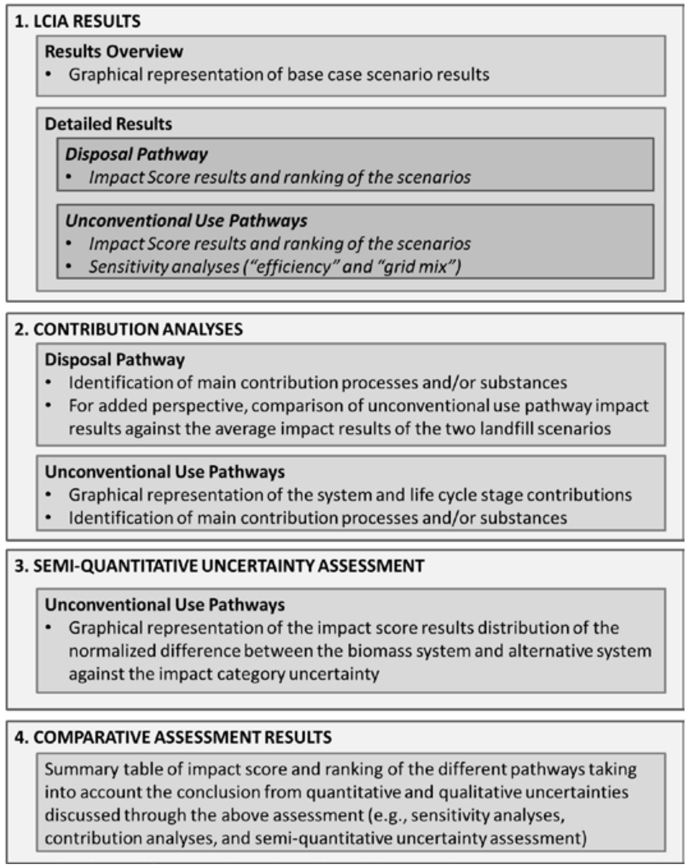


Figure 5.1 Flow of the Four-Step Interpretation Approach

1) LCIA Results

For each impact pathway, the environmental impact score was calculated as follows:

$$IS_{P,i} = IS_{P,i,Bio} - IS_{P,i,AS}$$

Where:

$IS_{P,i}$: Impact score of the pathway P for impact category i;

$IS_{P,i,Bio}$: Impact score of the biomass system in pathway P for impact category i; and

$IS_{P,i,AS}$: Impact score of the alternative system in pathway P for impact category i.

Also, to present the overall LCIA results for all impact categories and scenarios in a single graphical figure, the impact scores have been normalized. In this study, each impact score was normalized against that of the pathway for which the absolute value of the impact score under the base case scenario was the greatest. This approach means that all the normalized values for the 54 base case scenarios are bounded by 100% and -100%, and that the base case scenario impact score used for normalization varies for each impact category.

For a given pathway and scenario, a positive impact score on a given impact category means a net potential environmental impact for that pathway on the studied impact category. In other words, the potential environmental impacts from the management processes of the residues are greater than the impacts of the displaced alternative system. In contrast, a negative impact score for a given impact pathway on a specific impact category means that, for this impact category, the pathway results in a net environmental benefit. This graph of the overall results shows the variability, where present, of the impact scores for the 54 base case scenarios, the ranking of the pathways in comparison to each other, and whether the pathways would result in larger or smaller potential impacts relative to the alternative system.

The detailed LCIA results begin with tables listing the impact scores for all scenarios, as well as a ranking of the scenarios against each other, followed by a graphical presentation of the sensitivity analyses. To determine whether a scenario generated impact scores of greater or less than zero, and whether it generated different potential impacts compared to other scenarios, an uncertainty criterion was used per impact category. The uncertainty criterion was derived from the uncertainties for fate, exposure, and effect described by Humbert et al. (2005) and personal communication with the first author (see Table 5.1).

The tabulation of detailed LCIA scores was based on a synthesis of a large array of base case and sensitivity analysis results. In the case of the “efficiency” sensitivity analyses, for instance, an impact score comparison matrix of 154 x 154 scenario results per impact category was generated. For the “grid mix” sensitivity analyses, an impact score comparison matrix of 158 x 158 scenario results per impact category.

To rank the results, the calculated environmental impact score for each scenario was first identified as lower than, higher than, or equal to other scenarios based on the impact category uncertainty criteria (see Table 5.1). Frequency tables of these comparisons were then compiled. From the frequency tables, the scenarios were subsequently ranked according to the number of times their impact score within each sensitivity analysis was identified as lower, higher, or equal. Scenarios for which the impact score ranked lower than that of 90% of the scenarios analyzed were identified as “Among the top 10%” of scenarios with lowest impact score. In contrast, scenarios for which the impact score ranked higher than that of 90% of the scenarios analyzed were identified as “Among the bottom 10%”. Tables summarizing the matrices results were produced as shown and explained in Figure 5.2. The resulting tables illustrate the estimated environmental impacts of a scenario and how that scenario ranks in comparison to all other scenarios within a sensitivity analysis. Tables can be read by line, column, biomass system, and identical alternative system, or for the entire pathway. Each line provides the results for one scenario, while a column provides the results for all scenarios for one impact category. Top performing scenarios were identified as those with impact scores of less than zero for more than seven impact scores or those within the top 10% for more than seven impact scores, and are highlighted in blue.

For the graphical representation of the sensitivity analyses, the impact score of all base case scenarios within the pathway and the results from the related sensitivity analyses are normalized against the absolute value of the scenario with the maximum potential environmental impact of the 54 scenarios for each impact category. In other words, the impact scores are normalized with the same values as those presented in the overview of results. The sensitivity analysis results are presented in two graphs, one for the “efficiency” sensitivity analyses and the one for the “gird mix” sensitivity analyses. The graphs provide an indication of the overall robustness of the results of this study.

Table 5.1 Life Cycle Impact Assessment Uncertainty Criteria

Impact Indicator	Qualitative Uncertainty Assessment for Fate, Exposure, and Effect by Humbert et al. (2005)	Quantitative Uncertainty Criteria Derived from Personal Communication with LCA Expert and Lead Author of Humbert et al. (2005)
Ozone depletion	medium	± 30%
Global warming	low	± 10%
Smog	medium	± 30%
Acidification	Low	± 10%
Eutrophication	Low	± 10%
Carcinogens*	high	± 50%
Non-carcinogens*	Higher than for carcinogens	± 60%
Respiratory effects	low	± 10%
Ecotoxicity	high	± 50%
Fossil fuel depletion	low	± 10%

* In TRACI the nomenclature, "carcinogenics" and "non carcinogenics" rather than the more common terminology of "carcinogens" and "non carcinogens". In this report, TRACI nomenclature is used in the results figures.

2) Contribution Analyses

To explain the basis for the impact score results, contribution analyses were performed for the disposal pathway and the unconventional use pathways. In a contribution analysis, the relative contributions of life cycle stages, individual unit processes, or substances to the total life cycle impact assessment results are examined by impact category to determine which factors have the biggest influence on the results. The information from the contribution analysis can be used, for instance, to further investigate the actual environmental risk of a process (e.g., via risk assessment) as opposed to its potential environmental impact and/or to identify opportunities for improvement.

The contribution analysis was first performed on the disposal pathway. Thereafter, to gain perspective on the unconventional use pathway base case scenarios prior to their contribution analyses, the results were compared to the average of the results of the two landfill scenarios within the disposal pathway. The comparison of the impact score results of unconventional use pathway scenarios against the value of the average impact score of the two landfill scenarios was then presented graphically. This comparison, coupled with an understanding of the main landfill contributing process and/or substances, helps put the results in perspective.

Contribution analyses were then applied to the unconventional use pathways where the impact score results were broken down by system (biomass, alternative) and biomass system life cycle stages (production, transport, use/combustion). The biomass production life cycle stage includes emissions from biomass production and related upstream emissions included in the system boundaries. The biomass transport life cycle stage includes the emissions of transporting the biomass product (e.g., pellets) from the production location to their use location. The biomass use/combustion life cycle stage includes the emissions from using/burning the biomass. The results were presented graphically and substances contributing to the systems' life cycle stages detailed in a table. For the graphical representation, the potential environmental impacts of the various systems and life cycle stages were normalized once again against the absolute value of the scenario with the maximum potential environmental impact of the 54 scenarios for each impact category; therefore, the reference scenario varies for each impact category. Also, to add perspective to these results, the landfill scenario results were included in the graph. The accompanying table specifies which life cycle stage and substances are the main contributors to the different impact categories, for both the biomass and alternative systems.

3) Semi-Quantitative Uncertainty Assessment

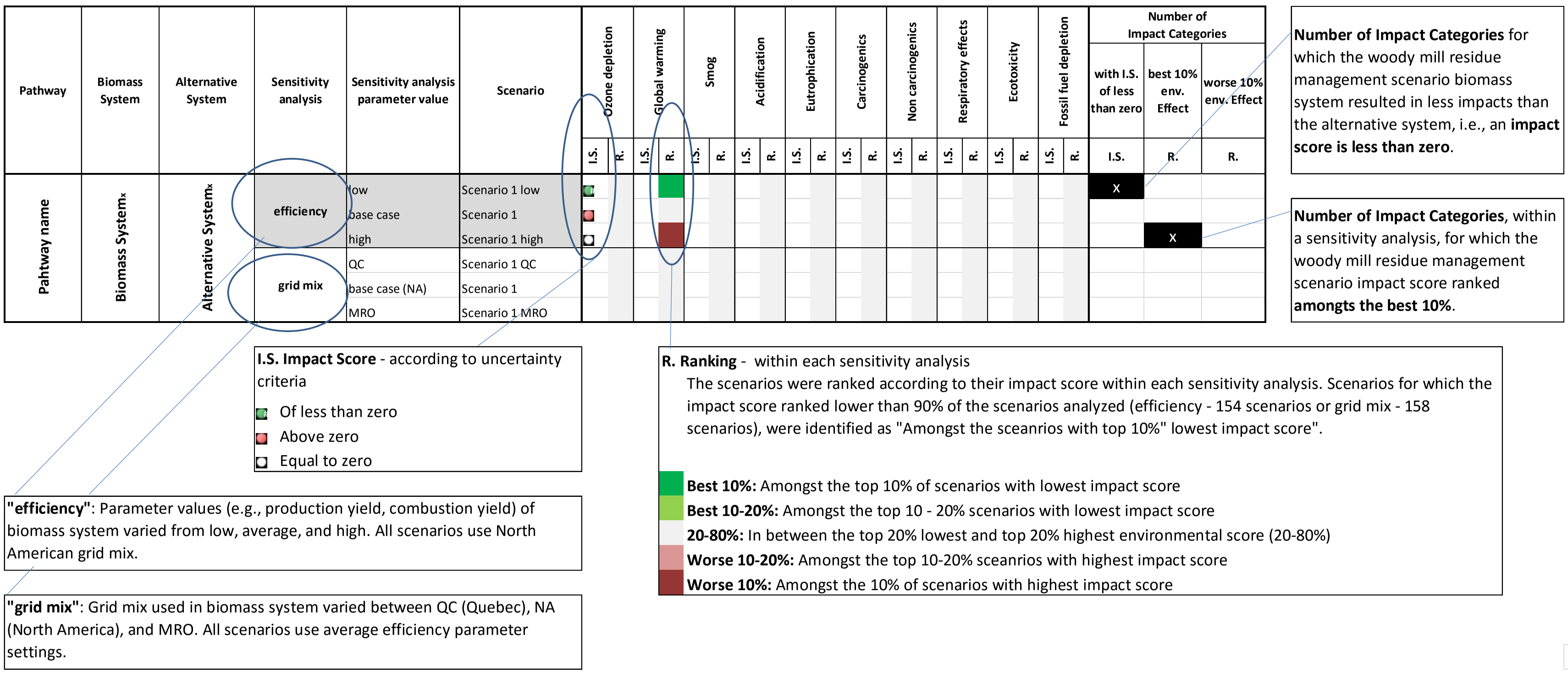
LCA models contain various types of uncertainty, both in terms of the model parameters themselves (e.g., estimated production yield, environmental release emission factors, etc.) and in terms of the degree to which a given impact category can be accurately modeled, mathematically.

Uncertainty relative to "efficiency" was discussed in the previous interpretation step, and uncertainty relative to impact categories is presented in Table 5.1, above. Given that this study is a screening-level LCA, an additional ± 10% uncertainty on parameters such as production yield was assumed to account for cumulative parameters uncertainty over the biomass system life cycle.

Impact scores were assumed to have resulted in notable differences in potential impacts if the range of results obtained from the normalized difference between the biomass system and alternative system, after mathematically incorporating parameter uncertainty and "efficiency" parameter settings, was greater than the uncertainty of the impact category itself.

4) Comparative Assessment Results

A synthesis of the ranking of the pathways and the trade-offs related to their environmental profiles are summarized in Table 5.2 and discussed below.



Note: In the figure, base case results are depicted twice, once under the efficiency sensitivity analysis and once under the grid mix sensitivity analysis.

Figure 5.2 Explanation of Impact Score and Ranking Results Tables

5.2 LCIA Results

5.2.1 *Results Overview*

The potential environmental impacts of the 54 base case scenarios are shown in Figure 5.3, normalized against the absolute value of the scenario with the maximum potential environmental impact of the 54 scenarios for each impact category (i.e., the base case scenario used varies for each impact category). In this figure, the average impact scores of the base case scenarios within the same pathway were calculated and are shown with a geometric marker. Note that the CHP Pathway was separated into CHP with high heat-to-power ratio (CHPh) and CHP with low heat-to-power ratio (CHPe) for ease of scenario comparison. The error bars represent the distribution of the impact score of the base case scenarios within each pathway. For the disposal and horticultural growing media pathways, an error bar is shown only for the global warming indicator, as only parameters related to global warming were tested for those pathways. Values below zero represent woody mill residues management options with potential net environmental benefits, and values above zero represent woody mill residues management options with net potential impacts, considering the biomass system and the displaced alternative system examined in each scenario.

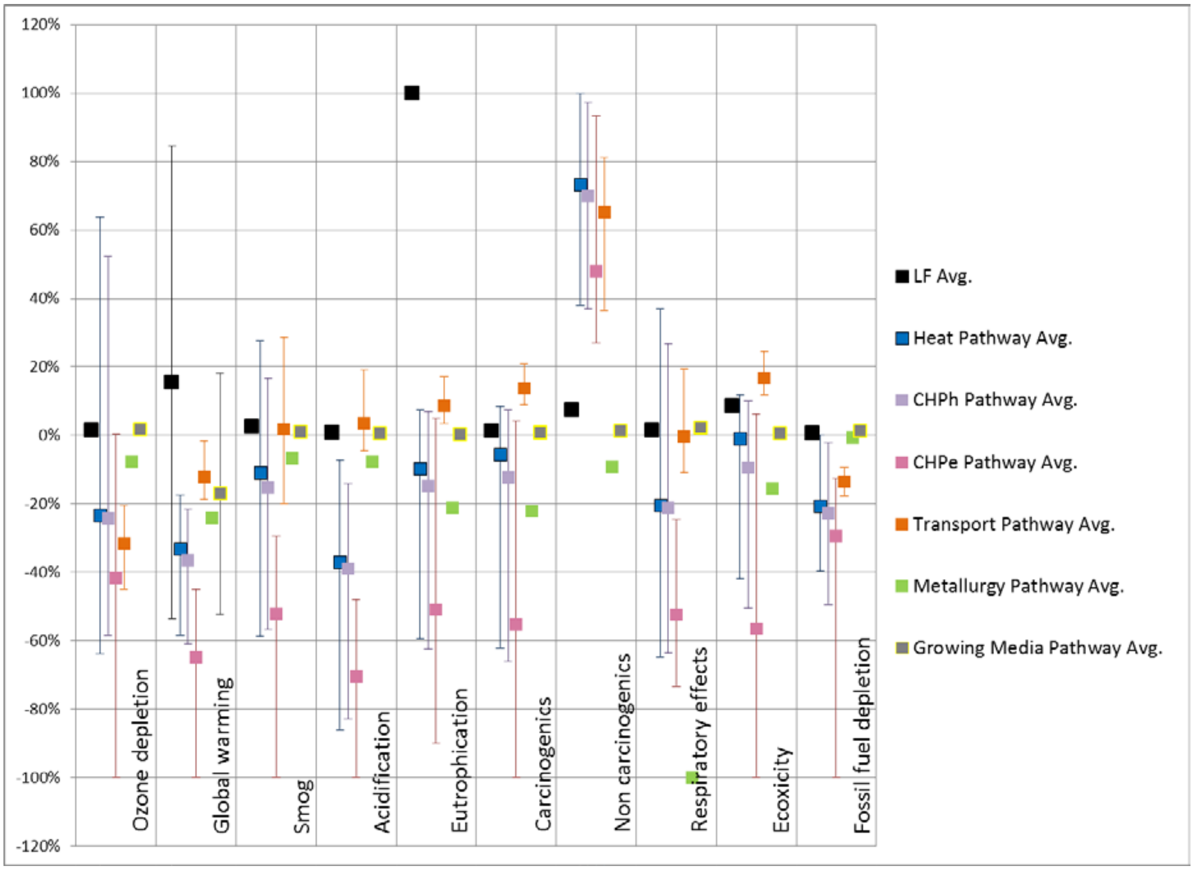


Figure 5.3 All Pathways Potential Environmental Impacts for Base Case Scenarios Normalized Against the Absolute Value of the Scenario with the Maximum Potential Environmental Impact of the 54 Scenarios for Each Impact Category [Geometric markers represent the average of base case scenarios for a pathway while bars represent distribution of base case scenarios for that pathway.]

Several observations can be made regarding the results for the unconventional use pathways.

In comparison to the disposal pathway studied in this report (landfilling), the estimated environmental impact scores for the five unconventional use pathways are, more often than not, equal to or lower than those for the disposal pathway. This indicates that managing woody mill residues through unconventional use pathways is anticipated to result in lower potential impacts or greater environmental benefits compared to landfilling residues.

Figure 5.3 shows that on average, the heat, CHP, and metallurgy pathways result in impact scores of less than zero for most impact categories, indicating a net benefit. The growing media pathway results are more neutral compared to other pathways (i.e., environmental impact scores are close to zero). Finally, the transport pathway results have the highest number of impact categories with impact scores above zero, meaning a net potential impact, compared to the other base case scenarios.

The normalized potential environmental impact scores of the heat pathway and the combined heat and power pathways (CHPh and CHPe) vary quite significantly depending on impact category. Given that results have been normalized with the maximum value of a different base case scenario for each impact category, however, the variability of results for each pathway shown in Figure 5.3 cannot be compared directly across impact categories and thus the results have been explored further in the disposal pathway contribution analysis below in Section 5.3.1.

Figure 5.3 also illustrates that the heat, combined heat and power (CHPh and CHPe), and transport pathways present impact scores of above zero (net impact) for the non-carcinogens category, while all unconventional use pathways, except for horticultural growing media, result in impact scores of less than zero (net benefit) for the global warming category. Contribution analyses performed for these pathways and summarized in Section 5.3 provide more information as to the processes or substances driving these results.

In sum, managing woody mill residues through their use in the metallurgy or in CHP units maximized for electricity production (CHPe) appear to generate potential environmental benefits over all or most impact categories. The latter (CHPe), for which the normalized results show the best (i.e., lowest) impact scores for nine impact categories out of ten, is likely the pathway with the highest number of individual scenarios with the greatest number of impact categories with impact scores below zero. In contrast, the normalized results in Figure 5.3 show that the use of woody residue as horticultural growing media appears to be an environmentally neutral pathway for nine out of ten impact categories, while the transport fuel use pathway yields impact scores above zero (i.e., a net potential impact) for most impact categories, suggesting that these pathways will contain most of the individual scenarios with impact scores of zero or greater. Detailed pathway-specific analyses are necessary, however, to confirm whether these trends in normalized values are indicative of similar trends in scenario-specific results.

5.2.2 *Detailed Results*

This section details results of the disposal and unconventional use pathways by presenting the results of the sensitivity analyses and summary tables of all scenario impact scores and ranking. Scenarios have been ranked against the different efficiency (low, base case, high) or grid mix [QC, NA (base case), MRO] scenarios from all other pathways (154 and 158 scenarios, respectively).

5.2.2.1 *Disposal Pathway*

For the disposal pathway, landfilling the woody mill residues was assessed with two scenarios: landfill high emissions (LF_highCO2e) and landfill low emissions (LF_lowCO2e). Parameters used to represent the high emissions scenario reflect maximized biogenic CO_2e releases, and thus, maximized methane releases and minimized stored carbon. Parameters used to represent the low emissions scenario reflect minimized biogenic CO_2e emissions, and minimized methane releases and maximum stored carbon. No sensitivity analysis was performed on these two scenarios.

The detailed results show that managing woody mill residues through landfilling generates impact scores of less than zero (i.e., a net potential environmental benefit) only for global warming when the landfilling system is modeled with parameters minimizing the CO_2e emissions (i.e., LF_lowCO2e) In this scenario, the carbon stored in the landfill was enough to offset emissions of methane, thus leading to an environmental benefit for the global warming impact category. When modeled with parameters maximizing CO_2e emissions (i.e., LF_highCO2e), not only does this scenario generate a positive impact score, but it is ranked among the worst 10% of scenarios. In this case, there is little carbon stored in the landfill to offset emissions of methane. Both landfill scenarios are also among the worst scenarios for the ozone depletion, acidification, eutrophication, respiratory effects, and fossil fuel depletion impact categories. Non-carcinogens is the only impact category where the landfill scenarios rank among the top 20% scenarios with lowest impact score. The primary contributing processes and substances to these estimated environmental impacts are detailed in Section 5.3 of this report.

In sum, the results show that managing woody mill residues by disposal in landfill produces impact scores of greater than zero for all impact categories except in the case of global warming, where this impact category's results depend on the selected scenario parameters.

5.2.2.2 *Unconventional Use Pathways*

5.2.2.2.1 *Heat Pathway*

For the heat pathway, the potential environmental impacts of 12 base case scenarios and their associated efficiency and grid mix sensitivity analyses were compiled. Detailed results of the impact scores and ranking for each scenario are shown in Table 5.2, and graphically in Figures 5.4 and 5.5.

As can be seen in Table 5.2, the scenario with the highest number of impact categories with scores of less than zero (i.e., net benefit) regardless of the efficiency of the system or the grid mix used is *syngas in alternative to coal*. In contrast, the scenario with the highest number of impact categories with impact scores of greater than zero (i.e., net impact) regardless of the efficiency of the system or the grid mix used is *pellet in alternative to natural gas*.

Looking at the results of Table 5.2 by column, results from almost all scenarios indicate impact scores of less than zero for global warming, acidification, and fossil fuel depletion. That said, almost all scenarios result in impact scores of greater than zero for non-carcinogens.

When looking at the results of Table 5.2 grouped by their biomass system, the pellet biomass system scenarios have the lowest number of impact categories with impact scores of less than zero. Furthermore, many of the pellet scenarios rank among the bottom 20% scenarios with highest impact score for ozone depletion, smog, and respiratory effects. The syngas biomass system scenarios have the highest number of impact categories with impact scores less than zero in comparison to the other biomass systems, while the results of the methane biomass system fall in between those of the pellet and syngas scenarios.

When grouping the scenarios by their alternative system, coal use scenarios have a higher number of impact categories with impact scores of less than zero.

These results are further explained Section 5.3 of this report, where the main contributing processes and substances to these environmental impacts are detailed.

Table 5.2 Heat Pathway Environmental Impact Score (I.S.) and Ranking (R.) Results

[Impact category columns (I.S. and R. for each): Ozone depletion, Global warming, Smog, Acidification, Eutrophication, Carcinogenics, Non carcinogenics, Respiratory effects, Ecotoxicity, Fossil fuel depletion]

Pathway	Biomass System	Alternative System	Sensitivity analysis	Sensitivity analysis parameter value	Scenario	Number of Impact Categories: I.S. of less than zero (I.S.)	Number of Impact Categories: best 10% env. Effect (R.)	Number of Impact Categories: worse 10% env. Effect (R.)
Heat	Pellet	Natural Gas	efficiency	low	low_H_Pellet_NG	3	0	6
Heat	Pellet	Natural Gas	efficiency	average	H_Pellet_NG	3	0	3
Heat	Pellet	Natural Gas	efficiency	high	high_H_Pellet_NG	3	1	1
Heat	Pellet	Natural Gas	grid mix	QC	QC_H_Pellet_NG	3	1	1
Heat	Pellet	Natural Gas	grid mix	NA	H_Pellet_NG	3	1	1
Heat	Pellet	Natural Gas	grid mix	MRO	MRO_H_Pellet_NG	3	1	2
Heat	Pellet	No.2 Fuel Oil	efficiency	low	low_H_Pellet_F2	2	0	5
Heat	Pellet	No.2 Fuel Oil	efficiency	average	H_Pellet_F2	4	0	2
Heat	Pellet	No.2 Fuel Oil	efficiency	high	high_H_Pellet_F2	5	0	2
Heat	Pellet	No.2 Fuel Oil	grid mix	QC	QC_H_Pellet_F2	4	0	2
Heat	Pellet	No.2 Fuel Oil	grid mix	NA	H_Pellet_F2	4	0	2
Heat	Pellet	No.2 Fuel Oil	grid mix	MRO	MRO_H_Pellet_F2	3	0	2
Heat	Pellet	No.6 Fuel Oil	efficiency	low	low_H_Pellet_F6	3	0	3
Heat	Pellet	No.6 Fuel Oil	efficiency	average	H_Pellet_F6	5	0	0
Heat	Pellet	No.6 Fuel Oil	efficiency	high	high_H_Pellet_F6	6	0	0
Heat	Pellet	No.6 Fuel Oil	grid mix	QC	QC_H_Pellet_F6	5	0	0
Heat	Pellet	No.6 Fuel Oil	grid mix	NA	H_Pellet_F6	5	0	0
Heat	Pellet	No.6 Fuel Oil	grid mix	MRO	MRO_H_Pellet_F6	4	0	0
Heat	Pellet	Coal	efficiency	low	low_H_Pellet_Coal	4	0	2
Heat	Pellet	Coal	efficiency	average	H_Pellet_Coal	7	0	2
Heat	Pellet	Coal	efficiency	high	high_H_Pellet_Coal	8	1	1
Heat	Pellet	Coal	grid mix	QC	QC_H_Pellet_Coal	8	0	1
Heat	Pellet	Coal	grid mix	NA	H_Pellet_Coal	7	0	2
Heat	Pellet	Coal	grid mix	MRO	MRO_H_Pellet_Coal	8	0	2
Heat	Syngas	Natural Gas	efficiency	low	low_H_SG_NG	6	0	0
Heat	Syngas	Natural Gas	efficiency	average	H_SG_NG	6	0	0
Heat	Syngas	Natural Gas	efficiency	high	high_H_SG_NG	7	1	0
Heat	Syngas	Natural Gas	grid mix	QC	QC_H_SG_NG	6	0	0
Heat	Syngas	Natural Gas	grid mix	NA	H_SG_NG	6	0	0
Heat	Syngas	Natural Gas	grid mix	MRO	MRO_H_SG_NG	6	0	0
Heat	Syngas	No.2 Fuel Oil	efficiency	low	low_H_SG_F2	6	0	0
Heat	Syngas	No.2 Fuel Oil	efficiency	average	H_SG_F2	7	0	0
Heat	Syngas	No.2 Fuel Oil	efficiency	high	high_H_SG_F2	7	1	0
Heat	Syngas	No.2 Fuel Oil	grid mix	QC	QC_H_SG_F2	7	0	0
Heat	Syngas	No.2 Fuel Oil	grid mix	NA	H_SG_F2	7	0	0
Heat	Syngas	No.2 Fuel Oil	grid mix	MRO	MRO_H_SG_F2	7	0	0
Heat	Syngas	No.6 Fuel Oil	efficiency	low	low_H_SG_F6	6	0	0
Heat	Syngas	No.6 Fuel Oil	efficiency	average	H_SG_F6	7	0	0
Heat	Syngas	No.6 Fuel Oil	efficiency	high	high_H_SG_F6	7	2	0
Heat	Syngas	No.6 Fuel Oil	grid mix	QC	QC_H_SG_F6	7	0	0
Heat	Syngas	No.6 Fuel Oil	grid mix	NA	H_SG_F6	7	0	0
Heat	Syngas	No.6 Fuel Oil	grid mix	MRO	MRO_H_SG_F6	7	0	0
Heat	Syngas	Coal	efficiency	low	low_H_SG_Coal	7	0	1
Heat	Syngas	Coal	efficiency	average	H_SG_Coal	9	0	0
Heat	Syngas	Coal	efficiency	high	high_H_SG_Coal	9	3	0
Heat	Syngas	Coal	grid mix	QC	QC_H_SG_Coal	9	0	0
Heat	Syngas	Coal	grid mix	NA	H_SG_Coal	9	0	0
Heat	Syngas	Coal	grid mix	MRO	MRO_H_SG_Coal	9	0	0
Heat	Methane	Natural Gas	efficiency	low	low_H_CH4_NG	5	0	1
Heat	Methane	Natural Gas	efficiency	average	H_CH4_NG	5	0	0
Heat	Methane	Natural Gas	efficiency	high	high_H_CH4_NG	5	0	0
Heat	Methane	Natural Gas	grid mix	QC	QC_H_CH4_NG	5	0	0
Heat	Methane	Natural Gas	grid mix	NA	H_CH4_NG	5	0	0
Heat	Methane	Natural Gas	grid mix	MRO	MRO_H_CH4_NG	5	0	2
Heat	Methane	No.2 Fuel Oil	efficiency	low	low_H_CH4_F2	4	0	1
Heat	Methane	No.2 Fuel Oil	efficiency	average	H_CH4_F2	5	0	0
Heat	Methane	No.2 Fuel Oil	efficiency	high	high_H_CH4_F2	5	0	0
Heat	Methane	No.2 Fuel Oil	grid mix	QC	QC_H_CH4_F2	5	0	0
Heat	Methane	No.2 Fuel Oil	grid mix	NA	H_CH4_F2	5	0	0
Heat	Methane	No.2 Fuel Oil	grid mix	MRO	MRO_H_CH4_F2	5	0	2
Heat	Methane	No.6 Fuel Oil	efficiency	low	low_H_CH4_F6	5	0	0
Heat	Methane	No.6 Fuel Oil	efficiency	average	H_CH4_F6	5	0	0
Heat	Methane	No.6 Fuel Oil	efficiency	high	high_H_CH4_F6	6	0	0
Heat	Methane	No.6 Fuel Oil	grid mix	QC	QC_H_CH4_F6	7	0	0
Heat	Methane	No.6 Fuel Oil	grid mix	NA	H_CH4_F6	5	0	0
Heat	Methane	No.6 Fuel Oil	grid mix	MRO	MRO_H_CH4_F6	5	0	2
Heat	Methane	Coal	efficiency	low	low_H_CH4_Coal	5	0	1
Heat	Methane	Coal	efficiency	average	H_CH4_Coal	7	0	1
Heat	Methane	Coal	efficiency	high	high_H_CH4_Coal	9	0	1
Heat	Methane	Coal	grid mix	QC	QC_H_CH4_Coal	9	0	0
Heat	Methane	Coal	grid mix	NA	H_CH4_Coal	7	0	1
Heat	Methane	Coal	grid mix	MRO	MRO_H_CH4_Coal	7	0	1

LEGEND According to uncertainty criteria, impact score : Less than zero Greater than zero Neutral

Ranked amongst the: best 10% best 10-20% worse 10-20% worse 10% In between best 20% and worse 20%

top performing scenarios with more than seven impact scores with impact score of less than zero or within the top 10% of scenarios with lowest impact score

Note: In the table above, base case results are depicted twice, once under the efficiency sensitivity analysis (showed as average) and once under the grid mix sensitivity analysis (showed as NA).

The heat pathway scenarios are sensitive to the relative efficiency of the biomass system as seen in Figure 5.4, where the error bars represent the results of the "efficiency" sensitivity analyses. Lower biomass system efficiency (e.g., via lower production yield or combustion efficiency) results in higher impact scores and vice versa. This is anticipated, given that higher combustion efficiency is known to reduce most environmental releases (NCASI 2004). It can also be seen from Figure 5.5 that the scenarios from the heat pathway are not sensitive to a change in grid mix, despite the electricity mixes tested in sensitivity analysis having very different environmental profiles. This is likely because the relative environmental effects due to the electricity component of the scenarios are small in comparison to those within the combustion system itself. Hence, the potential environmental impacts of the heat pathway are not geographically dependent when it comes to the locally available grid mix.

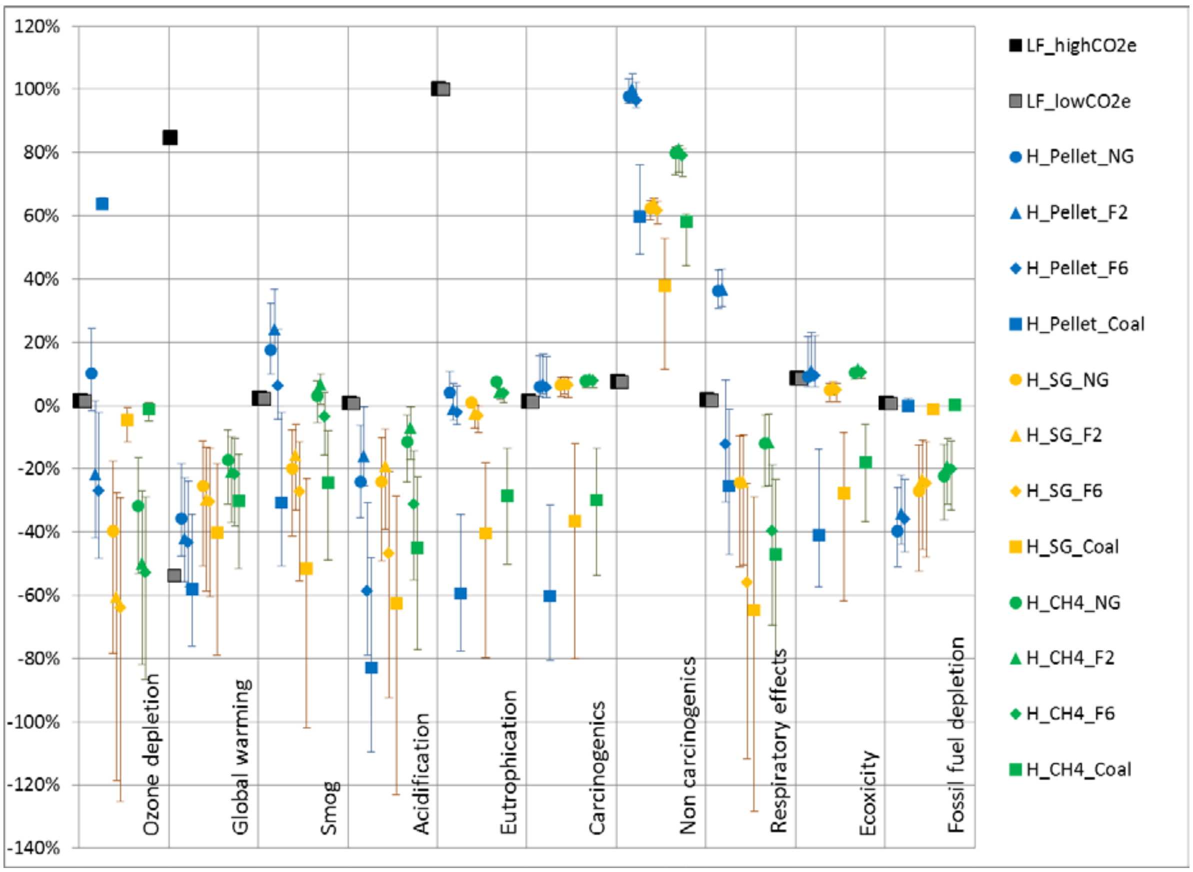


Figure 5.4 Heat Pathway Scenarios Potential Environmental Impacts Normalized Against the Absolute Value of the Scenario with the Maximum Potential Environmental Impact of the 54 Scenarios for Each Impact Category [Geographic markers represent base case scenarios, while error bars represent scenarios with parameters representing minimum and maximum efficiency across the biomass system value chain.]

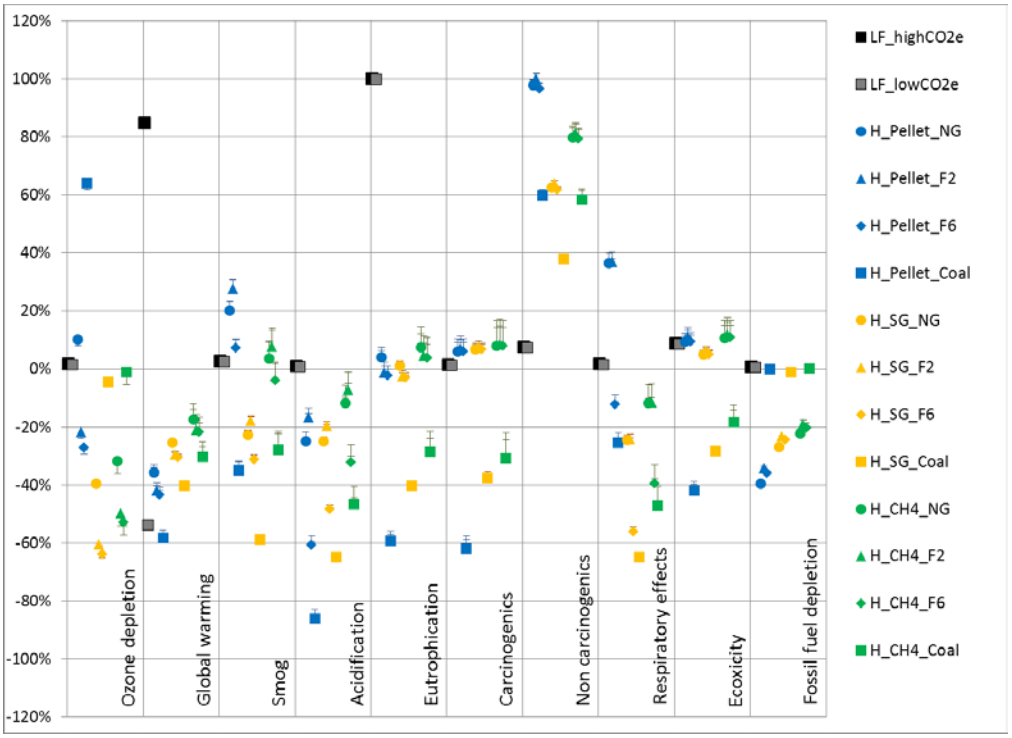


Figure 5.5 Heat Pathway Scenarios Potential Environmental Impacts Normalized Against the Absolute Value of the Scenario with the Maximum Potential Environmental Impact of the 54 Scenarios for Each Impact Category
[Geographic marker represents base case scenarios, while error bars represent scenario with grid mix representing Quebec and MRO region across the biomass system value chain.]

5.2.2.2.2 *Combined Heat and Power Pathway*

The CHP pathway was separated between CHP with high heat-to-power ratio (CHPh) and low heat-to-power ratio (CHPe) to limit the number of scenarios under this pathway and for ease of interpretation and clear presentation of the results.

5.2.2.2.2.1 *CHP Maximized for Heat Production (High Heat-to-Power Ratio)*

For the combined heat and power pathway maximized for heat production, the potential environmental impacts of 15 base case scenarios and their associated sensitivity analyses were compiled. The impact scores and their rankings of all scenarios are shown in Table 5.3, and graphically in Figures 5.6 and 5.7.

In Table 5.3, it can be seen that the scenarios with the highest number of impact categories with impact scores of less than zero (i.e., net benefit) regardless of the efficiency of the system or the grid mix used are *syngas in alternative to coal* and *methane in alternative to coal*. In contrast, the scenario with the highest number of impact categories with impact scores of greater than zero (i.e., net impact) regardless of the efficiency of the system or the grid mix used is *pellet in alternative to natural gas for heat and electricity production*.

Looking at the results of Table 5.3 by column, results from all scenarios indicate improved impact scores for global warming, acidification, and fossil fuel depletion. In contrast, all scenarios result in net environmental impact scores for non-carcinogens.

When looking at one biomass system at a time, the results of Table 5.3 for pellets show that these scenarios have the lowest number of impact categories with impact scores of less than zero in comparison to the other biomass systems. Furthermore, many of the pellet scenarios rank among the bottom 20% scenarios with highest impact score for ozone depletion, smog, and respiratory effects. Interestingly, when combined heat and electricity are produced with average-to-high efficiency pellet systems instead of heat from coal and electricity from North America or MRO regions, eight impact categories out of ten show potential impact scores of less than zero. In contrast, impact scores of greater than zero are seen for ozone depletion and non-carcinogens. In addition, for ozone depletion, the impact score is among the worst 10% of all scenarios. Otherwise, one other pellet-based system configuration is of interest because of its high number of impact categories with favorable scores (i.e., impact scores of less than zero): high efficiency pellets to replace No. 6 fuel oil/North American average electricity.

As for the syngas biomass system, except when used in replacement of natural gas for heat and electricity production, seven to nine impact categories out of ten indicate impact scores of less than zero whatever the efficiency or grid mix of the biomass system, and three impact categories (carcinogens, non-carcinogens, and ecotoxicity) result in impact scores of greater than or equal to zero.

For the methane biomass system, the results show that seven to nine impact categories out of ten indicate impact scores of less than zero when replacing coal/electricity. Otherwise, if methane replaces natural gas/electricity, natural gas/natural gas, No. 2 fuel oil/electricity, or No. 6 fuel oil/electricity, the number of impact categories with impact scores of less than zero is, on average, six out of ten. Impact categories that result in impact scores equal to or greater than zero include smog, eutrophication, carcinogens, non-carcinogens, and ecotoxicity.

Table 5.3 Combined Heat and Power Pathway Maximized for Heat Production Environmental Impact Score and Ranking Results

Pathway	Biomass System	Alternative System	Sensitivity analysis	Sensitivity analysis parameter value	Scenario	Number of Impact Categories: I.S. of less than zero (I.S.)	Number of Impact Categories: best 10% env. Effect (R.)	Number of Impact Categories: worse 10% env. Effect (R.)
Combined Heat and electricity - heat maximized	Pellet	Natural gas - Electricity	efficiency	low	low_CHPh_Pellet_NG_E	4	0	3
				average	CHPh_Pellet_NG_E	4	0	2
				high	high_CHPh_Pellet_NG_E	6	0	0
			grid mix	QC	QC_CHPh_Pellet_NG_E	4	0	3
				NA	CHPh_Pellet_NG_E	4	0	2
				MRO	MRO_CHPh_Pellet_NG_E	6	0	1
		Natrual gas - Natural gas	efficiency	low	low_CHPh_Pellet_NG_2X	3	0	5
				average	CHPh_Pellet_NG_2X	3	0	1
				high	high_CHPh_Pellet_NG_2X	3	1	0
			grid mix	QC	QC_CHPh_Pellet_NG_2X	3	1	1
				NA	CHPh_Pellet_NG_2X	3	1	1
				MRO	MRO_CHPh_Pellet_NG_2X	3	1	1
		No.2 Fuel oil - Electricity	efficiency	low	low_CHPh_Pellet_F2_E	4	0	2
				average	CHPh_Pellet_F2_E	4	0	1
				high	high_CHPh_Pellet_F2_E	6	0	0
			grid mix	QC	QC_CHPh_Pellet_F2_E	4	0	2
				NA	CHPh_Pellet_F2_E	4	0	1
				MRO	MRO_CHPh_Pellet_F2_E	6	0	0
		No.6 Fuel oil - Electricity	efficiency	low	low_CHPh_Pellet_F6_E	4	0	1
				average	CHPh_Pellet_F6_E	5	0	0
				high	high_CHPh_Pellet_F6_E	8	0	0
			grid mix	QC	QC_CHPh_Pellet_F6_E	4	0	0
				NA	CHPh_Pellet_F6_E	5	0	0
				MRO	MRO_CHPh_Pellet_F6_E	7	0	0
		Coal - Electricity	efficiency	low	low_CHPh_Pellet_Coal_E	5	0	2
				average	CHPh_Pellet_Coal_E	8	0	1
				high	high_CHPh_Pellet_Coal_E	8	1	1
			grid mix	QC	QC_CHPh_Pellet_Coal_E	6	0	2
				NA	CHPh_Pellet_Coal_E	8	0	1
				MRO	MRO_CHPh_Pellet_Coal_E	8	1	1

(Continued on next page. See note at end of table.)

Table 5.3 Continued

Pathway	Biomass System	Alternative System	Sensitivity analysis	Sensitivity analysis parameter value	Scenario	Ozone depletion	Global warming	Smog	Acidification	Eutrophication	Carcinogenics	Non carcinogenics	Respiratory effects	Ecotoxicity	Fossil fuel depletion	Number of Impact Categories: I.S. of less than zero (I.S.)	Number of Impact Categories: best 10% env. Effect (R.)	Number of Impact Categories: worse 10% env. Effect (R.)
Combined Heat and electricity - heat maximized	Syngas	Natural gas - Electricity	efficiency	low	low_CHPh_SG_NG_E											7	0	0
				average	CHPh_SG_NG_E											7	0	0
				high	high_CHPh_SG_NG_E											9	0	0
			grid mix	QC	QC_CHPh_SG_NG_E											7	0	0
				NA	CHPh_SG_NG_E											7	0	0
				MRO	MRO_CHPh_SG_NG_E											9	0	0
		Natrual gas - Natural gas	efficiency	low	low_CHPh_SG_NG_2X											6	0	0
				average	CHPh_SG_NG_2X											6	0	0
				high	high_CHPh_SG_NG_2X											7	1	0
			grid mix	QC	QC_CHPh_SG_NG_2X											7	0	0
				NA	CHPh_SG_NG_2X											6	0	0
				MRO	MRO_CHPh_SG_NG_2X											6	0	0
		No.2 Fuel oil - Electricity	efficiency	low	low_CHPh_SG_F2_E											7	0	0
				average	CHPh_SG_F2_E											7	0	0
				high	high_CHPh_SG_F2_E											9	1	0
			grid mix	QC	QC_CHPh_SG_F2_E											7	0	0
				NA	CHPh_SG_F2_E											7	0	0
				MRO	MRO_CHPh_SG_F2_E											9	0	0
		No.6 Fuel oil - Electricity	efficiency	low	low_CHPh_SG_F6_E											7	0	0
				average	CHPh_SG_F6_E											7	0	0
				high	high_CHPh_SG_F6_E											9	2	0
			grid mix	QC	QC_CHPh_SG_F6_E											7	0	0
				NA	CHPh_SG_F6_E											7	0	0
				MRO	MRO_CHPh_SG_F6_E											9	0	0
		Coal - Electricity	efficiency	low	low_CHPh_SG_Coal_E											9	0	0
				average	CHPh_SG_Coal_E											9	0	0
				high	high_CHPh_SG_Coal_E											9	4	0
			grid mix	QC	QC_CHPh_SG_Coal_E											9	0	0
				NA	CHPh_SG_Coal_E											9	0	0
				MRO	MRO_CHPh_SG_Coal_E											9	0	0

(Continued on next page. See note at end of table.)

Table 5.3 Continued

Pathway	Biomass System	Alternative System	Sensitivity analysis	Sensitivity analysis parameter value	Scenario	Ozone depletion I.S.	Ozone depletion R.	Global warming I.S.	Global warming R.	Smog I.S.	Smog R.	Acidification I.S.	Acidification R.	Eutrophication I.S.	Eutrophication R.	Carcinogenics I.S.	Carcinogenics R.	Non carcinogenics I.S.	Non carcinogenics R.	Respiratory effects I.S.	Respiratory effects R.	Ecotoxicity I.S.	Ecotoxicity R.	Fossil fuel depletion I.S.	Fossil fuel depletion R.	Number of Impact Categories: I.S. of less than zero (I.S.)	Number of Impact Categories: best 10% env. Effect (R.)	Number of Impact Categories: worse 10% env. Effect (R.)
Combined Heat and electricity - heat maximized	Methane	Natural gas - Electricity	efficiency	low	low_CHPh_CH4_NG_E	−		−	worse 10-20%	+	worse 10-20%	−		+		○		+		−		○		−		5	0	0
				average	CHPh_CH4_NG_E	−		−		○		−		−		○		+		−		○		−		6	0	0
				high	high_CHPh_CH4_NG_E	−		−		−		−		−		○		+		−		○		−		7	0	0
			grid mix	QC	QC_CHPh_CH4_NG_E	−		−		○		−		+		○		+		−		○		−		5	0	0
				NA	CHPh_CH4_NG_E	−		−		○		−		−		○		+		−		○		−		6	0	0
				MRO	MRO_CHPh_CH4_NG_E	−		−		○		−		−		○		+		−		○		−		6	0	0
		Natrual gas - Natural gas	efficiency	low	low_CHPh_CH4_NG_2X	−		−	worse 10-20%	○		−		+	worse 10-20%	+		+		−		+		−		5	0	0
				average	CHPh_CH4_NG_2X	−		−		○		−		+	worse 10-20%	+		+		−		+		−		5	0	0
				high	high_CHPh_CH4_NG_2X	−		−		−		−		+	worse 10-20%	+		+		−		+		−	best 10-20%	6	0	0
			grid mix	QC	QC_CHPh_CH4_NG_2X	−		−		−		−		+		○		+		−		+		−		6	0	0
				NA	CHPh_CH4_NG_2X	−		−		○		−		+	worse 10-20%	+		+		−		+		−		5	0	0
				MRO	MRO_CHPh_CH4_NG_2X	−		−		○		−		+	worse 10%	+	worse 10%	+		−		+	worse 10-20%	−		5	0	2
		No.2 Fuel oil - Electricity	efficiency	low	low_CHPh_CH4_F2_E	−		−	worse 10-20%	+	worse 10-20%	−	worse 10-20%	○		○		+		−		+		−		5	0	0
				average	CHPh_CH4_F2_E	−		−		○		−		−		○		+		−		○		−		6	0	0
				high	high_CHPh_CH4_F2_E	−		−		○		−		−		○		+		−		○		−		6	0	0
			grid mix	QC	QC_CHPh_CH4_F2_E	−		−		+	worse 10-20%	−		−		○		+		−		○		−		6	0	0
				NA	CHPh_CH4_F2_E	−		−		○		−		−		○		+		−		○		−		6	0	0
				MRO	MRO_CHPh_CH4_F2_E	−		−		○		−		−		○		+		−		○		−		6	0	0
		No.6 Fuel oil - Electricity	efficiency	low	low_CHPh_CH4_F6_E	−		−	worse 10-20%	○		−		○		○		+		−		○		−		5	0	0
				average	CHPh_CH4_F6_E	−		−		○		−		−		○		+		−		○		−		6	0	0
				high	high_CHPh_CH4_F6_E	−	best 10-20%	−		−		−		−		○		+		−	best 10-20%	○		−		7	0	0
			grid mix	QC	QC_CHPh_CH4_F6_E	−		−		○		−		−		○		+		−		○		−		6	0	0
				NA	CHPh_CH4_F6_E	−		−		○		−		−		○		+		−		○		−		6	0	0
				MRO	MRO_CHPh_CH4_F6_E	−		−		○		−		−		○		+		−		○		−		6	0	0
		Coal - Electricity	efficiency	low	low_CHPh_CH4_COAL_E	−		−		○		−		−		−		+		−		○		−	worse 10%	7	0	1
				average	CHPh_CH4_COAL_E	−		−		−		−		−		−		+		−		−		−	worse 10-20%	9	0	0
				high	high_CHPh_CH4_COAL_E	−		−		−		−		−		−		+		−	best 10-20%	−		−	worse 10-20%	9	0	0
			grid mix	QC	QC_CHPh_CH4_COAL_E	−		−		−		−		−		−		+		−		−		−	worse 10-20%	9	0	0
				NA	CHPh_CH4_COAL_E	−		−		−		−		−		−		+		−		−		−		9	0	0
				MRO	MRO_CHPh_CH4_COAL_E	−		−		−		−		−		−		+		−		−		−		9	0	0

LEGEND According to uncertainty criteria, impact score : − Less than zero + Greater than zero ○ Neutral

Ranked amongst the: best 10% best 10-20% worse 10-20% worse 10% In between best 20% and worse 20%

top performing scenarios with more than seven impact scores with impact score of less than zero or within the top 10% of scenarios with lowest impact score

Note: In the table above, base case results are depicted twice, once under the efficiency sensitivity analysis (showed as average) and once under the grid mix sensitivity analysis (showed as NA).

The results for sensitivity analyses to gauge the effect of the efficiency of the combined heat and power maximized for heat production scenarios (CHPh) are shown in Figure 5.6 and are very similar to those of the heat pathway shown in Figure 5.4, with good reason. For the heat pathway and combined heat and power pathway, the biomass systems are the same; only the alternative system varies. Adding electricity to the alternative systems slightly increases the number of impact scores less than zero for most scenarios and it renders the CHPh scenarios sensitive to the change of grid mix, as illustrated in Figure 5.7.

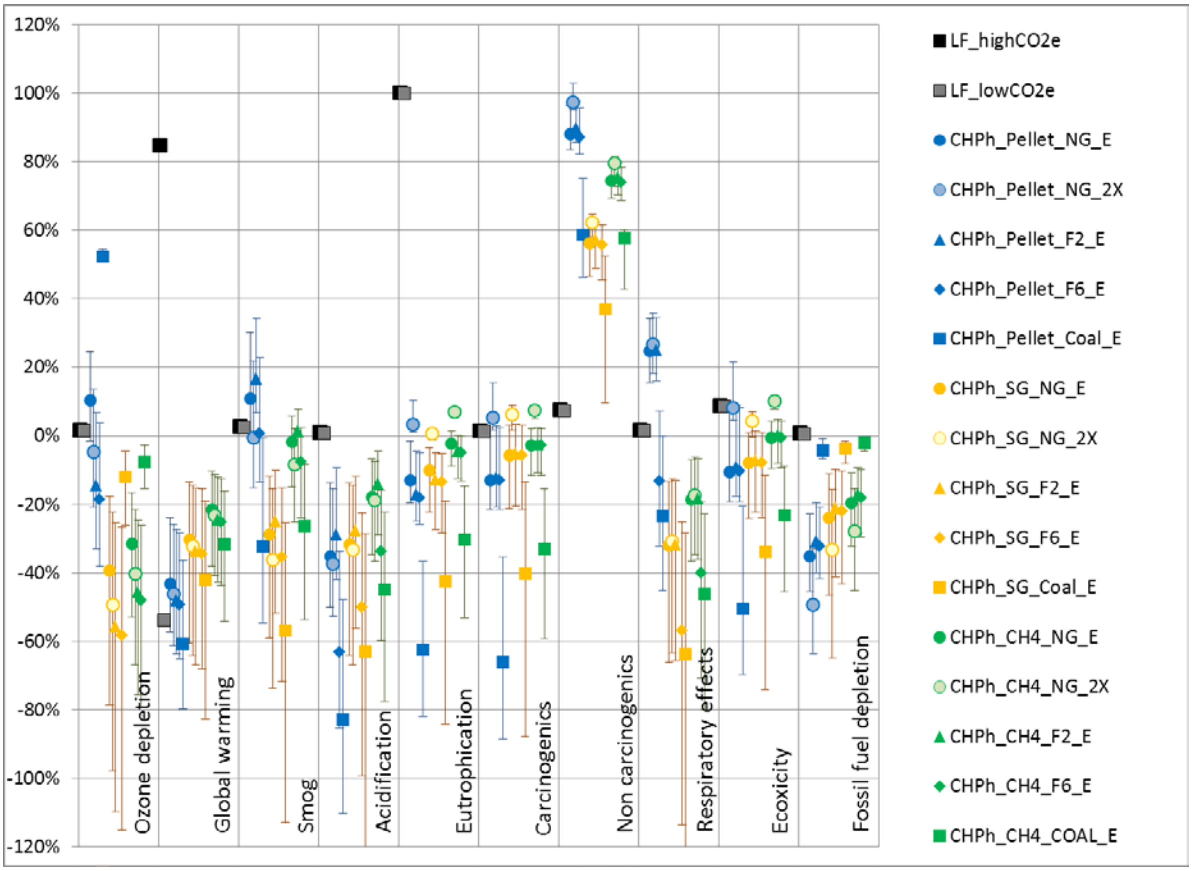


Figure 5.6 Combined Heat and Power Pathway Scenarios Maximized for Heat Production Potential Environmental Impacts Normalized Against the Absolute Value of the Scenario with the Maximum Potential Environmental Impact of the 54 Scenarios for Each Impact Category
[Geographic marker represents base case scenarios, while error bars represent scenario with parameters representing minimum and maximum efficiency across the biomass system value chain.]

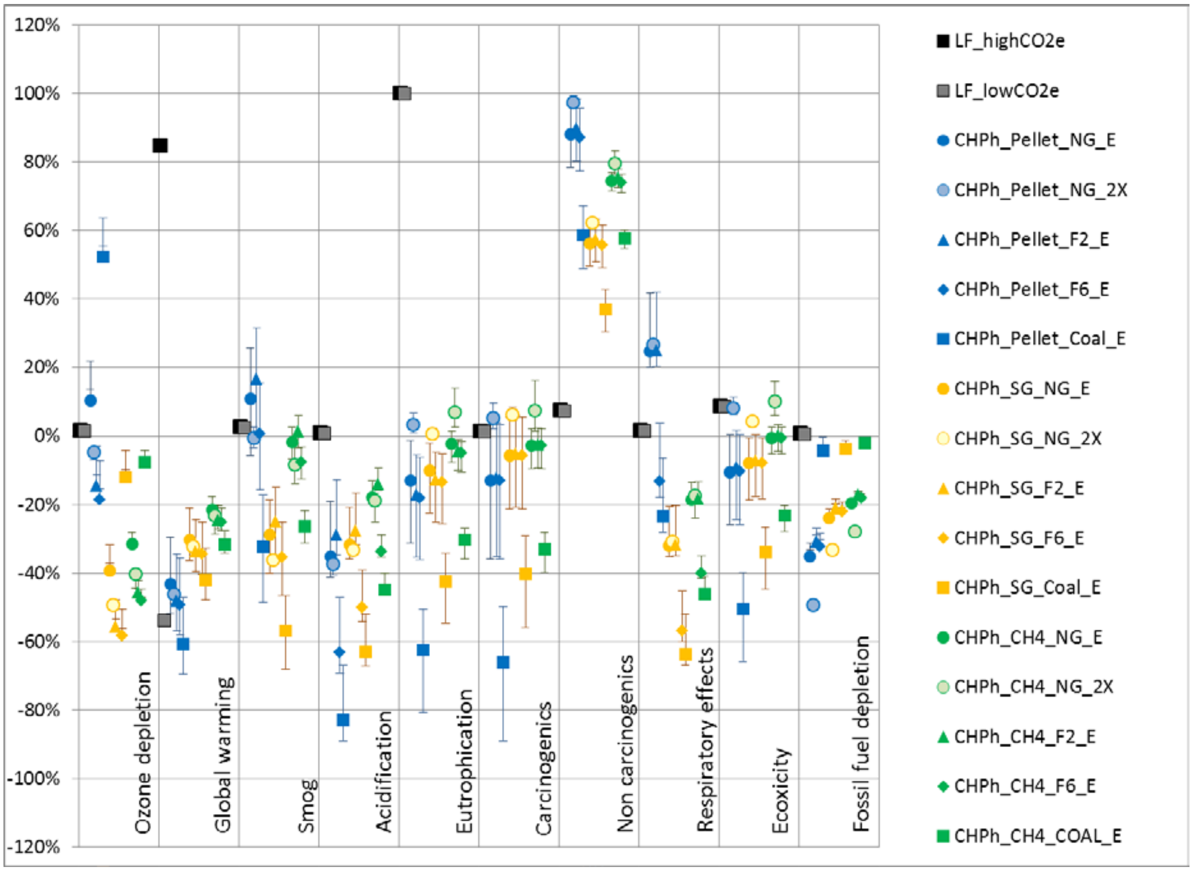


Figure 5.7 Combined Heat and Power Pathway Scenarios Maximized for Heat Production Potential Environmental Impacts Normalized Against the Absolute Value of the Scenario with the Maximum Potential Environmental Impact of the 54 Scenarios for Each Impact Category [Geographic marker represents base case scenarios, while error bars represent scenario with grid mix representing Quebec and MRO region across the biomass system value chain and for the electricity replaced in the alternative system.]

5.2.2.2.2.2 *CHP Maximized for Electricity Production (Low Heat-to-Power Ratio)*

For the combined heat and power pathway maximized for electricity production, the potential environmental impacts of 15 base case scenarios and their associated efficiency and grid mix sensitivity analyses were compiled. The impact scores and the rankings of all scenarios are shown in Table 5.4, and graphically in Figures 5.8 and 5.9.

As seen in Table 5.4, the scenarios result in seven to nine impact categories having impact scores of less than zero (i.e., net benefit), except when heat and electricity are produced and used in areas where the grid mix is mainly based on hydroelectricity (QC) or when the biomass system replaces natural gas for heat and electricity. Ozone depletion, smog, and non-carcinogens are the impact categories for which the impact score results show impact scores equal to or greater than zero. Moreover, most of the impact scores for the pellet and syngas biomass system scenarios are among the top 20% of scenarios with the lowest impact scores.

Looking at Table 5.4 by column, it can be observed that impact scores are less than zero for most scenarios when it comes to global warming, smog, acidification, eutrophication, respiratory effects, and fossil fuel depletion. In contrast, impact score results are zero or greater when it comes to non-carcinogens.

When looking at one biomass system at a time, the results shown in Table 5.4 for pellets illustrate that when pellets are used to produce heat and electricity with average-to-high efficiency, displacing electricity supplied by the North American or MRO electricity mix, eight impact categories out of ten show impact scores of less than zero. Results for ozone depletion and non-carcinogens are equal to or greater than zero. If pellets with low efficiency parameters are used to produce heat and electricity, displacing electricity supplied by North American electricity mix, the smog impact category score is no longer less than zero, thus reducing the number of impact categories with scores less than zero to seven out of ten. If pellets are used to produce heat and electricity with base case parameter efficiency settings, displacing electricity supplied by the Quebec electricity mix, only two impact categories have impact scores of less than zero: eutrophication and ecotoxicity. As for pellet scenarios displacing natural gas as the heat and electricity energy source, it is interesting to note that for all scenarios except those with low efficiency parameter settings, the six impact categories out of ten that result in impact scores less than zero are also among the top 20% scenarios with the lowest impact score results.

For syngas, except when electricity is produced from the Quebec region in the alternative system or used in replacement of natural gas for heat and electricity production, nine categories out of ten have impact scores of less than zero regardless of the efficiency level of the biomass system. The non-carcinogens impact category is the one having impact scores equal to or greater than zero. Furthermore, for scenarios with high biomass efficiency or the MRO electricity mix, the scenarios almost all rank in the top 10% scenarios with the lowest impact score results for most impact categories.

For the methane biomass system, there are also nine out of ten impact categories that result in impact scores of less than zero, except when heat and electricity are produced and used in areas where the grid mix is mainly based on hydroelectricity (QC) or when the biomass system replaces natural gas for heat and electricity. Once again, the non-carcinogens impact scores are equal to or greater than zero.

Table 5.4 Combined Heat and Power Pathway Maximized for Electricity Production Environmental Impact Score and Ranking Results

Pathway	Biomass System	Alternative System	Sensitivity analysis	Sensitivity analysis parameter value	Scenario	Ozone depletion		Global warming		Smog		Acidification		Eutrophication		Carcinogenics		Non carcinogenics		Respiratory effects		Ecotoxicity		Fossil fuel depletion		Number of Impact Categories: I.S. of less than zero	Number of Impact Categories: best 10% env. Effect	Number of Impact Categories: worse 10% env. Effect
						I.S.	R.	I.S.	R.	I.S.	R.	I.S.	R.	I.S.	R.	I.S.	R.	I.S.	R.	I.S.	R.	I.S.	R.	I.S.	R.	I.S.	R.	R.
Combined Heat and electricity - power maximized	Pellet	Natural gas - Electricity	efficiency	low	low_CHPe_Pellet_NG_E																					7	0	1
				average	CHPe_Pellet_NG_E																					8	1	0
				high	high_CHPe_Pellet_NG_E																					8	3	0
			grid mix	QC	QC_CHPe_Pellet_NG_E																					2	0	5
				NA	CHPe_Pellet_NG_E																					8	4	0
				MRO	MRO_CHPe_Pellet_NG_E																					8	7	1
		Natrual gas - Natural gas	efficiency	low	low_CHPe_Pellet_NG_2X																					5	1	0
				average	CHPe_Pellet_NG_2X																					6	3	0
				high	high_CHPe_Pellet_NG_2X																					7	5	0
			grid mix	QC	QC_CHPe_Pellet_NG_2X																					7	5	0
				NA	CHPe_Pellet_NG_2X																					6	5	0
				MRO	MRO_CHPe_Pellet_NG_2X																					6	5	0
		No.2 Fuel oil - Electricity	efficiency	low	low_CHPe_Pellet_F2_E																					7	0	1
				average	CHPe_Pellet_F2_E																					8	1	0
				high	high_CHPe_Pellet_F2_E																					8	3	0
			grid mix	QC	QC_CHPe_Pellet_F2_E																					2	0	5
				NA	CHPe_Pellet_F2_E																					8	4	0
				MRO	MRO_CHPe_Pellet_F2_E																					8	7	1
		No.6 Fuel oil - Electricity	efficiency	low	low_CHPe_Pellet_F6_E																					7	0	1
				average	CHPe_Pellet_F6_E																					8	1	0
				high	high_CHPe_Pellet_F6_E																					8	3	0
			grid mix	QC	QC_CHPe_Pellet_F6_E																					2	0	5
				NA	CHPe_Pellet_F6_E																					8	4	0
				MRO	MRO_CHPe_Pellet_F6_E																					8	7	1
		Coal - Electricity	efficiency	low	low_CHPe_Pellet_Coal_E																					7	0	1
				average	CHPe_Pellet_Coal_E																					8	1	0
				high	high_CHPe_Pellet_Coal_E																					8	5	0
			grid mix	QC	QC_CHPe_Pellet_Coal_E																					2	0	6
				NA	CHPe_Pellet_Coal_E																					8	5	0
				MRO	MRO_CHPe_Pellet_Coal_E																					8	7	1

(Continued on next page. See notes at end of table.)

Table 5.4 Continued

Pathway	Biomass System	Alternative System	Sensitivity analysis	Sensitivity analysis parameter value	Scenario	Ozone depletion	Global warming	Smog	Acidification	Eutrophication	Carcinogenics	Non carcinogenics	Respiratory effects	Ecotoxicity	Fossil fuel depletion	Number of Impact Categories: I.S. of less than zero (I.S.)	Number of Impact Categories: best 10% env. Effect (R.)	Number of Impact Categories: worse 10% env. Effect (R.)
Combined Heat and electricity - power maximized	Syngas	Natural gas - Electricity	efficiency	low	low_CHPe_SG_NG_E											9	0	0
				average	CHPe_SG_NG_E											9	0	0
				high	high_CHPe_SG_NG_E											9	7	0
			grid mix	QC	QC_CHPe_SG_NG_E											4	0	1
				NA	CHPe_SG_NG_E											9	0	0
				MRO	MRO_CHPe_SG_NG_E											9	7	0
		Natrual gas - Natural gas	efficiency	low	low_CHPe_SG_NG_2X											6	0	0
				average	CHPe_SG_NG_2X											7	2	0
				high	high_CHPe_SG_NG_2X											7	6	0
			grid mix	QC	QC_CHPe_SG_NG_2X											7	3	0
				NA	CHPe_SG_NG_2X											7	3	0
				MRO	MRO_CHPe_SG_NG_2X											6	3	0
		No.2 Fuel oil - Electricity	efficiency	low	low_CHPe_SG_F2_E											9	0	0
				average	CHPe_SG_F2_E											9	0	0
				high	high_CHPe_SG_F2_E											9	7	0
			grid mix	QC	QC_CHPe_SG_F2_E											5	0	1
				NA	CHPe_SG_F2_E											9	0	0
				MRO	MRO_CHPe_SG_F2_E											9	7	0
		No.6 Fuel oil - Electricity	efficiency	low	low_CHPe_SG_F6_E											9	0	0
				average	CHPe_SG_F6_E											9	0	0
				high	high_CHPe_SG_F6_E											9	7	0
			grid mix	QC	QC_CHPe_SG_F6_E											3	0	1
				NA	CHPe_SG_F6_E											9	1	0
				MRO	MRO_CHPe_SG_F6_E											9	8	0
		Coal - Electricity	efficiency	low	low_CHPe_SG_Coal_E											9	0	0
				average	CHPe_SG_Coal_E											9	0	0
				high	high_CHPe_SG_Coal_E											9	8	0
			grid mix	QC	QC_CHPe_SG_Coal_E											3	0	2
				NA	CHPe_SG_Coal_E											9	1	0
				MRO	MRO_CHPe_SG_Coal_E											9	8	0

(Continued on next page. See notes at end of table.)

Table 5.4 Continued

Pathway	Biomass System	Alternative System	Sensitivity analysis	Sensitivity analysis parameter value	Scenario	Number of Impact Categories: I.S. of less than zero (I.S.)	best 10% env. Effect (R.)	worse 10% env. Effect (R.)
Combined Heat and electricity - power maximized	Methane	Natural gas - Electricity	efficiency	low	low_CHPe_CH4_NG_E	9	0	0
				average	CHPe_CH4_NG_E	9	0	0
				high	high_CHPe_CH4_NG_E	9	1	0
			grid mix	QC	QC_CHPe_CH4_NG_E	2	0	2
				NA	CHPe_CH4_NG_E	9	0	0
				MRO	MRO_CHPe_CH4_NG_E	9	3	0
		Natrual gas - Natural gas	efficiency	low	low_CHPe_CH4_NG_2X	6	0	0
				average	CHPe_CH4_NG_2X	6	1	0
				high	high_CHPe_CH4_NG_2X	6	3	0
			grid mix	QC	QC_CHPe_CH4_NG_2X	6	2	0
				NA	CHPe_CH4_NG_2X	6	2	0
				MRO	MRO_CHPe_CH4_NG_2X	6	2	1
		No.2 Fuel oil - Electricity	efficiency	low	low_CHPe_CH4_F2_E	9	0	0
				average	CHPe_CH4_F2_E	9	0	0
				high	high_CHPe_CH4_F2_E	9	1	0
			grid mix	QC	QC_CHPe_CH4_F2_E	2	0	2
				NA	CHPe_CH4_F2_E	9	0	0
				MRO	MRO_CHPe_CH4_F2_E	9	3	0
		No.6 Fuel oil - Electricity	efficiency	low	low_CHPe_CH4_F6_E	9	0	0
				average	CHPe_CH4_F6_E	9	0	0
				high	high_CHPe_CH4_F6_E	9	1	0
			grid mix	QC	QC_CHPe_CH4_F6_E	2	0	2
				NA	CHPe_CH4_F6_E	9	0	0
				MRO	MRO_CHPe_CH4_F6_E	9	3	0
		Coal - Electricity	efficiency	low	low_CHPe_CH4_Coal_E	9	0	0
				average	CHPe_CH4_Coal_E	9	0	0
				high	high_CHPe_CH4_Coal_E	9	1	0
			grid mix	QC	QC_CHPe_CH4_Coal_E	3	0	3
				NA	CHPe_CH4_Coal_E	9	0	0
				MRO	MRO_CHPe_CH4_Coal_E	9	3	0

Impact categories (I.S. / R. columns): Ozone depletion, Global warming, Smog, Acidification, Eutrophication, Carcinogenics, Non carcinogenics, Respiratory effects, Ecotoxicity, Fossil fuel depletion

LEGEND According to uncertainty criteria, impact score : Less than zero Greater than zero Neutral

Ranked amongst the: best 10% best 10-20% worse 10-20% worse 10% In between best 20% and worse 20%

top performing scenarios with more than seven impact scores with impact score of less than zero or within the top 10% of scenarios with lowest impact score

Note: In the table above, base case results are depicted twice, once under the efficiency sensitivity analysis (showed as average) and once under the grid mix sensitivity analysis (showed as NA).

Results for the sensitivity analyses show that the scenarios for the combined heat and power pathway maximized for electricity production are sensitive to the "efficiency" of the biomass system, as seen in Figure 5.8, and are also sensitive to the grid mix composition, as seen in Figure 5.9. Lower biomass system efficiency results in higher impact scores and vice versa. This is anticipated, given that higher combustion efficiency is known to reduce most environmental releases (NCASI 2004). In terms of the grid mix, using a MRO grid mix results in lower impact score results for most impact categories, while using a Quebec grid mix results in higher impact score results. As the energy produced by the alternative system is composed of 94.7% electricity supplied by the grid in four out of five scenarios, and because the electricity mixes tested in sensitivity analyses have very different environmental profiles, the choice of one mix versus another has a significant effect on the results.

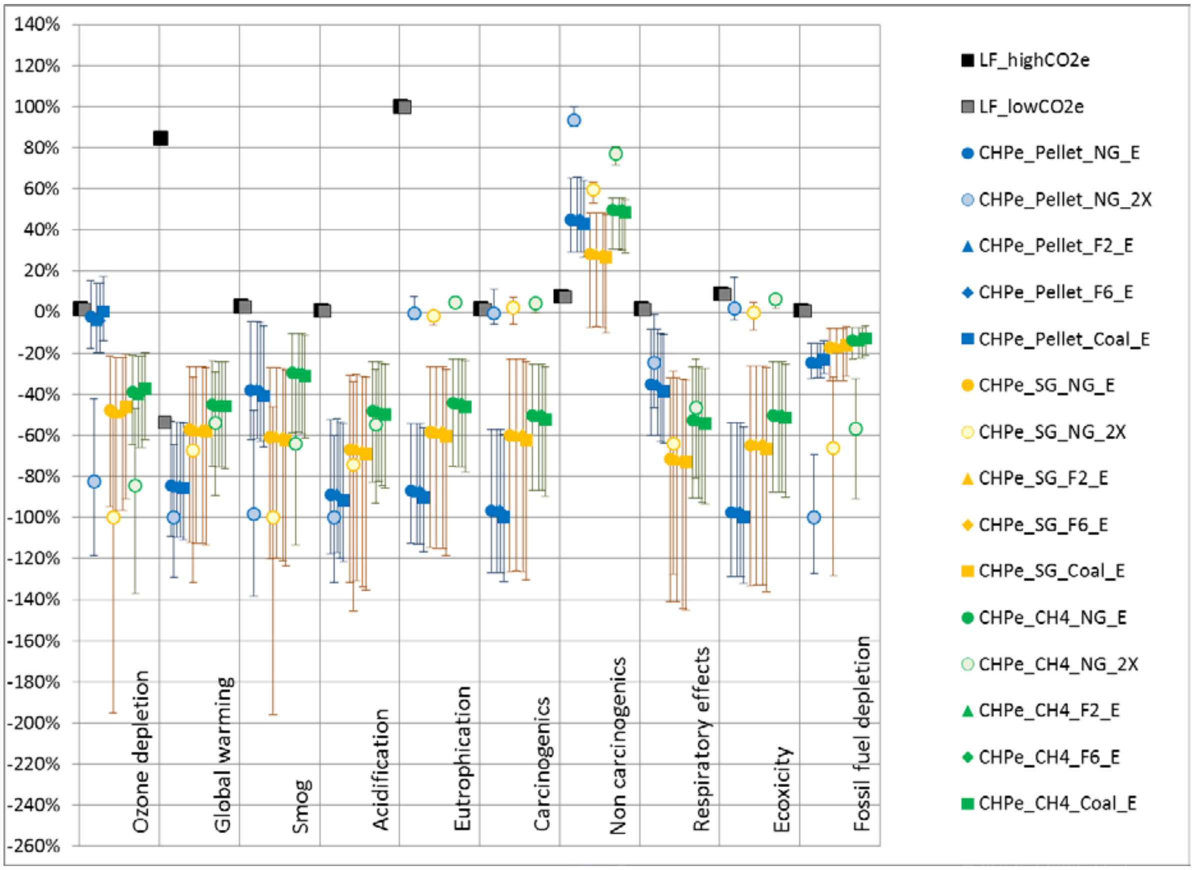


Figure 5.8 Combined Heat and Power Pathway Scenarios Maximized for Electricity Production Potential Environmental Impacts Normalized Against the Absolute Value of the Scenario with the Maximum Potential Environmental Impact of the 54 Scenarios for Each Impact Category [Geographic marker represents base case scenarios, while error bars represent scenario with parameters representing minimum and maximum efficiency across the biomass system value chain.]

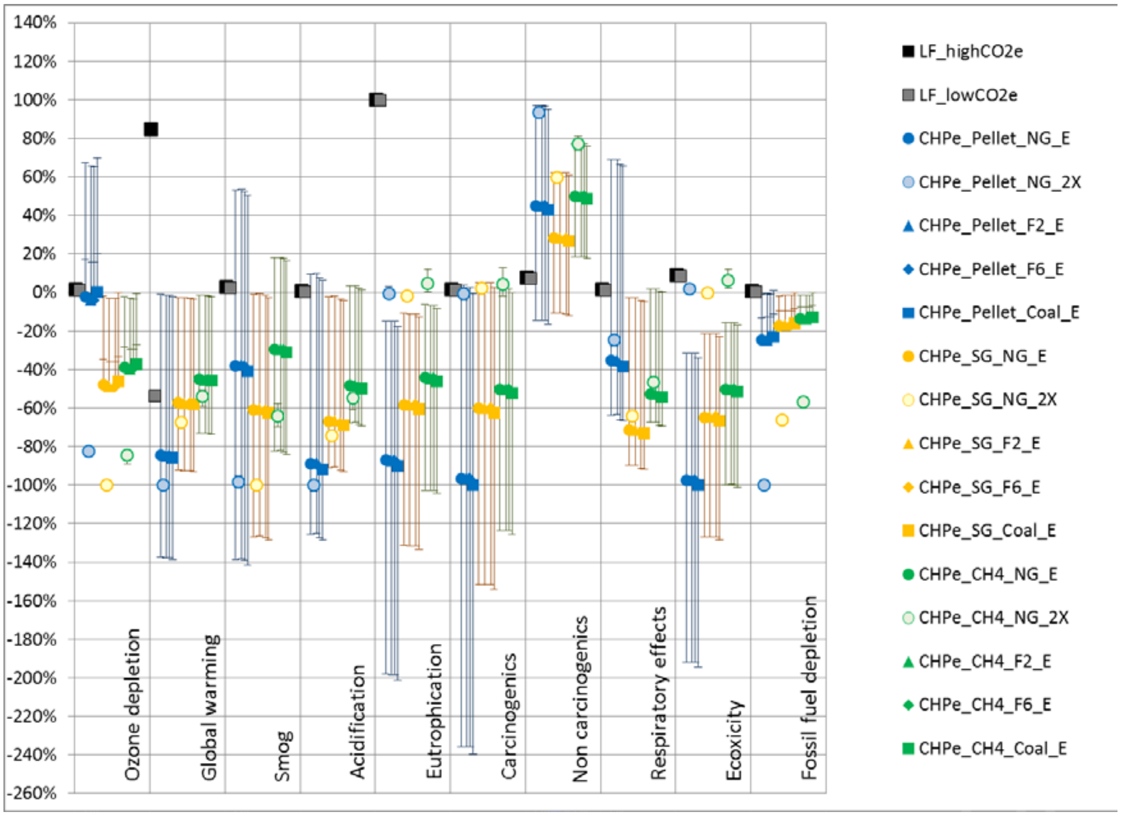


Figure 5.9 Combined Heat and Power Pathway Scenarios Maximized for Electricity Production Potential Environmental Impacts Normalized Against the Absolute Value of the Scenario with the Maximum Potential Environmental Impact of the 54 Scenarios for Each Impact Category [Geographic marker represents base case scenarios, while error bars represent scenario with grid mix representing Quebec and MRO region across the biomass system value chain and for the electricity replaced in the alternative system.]

5.2.2.2.3 *Transport Fuel Use Pathway*

For the transport use pathway, the potential environmental impacts of seven base case scenarios and their associated efficiency and grid mix sensitivity analyses where compiled. The resulting impact scores and the ranking of all scenarios are shown in Table 5.5, and graphically in Figures 5.10 and 5.11.

Table 5.5 shows that the scenarios with the highest number of impact categories with impact scores of less than zero (i.e., net benefit), regardless of the sensitivity analyses, are those associated with *methanol in alternative to diesel*. For those scenarios, there are four impact categories with impact scores greater than zero (i.e., net impact): eutrophication, carcinogens, non-carcinogens, and ecotoxicity. In contrast, scenarios with the lowest number of impact categories with impact scores less than zero, regardless of the sensitivity analyses, are those associated with *ethanol in alternative to gasoline*. For those scenarios, the two impact categories that always result in impact scores less than zero are ozone depletion and fossil fuel depletion. The impact category where impact scores are most often less than zero is global warming.

Looking at the results of Table 5.5 by column, all scenarios result in impact scores of less than zero for ozone depletion and fossil fuel, while most scenarios result in impact scores of less than zero for global warming. In contrast, all scenarios have impact scores of greater than zero for carcinogens, non-carcinogens, and ecotoxicity, and most scenarios have impact scores greater than zero for eutrophication.

For scenarios with ethanol as the biomass system, Table 5.5 shows, on average, three impact categories out of ten with impact scores of less than zero: ozone depletion, global warming, and fossil fuel depletion. The table also shows that the scenarios rank among the 10% of scenarios with highest impact score results for, on average, six impact categories out of ten. Of these six impact categories, five have impact scores of greater than zero: smog, acidification, eutrophication, carcinogens, and ecotoxicity.

Scenarios with methanol as the biomass system result in, on average, five impact categories with impact scores of less than zero: ozone depletion, global warming, smog, acidification, respiratory effects, and fossil fuel depletion. Scenarios with methane as the biomass system are very similar to the methanol scenarios with, on average, the same five impact categories having impact scores of less than zero. The main differences are for smog and acidification impact results, which are more variable for the methane scenarios. When grouping the scenarios by alternative system, it can be seen that when the biomass system is substituted by gasoline or natural gas, scenarios result more often than not in impacts scores greater than zero when it comes to smog, as they do when the biomass system is replaced by diesel.

Table 5.5 Transport Use Pathway Environmental Impact Score and Ranking Results

Pathway	Biomass System	Alternative System	Sensitivity analysis	Sensitivity analysis parameter value	Scenario	Number of Impact Categories: I.S. of less than zero (I.S.)	best 10% env. Effect (R.)	worse 10% env. Effect (R.)
Transport Fuel Use	Ethanol	Diesel	efficiency	low	low_TRSP_Ethanol_D	3	0	3
				average	TRSP_Ethanol_D	2	0	5
				high	high_TRSP_Ethanol_D	2	0	6
			grid mix	QC	QC_TRSP_Ethanol_D	5	0	0
				NA	TRSP_Ethanol_D	2	0	5
				MRO	MRO_TRSP_Ethanol_D	2	0	5
		Gasoline	efficiency	low	low_TRSP_Ethanol_P	3	0	3
				average	TRSP_Ethanol_P	3	0	6
				high	high_TRSP_Ethanol_P	3	0	7
			grid mix	QC	QC_TRSP_Ethanol_P	3	0	1
				NA	TRSP_Ethanol_P	3	0	5
				MRO	MRO_TRSP_Ethanol_P	2	0	7
	Methanol	Diesel	efficiency	low	low_TRSP_Methanol_D	6	0	0
				average	TRSP_Methanol_D	6	0	0
				high	high_TRSP_Methanol_D	6	0	2
			grid mix	QC	QC_TRSP_Methanol_D	6	0	0
				NA	TRSP_Methanol_D	6	0	0
				MRO	MRO_TRSP_Methanol_D	6	0	2
		Gasoline	efficiency	low	low_TRSP_Methanol_P	5	0	0
				average	TRSP_Methanol_P	5	0	0
				high	high_TRSP_Methanol_P	4	0	2
			grid mix	QC	QC_TRSP_Methanol_P	6	0	0
				NA	TRSP_Methanol_P	5	0	0
				MRO	MRO_TRSP_Methanol_P	4	0	2
	Methane	Diesel	efficiency	low	low_TRSP_CH4_D	4	0	2
				average	TRSP_CH4_D	5	0	0
				high	high_TRSP_CH4_D	6	0	0
			grid mix	QC	QC_TRSP_CH4_D	6	0	0
				NA	TRSP_CH4_D	5	0	0
				MRO	MRO_TRSP_CH4_D	4	0	4
		Gasoline	efficiency	low	low_TRSP_CH4_P	3	0	1
				average	TRSP_CH4_P	4	0	1
				high	high_TRSP_CH4_P	5	0	0
			grid mix	QC	QC_TRSP_CH4_P	5	0	0
				NA	TRSP_CH4_P	4	0	1
				MRO	MRO_TRSP_CH4_P	4	0	3
		Natural gas	efficiency	low	low_TRSP_CH4_NG	3	0	3
				average	TRSP_CH4_NG	5	0	1
				high	high_TRSP_CH4_NG	5	0	1
			grid mix	QC	QC_TRSP_CH4_NG	5	0	0
				NA	TRSP_CH4_NG	5	0	1
				MRO	MRO_TRSP_CH4_NG	3	0	3

LEGEND According to uncertainty criteria, impact score : Less than zero Greater than zero Neutral
Ranked amongst the: best 10% best 10-20% worse 10-20% worse 10% In between best 20% and worse 20%

Note: In the table above, base case results are depicted twice, once under the efficiency sensitivity analysis (showed as average) and once under the grid mix sensitivity analysis (showed as NA).

Results for the sensitivity analyses show that scenarios for the transport pathway with ethanol or methane as the biomass system are sometimes sensitive to the "efficiency" of the biomass system, as seen in Figure 5.10. This is expected, given that higher passenger car fuel efficiency is known to reduce most environmental releases [Information Unit for Conventions (IUC) United Nations Environment Programme 2000]. In terms of sensitivity to the grid mix, only scenarios with ethanol as the biomass system are affected, as seen in Figure 5.11. Upgrading ethanol from 95% to 99.7% purity is energy-consuming and as this energy is supplied by the grid, which can have very different environmental profiles, the choice of one mix versus another has a significant effect on the results.

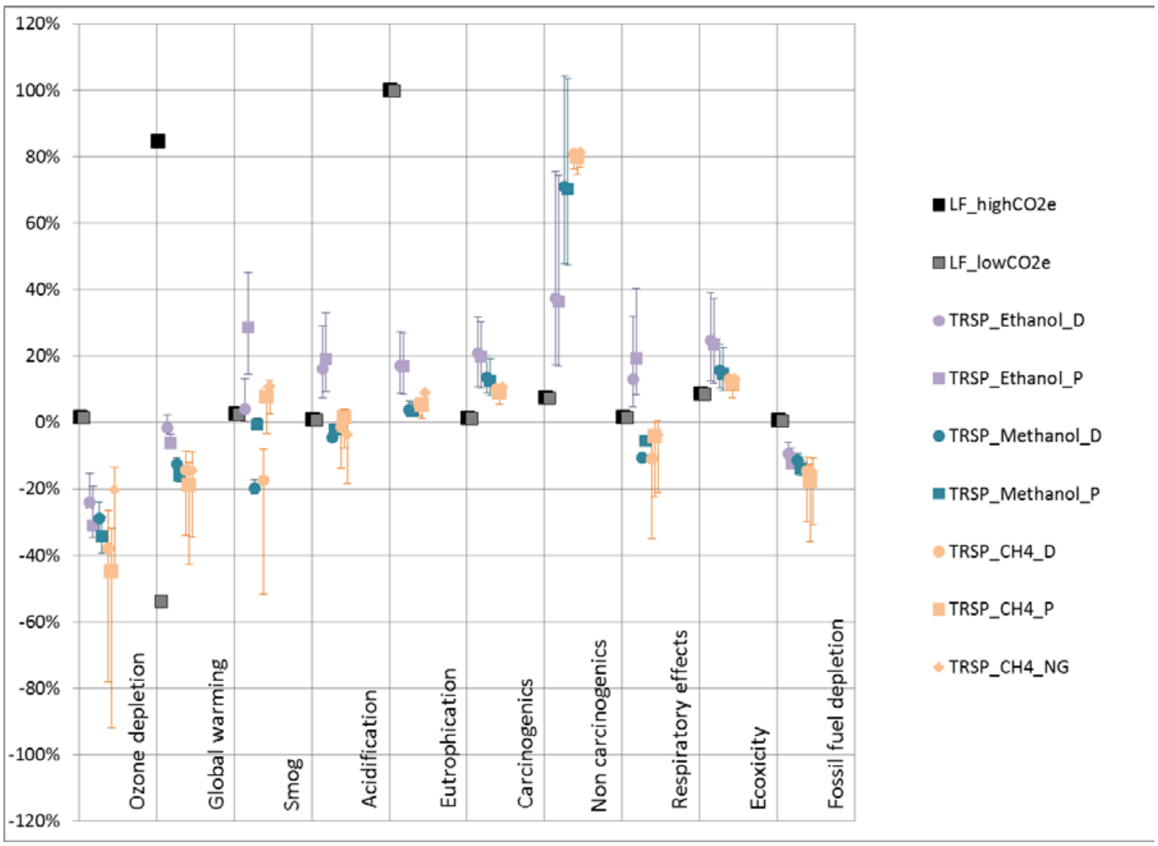


Figure 5.10 Transport Use Pathway Scenarios Potential Environmental Impacts Normalized Against the Absolute Value of the Scenario with the Maximum Potential Environmental Impact of the 54 Scenarios for Each Impact Category
[Geographic marker represents base case scenarios, while error bars represent scenario with parameters representing minimum and maximum efficiency across the biomass system value chain.]

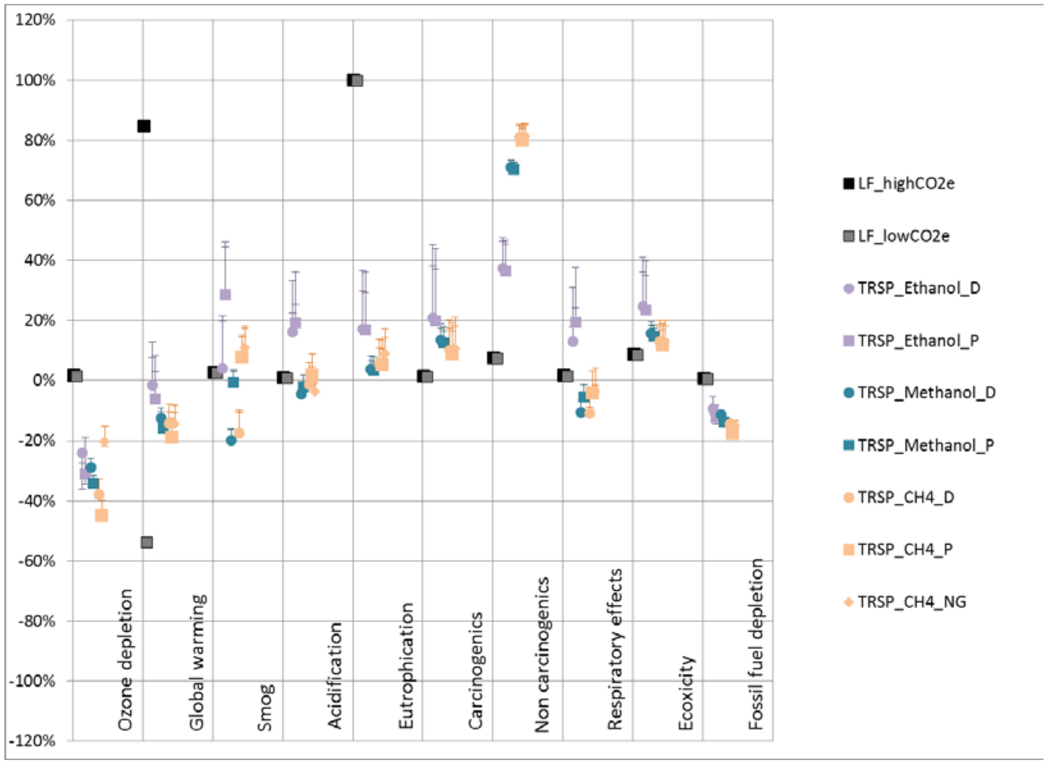


Figure 5.11 Transport Use Pathway Scenarios Potential Environmental Impacts Normalized Against the Absolute Value of the Scenario with the Maximum Potential Environmental Impact of the 54 Scenarios for Each Impact Category.
[Geographic marker represents base case scenarios, while error bars represent scenario with grid mix representing Quebec and MRO regions across the biomass system value chain.]

5.2.2.2.4 *Use in Metallurgy Pathway*

For the use in metallurgy pathway, only one scenario was assessed with all sensitivity analyses.

Table 5.6 shows that results from the use in metallurgy pathway indicate potential environmental neutrality for all impact categories, whichever efficiency and grid mix is used.

Table 5.6 Use in Metallurgy Pathway Environmental Impact Score and Ranking Results

Pathway	Biomass System	Alternative System	Sensitivity analysis	Sensitivity analysis parameter value	Scenario	Ozone depletion		Global warming		Smog		Acidification		Eutrophication		Carcinogenics		Non carcinogenics		Respiratory effects		Ecotoxicity		Fossil fuel depletion		Number of Impact Categories: I.S. of less than zero	best 10% env. Effect	worse 10% env. Effect
						I.S.	R.	I.S.	R.	I.S.	R.	I.S.	R.	I.S.	R.	I.S.	R.	I.S.	R.	I.S.	R.	I.S.	R.	I.S.	R.	I.S.	R.	R.
Use in Metallurgy	Charcoal	Coke	efficiency	low	low_Metl_Charcoal□Coe	Neutral		Neutral		Neutral		Neutral	worse 10-20%	Neutral		Neutral		Neutral	best 10%	Neutral	best 10-20%	Neutral		Neutral	worse 10%	0	1	1
				average	Metl_Charcoal□Coe	Neutral		Neutral		Neutral		Neutral		Neutral		Neutral		Neutral	best 10%	Neutral	best 10%	Neutral		Neutral	worse 10%	0	2	1
				high	high_Metl_Charcoal□Coe	Neutral		Neutral		Neutral		Neutral		Neutral		Neutral		Neutral	best 10%	Neutral	best 10%	Neutral		Neutral	worse 10%	0	2	1
			grid mix	QC	QC_Metl_Charcoal□Coe	Neutral		Neutral		Neutral		Neutral		Neutral		Neutral		Neutral	best 10%	Neutral	best 10%	Neutral		Neutral	worse 10-20%	0	2	0
				NA	Metl_Charcoal□Coe	Neutral		Neutral		Neutral		Neutral		Neutral		Neutral		Neutral	best 10%	Neutral	best 10%	Neutral		Neutral	worse 10%	0	2	1
				MRO	MRO_Metl_Charcoal□Coe	Neutral		Neutral		Neutral		Neutral		Neutral		Neutral		Neutral	best 10%	Neutral	best 10%	Neutral		Neutral	worse 10%	0	2	1

LEGEND According to uncertainty criteria, impact score : Less than zero Greater than zero Neutral
Ranked amongst the: best 10% best 10-20% worse 10-20% worse 10% In between best 20% and worse 20%

Note: In the table above, base case results are depicted twice, once under the efficiency sensitivity analysis (showed as average) and once under the grid mix sensitivity analysis (showed as NA).

Sensitivity analysis results, shown in Figure 5.12, indicate that the metallurgy pathway is sensitive to "efficiency", while Figure 5.13 shows that the metallurgy pathway is not sensitive to the grid mix used. It is expected that changes in the biomass system efficiency (e.g., production yield) affect the amount of biomass used in the pathway, and thus affect the associated environmental releases as 20% less or 30% more pig iron can be produced. In contrast, the contribution of the grid mix to the impact results is not sufficient for its variation to impact the results.

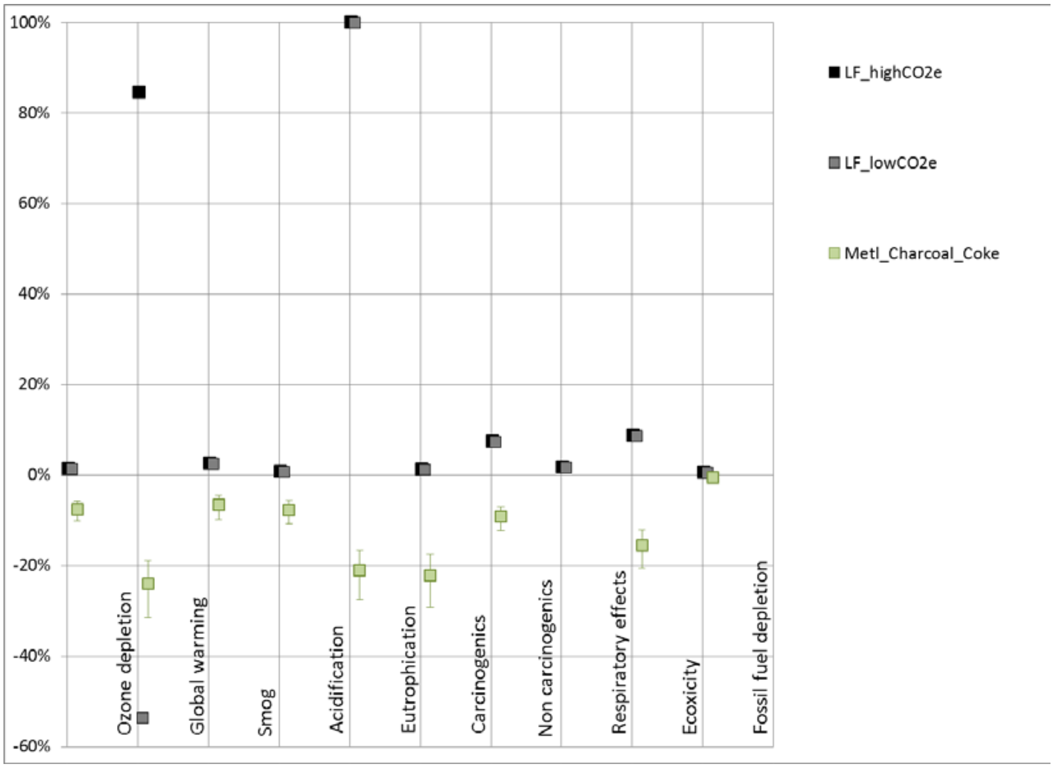


Figure 5.12 Use in Metallurgy Pathway Scenario Potential Environmental Impacts Normalized Against the Absolute Value of the Scenario with the Maximum Potential Environmental Impact of the 54 Scenarios for Each Impact Category
[Geographic marker represents base case scenario, while error bars represent scenario with parameters representing minimum and maximum efficiency across the biomass system value chain.]

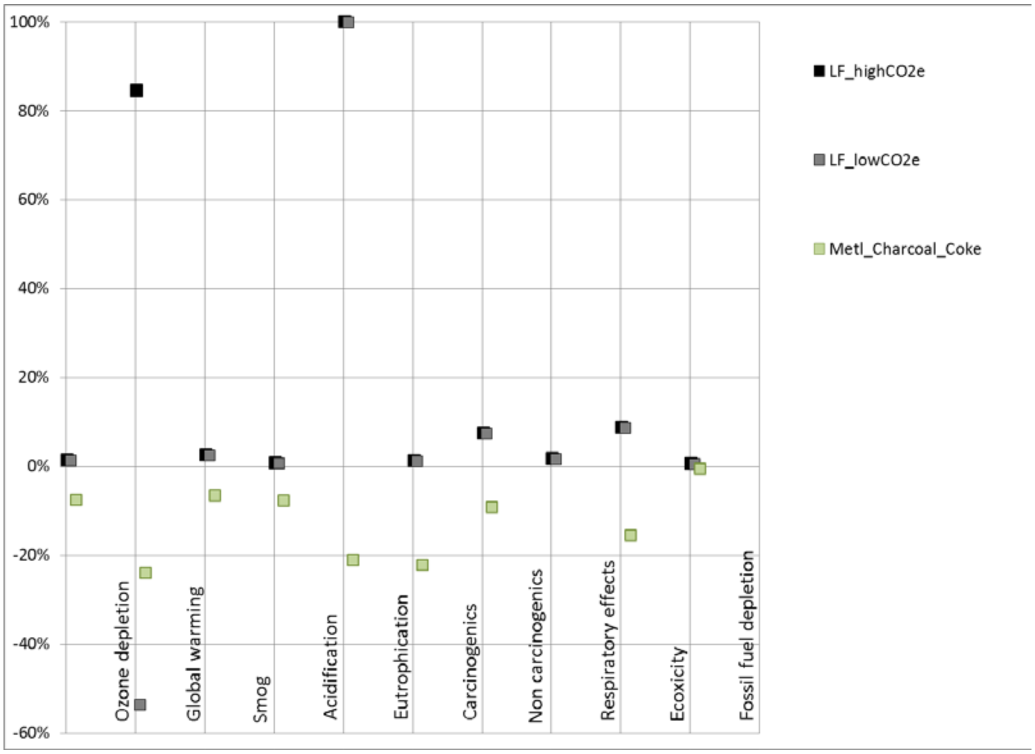


Figure 5.13 Use in Metallurgy Pathway Scenario Potential Environmental Impacts Normalized Against the Absolute Value of the Scenario with the Maximum Potential Environmental Impact of the 54 Scenarios for Each Impact Category
[Geographic marker represents base case scenario, while error bars represent scenario with grid mix representing Quebec and MRO region across the biomass system value chain.]

5.2.2.2.5 *Use as Horticultural Growing Media Pathway*

For the use as horticultural growing media pathway, two base case scenarios were assessed: bark mulch degradation with high GHG emissions in alternative to peat mulch degradation with low GHG emissions as the alternative system (GM_highMulch_Peat); and bark mulch degradation with low GHG emissions in alternative to peat degradation with high GHG emissions as the alternative system (GM-lowMulch_ Peat). Recall that for this pathway, only a “grid mix” sensitivity analysis was done, because the “efficiency” variations are inherently incorporated in these two base case scenarios.

As shown in Table 5.7, the use as horticultural growing media pathway base case results and those of the associated grid mix sensitivity analysis indicate impact scores of zero or greater for almost all impact categories (i.e., net impact). The only exception is for global warming, which results in impact scores less than zero if bark mulch stores carbon in the soil while peat moss emits GHGs. Hence, it is unclear whether bark mulch degradation in alternative to peat mulch degradation, when applied full-scale, will result in impact scores of less than zero when it comes to global warming.

Table 5.7 Use as Horticultural Growing Media Pathway Impact Score and Ranking Results

Pathway	Biomass System	Alternative System	Sensitivity analysis	Sensitivity analysis parameter value	Scenario	Ozone depletion I.S.	Ozone depletion R.	Global warming I.S.	Global warming R.	Smog I.S.	Smog R.	Acidification I.S.	Acidification R.	Eutrophication I.S.	Eutrophication R.	Carcinogenics I.S.	Carcinogenics R.	Non carcinogenics I.S.	Non carcinogenics R.	Respiratory effects I.S.	Respiratory effects R.	Ecotoxicity I.S.	Ecotoxicity R.	Fossil fuel depletion I.S.	Fossil fuel depletion R.	Number of Impact Categories: I.S. of less than zero (I.S.)	Number of Impact Categories: best 10% env. Effect (R.)	Number of Impact Categories: worse 10% env. Effect (R.)
Use as Horticultural Growing Media	Bark - high CO2e emission	Peat - low emission	efficiency	average	HGM_Bark_highCO2e_Peat	Greater than zero	worse 10-20%	Greater than zero	worse 10%	Neutral		Greater than zero	worse 10%	Greater than zero		Neutral		Greater than zero	best 10%	Greater than zero	worse 10-20%	Neutral		Greater than zero	worse 10%	0	1	3
			grid mix	QC	QC_HGM_Bark_highCO2e_Peat	Greater than zero	worse 10-20%	Greater than zero	worse 10%	Neutral		Greater than zero	worse 10-20%	Greater than zero		Greater than zero		Greater than zero	best 10%	Greater than zero	worse 10-20%	Greater than zero		Greater than zero	worse 10%	0	1	2
				NA	HGM_Bark_highCO2e_Peat	Greater than zero	worse 10-20%	Greater than zero	worse 10%	Neutral		Greater than zero	worse 10-20%	Greater than zero		Neutral		Greater than zero	best 10%	Greater than zero	worse 10-20%	Neutral		Greater than zero	worse 10%	0	1	2
				MRO	MRO_HGM_Bark_highCO2e_Peat	Greater than zero	worse 10-20%	Greater than zero	worse 10%	Neutral		Greater than zero	worse 10-20%	Neutral		Neutral		Neutral	best 10%	Greater than zero	worse 10-20%	Neutral		Greater than zero	worse 10%	0	1	2
	Bark - low CO2e emission	Peat - high emission	efficiency	average	HGM_Bark_lowCO2e_Peat	Greater than zero	worse 10-20%	Less than zero		Neutral		Greater than zero	worse 10%	Greater than zero		Neutral		Greater than zero	best 10%	Greater than zero	worse 10-20%	Neutral		Greater than zero	worse 10%	1	1	2
			grid mix	QC	QC_HGM_Bark_lowCO2e_Peat	Greater than zero	worse 10-20%	Less than zero		Neutral		Greater than zero	worse 10%	Greater than zero		Greater than zero		Greater than zero	best 10%	Greater than zero	worse 10-20%	Greater than zero		Greater than zero	worse 10%	1	1	2
				NA	HGM_Bark_lowCO2e_Peat	Greater than zero	worse 10-20%	Less than zero		Neutral		Greater than zero	worse 10-20%	Greater than zero		Neutral		Greater than zero	best 10%	Greater than zero	worse 10-20%	Neutral		Greater than zero	worse 10%	1	1	1
				MRO	MRO_HGM_Bark_lowCO2e_Peat	Greater than zero	worse 10-20%	Less than zero		Neutral		Greater than zero	worse 10-20%	Neutral		Neutral		Neutral	best 10%	Greater than zero	worse 10-20%	Neutral		Greater than zero	worse 10%	1	1	1

LEGEND According to uncertainty criteria, impact score : Less than zero Greater than zero Neutral
Ranked amongst the: best 10% best 10-20% worse 10-20% worse 10% In between best 20% and worse 20%

Note: In the table above, base case results are depicted twice, once under the efficiency sensitivity analysis (showed as average) and once under the grid mix sensitivity analysis (showed as NA).

Sensitivity analysis results are shown in Figure 5.14, illustrating that the horticultural growing media pathway is not sensitive to the grid mix used, although the electricity mixes tested in sensitivity analyses (i.e., North American, Quebec, and MRO electricity mixes) have very different environmental profiles. These results are not surprising considering the small amount of electricity used in the system.

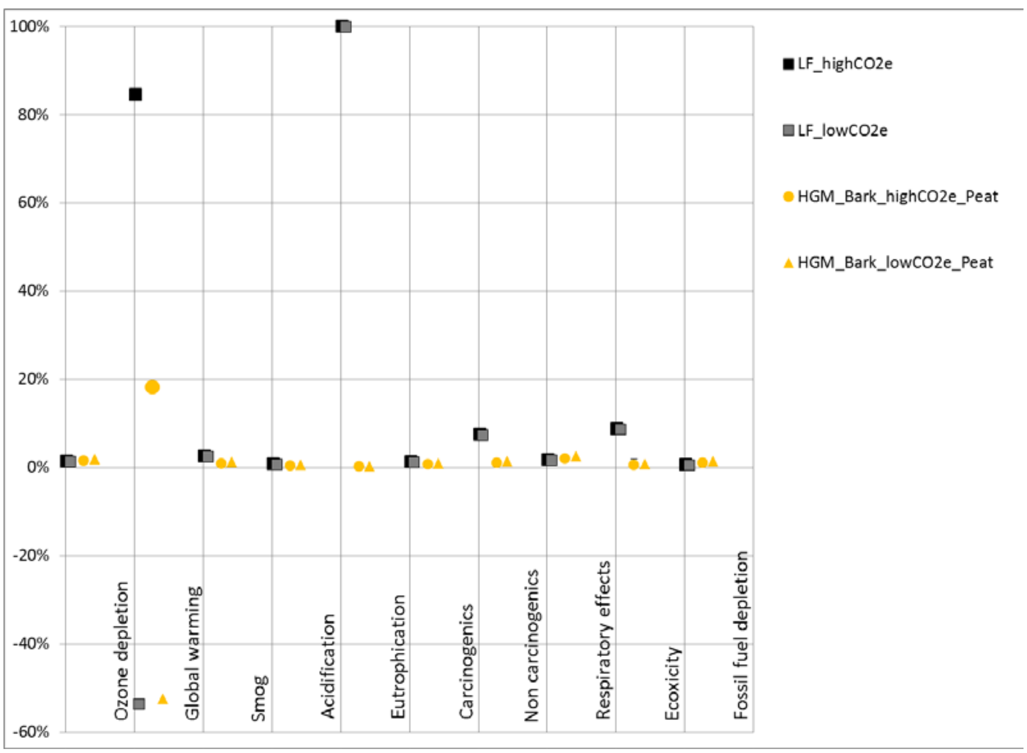


Figure 5.14 Use as Horticultural Growing Media Pathway Scenarios Potential Environmental Impacts Normalized Against the Absolute Value of the Scenario with the Maximum Potential Environmental Impact of the 54 Scenarios for Each Impact Category
[Geographic marker represents base case scenarios, while error bars represent scenario with grid mix representing Quebec and MRO region across the biomass system value chain.]

5.3 Contribution Analyses

As in the previous step of the interpretation approach, life cycle stages upstream of the biomass production (e.g., upstream of pellet production) were excluded; hence, the contribution analyses exclude the contribution of those upstream processes.

5.3.1 *Disposal Pathway Assessment*

The contribution analyses, detailed in Figure C1 and Table C1 of Appendix C, determined that the landfill life cycle emissions are contributing to more than 20% of the normalized impact score for only two impact categories: global warming and eutrophication. Moreover, it is the waste emissions life cycle grouping that is the key contributor to those impact categories. Landfill waste emissions are also the key contributors to carcinogens, non-carcinogens, and ecotoxicity. Emissions from landfill construction and landfill operation are the key contributors to the ozone depletion, smog, acidification, carcinogens, respiratory effects, and fossil fuel depletion impact categories.

These findings are consistent with what is found in the literature. Indeed, landfill waste emissions, i.e., landfill leachate and landfill GHG emissions, are known to be significant to landfilling life cycle emissions (Obersteiner et al. 2007).

Understanding the factors contributing to the environmental profile of the disposal pathway (landfilling) is useful when comparing the pathway to alternative unconventional pathways, thereby gaining perspective and insight into the genesis of the environmental profiles of the different scenarios.

The average potential environmental impacts of all the scenarios for a pathway, compared against the average impact score of the two landfill scenarios, are shown in Figure 5.15. Because the results of some impact categories have large variation, two differently scaled axes were used to highlight the smaller variability in some of the impact categories. Therefore, impact categories in gray are to be read with the axis on the right hand side of the figure, and the impact categories in white with the axis on the left hand side of the figure. In Figure 5.15, the average impact scores of all scenarios for a pathway are shown with a geometric marker, while the distribution of the impact scores of all the scenarios within a pathway are shown in the figure with error bars. The figure should be read as follows: values below zero represent woody mill residues management options with impact scores less than landfilling, and values above zero represent woody mill residues management options with impact scores greater than landfilling.

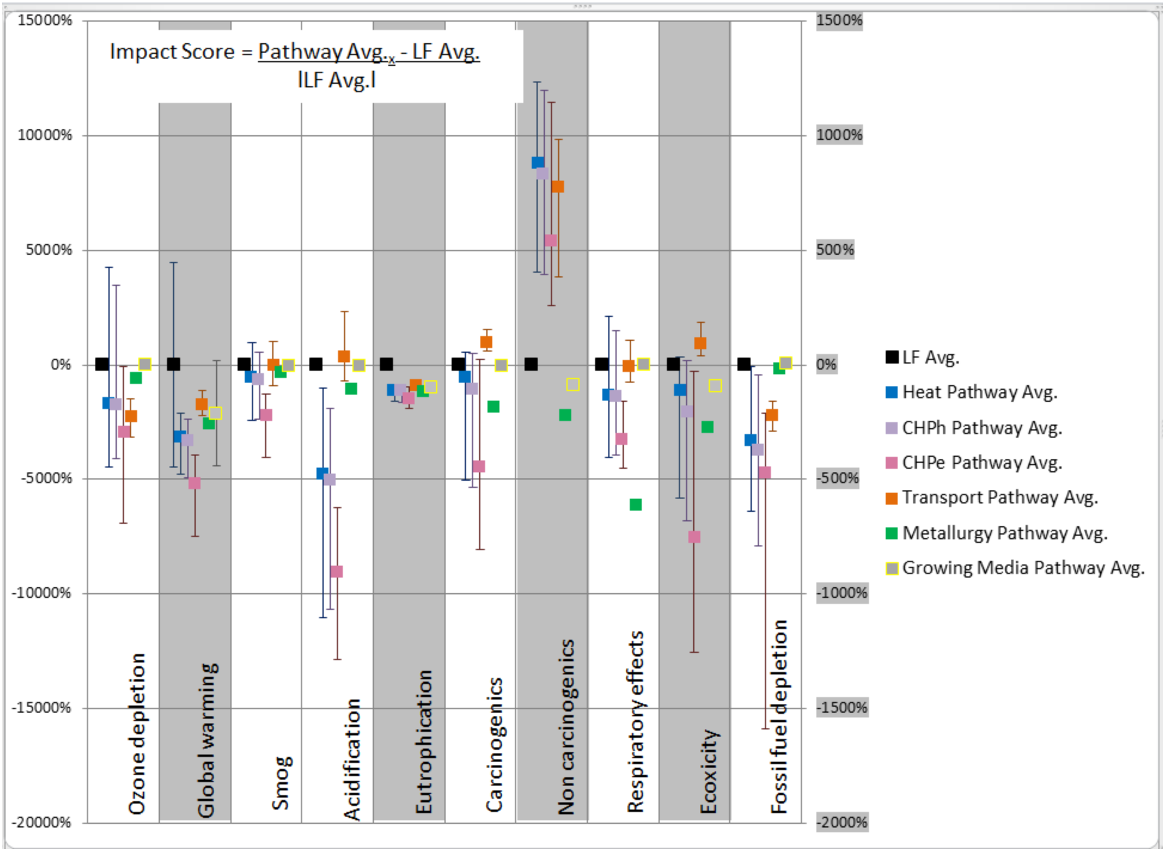


Figure 5.15 All Pathways Potential Environmental Impact for Average Scenarios Compared with Potential Environmental Impacts of Average Landfill Scenarios for each Impact Category [Geometric markers represent average value of scenarios for a pathway while bars represent distribution of scenarios for that pathway.]

In Figure 5.15, it can be seen that for impact categories where the landfill construction and landfill operation process groupings were identified as significant contributors (ozone depletion, smog, acidification, carcinogens, respiratory effects, fossil fuel depletion), the differences between many of the unconventional use pathways and the landfill scenarios are large, reaching more than 15000% in one case (white axis). This indicates that for these impact categories, emissions of contributing substances or consumption of resources are relatively low compared to those of, or avoided by, unconventional pathways, or in other words, that landfilling potentially contributes very little to these impact categories. For impact categories where only landfill waste emissions are the main contributor (global warming, eutrophication, non-carcinogens, ecotoxicity), the differences between the unconventional use pathways and the disposal pathway are of much smaller amplitude, reaching a maximum of 1200% (gray axis). This means that the potential environmental impacts of some scenarios from the unconventional use pathways are similar in scale as those associated with landfilling.

Another important observation from Figure 5.15 is that not all impact categories have the same range of variation. The greater the variation within an environmental indicator, the more discernible the effect of the alternative management options for that particular environmental indicator. The CHPe pathway presents the smallest impact scores compared to landfilling for eight impact categories out of ten, that is, except for eutrophication and non-carcinogens. For eutrophication, all pathways rank similarly compared to landfill. For non-carcinogens, it is the use in metallurgy or horticultural growing media pathways that provide the smallest impact scores. It is also interesting to note that the acidification indicator is the one for which the unconventional pathways, and more specifically the CHP and heat pathways, provides most benefits compared to landfilling. Finally, the ozone depletion, acidification and, to some extent, the fossil fuel depletion indicators show the most intra-pathway variation.

5.3.2 *Unconventional Use Pathways Assessments*

5.3.2.1 *Heat Pathway*

The following observations can be made from the contribution analyses (details are shown in Figure C2 and Table C.2 of Appendix C).

- When considering all biomass systems and all impact categories, the combustion life cycle stage of the pellet biomass system is a large contributor to the ozone depletion, smog, non-carcinogens, and respiratory effects impact categories. Combusting syngas and methane, according to these results, emit lower levels of substances contributing to these impact categories in comparison to pellet combustion.

- For ozone depletion, the syngas and methane biomass systems and the coal alternative system emit ozone-depleting substances that are on the order of those emitted by the landfill scenarios. In contrast, all other systems are major contributors to the ozone depletion impact category. Note, however, that available data for releases of the main contributing substance, tetrachloromethane (CFC-10), during pellet combustion indicate that it is unlikely to be emitted in significant quantities [five of six observed data points were non-detect (NCASI 2014a)] and no tetrachloromethane releases are reported for syngas or methane combustion. For No. 2 fuel oil, No. 6 fuel oil, and natural gas, bromotrifluoromethane (Halon 1301) was identified as the main contributing substance emitted during onshore natural gas and/or petroleum production in fire protection operations (Oil & Gas UK 2015). Halon 1301 continues to increase in the atmosphere, despite having been banned by the Montreal Protocol (by 1994 for developed countries and 2010 for developing countries), likely due to its gradual release from substantial banks in fire-extinguishing and other equipment (Hegglin et al. 2015). In light of this information, results of the heat scenarios are considered too uncertain to draw conclusions; hence, in this study, the results are considered environmentally neutral.

- For global warming, biomass systems are not key contributors, while they are for all alternatives systems, indicating that for all scenarios, the potential global warming environmental impact scores are less than zero. Landfill scenarios result in global warming impact scores that either well above zero (landfill high CO_2e) or well below zero (landfill low CO_2e); therefore, the results of the heat pathway scenarios are either much better than, or similar to, landfilling the residues. That said, the final results of this pathway will depend on the semi-quantitative uncertainty assessment presented in Section 5.4 of the report.

- For smog, the pellet and methane biomass systems and all alternative systems are key contributors to the associated impact category results. These contributions are through energy consumption and/or fuel combustion during production along with fuel combustion during use. Nitrogen oxides are the primary substances contributing to the smog impact category. Emission factors used in the modeled boiler emissions are reliable for pellets, and of undetermined reliability for fuel oil No. 2, fuel oil No. 6, natural gas and coal (NCASI 2014a). Emission factor uncertainty was not assessed for fuel production due to lack of readily-available data. Therefore, the final results of this pathway will depend on the semi-quantitative uncertainty assessment presented in Section 5.4 of the report.

- For acidification, the contributions of biomass systems to the normalized scores are less than 20% and are all of the same order of magnitude, while the alternative systems are all key contributors. The alternative system results can be grouped into two levels of contribution: No. 6 fuel oil and coal, which both contribute twice as much as natural gas or No. 2 fuel oil. This indicates that more environmental gains are anticipated to be made when the biomass system replaces No. 6 fuel oil or coal. Fuel combustion and their production are the main contributing life cycle stages for the alternative systems with the exception of coal, where only the combustion life cycle stage is a key contributor. More precisely, it is the emissions of sulfur dioxide and nitrogen oxides during fuel production and/or combustion that are the substances contributing to the impact scores of the alternative systems. As discussed above for smog, the uncertainty related to nitrogen oxides emission factors is not available, emission factors for sulfur dioxide for alternative system combustion are of undetermined reliability, and the uncertainty related to emission factors for fuel production was not assessed due to lack of readily available data. Nevertheless, the difference between the biomass system and No. 6 fuel oil and coal alternative systems is sufficiently large (roughly 40 to 70%) that it is reasonable to assume that these scenarios will result in impact scores of less than zero. For the remaining scenarios, the results can be considered environmentally neutral. That said, the final results of this pathway will depend on the semi-quantitative uncertainty assessment presented in Section 5.4 of the report.

- For eutrophication, it is interesting to note that only scenarios with coal as the alternative system contribute on the same level as landfill leachate. More precisely, it is the phosphate in water from coal mining operations (treatment of spoil and coal slurry) that is the main contributing substance to the assessment of the coal alternative system. Phosphate comes from the conversion of phosphorus contained in the spoil or slurry (Doka 2009). Scenarios with coal as the alternative system result in impact scores of less than zero and the remaining scenarios result in a neutral impact score; however, compared to landfill, all heat pathway scenarios result in lower impact scores. The semi-quantitative uncertainty assessment presented in Section 5.4 of the report will confirm or add nuance to these results.

- For carcinogens, the results show a similar trend to that of eutrophication except that it is Chromium VI in water that is the contributing substance to the impact score of the coal mining operations life cycle stage. Chromium VI comes from the conversion of chromium contained in the spoil or slurry (Doka 2009). Scenarios with coal as the alternative system result in impact scores of less than zero and the remaining scenarios result in a neutral impact score. However, the final results of this pathway will depend on the semi-quantitative uncertainty assessment presented in Section 5.4 of the report.

- For non-carcinogens, pellet combustion, syngas production, and methane production are the primary life cycle stages contributing to the impact score of the biomass system. As for the alternative systems, only the production of coal in the coal system is a key contributor to the impact score, based on arsenic and zinc emitted to water during coal mining spoil treatment, coal slurry, and from lignite ash. For the biomass systems, whether the life cycle stage of the biomass system contributing to the impacts is from the combustion of pellets or the production syngas or methane, it is the zinc in agricultural soil from wood ash spreading that is the main contributor to the results. Wood ash spreading on agricultural soil is a known practice and its application depends on the criteria established by local authorities. If wood ash spreading is not authorized, the wood ash is likely to be landfilled (NCASI file information, 2012). When zinc emitted to agricultural soils is excluded from the assessment, the biomass systems are no longer key contributors to the potential non-carcinogens environmental impact (results shown with a star in Figure 5.17). Based on this information, the contribution of zinc in agricultural soil was excluded from the final results, which in turn will depend on the semi-quantitative uncertainty assessment presented in Section 5.4 of the report.

- For respiratory effects, it is the combustion of pellets in the biomass system, along with the production and combustion of alternative fuels that are the primary contributors to the results for the different heat pathway scenarios. For pellet combustion, the emission of particles of less than 2.5 µm ($PM_{2.5}$) is the main contribution, while the emission of sulfur dioxide and $PM_{2.5}$ is the main contribution to the results for the alternative system. Emission factors for combustion were taken from the NCASI NPRI handbook (NCASI 2014a). The reliability of the combustion emission factors for sulfur dioxide and $PM_{2.5}$ is undetermined. Note that due to lack of direct emission data, pellet combustion emissions were modeled using general wood boiler data. Wood boilers are known to emit more particles than natural gas boilers. Given that methane composition and, to some extent, syngas composition resemble that of natural gas, it is reasonable to assume that particle emission from syngas and methane combustion resembles that of natural gas. Based on this information, it is reasonable that scenario results for pellets in alternative to No. 2 fuel oil and pellets in alternative to natural gas are more likely to result in impact scores of greater than zero, and that scenario results for syngas or methane in alternative to No. 6 fuel oil, and syngas or methane in alternative to coal are more likely to result in impact scores of less than zero, and that all other scenarios can be considered environmentally neutral. The final results of this pathway will depend on the semi-quantitative uncertainty assessment presented in Section 5.4 of the report.

- For ecotoxicity, the biomass system contributions to scenario impacts are of the same order of magnitude as those for landfill waste emissions (zinc and copper in water). Only coal as the alternative system is a major contributor the scenario results, due to metal leaching from coal mining waste (Doka 2009). For this impact category, it is reasonable to assume that scenarios with coal as the alternative system result in impact scores of less than zero, while all other scenarios result in impact that are environmentally neutral. That said, the final results of this pathway will depend on the semi-quantitative uncertainty assessment presented in Section 5.4 of the report.
- For fossil fuel depletion, as expected, the biomass systems are not major contributors, even though, for pellets, natural gas was model as fuel to dry the pellets in the production life cycle stage. Alternative systems involving No. 2 fuel oil, No. 6 fuel oil, and natural gas are the main contributors to this impact category, while coal is not. It is important to note that TRACI's fossil fuel depletion impact category is based on the potential for diminished availability of low cost/energy fossil fuel global supply (Bare et al. 2003). This method reflects the fact that more energy is needed to continue to supply No. 2 fuel oil, No. 6 fuel oil, and natural gas than coal based on declining global reserves. Hence, for scenarios where No. 2 fuel oil, No. 6 fuel oil, and natural gas are the alternative system, results will most likely yield impact scores of less than zero, while scenarios with coal as the alternative system will likely yield environmentally neutral impacts. The final results of this pathway will depend on the semi-quantitative uncertainty assessment presented in Section 5.4 of the report.

In sum, scenarios from the heat pathway, including qualitative uncertainty, result in impact scores of less than zero when it comes to global warming and, for scenarios with coal as alternative system, for acidification, eutrophication, carcinogens, and ecotoxicity. Impact scores of less than zero are also seen for syngas and methane scenarios that have No. 6 fuel oil or coal as the alternative system for the respiratory effects impact category. Impact scores greater than zero are anticipated for pellets scenarios with No. 2 fuel oil or natural gas as the alternative system, for respiratory effects. Otherwise, the scenarios are neutral or inconclusive due to life cycle inventory and impact uncertainty. The final results for this pathway will depend on the semi-quantitative uncertainty assessment presented in Section 5.4 of the report.

5.3.2.2 *Combined Heat and Power Pathway*

5.3.2.2.1 *CHP Maximized for Heat Production*

The environmental impacts score is determined by the estimated environmental impact of the biomass system per unit of heat and electricity produced relative to that of producing the same quantity of heat and electricity using the alternative system. As the biomass systems modeled in this pathway are identical to the ones presented in the heat pathway, the key contributing biomass systems, life cycle stages, and substances are identical; therefore, for interpretation of those results see Section 5.2.3.1. For the alternative system, 82% of the energy produced is for heat production and was modeled as for the heat pathway; hence, the results and contributing processes, life cycle stages and substances are very similar (see Figure C3 and Table C.3 in Appendix C for details). The differences in the results between the alternative systems of the heat pathway and CHPh pathway arise from the 18% of energy used for electricity, rather than heat, production. Because the North American grid mix is produced with 41% coal and 21% natural gas, the processes, life cycle stages, and substances identified as key contributors for the coal heat production and natural gas heat production also contribute to the alternative systems of the CHPh pathway when modeled with the North American grid mix for electricity production. The alternative system modeled with natural gas as fuel for heat and electricity production (NG_2X) results in absolute impact scores higher than the natural gas alternative system of the heat pathway because of the different combustion efficiencies for heat versus electricity production.

5.3.2.2.2 *CHP Maximized for Electricity Production*

The environmental impacts score is determined by estimating the environmental impact of the biomass system per unit of heat and electricity produced relative to that of producing the same quantity of heat and electricity using the alternative system. As the biomass systems modeled in this pathway are identical to the ones presented in the heat and CHPh pathway, the key contributing biomass systems, life cycle stages, and substances are identical; therefore, for interpretation of those results see Section 5.3.2.1. For the alternative system, 5% of the energy produced is for heat production and was modeled as for the heat pathway. The reason the impact score results for the alternative systems with North American grid mix used for electricity production are almost all identical is because electricity represents 94.8% of the energy supplied to the system and is produced with 41% coal and 21% natural gas, which have been identified as key contributing systems in the heat and CHPh pathways (see Figure C.4 and Table C.4 in Appendix C for details). Thus, the processes, life cycle stages, and substances identified as main contributors for the coal heat production and natural gas heat production also contribute to the alternative systems of the CHPe pathway that were modeled with the North American grid mix for electricity production. The alternative system modeled with natural gas as fuel for heat and electricity production (NG_2X) results in absolute impact scores higher than the natural gas alternative system of the heat pathway, because of the different combustion efficiencies for heat versus electricity production.

5.3.2.3 *Transport Fuel Use Pathway*

The following observations can be made from the contribution analyses (details are shown in Figure C.5 and Table C.5 of Appendix C).

- When considering all biomass systems and all impact categories together, it can be seen that the production life cycle stage of the ethanol biomass system is a large contributor for eight impact categories out of ten: global warming, smog, acidification, eutrophication, carcinogens, non-carcinogens, respiratory effects, and ecotoxicity. Using methanol or methane as transport fuel, according to these results, emits fewer substances contributing to these impact categories in comparison to the use of ethanol as transport fuel. Otherwise, the alternative systems are significant contributors to three impact categories out of ten, except for diesel, which is the main contributor to four impact categories out of ten. The impact categories in question are ozone depletion, global warming, respiratory effects, and smog for diesel. Also, the alternative systems results are just below the 20% normalized contribution bar for acidification and fossil fuel depletion. Note that all emission factors used to model the scenarios of the transport pathway were taken from the ecoinvent database and their uncertainty was not assessed in this study due to lack of readily available data. A semi-quantitative uncertainty was performed to account for the various uncertainty sources and is presented in Section 5.4 of this report.

- For ozone depletion, all alternative systems are main contributors. In terms of the alternative system, it is the emission of bromotrifluomethane (Halon 1301) from onshore petroleum and gas production that is the main contributing substance and life cycle stage. As stated previously, halon has been banned by the Montreal protocol and its continuous increase in the atmosphere is likely due to its gradual release from substantial banks in fire-extinguishing and other equipment (Hegglin et al. 2015). As halon banks become depleted, the impact score of the alternative systems will change; hence, to be conservative, the results of this study for this impact category are to be considered environmentally neutral.

- For global warming, the ethanol biomass system and the alternative systems are major contributors. More precisely, for the ethanol biomass system, it is the consumption of electricity to upgrade ethanol from 95% to 99.7% purity and the production of ethanol that are the significant contributors to the impact score. The electricity grid mix was modeled with the average North American production mix, which is produced mainly by coal (41%) and natural gas (21%), both of which emit carbon dioxide to air. In terms of the alternative systems, all are fossil fuel-based and emit carbon dioxide to air when combusted during the operation of the passenger car. For the base case scenarios, the ones with methanol or methane as the biomass system appear to result in impact scores of less than zero, while the results of the scenarios with ethanol as the biomass system are most likely environmentally neutral when uncertainty is considered. However, the final results of this pathway will depend on the semi-quantitative uncertainty assessment presented in Section 5.4 of the report.

- For smog, the ethanol biomass system and the diesel alternative system are significant contributors. For the ethanol biomass system, it is the emission of nitrogen oxides during combustion (operation of the passenger car), the consumption of electricity during the upgrade of the ethanol from 95% to 99.7% purity, and ethanol production that are the key contributing substances and life cycle stages. In terms of the diesel alternative system, nitrogen oxides emitted as a result of diesel combustion during operation of the passenger car is the main contributing substance and life cycle stage, respectively. The base case scenario for this pathway appears to result in impact scores of less than zero when methanol or methane are used in alternative to diesel, to result in impact scores greater than zero when ethanol or methane are used in alternative to gasoline or natural gas, and are environmentally neutral when ethanol is used in alternative to diesel and methanol is used in alternative to gasoline. The semi-quantitative uncertainty assessment presented in Section 5.4 of the report will confirm or add nuance to these results.

- For acidification, only the ethanol system is a key contributor. More precisely, emissions of sulfur dioxide and nitrogen oxide from the electricity production used in the upgrade of ethanol from 95% to 99.7% purity, along with ethanol production, are the main contributing substances and life cycle stages. While the scenarios for the ethanol biomass system appear to result in impact scores greater than zero, the results of the remaining scenarios are likely all environmentally neutral. That said, the final results of this pathway will depend on the semi-quantitative uncertainty assessment presented in Section 5.4 of the report.

- For eutrophication, as for acidification, only the ethanol system is a significant contributor. Once again, the production life cycle stage of ethanol, because of the use of electricity, is the main contributor. It is the emissions of phosphate and nitrate to water from the treatment of hard coal mining spoil that are the main contributing substances. Electricity produced from coal in the North American grid mix represents a share of 41%. Electricity is used to upgrade ethanol from 95% to 99.7% purity. All base case scenarios appear to result in scores of greater than zero for this impact category. However, the final results of this pathway will depend on the semi-quantitative uncertainty assessment presented in Section 5.4 of the report.

- For carcinogens, the ethanol and methane biomass systems are the key contributors. For both systems, it is the production life cycle stage that is the main contributor to the results; more precisely, the results are strongly affected by the consumption of electricity produced from coal during ethanol upgrade and methane production. Chromium IV is emitted to water from the treatment of coal mining spoil, coal slurry, and lignite ash. All base case scenarios appear to result in scores greater than zero for this impact category. The semi-quantitative uncertainty assessment presented in Section 5.4 of the report will confirm or add nuance to these results.

- For non-carcinogens, all biomass systems are significant contributors, and for all of them, it is the production life cycle stage that is the main contributing life cycle stage. Emissions of zinc to agricultural soil from wood ash spreading is one of the key contributing substances related to all three biomass systems. As discussed above for the heat pathway scenarios (see Section 5.3.2.1), zinc in agricultural soil from wood ash spreading can be excluded from this impact indicator; however, despite this exclusion, the biomass systems still remain as main contributors. For the ethanol biomass system, contributions are from zinc emitted to air during ethanol production process, and arsenic and zinc emitted to water during hard coal mining treatment of coal. In addition, coal is used to produce electricity as part of the North American grid mix, and is consumed during the ethanol upgrade process. For the methanol biomass system, contributions are from arsenic and zinc emitted to water from the preparation of various materials needed in the methanol production process. For methane, it is zinc emitted to air or water that is the main contributing substance. These emissions come from a variety of processes such as the use of coal in electricity production and treatment of wood ash in landfill. In sum, it appears that even when zinc emitted to agricultural soil is removed from the biomass systems, the scenario impact scores remain greater than zero. That said, the semi-quantitative uncertainty assessment presented in Section 5.4 of the report will confirm or add nuance to these results.

- For respiratory effects, the ethanol biomass system and all alternative systems are key contributors to the impact score results. For the ethanol biomass system, the contribution comes mainly from the production life cycle stage, and more precisely from the emission of sulfur dioxide and $PM_{2.5}$ emitted during the ethanol production process and the production of electricity used to upgrade ethanol. In terms of the alternative systems, it is the emissions of $PM_{2.5}$ during operation of the passenger car, and the emissions of both $PM_{2.5}$ and sulfur dioxide during fuel production that are the main contributing substances and life cycle stages. Base case scenarios result in impact scores greater than zero for scenarios with ethanol, and less than zero for scenarios with methanol or methane. However, the semi-quantitative uncertainty assessment presented in Section 5.4 of the report will confirm or add nuance to these results.

- For ecotoxicity, all biomass systems are significant contributors, primarily through their consumption of electricity and related processes. Emissions of copper and zinc to water are the main contributing substances. All scenarios result in impact scores greater than zero; however, the robustness of these results is verified in the semi-quantitative uncertainty assessment presented in Section 5.4 of the report.

- For fossil fuel depletion, all alternative systems are key contributors because of the nature of the fuels. Base case scenarios appear to all result in impact scores less than zero. The robustness of these results is investigated in the semi-quantitative uncertainty assessment presented in Section 5.4 of the report.

In sum, most of the scenarios for this pathway result in impact scores greater than or equal to zero for most impact categories. The semi-quantitative uncertainty assessment presented in Section5.4 of the report provides more perspective regarding the robustness of these results.

5.3.2.4 *Use in Metallurgy Pathway*

The contribution analyses determined that the biomass system is not a main contributor (see Figure C.6 and Table C.6 in Appendix C for details). In terms of the alternatives system, coke is a key contributor to global warming, eutrophication, carcinogens, respiratory effects, and ecotoxicity.

For the coke alternative system and global warming, it is the emission of carbon dioxide during coke use in pig iron production that is the main contributing substance and life cycle stage. For eutrophication, it is the emission of phosphate to water during hard coal mining spoil treatment that is the main contributing substance and process. Note, however, that the contribution of the coke alternative system is five times smaller than the contribution of landfilling to eutrophication. For carcinogens, it is also the hard coal mining spoil treatment that is the main contributing process due to emissions of chromium VI to water.

For respiratory effects, the contribution of the coke system is quite large. The main contributing process is coke cooking, where $PM_{2.5}$ is emitted. For ecotoxicity, it is zinc emitted to water during treatment of coal mining waste that is the main contributing substance and process.

In sum, the scenario model for the use in metallurgy pathway appears to result in impact scores of less than zero for all impact categories except fossil fuel depletion where the results are neutral. The robustness of the results for the use in metallurgy pathway is investigated in the semi-quantitative uncertainty assessment presented in Section 5.4 of the report.

5.3.2.5 *Use as Horticultural Growing Media Pathway*

The contribution analyses determined that the bark mulch biomass system is a main contributor only to global warming (see Figure C.7 and Table C.7 in Appendix C for details). For bark with “high CO_2e emissions”, it is the emissions of methane and nitrous oxide emitted during the use of bark mulch as it degrades that are the main contributing substances in the use life cycle stage. For bark with “low CO_2e emissions”, it is also emissions during bark mulch degradation that are the main contributing substances, except in this case they are carbon dioxide stored in soil and nitrous oxide emitted to air.

In comparison to landfill emissions, the bark mulch system either emits less methane in the case of the “high CO_2e” systems or stores less carbon in soil in the case of “low CO_2e” systems. In terms of the alternative systems, peat is a significant contributor to the global warming impact category.

For peat, it is the emissions of carbon dioxide to air during the production life cycle stage, and either carbon stored in soil when peat degrades or methane and nitrous oxide emitted during peat mulch degradation, that are the most significant contributors to the global warming impact category.

In sum, the scenarios modeled for the use as horticultural growing media pathway appear to result in impact scores near zero. The robustness of the results is investigated in the semi-quantitative uncertainty assessment presented in Section 5.4 of the report.

5.4 Semi-Quantitative Uncertainty Assessment

In this report, a semi-quantitative uncertainty assessment was performed for each scenario by compiling its impact scores with low efficiency and high efficiency, with an added fixed ± 10% parameter uncertainty on production and use/combustion of the biomass and alternative systems. Results were normalized by the maximum absolute value of the scenario’s biomass or alternative system. Because all compiled possibilities of a scenario were considered equally probable, it was assumed that a scenario results in impact scores different from zero if, and only if, all its possible impact scores result in the same conclusion when the normalized difference between the biomass system and alternative system is greater than the impact category uncertainty.

5.4.1 *Unconventional Use Pathways*

5.4.1.1 *Heat Production Pathway*

For the heat pathway, all scenarios result in impact scores less than zero for global warming, as do syngas scenarios for smog, acidification and respiratory effects (see Figure D.1 and Table D.1 in Appendix D for details). Syngas scenarios have the highest number of impact categories with scores less than zero: global warming, smog, acidification, respiratory effects, and eutrophication or fossil fuel depletion depending on whether the alternative is coal or one of the other investigated alternative systems. Scenarios with pellets as the biomass system are those with the least number of impact categories with scores less than zero and the highest number of categories with scores greater than zero. Scenarios with methane as the biomass system are similar to pellet scenarios, but with a slight increase in the number of impact categories with scores less than zero and a decrease in the number of impact categories with scores greater than zero. Interestingly, both scenarios with pellet or methane as the biomass system have a higher number of impact categories with scores less than zero when replaced by No. 6 fuel oil or coal than they do when substituted with natural gas or No. 2 fuel oil.

5.4.1.2 *Combined Heat and Power Production Pathway*

5.4.1.2.1 *CHP Maximized for Heat Production*

As for the heat pathway, all combined heat and power maximized for heat production pathway scenarios, result in impact scores less than zero for global warming, as do syngas scenarios for smog, acidification, respiratory effects, and fossil fuel depletion (see Figure D.2 and Table D.2 in Appendix D for details). Once again, scenarios modeled with the syngas biomass system result in the highest number of impact categories with impact scores less than zero, followed by scenarios with methane and pellets. Note that the scenario with methane in alternative to natural gas for heat and electricity production results in impact scores greater than zero for eutrophication, which is the only scenario and impact category with scores greater than zero for this pathway.

5.4.1.2.2 *CHP Maximized for Electricity Production*

The combined heat and power pathway maximized for electricity production shows impact scores less than zero for all scenarios for global warming, acidification, and fossil fuel depletion (see Figure D.3 and Table D.3 in Appendix D for details). Scenarios with syngas result in impact scores less than zero for the additional impact categories of smog and respiratory effects, while scenarios with methane result in one additional impact category, respiratory effects. In addition, all scenarios except those with natural gas for heat and electricity production as the alternative system result in impact scores less than zero for eutrophication, carcinogens, and ecotoxicity. Scenarios with syngas as the biomass system result in the highest number of impact categories with scores less than zero, followed by methane and pellets. Scenario results with natural gas for heat and electricity production as the alternative system have the lowest number of impact categories with scores less than zero. Referring back to the contribution analysis, the alternative system with coal as fuel was a main contributor to eutrophication, carcinogens, non-carcinogens, and ecotoxicity, while the natural gas alternative system was not. Hence, the natural gas systems do not offset the potential emissions of the biomass systems for those impact categories, given that the North American grid mix is produced largely by coal (41%).

Note that the scenarios with grid mix as the alternative electricity system are sensitive to a change in electricity production fuel, as shown in Section 5.2 of this report. Results compiled with a Quebec grid mix shown in Figure D.4 and detailed in Table D.4 of Appendix D indicate impact scores less than zero for a maximum of two impact categories for scenarios with syngas as biomass system and electricity supplied by the grid mix in the alternative system: eutrophication and fossil fuel depletion.

5.4.1.3 *Transport Fuel Use Pathway*

For the transport fuel use pathway, all scenarios result in impact scores of less than zero for fossil fuel depletion, as do methanol and methane scenarios for global warming (see Figure D.5 and Table D.5 in Appendix D for details). In contrast, ethanol scenarios result in impact scores greater than zero for acidification, eutrophication, carcinogens, and ecotoxicity. This unconventional use pathway has the scenarios with the highest number of impact categories with impact scores greater than zero. Scenarios with ethanol have the highest number of impact categories with impact scores greater than zero, followed by methanol. For the methane biomass system, there is only one impact category that results in an impact score greater than zero, and that is when methane is replaced by natural gas.

5.4.1.4 *Use in Metallurgy Pathway*

For the metallurgy pathway scenario, the impact score results for all impact categories are environmentally neutral. Results are shown in Figure D.6 and Table D.6 of Appendix D.

5.4.1.5 *Use as Horticultural Growing Media Pathway*

For the horticultural growing media pathway, the results of the two scenarios, which were the simulation of two possible extreme impact score results, were combined to calculate an average scenario and distribution of results. The average scenario results in environmental neutrality for all impact categories except fossil fuel depletion, where the results indicate impact scores greater than zero. Results are shown in Figure D.7 and Table D.7 in Appendix D.

5.5 Comparative Assessment Results

The unconventional use pathways studied in this report are based on generic data and sometimes represent technologies that have not reached commercialization; hence, impact score results may change over the coming years as more complete data sets are available and as technology progresses.

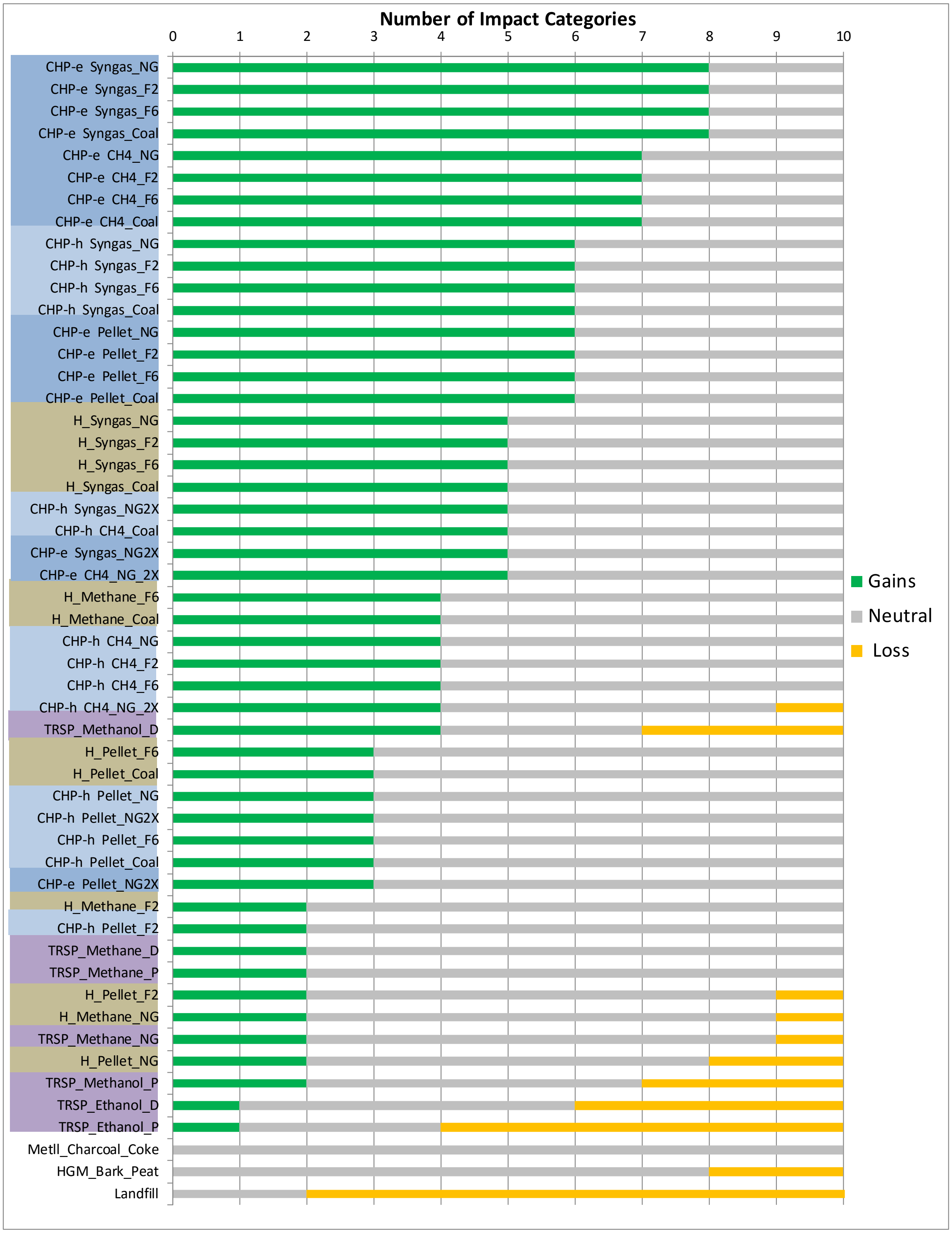
From the data presented in this report, along with the various interpretation steps undertaken, it can be seen in Figure 5.16 that when base case scenarios of all pathways are ranked against each other, the scenarios for the combined heat and power production pathway maximized for electricity production (CHPe) with the North American grid mix as substitute for electricity, produced by biomass converted to syngas, methane, or pellets, rank among the scenarios with the highest number of impact categories with impact scores of less than zero. Also included in the top ranking scenarios are those for combined heat and power production maximized for heat production (CHPh) produced by syngas in alternative to fossil fuel for heat production with the North American grid mix. These CHP scenarios are followed by syngas-based scenarios for the heat pathway (H). Biomass systems are identical for the heat production and combined heat and power pathways. When comparing the contribution of pellets, syngas, and methane, syngas was not found to be a significant contributing system and always had lower estimated impacts than the methane and pellet biomass systems. In terms of the alternative systems, their estimated impacts are very similar when it comes to the Heat and CHPh pathways, while the impacts are larger in the context of the CHPe pathway with the grid mix as the alternative system for electricity production.

In terms of the scenarios for the transport fuel use pathway (TRSP), they are found towards the bottom of the graph on Figure 5.16, i.e., they are among the scenarios with the lowest number of impact categories with impact scores less than zero. Moreover, the transport fuel use pathway has scenarios with the highest number of impact categories with impact scores greater than zero. From the transport fuel use pathway contribution analysis, it was shown that the alternative system was a main contributor for only four impact categories, while the ethanol, methanol, and methane biomass systems were main contributors to eight, one, and three impact categories, respectively. Moreover, the estimated impacts from the biomass systems were, more often than not, larger than those from the alternative systems. For ethanol, it is the consumption of electricity during its upgrade from 95% to 99.7% purity that is the main contributing process to most impact categories.

Note that ozone depletion impact category results were considered too uncertain to enable conclusions to be drawn; hence, results for that impact category are considered environmentally neutral. Also, for the impact category of non-carcinogens, zinc emitted to agricultural soil from wood ash spreading was considered to be environmentally neutral if spreading were to be authorized by local authorities, and thus these emissions were excluded.

Note that scenarios from the CHPe pathway with a grid mix as the alternative system are sensitive to the electricity production mix. When scenarios are modeled with the Quebec grid mix, where electricity is mainly produced with hydroelectricity, the CHPe scenarios with grid mix as the alternative electricity production system fall to the bottom of the graph, i.e., have only a maximum of two impact categories with impact scores less than zero.

In terms of the disposal pathway, the landfill scenarios do not contain an alternative system; hence, no biomass system emission offset occurs. As a result, almost all impact categories result in impact scores greater than zero. The two impact categories that are environmentally neutral are ozone depletion and global warming. As stated previously, the impact category of ozone depletion is considered environmentally neutral for all pathways. Results for global warming are environmentally neutral because of the uncertainty related to, or absence of, woody mill residues decomposition in landfill. Impact categories for which unconventional use pathway scenarios and disposal scenarios are the same order of magnitude are global warming, eutrophication, non-carcinogens, and ecotoxicity. For these impact categories, waste emissions from landfilling woody mill residues are the main contributor. This means that the potential environmental impacts of the unconventional use pathways for these impact categories are the same order of magnitude as the potential environmental impacts of waste emissions from landfilling woody mill residues. For the other impact categories, landfill construction and landfill operation process grouping were identified as main contributors to the disposal pathway, and the difference between many of the unconventional use pathways and the landfill scenarios are large. Hence, landfilling potentially contributes very little to these impact categories in comparison to most unconventional use pathway scenarios.



Legend

Pathway: CHPe | CHPh | Heat | Transport | All Other

Figure 5.16 All Pathway Base Case Scenarios, Uncertainty Included, Ranked by Number of Impact Categories with Impact Scores Less than Zero (i.e., favorable impact scores)

6.0 CONCLUSIONS

In this study, five unconventional use pathways and one disposal pathway for managing one dry tonne of woody mill residues were investigated. The unconventional use pathways considered were heat production using value-added fuels, combined heat and power production using value-added fuels, transport fuel use, use in metallurgy, and use as horticultural growing media. A total of 54 base case scenarios was assessed as possible management options within these pathways. Each unconventional use pathway was represented by scenarios built with a biomass system from which a substituted alternative system is subtracted in order for all scenarios to fulfill an equivalent function, managing one tonne of residues, thus rendering them comparable. The disposal pathway scenarios contained only a biomass system as they fulfill only one function, the management of one tonne of woody mill residues. Note that scenarios were built from generic data with some processes still at the development stage; therefore, the results could change over time as industry data become available and processes reach commercialization.

The results were analyzed through a four-step interpretation approach using the LCA impact assessment method TRACI from the United States Environmental Protection Agency. First, the results of the base case scenarios were presented along with those for the sensitivity analyses. The two sensitivity analyses, named “efficiency” and “grid mix”, tested the robustness of the results. The “efficiency” sensitivity analysis was used to explore the effect of variation of the parameters related to system efficiency, such as production yield and combustion yield. The “grid mix” sensitivity analysis investigated the effect of changing production and consumption location, which is often linked to the grid mix. Next, contribution analyses were performed to understand which life cycle stages, processes, and/or substances were contributing most significantly to the results. In the third step, a semi-quantitative uncertainty analysis was performed to account for inevitable variation and thus enable development of more robust conclusions. Finally, a ranking of the different pathway scenarios was performed, using all the information gained in the prior steps. The ranking of the scenarios provides an indication as to which pathway or pathways may yield the most potential environmental gains and in which parameter settings.

Results showed that the combined heat and power production pathway with a low heat-to-power ratio (i.e., maximized for electricity production) using a North American grid mix as electricity production in the alternative system ranked among the scenarios with the most impact categories with beneficial impact scores (i.e., less than zero). Scenarios with syngas as the biomass system in the heat production and combined heat and power production pathways were also among the scenarios with the most impact categories with impact scores lower than zero. In contrast, scenarios from the transport fuel use pathway and use in metallurgy pathway ranked among the scenarios with the most impact categories with impact scores greater than zero (i.e., net impact). In terms of the use as horticultural growing media pathway, the scenarios were environmentally neutral. Interestingly, all scenarios ranked better than landfilling for most impact categories, as the latter had the most impact categories with impact scores greater than zero. Note that in the final ranking, the impact category of ozone depletion was considered too uncertain to enable conclusions regarding whether impact scores were greater or less than zero. Also, results were compiled excluding contribution of zinc to agricultural soil from wood ash spreading, which affects results of the impact category non-carcinogens. In sum, based on the data and assumptions used in this study, converting biomass into syngas to produce heat or electricity to replace fossil fuel based energy appears to have the most favorable impact scores of the pathways examined.

This study provides a general assessment of potential attributes and trade-offs of various unconventional use pathways for managing woody mill residues. It is based on generic data and processes that have not necessarily reached commercialization; hence, the results may change over time. This study did not account for environmental considerations other than the ones incorporated in the TRACI impact method; therefore, no statement of environmental superiority of one scenario over another can be made. Furthermore, the technological and economic feasibility of the different pathways was not considered. Scenarios of interest should be further investigated using specific on-site data. Note that if the woody mill residues of interest are already used in a conventional use pathway, the effects of replacing the woody mill residues in their actual application by an alternative product would need to be accounted for through a consequential life cycle assessment.

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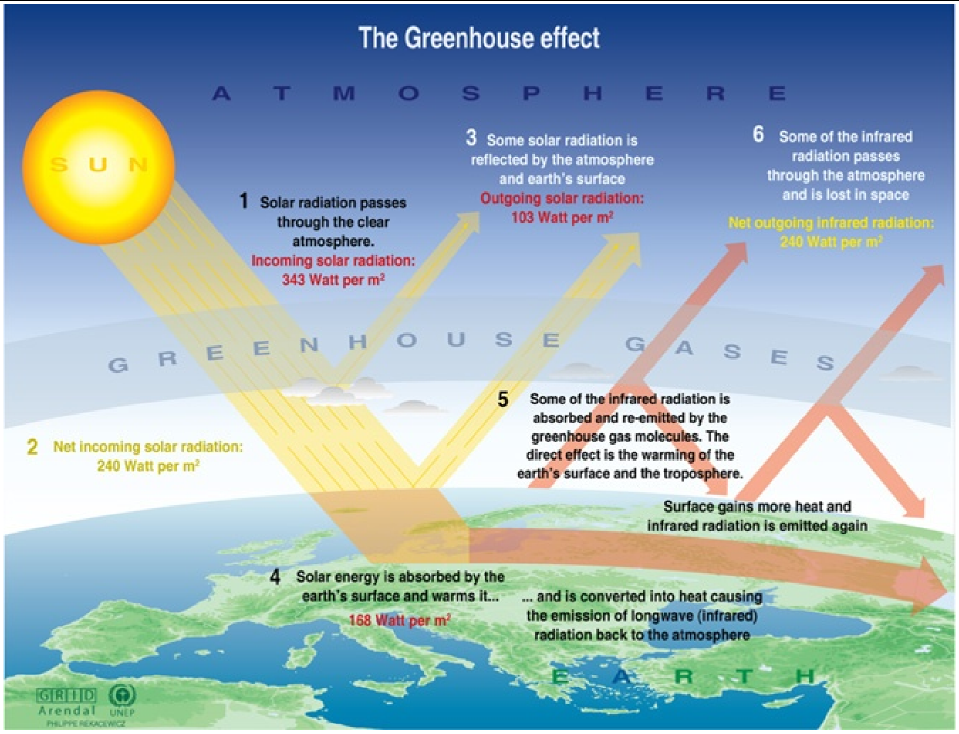
APPENDIX A

IMPACT INDICATOR DESCRIPTIONS

A.1. Global Warming

Global warming potential refers to the potential change in the earth's climate caused by the buildup of greenhouse gases that trap heat from the reflected sunlight that would have otherwise passed out of the earth's atmosphere (see Figure A.1).



SOURCES: Okanagan University College, Canada, Department of Geography, University of Oxford, School of Geography, United States Environmental Protection Agency (EPA), Washington; *Climate Change 1995, The Science of Climate Change, Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), UNEP and WMO (World Meteorological Organization*, Cambridge University Press, 1996. URL: http://www.grida.no/publications/vg/climate/page/3058.aspx, Cartographer/Designer: Philippe Rekacewicz, UNEP/ELECTRICITY GRID-Arendal

Figure A.1 Illustration of Greenhouse Effects

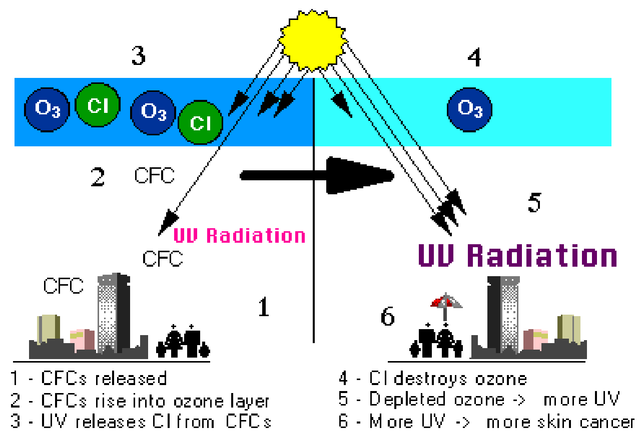
Global warming potential is computed in units of CO_2 equivalents. This means that the global warming potential for the different greenhouse gases is expressed as a function of carbon dioxide. In this study, the global warming potentials proposed by the International Panel on Climate Change (IPCC) in 2006 were used, along with a 100-year time horizon. Biogenic carbon accounting was undertaken using a stock change approach rather than a flow approach, as is typically used in LCA. In other words, the global warming potential of carbon uptake from the atmosphere and for emission of biogenic carbon dioxide was set to 0 instead of -1 and 1, as used in the flow accounting approach.

A.2. Ozone Depletion

Source : http://www.epa.gov/ozone/science/process.html

The ozone depletion process is depicted in Figure A.2.

> *"The ozone depletion process begins when CFCs and other ozone-depleting substances (ODS) are emitted into the atmosphere (1). Winds efficiently mix the troposphere and evenly distribute the gases. CFCs are extremely stable, and they do not dissolve in rain. After a period of several years, ODS molecules reach the stratosphere, about 10 kilometers above the Earth's surface (2). Strong UV light breaks apart the ODS molecule. CFCs, HCFCs, carbon tetrachloride, methyl chloroform, and other gases release chlorine atoms, and halons and methyl bromide release bromine atoms (3). It is these atoms that actually destroy ozone, not the intact ODS molecule. It is estimated that one chlorine atom can destroy over 100,000 ozone molecules before it is removed from the stratosphere (4)."*



SOURCE: USEPA (http://www.epa.gov/ozone/science/process.html)

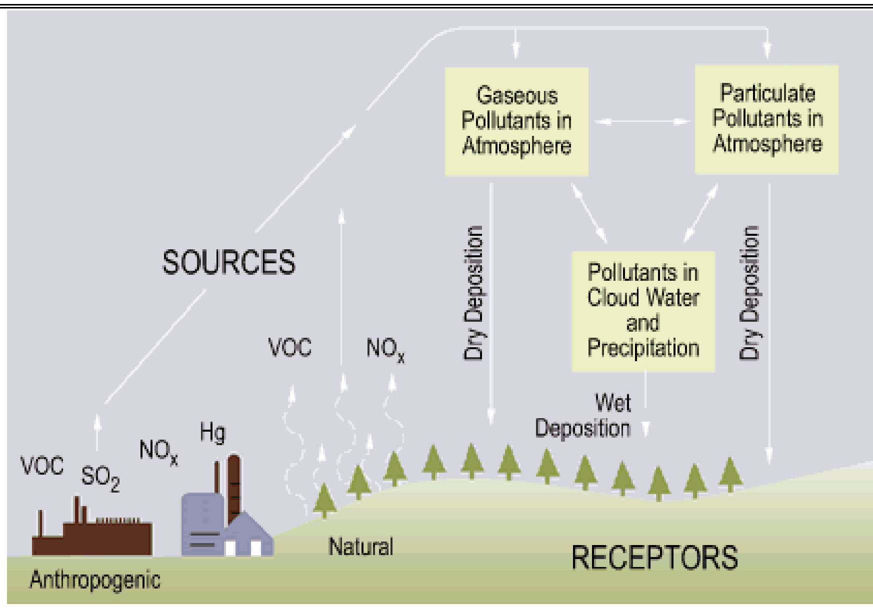
Figure A.2 Ozone Depletion Process

A.3. Acidification

Source: https://www.epa.gov/acidrain/what-acid-rain

The acidification process is shown in Figure A.3.

> *"'Acid rain'" is a broad term referring to a mixture of wet and dry deposition (deposited material) from the atmosphere containing higher than normal amounts of nitric and sulfuric acids. The precursors, or chemical forerunners, of acid rain formation result from both natural sources, such as volcanoes and decaying vegetation, and man-made sources, primarily releases of sulfur dioxide (SO_2) and nitrogen oxides (NO_x) resulting from fossil fuel combustion. In the United States, roughly 2/3 of all SO_2 and 1/4 of all NO_x come from electric power generation that relies on burning fossil fuels, like coal. Acid rain occurs when these gases react in the atmosphere with water, oxygen, and other chemicals to form various acidic compounds. The result is a mild solution of sulfuric acid and nitric acid. When sulfur dioxide and nitrogen oxides are released from power plants and other sources, prevailing winds blow these compounds across state and national borders, sometimes over hundreds of miles."*



SOURCE: USEPA (https://www.epa.gov/acidrain/what-acid-rain)

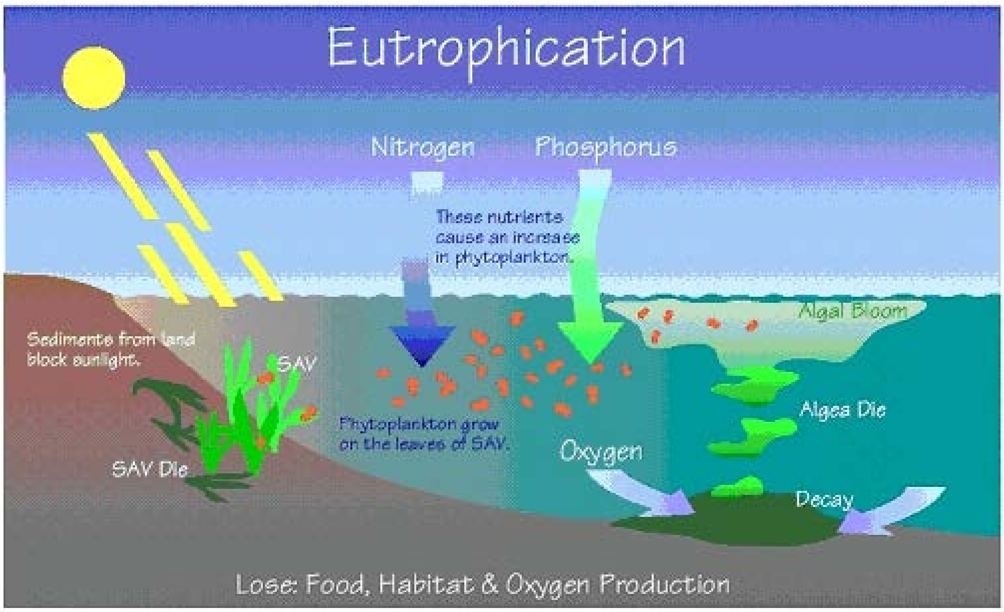
Figure A.3 Acidification Process

A.4. Eutrophication

Source: TRACI documentation (Bare et al. 2003)

The eutrophication process is depicted in Figure A.4.

> *"Eutrophication is the fertilization of surface waters by nutrients that were previously scarce. When a previously scarce (limiting) nutrient is added, it leads to the proliferation of aquatic photosynthetic plant life. This may lead to a chain of further consequences, including foul odor or taste, death or poisoning of fish or shellfish reduced biodiversity, or production of chemical compounds toxic to humans, marine mammals, or livestock. The limiting-nutrient issue is key to characterization analysis of phosphorus (P) and nitrogen (N) releases within LCIA. If equal quantities of N and P are released to a freshwater system that is strictly P limited, then the characterization factors for these two nutrients should account for this fact (e.g., the characterization factor for N should approach zero in this instance)."*



SOURCE: Florida International University (http://www.fiu.edu/~envstud/labs/nutrientanalysis.html)

Figure A.4 Eutrophication Process

A.5. Smog (Photochemical Oxidant Formation)

Source: TRACI documentation (Bare et al. 2003)

"Ozone (O_3) is a reactive oxidant gas produced naturally in trace amounts in the earth's atmosphere. Ozone in the troposphere leads to detrimental impacts on human health and ecosystems. The characterization point associated with photochemical oxidant formation is the formation of ozone molecules in the troposphere. Rates of ozone formation in the troposphere are governed by complex chemical reactions, which are influenced by ambient concentrations of nitrogen oxides (NO_x) and volatile organic compounds (VOCs), as well as the particular mix of VOCs, temperature, sunlight, and convective flows."

A.6. Respiratory Effects

Source: TRACI documentation (Bare et al. 2003)

"Ambient concentrations of particulate matter (PM) are strongly associated with changes in background rates of chronic and acute respiratory symptoms, as well as mortality rates. Ambient particulate concentrations are elevated by releases of primary particulates, measured variously as total suspended particulates, PM less than 10 µm in diameter (PM10), PM less than 2.5 µm in diameter (PM2.5), and by releases of sulfur dioxide and nitrogen oxides, which lead to the formation of the so-called secondary particulates sulfate and nitrate."

A.7. Fossil Fuel Depletion

Source: TRACI documentation (Bare et al. 2003)

"The fossil fuel depletion indicator takes into account the fact that continued extraction and production of fossil fuels tends to consume the most economically recoverable reserves first, so that continued extraction will become more energy intensive in the future. This is especially true once economically recoverable reserves of conventional petroleum and natural gas are consumed, leading to the need to use nonconventional sources, such as oil shale. For each fuel, present fuel, experts generated scenarios for replacement fuels at a point in the future when total cumulative consumption equals 5 times the present cumulative consumption. The current energy intensity (energy per unit of fuel delivered) for these future fuel extraction and production scenarios was specified. The increase in unit energy requirements per unit of consumption for each fuel provides an estimate of the incremental energy input "cost" per unit of consumption. These factors then provide a basis for weighting the consumption of different fossil fuel energy resources."

A.8. Carcinogens, Non-Carcinogens and Ecotoxicity

Source: TRACI documentation (Bare et al. 2003)

These three impact categories consist of a relative ranking of a large number of chemicals in terms of their potential to cause toxicological impacts.

REFERENCE

Bare, J.C., G.A. Norris, D.W. Pennington, and T. McKone. 2003. TRACI The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts. *Journal of Industrial Ecology* 6(3-4):49–78. http://dx.doi.org/10.1162/108819802766269539

APPENDIX B

IMPACT SCORE RESULTS

B.1 Base Case Scenarios

		Ozone depletion	Global warming	Smog	Acidification	Eutrophication	Carcinogenics	Non carcinogenics	Respiratory effects	Ecotoxicity	Fossil fuel depletion
		kg CFC-11 eq	kg CO2 eq	kg O3 eq	kg SO2 eq	kg N eq	CTUh	CTUh	kg PM2.5 eq	CTUe	MJ surplus
Landfill	LF_highCO2e	5.16E-06	2.44E+03	3.13E+00	1.12E-01	9.04E+00	1.22E-06	5.00E-05	1.29E-02	1.10E+03	5.18E+01
	LF_lowCO2e	5.16E-06	-1.55E+03	3.13E+00	1.12E-01	9.04E+00	1.22E-06	5.00E-05	1.29E-02	1.10E+03	5.18E+01
Heat	H_Pellet_NG	3.54E-05	-1.03E+03	2.51E+01	-3.56E+00	3.64E-01	5.85E-06	6.53E-04	2.83E-01	1.19E+03	-3.25E+03
	H_Pellet_F2	-7.66E-05	-1.21E+03	3.43E+01	-2.37E+00	-1.15E-01	6.65E-06	6.68E-04	2.87E-01	1.42E+03	-2.80E+03
	H_Pellet_F6	-9.53E-05	-1.25E+03	8.86E+00	-8.70E+00	-2.10E-01	5.81E-06	6.45E-04	-9.48E-02	1.21E+03	-2.95E+03
	H_Pellet_Coal	2.24E-04	-1.68E+03	-4.35E+01	-1.23E+01	-5.36E+00	-6.01E-05	4.00E-04	-1.98E-01	-5.33E+03	-1.48E+01
	H_SG_NG	-1.39E-04	-7.34E+02	-2.82E+01	-3.59E+00	8.89E-02	6.58E-06	4.18E-04	-1.90E-01	6.35E+02	-2.20E+03
	H_SG_F2	-2.12E-04	-8.55E+02	-2.22E+01	-2.82E+00	-2.23E-01	7.10E-06	4.28E-04	-1.88E-01	7.84E+02	-1.91E+03
	H_SG_F6	-2.24E-04	-8.82E+02	-3.88E+01	-6.94E+00	-2.85E-01	6.56E-06	4.12E-04	-4.37E-01	6.43E+02	-2.01E+03
	H_SG_Coal	-1.61E-05	-1.16E+03	-7.29E+01	-9.30E+00	-3.65E+00	-3.65E-05	2.53E-04	-5.04E-01	-3.62E+03	-9.40E+01
	H_CH4_NG	-1.11E-04	-5.00E+02	4.31E+00	-1.70E+00	6.76E-01	7.78E-06	5.34E-04	-9.26E-02	1.36E+03	-1.83E+03
	H_CH4_F2	-1.75E-04	-6.05E+02	9.54E+00	-1.03E+00	4.04E-01	8.23E-06	5.42E-04	-9.05E-02	1.49E+03	-1.57E+03
	H_CH4_F6	-1.86E-04	-6.29E+02	-4.91E+00	-4.62E+00	3.50E-01	7.76E-06	5.29E-04	-3.08E-01	1.37E+03	-1.65E+03
	H_CH4_Coal	-3.96E-06	-8.72E+02	-3.47E+01	-6.68E+00	-2.58E+00	-2.98E-05	3.90E-04	-3.67E-01	-2.35E+03	1.54E+01
CHP Heat	CHPh_Pellet_NG_E	3.64E-05	-1.24E+03	1.35E+01	-5.04E+00	-1.18E+00	-1.26E-05	5.89E-04	1.92E-01	-1.34E+03	-2.88E+03
	CHPh_Pellet_NG_2X	-1.68E-05	-1.33E+03	-7.39E-01	-5.35E+00	2.96E-01	5.00E-06	6.50E-04	2.08E-01	1.05E+03	-4.04E+03
	CHPh_Pellet_F2_E	-5.09E-05	-1.39E+03	2.06E+01	-4.12E+00	-1.55E+00	-1.20E-05	6.00E-04	1.95E-01	-1.16E+03	-2.52E+03
	CHPh_Pellet_F6_E	-6.55E-05	-1.42E+03	8.40E-01	-9.05E+00	-1.63E+00	-1.27E-05	5.82E-04	-1.03E-01	-1.33E+03	-2.64E+03
	CHPh_Pellet_Coal_E	1.83E-04	-1.75E+03	-4.00E+01	-1.19E+01	-5.65E+00	-6.41E-05	3.91E-04	-1.83E-01	-6.42E+03	-3.56E+02
	CHPh_SG_NG_E	-1.38E-04	-8.75E+02	-3.58E+01	-4.56E+00	-9.19E-01	-5.47E-06	3.76E-04	-2.50E-01	-1.01E+03	-1.96E+03
	CHPh_SG_NG_2X	-1.73E-04	-9.31E+02	-4.50E+01	-4.75E+00	4.49E-02	6.03E-06	4.15E-04	-2.40E-01	5.44E+02	-2.72E+03
	CHPh_SG_F2_E	-1.95E-04	-9.70E+02	-3.11E+01	-3.95E+00	-1.16E+00	-5.06E-06	3.83E-04	-2.48E-01	-8.98E+02	-1.73E+03
	CHPh_SG_F6_E	-2.05E-04	-9.91E+02	-4.40E+01	-7.17E+00	-1.21E+00	-5.49E-06	3.71E-04	-4.42E-01	-1.01E+03	-1.81E+03
	CHPh_SG_Coal_E	-4.25E-05	-1.21E+03	-7.06E+01	-9.01E+00	-3.83E+00	-3.90E-05	2.47E-04	-4.95E-01	-4.33E+03	-3.16E+02
	CHPh_CH4_NG_E	-1.11E-04	-6.23E+02	-2.29E+00	-2.55E+00	-2.03E-01	-2.73E-06	4.97E-04	-1.45E-01	-7.86E+01	-1.61E+03
	CHPh_CH4_NG_2X	-1.41E-04	-6.72E+02	-1.04E+01	-2.72E+00	6.38E-01	7.30E-06	5.32E-04	-1.36E-01	1.28E+03	-2.28E+03
	CHPh_CH4_F2_E	-1.60E-04	-7.05E+02	1.79E+00	-2.02E+00	-4.16E-01	-2.38E-06	5.04E-04	-1.43E-01	2.29E+01	-1.41E+03
	CHPh_CH4_F6_E	-1.69E-04	-7.23E+02	-9.48E+00	-4.82E+00	-4.58E-01	-2.75E-06	4.93E-04	-3.12E-01	-7.31E+01	-1.48E+03
	CHPh_CH4_COAL_E	-2.70E-05	-9.13E+02	-3.27E+01	-6.43E+00	-2.74E+00	-3.20E-05	3.85E-04	-3.58E-01	-2.97E+03	-1.79E+02

		Ozone depletion	Global warming	Smog	Acidification	Eutrophication	Carcinogenics	Non carcinogenics	Respiratory effects	Ecotoxicity	Fossil fuel depletion
		kg CFC-11 eq	kg CO2 eq	kg O3 eq	kg SO2 eq	kg N eq	CTUh	CTUh	kg PM2.5 eq	CTUe	MJ surplus
CHP Power	CHPe_Pellet_NG_E	-8.19E-06	-2.43E+03	-4.72E+01	-1.27E+01	-7.85E+00	-9.37E-05	3.01E-04	-2.75E-01	-1.24E+04	-2.03E+03
	CHPe_Pellet_NG_2X	-2.89E-04	-2.88E+03	-1.22E+02	-1.43E+01	-4.49E-02	-6.72E-07	6.24E-04	-1.91E-01	2.18E+02	-8.19E+03
	CHPe_Pellet_F2_E	-1.38E-05	-2.44E+03	-4.67E+01	-1.27E+01	-7.88E+00	-9.36E-05	3.02E-04	-2.75E-01	-1.24E+04	-2.00E+03
	CHPe_Pellet_F6_E	-1.47E-05	-2.44E+03	-4.80E+01	-1.30E+01	-7.88E+00	-9.37E-05	3.00E-04	-2.94E-01	-1.24E+04	-2.01E+03
	CHPe_Pellet_Coal_E	1.21E-06	-2.46E+03	-5.06E+01	-1.32E+01	-8.14E+00	-9.70E-05	2.88E-04	-2.99E-01	-1.27E+04	-1.86E+03
	CHPe_SG_NG_E	-1.67E-04	-1.65E+03	-7.53E+01	-9.56E+00	-5.27E+00	-5.83E-05	1.88E-04	-5.54E-01	-8.23E+03	-1.41E+03
	CHPe_SG_NG_2X	-3.51E-04	-1.94E+03	-1.24E+02	-1.06E+01	-1.77E-01	2.33E-06	3.98E-04	-5.00E-01	-1.18E+00	-5.43E+03
	CHPe_SG_F2_E	-1.71E-04	-1.66E+03	-7.50E+01	-9.53E+00	-5.29E+00	-5.83E-05	1.88E-04	-5.54E-01	-8.22E+03	-1.39E+03
	CHPe_SG_F6_E	-1.72E-04	-1.66E+03	-7.59E+01	-9.73E+00	-5.29E+00	-5.83E-05	1.88E-04	-5.67E-01	-8.23E+03	-1.40E+03
	CHPe_SG_Coal_E	-1.61E-04	-1.67E+03	-7.76E+01	-9.85E+00	-5.46E+00	-6.05E-05	1.80E-04	-5.70E-01	-8.44E+03	-1.30E+03
	CHPe_CH4_NG_E	-1.36E-04	-1.30E+03	-3.68E+01	-6.92E+00	-4.00E+00	-4.89E-05	3.33E-04	-4.10E-01	-6.37E+03	-1.13E+03
	CHPe_CH4_NG_2X	-2.96E-04	-1.56E+03	-7.95E+01	-7.83E+00	4.44E-01	4.07E-06	5.17E-04	-3.63E-01	8.06E+02	-4.64E+03
	CHPe_CH4_F2_E	-1.39E-04	-1.30E+03	-3.66E+01	-6.88E+00	-4.01E+00	-4.89E-05	3.33E-04	-4.10E-01	-6.37E+03	-1.12E+03
	CHPe_CH4_F6_E	-1.40E-04	-1.30E+03	-3.73E+01	-7.06E+00	-4.02E+00	-4.89E-05	3.33E-04	-4.21E-01	-6.37E+03	-1.12E+03
	CHPe_CH4_Coal_E	-1.31E-04	-1.32E+03	-3.88E+01	-7.16E+00	-4.16E+00	-5.08E-05	3.26E-04	-4.24E-01	-6.56E+03	-1.04E+03
Transport Fuel	TRSP_Ethanol_D	-8.44E-05	-4.77E+01	5.04E+00	2.30E+00	1.55E+00	2.02E-05	2.49E-04	1.01E-01	3.13E+03	-7.66E+02
	TRSP_Ethanol_P	-1.09E-04	-1.76E+02	3.55E+01	2.74E+00	1.52E+00	1.92E-05	2.43E-04	1.51E-01	2.98E+03	-1.02E+03
	TRSP_Methanol_D	-1.01E-04	-3.61E+02	-2.47E+01	-6.53E-01	3.40E-01	1.30E-05	4.74E-04	-8.28E-02	2.00E+03	-9.30E+02
	TRSP_Methanol_P	-1.20E-04	-4.62E+02	-6.65E-01	-3.11E-01	3.13E-01	1.21E-05	4.70E-04	-4.34E-02	1.88E+03	-1.13E+03
	TRSP_CH4_D	-1.33E-04	-4.09E+02	-2.17E+01	-2.02E-01	5.02E-01	9.81E-06	5.41E-04	-8.52E-02	1.67E+03	-1.19E+03
	TRSP_CH4_P	-1.58E-04	-5.41E+02	9.60E+00	2.42E-01	4.66E-01	8.71E-06	5.35E-04	-3.39E-02	1.51E+03	-1.45E+03
	TRSP_CH4_NG	-7.13E-05	-4.16E+02	1.34E+01	-5.49E-01	8.09E-01	1.03E-05	5.42E-04	-2.88E-02	1.67E+03	-1.24E+03
Charcoal	Metl_Charcoal_Coke	-2.66E-05	-6.91E+02	-8.21E+00	-1.11E+00	-1.90E+00	-2.15E-05	-6.11E-05	-7.79E-01	-1.97E+03	-4.94E+01
Mulch	GM_highMulch_Peat	5.50E-06	5.25E+02	1.22E+00	6.82E-02	2.32E-02	7.23E-07	7.36E-06	1.57E-02	6.90E+01	9.41E+01
	GM_lowMulch_Peat	6.72E-06	-1.51E+03	1.50E+00	8.33E-02	2.83E-02	8.83E-07	8.99E-06	1.92E-02	8.44E+01	1.15E+02

B.2. Low Efficiency

		Ozone depletion	Global warming	Smog	Acidification	Eutrophication	Carcinogenics	Non carcinogenics	Respiratory effects	Ecotoxicity	Fossil fuel depletion
		kg CFC-11 eq	kg CO2 eq	kg O3 eq	kg SO2 eq	kg N eq	CTUh	CTUh	kg PM2.5 eq	CTUe	MJ surplus
Heat	**H_Pellet_NG**	1.63E-04	8.69E+02	3.69E+01	4.46E+00	2.00E-01	6.80E-06	3.85E-05	2.51E-01	7.83E+02	2.48E+03
	H_Pellet_F2	2.43E-04	1.00E+03	3.04E+01	3.61E+00	5.42E-01	6.23E-06	2.77E-05	2.49E-01	6.20E+02	2.15E+03
	H_Pellet_F6	2.56E-04	1.03E+03	4.85E+01	8.12E+00	6.09E-01	6.83E-06	4.43E-05	5.21E-01	7.74E+02	2.26E+03
	H_Pellet_Coal	2.87E-05	1.34E+03	8.58E+01	1.07E+01	4.28E+00	5.38E-05	2.19E-04	5.94E-01	5.43E+03	1.70E+02
	H_SG_NG	7.16E-05	3.82E+02	1.62E+01	1.96E+00	8.80E-02	2.99E-06	1.69E-05	1.10E-01	3.44E+02	1.09E+03
	H_SG_F2	1.07E-04	4.40E+02	1.33E+01	1.59E+00	2.38E-01	2.74E-06	1.22E-05	1.09E-01	2.72E+02	9.46E+02
	H_SG_F6	1.13E-04	4.53E+02	2.13E+01	3.57E+00	2.68E-01	3.00E-06	1.95E-05	2.29E-01	3.40E+02	9.94E+02
	H_SG_Coal	1.26E-05	5.86E+02	3.77E+01	4.70E+00	1.88E+00	2.36E-05	9.61E-05	2.61E-01	2.39E+03	7.47E+01
	H_CH4_NG	7.51E-05	4.00E+02	1.70E+01	2.05E+00	9.23E-02	3.13E-06	1.78E-05	1.16E-01	3.61E+02	1.14E+03
	H_CH4_F2	1.12E-04	4.61E+02	1.40E+01	1.66E+00	2.50E-01	2.87E-06	1.28E-05	1.15E-01	2.86E+02	9.92E+02
	H_CH4_F6	1.18E-04	4.75E+02	2.23E+01	3.74E+00	2.81E-01	3.15E-06	2.04E-05	2.40E-01	3.57E+02	1.04E+03
	H_CH4_Coal	1.32E-05	6.15E+02	3.95E+01	4.93E+00	1.97E+00	2.48E-05	1.01E-04	2.74E-01	2.50E+03	7.84E+01
CHP Heat	**CHPh_Pellet_NG_E**	8.57E-05	-6.88E+02	3.73E+01	-1.99E+00	-1.36E-01	2.25E-06	6.43E-04	2.67E-01	1.02E+03	-1.87E+03
	CHPh_Pellet_NG_2X	4.73E-05	-7.49E+02	2.71E+01	-2.20E+00	9.31E-01	1.50E-05	6.87E-04	2.78E-01	2.74E+03	-2.71E+03
	CHPh_Pellet_F2_E	2.34E-05	-7.91E+02	4.25E+01	-1.33E+00	-4.02E-01	2.69E-06	6.51E-04	2.69E-01	1.15E+03	-1.61E+03
	CHPh_Pellet_F6_E	1.30E-05	-8.14E+02	2.83E+01	-4.84E+00	-4.55E-01	2.22E-06	6.38E-04	5.63E-02	1.02E+03	-1.70E+03
	CHPh_Pellet_Coal_E	1.91E-04	-1.05E+03	-7.65E-01	-6.85E+00	-3.32E+00	-3.44E-05	5.02E-04	-1.17E-03	-2.61E+03	-6.80E+01
	CHPh_SG_NG_E	-6.15E-05	-3.92E+02	-1.48E+01	-1.97E+00	-3.26E-01	2.94E-06	4.12E-04	-1.03E-01	1.13E+02	-9.12E+02
	CHPh_SG_NG_2X	-7.84E-05	-4.19E+02	-1.93E+01	-2.06E+00	1.43E-01	8.53E-06	4.32E-04	-9.80E-02	8.70E+02	-1.28E+03
	CHPh_SG_F2_E	-8.89E-05	-4.37E+02	-1.26E+01	-1.68E+00	-4.42E-01	3.14E-06	4.16E-04	-1.02E-01	1.69E+02	-8.02E+02
	CHPh_SG_F6_E	-9.34E-05	-4.47E+02	-1.88E+01	-3.22E+00	-4.66E-01	2.93E-06	4.10E-04	-1.95E-01	1.16E+02	-8.39E+02
	CHPh_SG_Coal_E	-1.55E-05	-5.52E+02	-3.16E+01	-4.11E+00	-1.72E+00	-1.32E-05	3.51E-04	-2.21E-01	-1.48E+03	-1.22E+02
	CHPh_CH4_NG_E	-5.81E-05	-3.01E+02	7.16E+00	-9.62E-01	1.32E-01	2.03E-06	4.66E-04	-5.33E-02	5.33E+02	-8.86E+02
	CHPh_CH4_NG_2X	-7.59E-05	-3.29E+02	2.43E+00	-1.06E+00	6.24E-01	7.89E-06	4.86E-04	-4.81E-02	1.33E+03	-1.27E+03
	CHPh_CH4_F2_E	-8.69E-05	-3.48E+02	9.51E+00	-6.58E-01	9.66E-03	2.24E-06	4.70E-04	-5.24E-02	5.91E+02	-7.70E+02
	CHPh_CH4_F6_E	-9.16E-05	-3.59E+02	3.00E+00	-2.28E+00	-1.46E-02	2.02E-06	4.64E-04	-1.50E-01	5.36E+02	-8.09E+02
	CHPh_CH4_COAL_E	-9.85E-06	-4.68E+02	-1.04E+01	-3.20E+00	-1.33E+00	-1.49E-05	4.01E-04	-1.77E-01	-1.14E+03	-5.71E+01

		Ozone depletion	Global warming	Smog	Acidification	Eutrophication	Carcinogenics	Non carcinogenics	Respiratory effects	Ecotoxicity	Fossil fuel depletion
		kg CFC-11 eq	kg CO2 eq	kg O3 eq	kg SO2 eq	kg N eq	CTUh	CTUh	kg PM2.5 eq	CTUe	MJ surplus
CHP Power	CHPe_Pellet_NG_E	5.39E-05	-1.53E+03	-5.91E+00	-7.46E+00	-4.89E+00	-5.56E-05	4.38E-04	-6.62E-02	-6.87E+03	-1.26E+03
	CHPe_Pellet_NG_2X	-1.47E-04	-1.86E+03	-5.95E+01	-8.61E+00	6.82E-01	1.09E-05	6.69E-04	-6.56E-03	2.15E+03	-5.67E+03
	CHPe_Pellet_F2_E	4.99E-05	-1.54E+03	-5.58E+00	-7.42E+00	-4.91E+00	-5.55E-05	4.38E-04	-6.61E-02	-6.86E+03	-1.24E+03
	CHPe_Pellet_F6_E	4.93E-05	-1.54E+03	-6.49E+00	-7.64E+00	-4.91E+00	-5.56E-05	4.38E-04	-7.97E-02	-6.87E+03	-1.25E+03
	CHPe_Pellet_Coal_E	6.06E-05	-1.56E+03	-8.35E+00	-7.77E+00	-5.10E+00	-5.79E-05	4.29E-04	-8.34E-02	-7.10E+03	-1.14E+03
	CHPe_SG_NG_E	-7.55E-05	-7.64E+02	-3.38E+01	-4.37E+00	-2.42E+00	-2.25E-05	3.22E-04	-2.49E-01	-3.35E+03	-6.46E+02
	CHPe_SG_NG_2X	-1.64E-04	-9.06E+02	-5.74E+01	-4.88E+00	3.38E-02	6.75E-06	4.24E-04	-2.23E-01	6.09E+02	-2.58E+03
	CHPe_SG_F2_E	-7.73E-05	-7.67E+02	-3.37E+01	-4.35E+00	-2.42E+00	-2.24E-05	3.23E-04	-2.49E-01	-3.35E+03	-6.39E+02
	CHPe_SG_F6_E	-7.75E-05	-7.67E+02	-3.41E+01	-4.45E+00	-2.42E+00	-2.25E-05	3.22E-04	-2.55E-01	-3.35E+03	-6.41E+02
	CHPe_SG_Coal_E	-7.25E-05	-7.74E+02	-3.49E+01	-4.51E+00	-2.50E+00	-2.35E-05	3.18E-04	-2.57E-01	-3.45E+03	-5.95E+02
	CHPe_CH4_NG_E	-7.28E-05	-6.91E+02	-1.28E+01	-3.48E+00	-2.06E+00	-2.46E-05	3.71E-04	-2.07E-01	-3.10E+03	-6.06E+02
	CHPe_CH4_NG_2X	-1.65E-04	-8.39E+02	-3.75E+01	-4.01E+00	5.09E-01	6.03E-06	4.78E-04	-1.79E-01	1.05E+03	-2.64E+03
	CHPe_CH4_F2_E	-7.46E-05	-6.94E+02	-1.26E+01	-3.47E+00	-2.07E+00	-2.46E-05	3.72E-04	-2.07E-01	-3.10E+03	-5.99E+02
	CHPe_CH4_F6_E	-7.49E-05	-6.94E+02	-1.30E+01	-3.57E+00	-2.07E+00	-2.46E-05	3.71E-04	-2.13E-01	-3.10E+03	-6.01E+02
	CHPe_CH4_Coal_E	-6.97E-05	-7.01E+02	-1.39E+01	-3.63E+00	-2.15E+00	-2.57E-05	3.67E-04	-2.15E-01	-3.21E+03	-5.53E+02
Transport Fuel	TRSP_Ethanol_D	-5.30E-05	-5.81E+01	3.01E-01	1.08E+00	7.94E-01	1.05E-05	1.16E-04	3.63E-02	1.60E+03	-4.81E+02
	TRSP_Ethanol_P	-6.72E-05	-1.33E+02	1.80E+01	1.33E+00	7.74E-01	9.91E-06	1.12E-04	6.53E-02	1.51E+03	-6.26E+02
	TRSP_Methanol_D	-8.40E-05	-3.08E+02	-2.13E+01	-6.46E-01	1.93E-01	8.52E-06	3.20E-04	-7.67E-02	1.32E+03	-7.69E+02
	TRSP_Methanol_P	-9.96E-05	-3.91E+02	-1.82E+00	-3.69E-01	1.71E-01	7.83E-06	3.16E-04	-4.47E-02	1.22E+03	-9.29E+02
	TRSP_CH4_D	-9.30E-05	-2.52E+02	-9.89E+00	2.50E-01	5.78E-01	1.03E-05	5.44E-04	-3.78E-02	1.72E+03	-8.42E+02
	TRSP_CH4_P	-1.11E-04	-3.49E+02	1.31E+01	5.77E-01	5.51E-01	9.44E-06	5.40E-04	-2.18E-05	1.60E+03	-1.03E+03
	TRSP_CH4_NG	-4.77E-05	-2.57E+02	1.59E+01	-6.18E-03	8.04E-01	1.06E-05	5.45E-04	3.78E-03	1.72E+03	-8.73E+02
Charcoal	Metl_Charcoal_Coke	-2.02E-05	-5.46E+02	-5.45E+00	-8.06E-01	-1.50E+00	-1.69E-05	-4.69E-05	-6.20E-01	-1.53E+03	-2.83E+01

B.3. High Efficiency

		Ozone depletion	Global warming	Smog	Acidification	Eutrophication	Carcinogenics	Non carcinogenics	Respiratory effects	Ecotoxicity	Fossil fuel depletion
		kg CFC-11 eq	kg CO2 eq	kg O3 eq	kg SO2 eq	kg N eq	CTUh	CTUh	kg PM2.5 eq	CTUe	MJ surplus
Heat	H_Pellet_NG	2.88E-04	1.53E+03	6.52E+01	7.87E+00	3.54E-01	1.20E-05	6.81E-05	4.44E-01	1.38E+03	4.37E+03
	H_Pellet_F2	4.29E-04	1.77E+03	5.36E+01	6.38E+00	9.57E-01	1.10E-05	4.90E-05	4.39E-01	1.09E+03	3.80E+03
	H_Pellet_F6	4.53E-04	1.82E+03	8.56E+01	1.43E+01	1.08E+00	1.21E-05	7.83E-05	9.20E-01	1.37E+03	4.00E+03
	H_Pellet_Coal	5.07E-05	2.36E+03	1.51E+02	1.89E+01	7.56E+00	9.51E-05	3.87E-04	1.05E+00	9.59E+03	3.01E+02
	H_SG_NG	2.87E-04	1.53E+03	6.48E+01	7.83E+00	3.52E-01	1.19E-05	6.77E-05	4.41E-01	1.38E+03	4.35E+03
	H_SG_F2	4.27E-04	1.76E+03	5.33E+01	6.34E+00	9.52E-01	1.10E-05	4.87E-05	4.37E-01	1.09E+03	3.78E+03
	H_SG_F6	4.50E-04	1.81E+03	8.51E+01	1.43E+01	1.07E+00	1.20E-05	7.79E-05	9.15E-01	1.36E+03	3.97E+03
	H_SG_Coal	5.04E-05	2.35E+03	1.51E+02	1.88E+01	7.52E+00	9.46E-05	3.84E-04	1.04E+00	9.54E+03	2.99E+02
	H_CH4_NG	2.06E-04	1.10E+03	4.66E+01	5.62E+00	2.53E-01	8.58E-06	4.86E-05	3.17E-01	9.88E+02	3.12E+03
	H_CH4_F2	3.07E-04	1.26E+03	3.83E+01	4.56E+00	6.83E-01	7.87E-06	3.50E-05	3.14E-01	7.82E+02	2.72E+03
	H_CH4_F6	3.23E-04	1.30E+03	6.11E+01	1.02E+01	7.69E-01	8.62E-06	5.59E-05	6.57E-01	9.77E+02	2.85E+03
	H_CH4_Coal	3.62E-05	1.68E+03	1.08E+02	1.35E+01	5.40E+00	6.79E-05	2.76E-04	7.50E-01	6.85E+03	2.15E+02
CHP Heat	CHPh_Pellet_NG_E	-5.35E-06	-1.65E+03	-7.45E-01	-7.17E+00	-1.77E+00	-2.09E-05	5.57E-04	1.21E-01	-2.46E+03	-3.72E+03
	CHPh_Pellet_NG_2X	-7.32E-05	-1.76E+03	-1.89E+01	-7.56E+00	1.09E-01	1.55E-06	6.35E-04	1.41E-01	5.82E+02	-5.20E+03
	CHPh_Pellet_F2_E	-1.15E-04	-1.84E+03	8.28E+00	-6.01E+00	-2.25E+00	-2.01E-05	5.72E-04	1.24E-01	-2.24E+03	-3.27E+03
	CHPh_Pellet_F6_E	-1.34E-04	-1.88E+03	-1.67E+01	-1.22E+01	-2.34E+00	-2.10E-05	5.49E-04	-2.51E-01	-2.45E+03	-3.42E+03
	CHPh_Pellet_Coal_E	1.80E-04	-2.30E+03	-6.81E+01	-1.58E+01	-7.40E+00	-8.57E-05	3.08E-04	-3.52E-01	-8.87E+03	-5.40E+02
	CHPh_SG_NG_E	-2.76E-04	-1.74E+03	-7.34E+01	-9.20E+00	-2.00E+00	-2.08E-05	3.11E-04	-5.14E-01	-3.07E+03	-3.83E+03
	CHPh_SG_NG_2X	-3.43E-04	-1.85E+03	-9.14E+01	-9.59E+00	-1.30E-01	1.58E-06	3.88E-04	-4.94E-01	-3.84E+01	-5.31E+03
	CHPh_SG_F2_E	-3.85E-04	-1.92E+03	-6.44E+01	-8.05E+00	-2.47E+00	-2.00E-05	3.26E-04	-5.11E-01	-2.84E+03	-3.38E+03
	CHPh_SG_F6_E	-4.03E-04	-1.96E+03	-8.92E+01	-1.42E+01	-2.56E+00	-2.08E-05	3.03E-04	-8.84E-01	-3.06E+03	-3.53E+03
	CHPh_SG_Coal_E	-9.15E-05	-2.38E+03	-1.40E+02	-1.78E+01	-7.60E+00	-8.52E-05	6.37E-05	-9.85E-01	-9.44E+03	-6.68E+02
	CHPh_CH4_NG_E	-1.86E-04	-1.10E+03	-1.85E+01	-4.96E+00	-7.96E-01	-1.12E-05	4.63E-04	-2.85E-01	-1.21E+03	-2.64E+03
	CHPh_CH4_NG_2X	-2.35E-04	-1.18E+03	-3.14E+01	-5.24E+00	5.49E-01	4.89E-06	5.19E-04	-2.71E-01	9.66E+02	-3.70E+03
	CHPh_CH4_F2_E	-2.65E-04	-1.23E+03	-1.20E+01	-4.13E+00	-1.13E+00	-1.06E-05	4.74E-04	-2.82E-01	-1.05E+03	-2.32E+03
	CHPh_CH4_F6_E	-2.78E-04	-1.26E+03	-2.99E+01	-8.56E+00	-1.20E+00	-1.12E-05	4.58E-04	-5.50E-01	-1.20E+03	-2.43E+03
	CHPh_CH4_COAL_E	-5.39E-05	-1.56E+03	-6.66E+01	-1.11E+01	-4.81E+00	-5.74E-05	2.86E-04	-6.23E-01	-5.78E+03	-3.72E+02

		Ozone depletion	Global warming	Smog	Acidification	Eutrophication	Carcinogenics	Non carcinogenics	Respiratory effects	Ecotoxicity	Fossil fuel depletion
		kg CFC-11 eq	kg CO2 eq	kg O3 eq	kg SO2 eq	kg N eq	CTUh	CTUh	kg PM2.5 eq	CTUe	MJ surplus
CHP Power	CHPe_Pellet_NG_E	-6.16E-05	-3.15E+03	-7.72E+01	-1.68E+01	-1.02E+01	-1.23E-04	1.94E-04	-4.67E-01	-1.64E+04	-2.64E+03
	CHPe_Pellet_NG_2X	-4.17E-04	-3.72E+03	-1.72E+02	-1.89E+01	-3.30E-01	-5.60E-06	6.02E-04	-3.61E-01	-4.70E+02	-1.04E+04
	CHPe_Pellet_F2_E	-6.86E-05	-3.16E+03	-7.66E+01	-1.68E+01	-1.02E+01	-1.23E-04	1.95E-04	-4.67E-01	-1.64E+04	-2.62E+03
	CHPe_Pellet_F6_E	-6.98E-05	-3.16E+03	-7.82E+01	-1.72E+01	-1.02E+01	-1.23E-04	1.94E-04	-4.91E-01	-1.64E+04	-2.63E+03
	CHPe_Pellet_Coal_E	-4.97E-05	-3.19E+03	-8.15E+01	-1.74E+01	-1.05E+01	-1.27E-04	1.78E-04	-4.97E-01	-1.68E+04	-2.44E+03
	CHPe_SG_NG_E	-3.32E-04	-3.23E+03	-1.49E+02	-1.88E+01	-1.04E+01	-1.22E-04	-4.97E-05	-1.10E+00	-1.69E+04	-2.76E+03
	CHPe_SG_NG_2X	-6.85E-04	-3.80E+03	-2.44E+02	-2.08E+01	-5.67E-01	-5.53E-06	3.56E-04	-9.94E-01	-1.09E+03	-1.05E+04
	CHPe_SG_F2_E	-3.39E-04	-3.24E+03	-1.49E+02	-1.88E+01	-1.04E+01	-1.22E-04	-4.87E-05	-1.10E+00	-1.69E+04	-2.73E+03
	CHPe_SG_F6_E	-3.40E-04	-3.24E+03	-1.50E+02	-1.91E+01	-1.04E+01	-1.22E-04	-5.02E-05	-1.12E+00	-1.69E+04	-2.74E+03
	CHPe_SG_Coal_E	-3.20E-04	-3.27E+03	-1.54E+02	-1.94E+01	-1.07E+01	-1.26E-04	-6.55E-05	-1.13E+00	-1.73E+04	-2.56E+03
	CHPe_CH4_NG_E	-2.26E-04	-2.17E+03	-7.31E+01	-1.19E+01	-6.80E+00	-8.41E-05	2.04E-04	-7.05E-01	-1.12E+04	-1.87E+03
	CHPe_CH4_NG_2X	-4.80E-04	-2.57E+03	-1.41E+02	-1.33E+01	2.36E-01	-2.14E-07	4.95E-04	-6.29E-01	2.15E+02	-7.43E+03
	CHPe_CH4_F2_E	-2.31E-04	-2.17E+03	-7.27E+01	-1.18E+01	-6.82E+00	-8.41E-05	2.05E-04	-7.05E-01	-1.11E+04	-1.85E+03
	CHPe_CH4_F6_E	-2.32E-04	-2.18E+03	-7.38E+01	-1.21E+01	-6.82E+00	-8.41E-05	2.04E-04	-7.22E-01	-1.12E+04	-1.86E+03
	CHPe_CH4_Coal_E	-2.18E-04	-2.20E+03	-7.61E+01	-1.23E+01	-7.06E+00	-8.71E-05	1.93E-04	-7.26E-01	-1.15E+04	-1.73E+03
Transport Fuel	TRSP_Ethanol_D	-9.02E-05	6.27E+01	1.66E+01	4.17E+00	2.48E+00	3.08E-05	5.05E-04	2.49E-01	4.96E+03	-8.18E+02
	TRSP_Ethanol_P	-1.22E-04	-1.03E+02	5.60E+01	4.73E+00	2.43E+00	2.94E-05	4.97E-04	3.14E-01	4.76E+03	-1.14E+03
	TRSP_Methanol_D	-1.15E-04	-3.95E+02	-2.68E+01	-5.35E-01	5.77E-01	1.95E-05	6.97E-04	-8.00E-02	2.99E+03	-1.07E+03
	TRSP_Methanol_P	-1.38E-04	-5.15E+02	1.69E+00	-1.30E-01	5.44E-01	1.85E-05	6.92E-04	-3.32E-02	2.85E+03	-1.31E+03
	TRSP_CH4_D	-2.74E-04	-9.78E+02	-6.43E+01	-1.96E+00	1.89E-01	7.36E-06	5.11E-04	-2.72E-01	1.23E+03	-2.45E+03
	TRSP_CH4_P	-3.22E-04	-1.23E+03	-4.13E+00	-1.10E+00	1.21E-01	5.23E-06	4.98E-04	-1.73E-01	9.34E+02	-2.94E+03
	TRSP_CH4_NG	-1.56E-04	-9.90E+02	3.14E+00	-2.63E+00	7.82E-01	8.36E-06	5.14E-04	-1.63E-01	1.23E+03	-2.53E+03
Charcoal	Metl_Charcoal_Coke	-3.59E-05	-9.07E+02	-1.23E+01	-1.56E+00	-2.50E+00	-2.83E-05	-8.19E-05	-1.01E+00	-2.62E+03	-7.93E+01

B.4. MRO Grid Mix

		Ozone depletion	Global warming	Smog	Acidification	Eutrophication	Carcinogenics	Non carcinogenics	Respiratory effects	Ecotoxicity	Fossil fuel depletion
		kg CFC-11 eq	kg CO2 eq	kg O3 eq	kg SO2 eq	kg N eq	CTUh	CTUh	kg PM2.5 eq	CTUe	MJ surplus
Heat	**H_Pellet_NG**	3.33E-05	-9.78E+02	2.90E+01	-3.39E+00	6.83E-01	1.01E-05	6.66E-04	2.90E-01	1.58E+03	-3.28E+03
	H_Pellet_F2	-7.88E-05	-1.16E+03	3.82E+01	-2.21E+00	2.04E-01	1.09E-05	6.81E-04	2.94E-01	1.80E+03	-2.83E+03
	H_Pellet_F6	-9.75E-05	-1.20E+03	1.28E+01	-8.53E+00	1.09E-01	1.01E-05	6.58E-04	-8.78E-02	1.59E+03	-2.98E+03
	H_Pellet_Coal	2.22E-04	-1.63E+03	-3.95E+01	-1.21E+01	-5.04E+00	-5.58E-05	4.13E-04	-1.91E-01	-4.94E+03	-4.50E+01
	H_SG_NG	-1.40E-04	-7.10E+02	-2.62E+01	-3.50E+00	2.49E-01	8.74E-06	4.24E-04	-1.87E-01	8.27E+02	-2.22E+03
	H_SG_F2	-2.13E-04	-8.31E+02	-2.02E+01	-2.73E+00	-6.30E-02	9.26E-06	4.34E-04	-1.84E-01	9.76E+02	-1.92E+03
	H_SG_F6	-2.25E-04	-8.57E+02	-3.68E+01	-6.85E+00	-1.25E-01	8.71E-06	4.19E-04	-4.34E-01	8.35E+02	-2.02E+03
	H_SG_Coal	-1.72E-05	-1.14E+03	-7.09E+01	-9.22E+00	-3.49E+00	-3.43E-05	2.59E-04	-5.01E-01	-3.43E+03	-1.09E+02
	H_CH4_NG	-1.16E-04	-4.04E+02	1.21E+01	-1.37E+00	1.30E+00	1.62E-05	5.58E-04	-7.89E-02	2.11E+03	-1.89E+03
	H_CH4_F2	-1.79E-04	-5.10E+02	1.73E+01	-6.99E-01	1.03E+00	1.67E-05	5.67E-04	-7.68E-02	2.24E+03	-1.63E+03
	H_CH4_F6	-1.90E-04	-5.33E+02	2.87E+00	-4.30E+00	9.76E-01	1.62E-05	5.54E-04	-2.94E-01	2.12E+03	-1.71E+03
	H_CH4_Coal	-8.27E-06	-7.76E+02	-2.69E+01	-6.36E+00	-1.96E+00	-2.14E-05	4.14E-04	-3.53E-01	-1.60E+03	-4.40E+01
CHP Heat	**CHPh_Pellet_NG_E**	4.77E-05	-1.49E+03	-6.97E+00	-5.90E+00	-2.83E+00	-3.47E-05	5.24E-04	1.56E-01	-3.30E+03	-2.72E+03
	CHPh_Pellet_NG_2X	-1.90E-05	-1.28E+03	3.23E+00	-5.18E+00	6.15E-01	9.30E-06	6.62E-04	2.15E-01	1.43E+03	-4.07E+03
	CHPh_Pellet_F2_E	-3.96E-05	-1.64E+03	1.94E-01	-4.98E+00	-3.20E+00	-3.41E-05	5.35E-04	1.59E-01	-3.12E+03	-2.37E+03
	CHPh_Pellet_F6_E	-5.42E-05	-1.67E+03	-1.96E+01	-9.91E+00	-3.27E+00	-3.48E-05	5.17E-04	-1.39E-01	-3.29E+03	-2.49E+03
	CHPh_Pellet_Coal_E	1.95E-04	-2.00E+03	-6.04E+01	-1.27E+01	-7.29E+00	-8.62E-05	3.26E-04	-2.19E-01	-8.39E+03	-1.99E+02
	CHPh_SG_NG_E	-1.31E-04	-1.05E+03	-4.97E+01	-5.14E+00	-2.04E+00	-2.05E-05	3.31E-04	-2.75E-01	-2.35E+03	-1.85E+03
	CHPh_SG_NG_2X	-1.74E-04	-9.07E+02	-4.31E+01	-4.67E+00	2.05E-01	8.18E-06	4.22E-04	-2.36E-01	7.35E+02	-2.74E+03
	CHPh_SG_F2_E	-1.88E-04	-1.14E+03	-4.50E+01	-4.54E+00	-2.28E+00	-2.01E-05	3.39E-04	-2.73E-01	-2.24E+03	-1.62E+03
	CHPh_SG_F6_E	-1.97E-04	-1.16E+03	-5.79E+01	-7.75E+00	-2.33E+00	-2.06E-05	3.27E-04	-4.67E-01	-2.35E+03	-1.70E+03
	CHPh_SG_Coal_E	-3.48E-05	-1.38E+03	-8.46E+01	-9.59E+00	-4.95E+00	-5.41E-05	2.03E-04	-5.19E-01	-5.67E+03	-2.10E+02
	CHPh_CH4_NG_E	-1.07E-04	-6.98E+02	-8.40E+00	-2.80E+00	-6.95E-01	-9.35E-06	4.77E-04	-1.55E-01	-6.67E+02	-1.57E+03
	CHPh_CH4_NG_2X	-1.45E-04	-5.76E+02	-2.59E+00	-2.39E+00	1.26E+00	1.57E-05	5.56E-04	-1.22E-01	2.03E+03	-2.34E+03
	CHPh_CH4_F2_E	-1.57E-04	-7.80E+02	-4.32E+00	-2.28E+00	-9.08E-01	-9.00E-06	4.84E-04	-1.54E-01	-5.65E+02	-1.37E+03
	CHPh_CH4_F6_E	-1.65E-04	-7.98E+02	-1.56E+01	-5.08E+00	-9.50E-01	-9.37E-06	4.74E-04	-3.23E-01	-6.61E+02	-1.43E+03
	CHPh_CH4_COAL_E	-2.37E-05	-9.88E+02	-3.88E+01	-6.69E+00	-3.24E+00	-3.86E-05	3.65E-04	-3.69E-01	-3.56E+03	-1.32E+02

		Ozone depletion	Global warming	Smog	Acidification	Eutrophication	Carcinogenics	Non carcinogenics	Respiratory effects	Ecotoxicity	Fossil fuel depletion
		kg CFC-11 eq	kg CO2 eq	kg O3 eq	kg SO2 eq	kg N eq	CTUh	CTUh	kg PM2.5 eq	CTUe	MJ surplus
CHP Power	CHPe_Pellet_NG_E	6.09E-05	-3.96E+03	-1.72E+02	-1.80E+01	-1.79E+01	-2.29E-04	-9.63E-05	-4.94E-01	-2.44E+04	-1.07E+03
	CHPe_Pellet_NG_2X	-2.92E-04	-2.83E+03	-1.18E+02	-1.42E+01	2.74E-01	3.62E-06	6.36E-04	-1.84E-01	5.99E+02	-8.22E+03
	CHPe_Pellet_F2_E	5.53E-05	-3.97E+03	-1.72E+02	-1.79E+01	-1.79E+01	-2.29E-04	-9.56E-05	-4.94E-01	-2.44E+04	-1.05E+03
	CHPe_Pellet_F6_E	5.44E-05	-3.97E+03	-1.73E+02	-1.82E+01	-1.79E+01	-2.29E-04	-9.67E-05	-5.13E-01	-2.44E+04	-1.06E+03
	CHPe_Pellet_Coal_E	7.03E-05	-3.99E+03	-1.75E+02	-1.84E+01	-1.82E+01	-2.32E-04	-1.09E-04	-5.18E-01	-2.47E+04	-9.11E+02
	CHPe_SG_NG_E	-1.22E-04	-2.66E+03	-1.57E+02	-1.30E+01	-1.19E+01	-1.47E-04	-7.31E-05	-6.99E-01	-1.61E+04	-7.79E+02
	CHPe_SG_NG_2X	-3.52E-04	-1.92E+03	-1.22E+02	-1.05E+01	-1.72E-02	4.48E-06	4.05E-04	-4.96E-01	1.90E+02	-5.44E+03
	CHPe_SG_F2_E	-1.26E-04	-2.66E+03	-1.57E+02	-1.30E+01	-1.19E+01	-1.47E-04	-7.26E-05	-6.99E-01	-1.61E+04	-7.65E+02
	CHPe_SG_F6_E	-1.26E-04	-2.66E+03	-1.58E+02	-1.32E+01	-1.19E+01	-1.47E-04	-7.34E-05	-7.11E-01	-1.61E+04	-7.70E+02
	CHPe_SG_Coal_E	-1.16E-04	-2.68E+03	-1.60E+02	-1.33E+01	-1.21E+01	-1.49E-04	-8.13E-05	-7.14E-01	-1.63E+04	-6.74E+02
	CHPe_CH4_NG_E	-9.98E-05	-2.10E+03	-1.02E+02	-9.67E+00	-9.28E+00	-1.20E-04	1.25E-04	-5.26E-01	-1.27E+04	-6.29E+02
	CHPe_CH4_NG_2X	-3.00E-04	-1.46E+03	-7.17E+01	-7.50E+00	1.07E+00	1.25E-05	5.42E-04	-3.49E-01	1.55E+03	-4.70E+03
	CHPe_CH4_F2_E	-1.03E-04	-2.11E+03	-1.02E+02	-9.64E+00	-9.29E+00	-1.20E-04	1.25E-04	-5.25E-01	-1.27E+04	-6.16E+02
	CHPe_CH4_F6_E	-1.04E-04	-2.11E+03	-1.03E+02	-9.82E+00	-9.29E+00	-1.20E-04	1.24E-04	-5.36E-01	-1.27E+04	-6.20E+02
	CHPe_CH4_Coal_E	-9.45E-05	-2.12E+03	-1.04E+02	-9.92E+00	-9.44E+00	-1.22E-04	1.17E-04	-5.39E-01	-1.29E+04	-5.37E+02
Transport Fuel	TRSP_Ethanol_D	-9.64E-05	2.19E+02	2.67E+01	3.22E+00	3.30E+00	4.37E-05	3.18E-04	1.39E-01	5.22E+03	-9.32E+02
	TRSP_Ethanol_P	-1.21E-04	9.01E+01	5.72E+01	3.65E+00	3.27E+00	4.27E-05	3.12E-04	1.89E-01	5.07E+03	-1.18E+03
	TRSP_Methanol_D	-1.04E-04	-3.00E+02	-1.98E+01	-4.46E-01	7.37E-01	1.83E-05	4.90E-04	-7.42E-02	2.48E+03	-9.67E+02
	TRSP_Methanol_P	-1.23E-04	-4.02E+02	4.26E+00	-1.04E-01	7.09E-01	1.75E-05	4.85E-04	-3.47E-02	2.36E+03	-1.16E+03
	TRSP_CH4_D	-1.38E-04	-2.96E+02	-1.24E+01	1.86E-01	1.25E+00	1.98E-05	5.70E-04	-6.89E-02	2.56E+03	-1.27E+03
	TRSP_CH4_P	-1.63E-04	-4.28E+02	1.88E+01	6.30E-01	1.21E+00	1.87E-05	5.64E-04	-1.77E-02	2.40E+03	-1.52E+03
	TRSP_CH4_NG	-7.64E-05	-3.02E+02	2.26E+01	-1.61E-01	1.55E+00	2.03E-05	5.72E-04	-1.25E-02	2.56E+03	-1.31E+03
Charcoal	Metl_Charcoal_Coke	-2.70E-05	-6.81E+02	-7.35E+00	-1.07E+00	-1.83E+00	-2.06E-05	-5.83E-05	-7.77E-01	-1.89E+03	-5.60E+01
Mulch	GM_highMulch_Peat	5.71E-06	5.21E+02	9.01E-01	5.55E-02	-2.94E-03	3.71E-07	6.34E-06	1.52E-02	3.93E+01	9.69E+01
	GM_lowMulch_Peat	6.97E-06	-7.81E+02	1.10E+00	6.78E-02	-3.59E-03	4.54E-07	7.74E-06	1.86E-02	4.81E+01	1.18E+02

B.5. Quebec Grid Mix

		Ozone depletion	Global warming	Smog	Acidification	Eutrophication	Carcinogenics	Non carcinogenics	Respiratory effects	Ecotoxicity	Fossil fuel depletion
		kg CFC-11 eq	kg CO2 eq	kg O3 eq	kg SO2 eq	kg N eq	CTUh	CTUh	kg PM2.5 eq	CTUe	MJ surplus
Heat	**H_Pellet_NG**	2.77E-05	-1.10E+03	2.15E+01	-4.01E+00	1.56E-01	2.79E-06	6.42E-04	2.58E-01	9.19E+02	-3.31E+03
	H_Pellet_F2	-8.44E-05	-1.29E+03	3.07E+01	-2.82E+00	-3.23E-01	3.58E-06	6.57E-04	2.61E-01	1.15E+03	-2.86E+03
	H_Pellet_F6	-1.03E-04	-1.33E+03	5.27E+00	-9.14E+00	-4.18E-01	2.75E-06	6.34E-04	-1.21E-01	9.31E+02	-3.01E+03
	H_Pellet_Coal	2.16E-04	-1.76E+03	-4.71E+01	-1.28E+01	-5.57E+00	-6.32E-05	3.89E-04	-2.24E-01	-5.60E+03	-7.64E+01
	H_SG_NG	-1.43E-04	-7.72E+02	-3.00E+01	-3.81E+00	-1.52E-02	5.05E-06	4.12E-04	-2.03E-01	5.01E+02	-2.23E+03
	H_SG_F2	-2.16E-04	-8.93E+02	-2.40E+01	-3.04E+00	-3.27E-01	5.57E-06	4.22E-04	-2.01E-01	6.50E+02	-1.94E+03
	H_SG_F6	-2.28E-04	-9.20E+02	-4.06E+01	-7.16E+00	-3.89E-01	5.02E-06	4.07E-04	-4.50E-01	5.09E+02	-2.04E+03
	H_SG_Coal	-2.00E-05	-1.20E+03	-7.47E+01	-9.52E+00	-3.75E+00	-3.80E-05	2.47E-04	-5.17E-01	-3.75E+03	-1.25E+02
	H_CH4_NG	-1.27E-04	-6.49E+02	-2.74E+00	-2.58E+00	2.69E-01	1.77E-06	5.12E-04	-1.43E-01	8.26E+02	-1.95E+03
	H_CH4_F2	-1.90E-04	-7.55E+02	2.49E+00	-1.91E+00	-3.73E-03	2.22E-06	5.20E-04	-1.41E-01	9.56E+02	-1.69E+03
	H_CH4_F6	-2.01E-04	-7.78E+02	-1.20E+01	-5.50E+00	-5.77E-02	1.75E-06	5.07E-04	-3.58E-01	8.33E+02	-1.78E+03
	H_CH4_Coal	-1.92E-05	-1.02E+03	-4.18E+01	-7.56E+00	-2.99E+00	-3.58E-05	3.68E-04	-4.17E-01	-2.89E+03	-1.06E+02
CHP Heat	**CHPh_Pellet_NG_E**	7.65E-05	-8.51E+02	3.20E+01	-2.74E+00	-1.13E-01	3.13E-06	6.45E-04	3.25E-01	3.18E+01	-2.56E+03
	CHPh_Pellet_NG_2X	-2.46E-05	-1.40E+03	-4.33E+00	-5.79E+00	8.84E-02	1.94E-06	6.39E-04	1.82E-01	7.78E+02	-4.11E+03
	CHPh_Pellet_F2_E	-1.09E-05	-9.95E+02	3.91E+01	-1.81E+00	-4.86E-01	3.75E-06	6.57E-04	3.28E-01	2.10E+02	-2.21E+03
	CHPh_Pellet_F6_E	-2.55E-05	-1.03E+03	1.93E+01	-6.74E+00	-5.60E-01	3.10E-06	6.39E-04	2.99E-02	4.16E+01	-2.33E+03
	CHPh_Pellet_Coal_E	2.23E-04	-1.36E+03	-2.15E+01	-9.56E+00	-4.58E+00	-4.83E-05	4.48E-04	-5.06E-02	-5.05E+03	-3.80E+01
	CHPh_SG_NG_E	-1.11E-04	-6.08E+02	-2.32E+01	-2.98E+00	-1.91E-01	5.27E-06	4.14E-04	-1.60E-01	-7.74E+01	-1.74E+03
	CHPh_SG_NG_2X	-1.77E-04	-9.69E+02	-4.68E+01	-4.98E+00	-5.92E-02	4.49E-06	4.10E-04	-2.53E-01	4.10E+02	-2.75E+03
	CHPh_SG_F2_E	-1.68E-04	-7.02E+02	-1.85E+01	-2.38E+00	-4.34E-01	5.68E-06	4.22E-04	-1.58E-01	3.90E+01	-1.51E+03
	CHPh_SG_F6_E	-1.78E-04	-7.23E+02	-3.14E+01	-5.60E+00	-4.82E-01	5.25E-06	4.10E-04	-3.52E-01	-7.10E+01	-1.59E+03
	CHPh_SG_Coal_E	-1.53E-05	-9.40E+02	-5.80E+01	-7.44E+00	-3.10E+00	-2.83E-05	2.86E-04	-4.04E-01	-3.39E+03	-9.98E+01
	CHPh_CH4_NG_E	-9.87E-05	-5.06E+02	3.24E+00	-1.86E+00	1.16E-01	1.97E-06	5.14E-04	-1.05E-01	3.21E+02	-1.52E+03
	CHPh_CH4_NG_2X	-1.56E-04	-8.21E+02	-1.74E+01	-3.60E+00	2.30E-01	1.29E-06	5.10E-04	-1.86E-01	7.46E+02	-2.40E+03
	CHPh_CH4_F2_E	-1.48E-04	-5.88E+02	7.32E+00	-1.33E+00	-9.67E-02	2.32E-06	5.20E-04	-1.03E-01	4.23E+02	-1.32E+03
	CHPh_CH4_F6_E	-1.57E-04	-6.06E+02	-3.95E+00	-4.14E+00	-1.39E-01	1.95E-06	5.10E-04	-2.73E-01	3.27E+02	-1.39E+03
	CHPh_CH4_COAL_E	-1.51E-05	-7.96E+02	-2.72E+01	-5.74E+00	-2.43E+00	-2.73E-05	4.02E-04	-3.19E-01	-2.57E+03	-8.37E+01

		Ozone depletion	Global warming	Smog	Acidification	Eutrophication	Carcinogenics	Non carcinogenics	Respiratory effects	Ecotoxicity	Fossil fuel depletion
		kg CFC-11 eq	kg CO2 eq	kg O3 eq	kg SO2 eq	kg N eq	CTUh	CTUh	kg PM2.5 eq	CTUe	MJ surplus
CHP Power	CHPe_Pellet_NG_E	2.36E-04	-3.20E+01	6.59E+01	1.36E+00	-1.32E+00	2.58E-06	6.48E-04	5.37E-01	-4.00E+03	-8.59E+01
	CHPe_Pellet_NG_2X	-2.97E-04	-2.96E+03	-1.26E+02	-1.48E+01	-2.53E-01	-3.74E-06	6.13E-04	-2.17E-01	-5.68E+01	-8.25E+03
	CHPe_Pellet_F2_E	2.31E-04	-4.12E+01	6.63E+01	1.42E+00	-1.35E+00	2.62E-06	6.49E-04	5.37E-01	-3.99E+03	-6.33E+01
	CHPe_Pellet_F6_E	2.30E-04	-4.33E+01	6.51E+01	1.11E+00	-1.35E+00	2.58E-06	6.47E-04	5.18E-01	-4.00E+03	-7.10E+01
	CHPe_Pellet_Coal_E	2.46E-04	-6.46E+01	6.25E+01	9.27E-01	-1.61E+00	-7.13E-07	6.35E-04	5.13E-01	-4.32E+03	7.54E+01
	CHPe_SG_NG_E	-6.83E-06	-7.40E+01	-1.05E+00	-3.10E-01	-9.80E-01	4.91E-06	4.16E-04	-2.12E-02	-2.71E+03	-1.31E+02
	CHPe_SG_NG_2X	-3.55E-04	-1.98E+03	-1.26E+02	-1.08E+01	-2.82E-01	7.91E-07	3.93E-04	-5.13E-01	-1.35E+02	-5.46E+03
	CHPe_SG_F2_E	-1.05E-05	-8.00E+01	-7.53E-01	-2.71E-01	-9.95E-01	4.93E-06	4.16E-04	-2.11E-02	-2.70E+03	-1.16E+02
	CHPe_SG_F6_E	-1.11E-05	-8.14E+01	-1.58E+00	-4.77E-01	-9.98E-01	4.91E-06	4.16E-04	-3.35E-02	-2.71E+03	-1.21E+02
	CHPe_SG_Coal_E	-6.98E-07	-9.53E+01	-3.28E+00	-5.95E-01	-1.17E+00	2.76E-06	4.08E-04	-3.69E-02	-2.92E+03	-2.59E+01
	CHPe_CH4_NG_E	-7.74E-06	-3.97E+01	2.25E+01	4.78E-01	-5.73E-01	1.65E-06	5.15E-04	1.58E-02	-1.97E+03	-1.11E+02
	CHPe_CH4_NG_2X	-3.11E-04	-1.70E+03	-8.66E+01	-8.71E+00	3.63E-02	-1.94E-06	4.95E-04	-4.13E-01	2.71E+02	-4.76E+03
	CHPe_CH4_F2_E	-1.09E-05	-4.49E+01	2.28E+01	5.11E-01	-5.87E-01	1.67E-06	5.16E-04	1.59E-02	-1.97E+03	-9.81E+01
	CHPe_CH4_F6_E	-1.15E-05	-4.61E+01	2.21E+01	3.32E-01	-5.89E-01	1.65E-06	5.15E-04	5.03E-03	-1.97E+03	-1.02E+02
	CHPe_CH4_Coal_E	-2.39E-06	-5.82E+01	2.06E+01	2.29E-01	-7.36E-01	-2.22E-07	5.08E-04	2.10E-03	-2.16E+03	-1.92E+01
Transport Fuel	TRSP_Ethanol_D	-1.27E-04	-4.64E+02	-1.46E+01	-1.45E-01	4.20E-01	3.51E-06	1.89E-04	-3.98E-02	1.66E+03	-1.10E+03
	TRSP_Ethanol_P	-1.51E-04	-5.93E+02	1.59E+01	2.89E-01	3.85E-01	2.43E-06	1.83E-04	1.02E-02	1.51E+03	-1.35E+03
	TRSP_Methanol_D	-1.11E-04	-4.55E+02	-2.92E+01	-1.21E+00	8.26E-02	9.17E-06	4.61E-04	-1.15E-01	1.66E+03	-1.01E+03
	TRSP_Methanol_P	-1.30E-04	-5.57E+02	-5.13E+00	-8.67E-01	5.52E-02	8.32E-06	4.56E-04	-7.54E-02	1.54E+03	-1.20E+03
	TRSP_CH4_D	-1.51E-04	-5.87E+02	-3.00E+01	-1.25E+00	1.81E-02	2.68E-06	5.15E-04	-1.45E-01	1.03E+03	-1.34E+03
	TRSP_CH4_P	-1.76E-04	-7.19E+02	1.23E+00	-8.01E-01	-1.75E-02	1.58E-06	5.09E-04	-9.40E-02	8.80E+02	-1.59E+03
	TRSP_CH4_NG	-8.94E-05	-5.93E+02	5.01E+00	-1.59E+00	3.26E-01	3.20E-06	5.17E-04	-8.88E-02	1.03E+03	-1.38E+03
Charcoal	Metl_Charcoal_Coke	-2.82E-05	-7.08E+02	-8.98E+00	-1.20E+00	-1.95E+00	-2.22E-05	-6.34E-05	-7.84E-01	-2.03E+03	-6.28E+01
Mulch	GM_highMulch_Peat	6.18E-06	5.32E+02	1.54E+00	1.08E-01	4.34E-02	1.06E-06	8.85E-06	1.80E-02	2.30E+02	9.95E+01
	GM_lowMulch_Peat	7.56E-06	-7.68E+02	1.88E+00	1.32E-01	5.30E-02	1.29E-06	1.08E-05	2.21E-02	2.81E+02	1.22E+02

APPENDIX C

RESULTS OF THE CONTRIBUTION ANALYSES

C.1. Disposal Pathway

For this pathway, the contribution analysis of disposal pathway landfill scenarios includes three life cycle groups: landfill construction, landfill operation, and waste emissions. Landfill construction includes emissions from building a landfill and related upstream emissions included in the system boundaries (e.g., transport of construction material). Landfill operation includes the emissions of machines used to spread and compact the waste in the landfill and related upstream emissions (e.g., diesel production). Waste emissions include the emissions of waste decomposing in the landfill.

Figure C.1 shows the potential environmental impacts of the landfill life cycle emissions grouping and normalized once again, against the absolute value of the scenario with the maximum potential environmental impact of the 54 scenarios for each impact category. Table C.1 specifies which grouped landfill life cycle emissions and related substances are the main contributors to the impact categories.

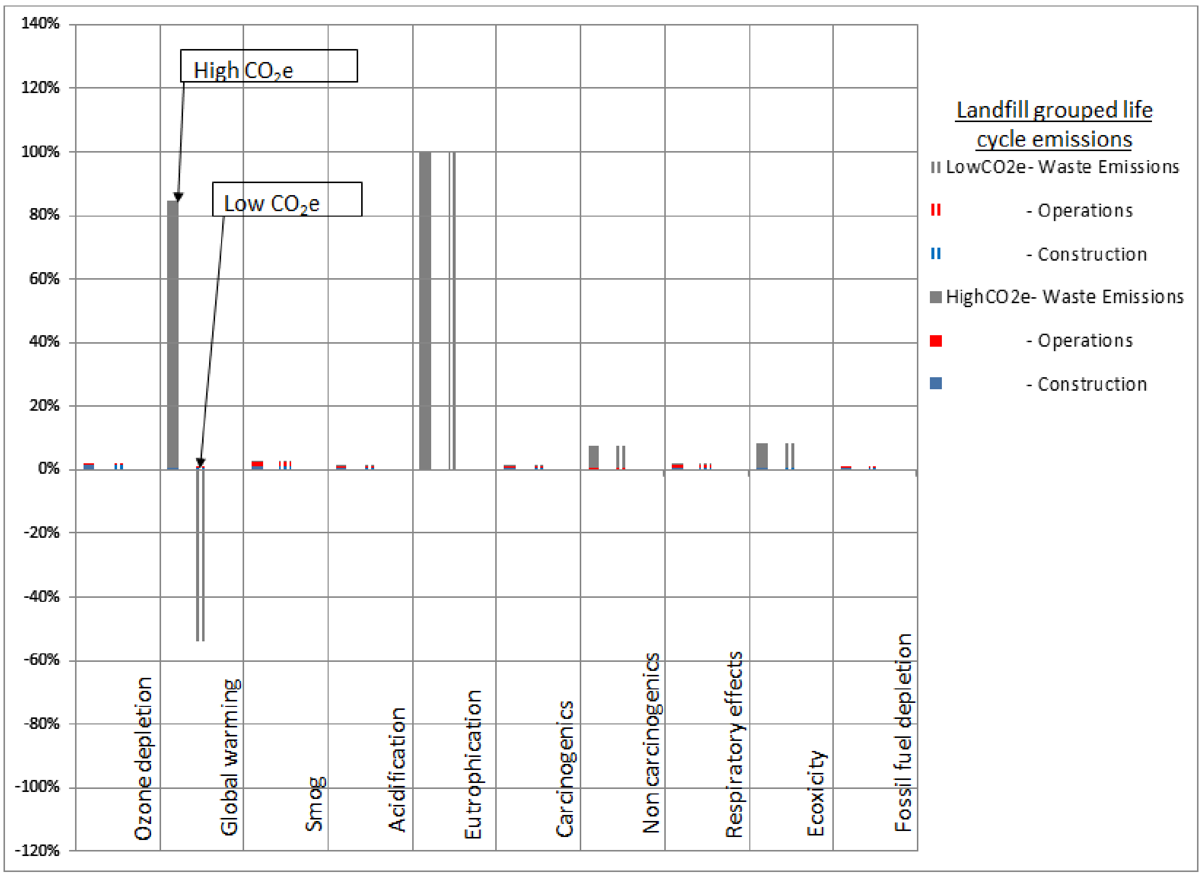


Figure C.1 Disposal Pathway Grouped Landfill Life Cycle Emissions Contribution to Potential Environmental Impacts Normalized Against the Absolute Value of the Scenario with the Maximum Potential Environmental Impact of the 54 Scenarios for Each Impact Category

Table C.1 Disposal Pathway Landfill Scenarios Contributing Substances for All Impact Categories
[Impact categories with potential environmental impact of more than 20% highlighted in white.]

Impact Category	Grouped Landfill Emissions - Process	Contributing Substance(s)
Ozone depletion	Landfill construction – transport of material Landfill operation –machine operation	Methane, bromotrifluoro, Halon 1301 to air emitted during crude oil production
Global warming	Waste emissions	Methane to air in the case of the highCO_2e landfill scenario and carbon storage in the case of the lowCO_2e landfill scenario
Smog	Landfill construction – transport of material Landfill operation –machine operation	Nitrogen oxides to air
Acidification	Landfill construction – transport of material Landfill operation –machine operation	Nitrogen oxides and Sulfur dioxide to air
Eutrophication	Waste emissions – short term leachate treatment and incineration of resulting sludge	COD and BOD_5 to water
Carcinogens	Landfill construction – facility infrastructure materials production Landfill operation – material production for machine construction	Chromium VI to water
	Waste emissions – short term leachate treatment and incineration of resulting sludge	Arsenic to water
Non-carcinogens	Waste emissions – short term leachate treatment and incineration of resulting sludge	Mercury, Arsenic and Zinc to water
Respiratory effects	Landfill construction – operation of transport lorry Landfill operation – machine operation	Sulfur dioxide and particulates $< 2.5\mu m$ to air
Ecotoxicity	Waste emissions – short term leachate treatment and incineration of resulting sludge	Zinc and copper to water
Fossil fuel depletion	Landfill construction – transport of material and bitumen production used to build the landfill Landfill operation –machine operation	Oil and natural gas

C.2. Unconventional Use Pathway

C.2.1. Heat Production Pathway

For this pathway, the contribution analysis results were broken down by system (biomass, alternative), and biomass system life cycle stage (production, transport, combustion). The production life cycle stage includes emissions from biomass production and related upstream emissions included in the system boundaries. The biomass transport life cycle stage includes the emissions of transporting the biomass product (e.g., pellets) from the production location to their use location. The combustion life cycle stage includes the emissions of burning the fuel to generate heat. All life cycle stages of the alternative systems were grouped together for the purpose of the contribution analysis presented in Figure C.2.

The potential environmental impacts of the systems and life cycle stages were normalized against the absolute value of the scenario with the maximum potential environmental impact of the 54 scenarios for each impact category (i.e., the base case scenario used varies for each impact category). The environmental impacts score is determined using the estimated environmental impact of the biomass system per unit of heat produced relative to that of producing the same quantity of heat using the alternative system. In Figure C.2, the contribution of each biomass system's life cycle stage is shown with a bar (positive values) as is the contribution of the disposal pathway (landfill) for added perspective. The contributions of the alternative systems for each of the scenarios are shown with a geographic marker in line with their respective biomass system (negative values). The sum of the results from each biomass system and alternative system corresponds to the base case results of the scenarios shown with geometric markers in Figure 5.4.

Table C.2 specifies the life cycle stage or process and substances that are the main contributors to the different impact categories, for both the biomass and alternative systems.

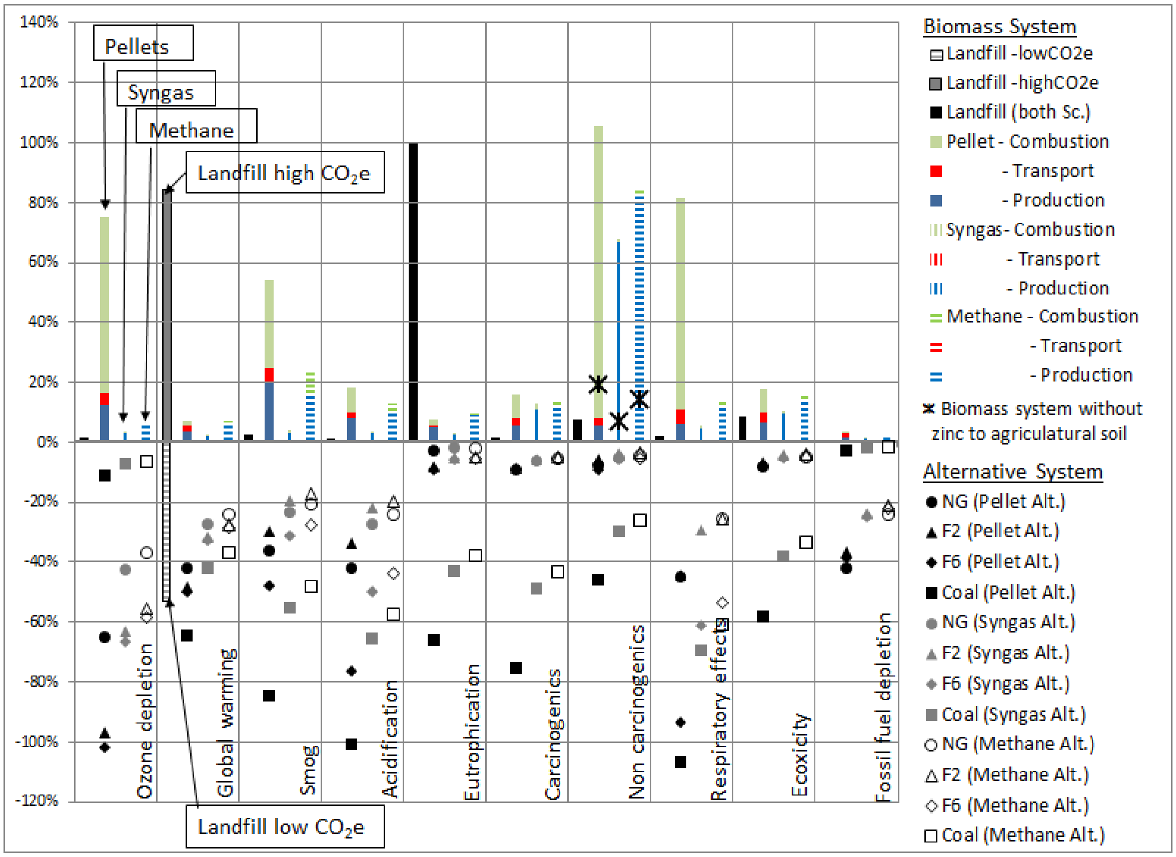


Figure C2 Heat Pathway Biomass Systems Life Cycle Stage and Alternative System Contribution to Potential Environmental Impacts Normalized Against the Absolute Value of the Scenario with the Maximum Potential Environmental Impact of the 54 Scenarios for Each Impact Category [Bars represent biomass systems life cycle stage contribution while geometric markers represent alternative system contribution**.** For Non-carcinogens, the "⁎" symbol represents the impact score for the biomass system without the contribution of zinc to agricultural soil.]

Table C.2 Heat Pathway System – Contributing Substances for Impact Categories with Potential Environmental Impact of More than 20% of the Normalized Score

	Biomass System		Alternative System	
Impact Category	**Biomass - life cycle stage**	**Contributing substance**	**Alternative system - process**	**Contributing substance**
Ozone depletion*	Pellets – Combustion	Methane, tetrachloro CFC-10 to air	Natural gas, No. 2 fuel oil, and No. 6 fuel oil – Onshore, natural gas and petroleum production	Methane, bromotrifluoro-, Halon 1301 to air
Global Warming			All systems – Combustion	Carbon dioxide to air
Smog	Pellets – Combustion, and Production (electricity used for pellet production) Methane – Production and combustion	Nitrogen oxides to air	All systems – Fuel combustion and production	Nitrogen oxides to air
Acidification			All systems – Fuel combustion All systems except coal – Production	Sulfur dioxide and nitrogen oxides to air
Eutrophication			Coal – Treatment of spoil from coal mining and coal slurry	Phosphate to water
Carcinogens			Coal – Treatment of spoil from coal mining and coal slurry	Chromium VI to water
Non-carcinogens	Pellets – Combustion Syngas – Production Methane – Production	Zinc to agricultural soil from wood ash spreading**	Coal – Treatment of spoil form coal mining, coal slurry and lignite ash	Arsenic and zinc to water
Respiratory effects	Pellets – Combustion	Particulates of less 2.5 µm to air	Natural gas and No. 2 fuel oil – Production No. 2 fuel oil, No. 6 fuel oil, and coal – Combustion	Sulfur dioxide and particulates of less than 2.5µm to air
Ecotoxicity			Coal – Treatment of spoil form coal mining, coal slurry and lignite ash	Zinc, nickel, chromium VI, vanadium, and copper to water

Table C.2 Continued

Impact Category	Biomass System		Alternative System	
	Biomass - life cycle stage	**Contributing substance**	**Alternative system - process**	**Contributing substance**
Fossil fuel depletion			Natural gas, No. 2 fuel oil, and No. 6 fuel oil – Production	Natural gas and crude oil

* Presence of ozone depleting substances in either the biomass or alternative system is judged too uncertain to be considered in the results; hence, the results of all scenarios for this impact category are considered environmentally neutral.
** When zinc emitted to agricultural soils is excluded from the assessment, the biomass systems are no longer main contributors to the potential non-carcinogens environmental impact.

C.2.2. Combined Heat and Power Production Pathway

C.2.2.1. CHP Maximized for Heat Production

For this pathway, the contribution assessment results were broken down by system (biomass, alternative) and biomass life cycle stage (production, transport, use/combustion). The biomass production life cycle stage includes emissions from biomass production and related upstream emissions included in the system boundaries. The biomass transport life cycle stage includes the emissions of transporting the biomass product (e.g., pellets) from the production location to their use location. The biomass use/combustion life cycle stage includes the emissions from burning the biomass to generate heat and electricity. All life cycle stages of the alternative systems were grouped together for the purpose of the contribution analysis presented in Figure C.3.

The potential environmental impacts of the various systems and life cycle stages were normalized against the absolute value of the scenario with the maximum potential environmental impact of the 54 scenarios for each impact category (i.e., the base case scenario used varies for each impact category). In Figure C.3 the contribution of each biomass system's life cycle stages is shown with bar (positive values) as is the contribution of the disposal pathway (landfill) for added perspective. The contributions of the alternative systems for each of the scenarios are shown with a geographic marker in line with their respective biomass system (negative value). The sum of the biomass system results and alternative system results corresponds to the base case scenario results shown in Figure 5.6 with geometric markers.

The contributions of the biomass systems shown in Figure C.3 are identical to the ones shown in Figure C.2 for the heat pathway; it is the contributions of the alternative systems that are different. The biomass system life cycle stage contributions provided earlier in Table C.2 are reproduced in Table C.3 for reference, in addition to the contributions of the alternative system for the CHPh pathway.

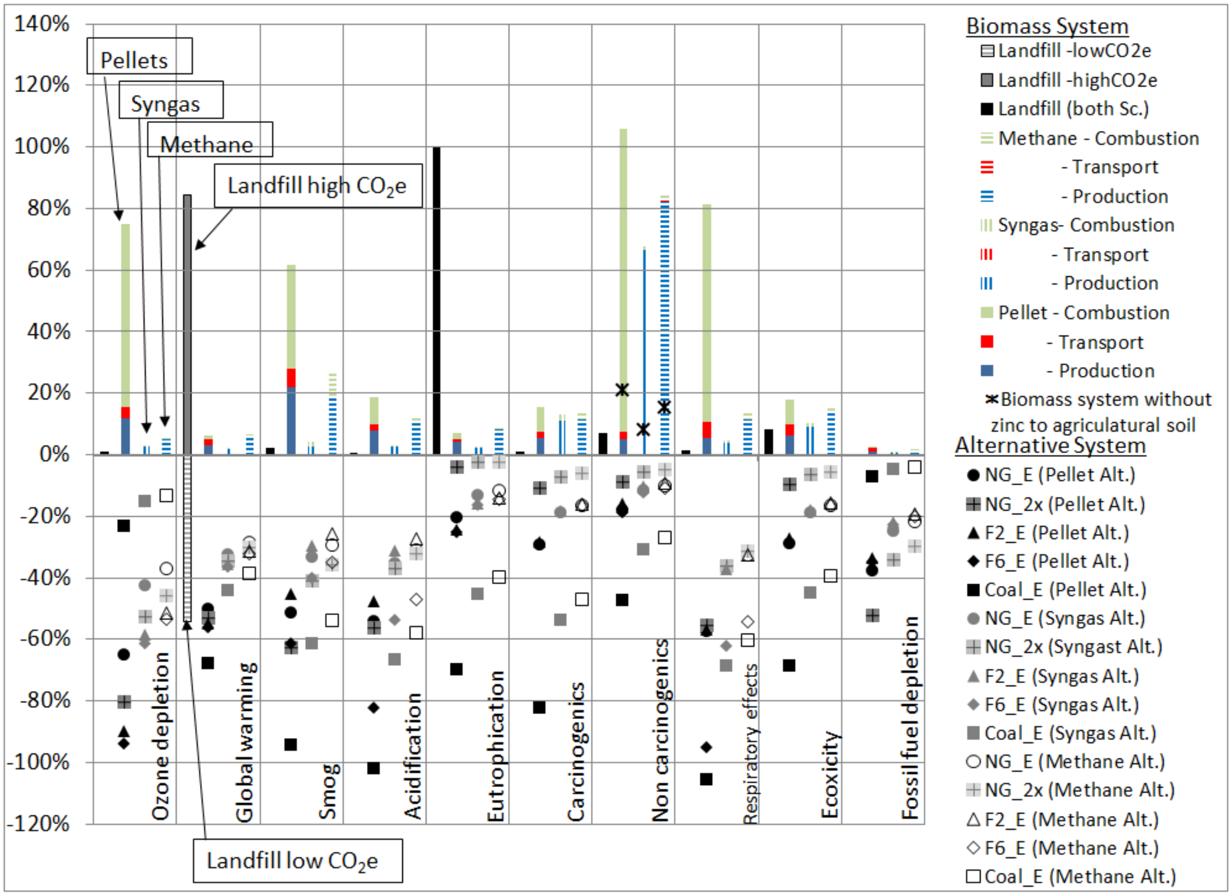


Figure C3 Combined Heat and Power Pathway Maximized for Heat Production Biomass Systems Life Cycle Stage Contribution to Potential Environmental Impacts Normalized Against the Absolute Value of the Scenario with the Maximum Potential Environmental Impact of the 54 Scenarios for Each Impact Category [Bars represent biomass systems life cycle stage contribution while geometric markers represent alternative system contribution. For Non-carcinogens, the "*" symbol represents the impact score for the biomass system without the contribution of zinc to agricultural soil.]

Table C.3 Combined Heat and Power Pathway Maximized for Heat Production System – Contributing Substances for Impact Categories with Potential Environmental Impact of More than 20% of the Normalized Score

Impact Category	Biomass System		Alternative System	
	Biomass - life cycle stage	**Contributing substance**	**Alternative system – process**	**Contributing substance**
Ozone depletion*	Pellets – Combustion	Methane, tetrachloro CFC-10 to air	Natural gas, No. 2 fuel oil, and No. 6 fuel oil – Onshore, natural gas and petroleum production for heat production Coal – Onshore natural gas and petroleum production for electricity production from natural gas	Methane, bromotrifluoro-, Halon 1301 to air
Global Warming			All systems – fossil fuel combustion for heat and electricity generation	Carbon dioxide to air
Smog	Pellets – Production and combustion Methane – Production and combustion	Nitrogen oxides to air	All systems – Fossil fuel combustion and production for heat and electricity generation	Nitrogen oxides to air
Acidification			All systems – Fossil fuel combustion for heat and electricity generation All systems except coal – Fossil fuel production for heat and electricity generation	Sulfur dioxide and nitrogen oxides to air
Eutrophication			All systems except NG_2x – Coal for heat and electricity generation – Treatment of spoil from coal mining and coal slurry	Phosphate to water

Table C.3 Continued

Impact Category	Biomass System		Alternative System	
	Biomass - life cycle stage	Contributing substance	Alternative system – process	Contributing substance
Carcinogens			All systems except NG_2x – Coal for heat and electricity generation – Treatment of spoil from coal mining and coal slurry	Chromium VI to water
Non-Carcinogens	Pellets – Combustion Syngas – Production Methane – Production	Zinc in agricultural soil from wood ash spreading**	Coal (Coal_E) – For heat and electricity generation – Treatment of spoil from coal mining and coal slurry	Arsenic and zinc to water
Respiratory effects	Pellets – Combustion	Particulates of less 2.5um to air	Natural gas (NG_E, NG_2X) and No. 2 fuel oil (F2_E) – Production for heat production No. 2 fuel oil (F2_E), No. 6 fuel oil (F6_E), and coal (Coal_E) – Combustion for heat and electricity generation	Sulfur dioxide and particulates of less than 2.5µm to air
Ecotoxicity			All systems except NG_2X – Coal used for heat or electricity production – Treatment of spoil form coal mining, coal slurry and lignite ash	Zinc, nickel, chromium VI, vanadium, and copper to water
Fossil fuel depletion			Natural gas (NG_E, NG_2X), No. 2 fuel oil (F2_E), and No. 6 fuel oil (F6_E) – Production for heat generation	Natural gas and crude oil

* Presence of ozone-depleting substances in either the biomass or alternative system is judged too uncertain to be considered the results; hence, the results of all scenarios for this impact category are considered environmentally neutral.

** When zinc emitted to agricultural soils is excluded from the assessment, the biomass systems are no longer primary contributors to the potential non-carcinogens environmental impact.

C.2.2.2. CHP Maximized for Electricity Production

For this pathway, the contribution assessment results were broken down by system (biomass, alternative) and biomass life cycle stage (production, transport, use/combustion). The biomass production life cycle stage includes emissions from biomass production and related upstream emissions included in the system boundaries. The biomass transport life cycle stage includes the emissions of transporting the biomass product (e.g., pellets) from the production location to their use location. The biomass use/combustion life cycle stage includes the emissions from burning the biomass to generate heat and electricity. All life cycle stages of the alternative systems were grouped together for the purpose of the contribution analysis presented in Figure C.4.

The potential environmental impacts of the various systems and life cycle stages were normalized against the absolute value of the scenario with the maximum potential environmental impact of the 54 scenarios for each impact category (i.e., the base case scenario used varies for each impact category). In Figure C.4, the contribution of each biomass system's life cycle stages is shown with bar (positive values). The contributions of the alternative systems for each of the scenarios are shown with a geographic marker in line with their respective biomass system (negative value). The sum of the biomass system results and alternative system results corresponds with the base case scenario results shown in Figure 5.8 with geometric markers.

The contributions of the biomass systems shown in Figure C.4 are identical to the ones shown in Figures C.2 and C.3 for the heat and CHPh pathways, respectively; it is the contributions of the alternative systems that are different. The contributions of biomass system life cycle stages shown earlier in Table C.2 are reproduced in Table C.4, for reference, in addition to the contributions of the alternative system for the CHPe pathway.

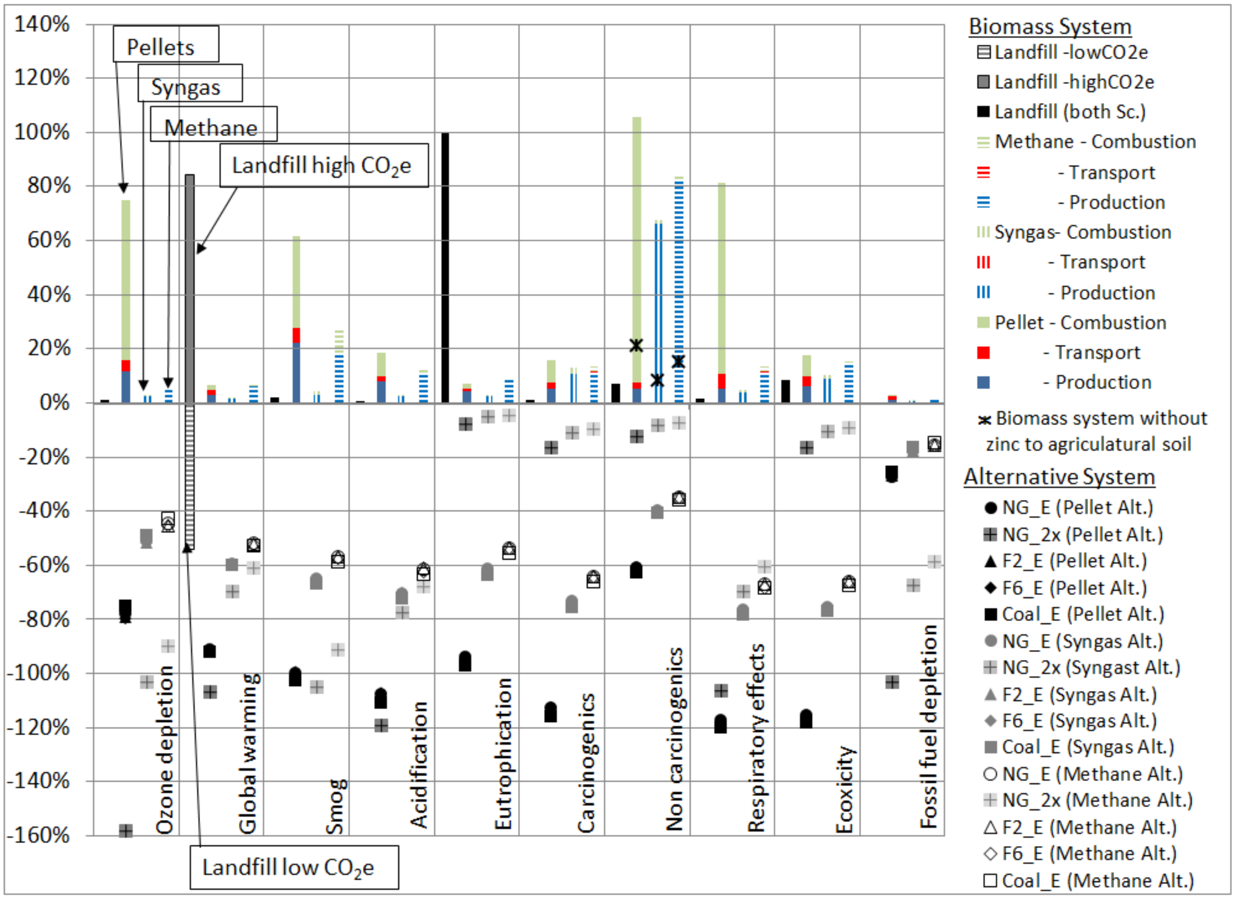


Figure C4 Combined Heat and Power Pathway Maximized for Electricity Production Biomass Systems Life Cycle Stage Contribution to Potential Environmental Impacts Normalized Against the Absolute Value of the Scenario with the Maximum Potential Environmental Impact of the 54 Scenarios for Each Impact Category [Bars represent biomass systems life cycle stage contribution while geometric markers represent alternative system contribution**.** For Non-carcinogens, the "*" symbol represents the impact score for the biomass system without the contribution of zinc to agricultural soil.]

Table C.4 Combined Heat and Power Pathway Maximized for Heat Production System – Contributing Substances for Impact Categories with Potential Environmental Impact of More than 20% of the Normalized Score

	Biomass System		Alternative System	
Impact Category	**Biomass - life cycle stage**	**Contributing substance**	**Alternative system**	**Contributing substance**
Ozone depletion	Pellets – Combustion	Methane, tetrachloro CFC-10 to air	Natural gas only (NG_2X) – Onshore, natural gas and petroleum production All other systems – Onshore, natural gas and petroleum production; Production of uranium enrich; and hard coal combustion for electricity generation	Methane, bromotrifluoro-, Halon 1301 to air Methane, bromotrifluoro-, Halon 1301 to air; Ethane, 1,2 dichloro-1,1,2,2-tetrafluoro, CFC-114 to air; and Methane, monochloro, R-40
Global Warming			All systems – Fossil fuel combustion (mainly coal and natural gas)	Carbon dioxide to air
Smog	Pellets – Production and combustion Methane – Production and combustion	Nitrogen oxides to air	All systems except NG_2X – electricity production from hard coal Natural gas only (NG_2X) – Combustion for heat and electricity generation and electricity used at compressor station	Nitrogen oxides to air
Acidification			All systems – Natural gas and coal combustion for heat and electricity generation; and natural gas production	Sulfur dioxide and nitrogen oxides to air
Eutrophication			All systems except NG_2X – Coal – Treatment of spoil from coal mining and coal slurry	Phosphate to water

Table C.4 Continued

Impact Category	Biomass System		Alternative System	
	Biomass - life cycle stage	Contributing substance	Alternative system	Contributing substance
Carcinogens			All systems except NG_2X – Coal – Treatment of spoil from coal mining and coal slurry	Chromium VI to water
Non-Carcinogens	Pellets – Combustion Syngas – Production Methane – Production	Zinc in agricultural soil from wood ash spreading	All systems except NG_2X – Coal – Treatment of spoil from coal mining and coal slurry	Arsenic and zinc to water
Respiratory effects	Pellets – Combustion	Particulates of less 2.5um to air	Natural gas (NG_E, NG_2X) and No. 2 fuel oil (F2_E) – Production No. 2 fuel oil (F2_E), No. 6 fuel oil (F6_E), and coal (Coal_E) – Combustion	Sulfur dioxide and particulates of less than 2.5μm to air
Ecotoxicity			All systems except NG_2X – Coal – Treatment of spoil from coal mining, coal slurry and lignite ash	Zinc, nickel, chromium VI, vanadium, and copper to water
Fossil fuel depletion			Natural gas only (NG_2X) – Production	Natural gas

* Presence of ozone depleting substances in either the biomass or alternative system is judged too uncertain to be considered the results; hence, the results of all scenarios for this impact category are considered environmentally neutral.

** When zinc emitted to agricultural soils is excluded from the assessment, the biomass systems are no longer main contributors to the potential non-carcinogens environmental impact.

C.2.3. Transport Fuel Use Pathway

For this pathway, the contribution assessment results were broken down by system (biomass, alternative) and biomass life cycle stage (production, and use/combustion). The biomass production life cycle stage includes emissions from biomass production and related upstream emissions included in the system boundaries. The biomass use/combustion life cycle stage includes the emissions of combustion the biomass product to enable a car to travel a certain distance. All life cycle stages of the alternative systems were grouped together for the purpose of the contribution analysis presented in Figure C.5.

The potential environmental impacts of the various systems and life cycle stages were normalized against the absolute value of the scenario with the maximum potential environmental impact of the 54 scenarios for each impact category (i.e., the base case scenario used varies for each impact category). In Figure C.5, the contributions of each biomass system's life cycle stages are shown with bars (positive values). The contributions of the alternative systems for each of the scenarios are shown with a geographic marker in line with their respective biomass system (negative value). The sum of the biomass system results and alternative system results corresponds to the base case scenario results shown in Figure 5.10 with geometric markers.

The environmental impacts score is determined by estimating the environmental impact of the biomass system per unit of kilometers travelled by a vehicle relative to that of enabling a vehicle to travel the same distance using the alternative system. Figure C.5 shows the variables contributing to the results and, for the biomass system, further details regarding each life cycle stage. Table C.5 specifies the life cycle stage or process and substances that are the main contributors to the different impact categories for the biomass and alternative systems.

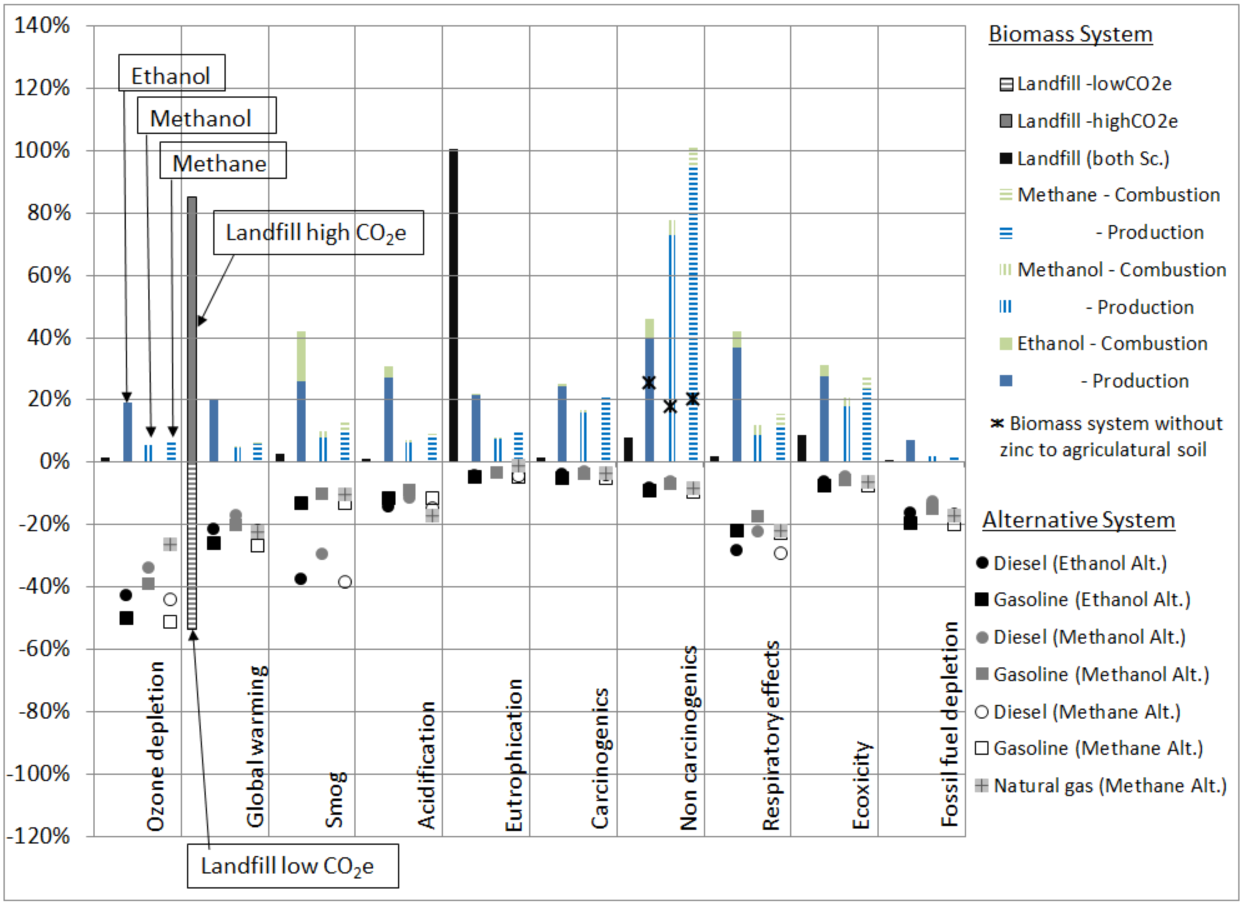


Figure C.5 Transport Use Pathway Biomass Systems Life Cycle Stage Contribution to Potential Environmental Impacts Normalized Against the Absolute Value of the Scenario with the Maximum Potential Environmental Impact of the 54 Scenarios for Each Impact Category [Bars represent biomass systems life cycle stage contribution while geometric markers represent alternative system contribution. For Non-carcinogens, the "⁎" symbol represents the impact score for the biomass system without the contribution of zinc to agricultural soil.]

Table C.5 Transport Use Pathway System – Contributing Substances for Impact Categories with Potential Environmental Impact of More than 20% of the Normalized Score

Impact Category	Biomass System		Alternative System	
	Biomass - life cycle stage	**Contributing substance**	**Alternative system - process**	**Contributing substance**
Ozone depletion*			All systems – Onshore petroleum and gas production	Methane, bromotrifluoro, Halon 1301 to air
Global warming	Ethanol – Production: electricity consumed during upgrade of the ethanol (from 95% to 99.7%) and ethanol (95%) production	Carbon dioxide to air	All systems – Operation of the passenger car	Carbon dioxide to air
Smog	Ethanol – Combustion Ethanol – Production: electricity consumed during upgrade of the ethanol (from 95% to 99.7%) and ethanol (95%) production	Nitrogen oxides to air	Diesel – Operation of the passenger car	Nitrogen oxides to air
Acidification	Ethanol – Production: electricity consumed during upgrade of the ethanol (from 95% to 99.7%) and ethanol (95%) production	Sulfur dioxide and nitrogen oxides to air		
Eutrophication	Ethanol – Production: treatment of spoil from hard coal mining, coal used to produce electricity consumed to upgrade ethanol (from 95% to 99.7%)	Phosphate and nitrate to water		
Carcinogens	Ethanol – Production: electricity produced from coal consumed during upgrade of the ethanol (from 95% to 99.7%) Methane – Production: electricity produced from coal consumed for methane production	Chromium IV to water		

Table C.5 Continued

Impact Category	Biomass System		Alternative System	
	Biomass - life cycle stage	**Contributing substance**	**Alternative system - process**	**Contributing substance**
Non-Carcinogens	Ethanol – Production: wood ash management from ethanol (95%) production and treatment of spoil from hard coal mining, coal used to produce electricity consumed to upgrade ethanol (from 95% to 99.7%) Methanol – Production: wood ash management from syngas production Methane – Production: wood ash management from methane production	Zinc in agricultural soil from wood ash spreading**		
Respiratory effects	Ethanol – Production: the ethanol production process and from electricity produced from coal and consumed to upgrade ethanol (from 95% to 99.7%)	Sulfur dioxide and particulates of less than 2,5µm to air	All systems – Operation of the passenger car All systems – Production	Particulates of less than 2,5µm to air Particulates of less than 2,5µm and sulfur dioxide to air
Ecotoxicity	Ethanol – Production: electricity consumed (electricity distribution and coal mining) Methanol – Production: electricity consumed (coal mining) and treatment of waste from nickel production (nickel is used in methanol production) Methane – Production: electricity consumed (electricity distribution and coal mining)	Copper and zinc to water		

Table C.5 Continued

Impact Category	Biomass System		Alternative System	
	Biomass - life cycle stage	**Contributing substance**	**Alternative system - process**	**Contributing substance**
Fossil fuel depletion			Diesel and Gasoline – Production Natural gas – Production	Oil Natural gas

* Presence of ozone depleting substances in either the biomass or alternative system is judged too uncertain to be considered the results; hence, the results of all scenarios for this impact category are considered environmentally neutral.
** When zinc emitted to agricultural soils is excluded from the assessment, the biomass systems remain main contributors to the potential non-carcinogens environmental impact.

C.2.4. Use in Metallurgy Pathway

For this pathway, the contribution assessment results were broken down by system (biomass, alternative) and biomass life cycle stage (production, transport, use/combustion). The biomass production life cycle stage includes emissions from biomass production and related upstream emissions included in the system boundaries. The biomass transport life cycle stage includes the emissions of transporting the biomass product (e.g., charcoal) from the production location to their use location. The biomass use/combustion life cycle stage includes the emissions of using the biomass product as reductant agent in pig iron production (metallurgy pathway). All life cycle stages of the alternative system were grouped together for the purpose of the contribution analysis presented in Figure C.6.

The potential environmental impacts of the various systems and life cycle stages were normalized against the absolute value of the scenario with the maximum potential environmental impact of the 54 scenarios for each impact category (i.e., the base case scenario used varies for each impact category). In Figure C.6, the contributions of the biomass system's life cycle stages are shown with bars (positive values). The contributions of the alternative systems for each of the scenarios are shown with a geographic marker in line with their respective biomass system (negative value). The sum of the biomass system results and alternative system results corresponds to the base case scenario results shown in Figure 5.12 with geometric markers.

Figure C.6 shows key contributing systems and biomass life cycle stages, while Table C.6 further specifies the substances that are the biggest contributors to each impact category.

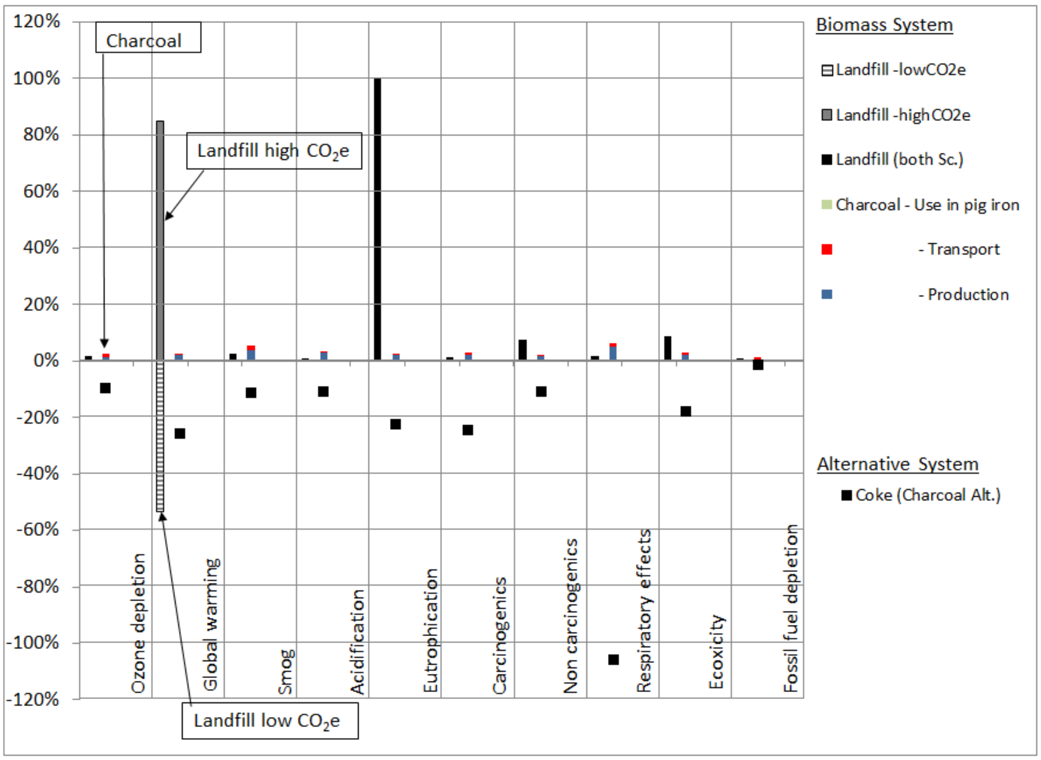


Figure C.6 Use in Metallurgy Pathway Biomass Systems Life Cycle Stage Contribution to Potential Environmental Impacts Normalized Against the Absolute Value of the Scenario with the Maximum Potential Environmental Impact of the 54 Scenarios for Each Impact Category [Bars represent biomass systems life cycle stage contribution while geometric markers represent alternative system contribution.]

Table C.6 Use in Metallurgy Pathway System – Contributing Substances for Impact Categories with Potential Environmental Impact of More than 20% of the Normalized Score

Impact Category	Biomass System		Alternative System	
	Biomass – life cycle stage	**Contributing substance**	**Alternative system – process**	**Contributing substance**
Ozone depletion				
Global warming			Coke – Use of coke in pig iron production	Carbon dioxide to air
Smog				
Acidification				
Eutrophication			Coke – Spoil from hard coal mining	Phosphate to water
Carcinogens			Coke – Spoil from hard coal mining	Chromium VI to water
Non-carcinogens				
Respiratory effects			Coke – Coke cooking	Particulates of less than 2.5µm to air
Ecotoxicity			Coke – Coal mining waste	Zinc to water
Fossil fuel depletion				

C.2.5. Use as Horticultural Growing Media Pathway

For this pathway, the contribution assessment results were broken down by system (biomass, alternative) and biomass life cycle stage (production, transport, use/combustion). The biomass production life cycle stage includes emissions from biomass production and related upstream emissions included in the system boundaries. The biomass transport life cycle stage includes the emissions of transporting the biomass product (e.g., bark mulch) from the production location to their use location. The biomass use/combustion life cycle stage includes the emissions of using the biomass product to enable plants to grow (horticultural growing media pathway). All life cycle stages of the alternative systems were grouped together for the purpose of the contribution analysis presented in Figure C.7.

The potential environmental impacts of the various systems and life cycle stages were normalized against the absolute value of the scenario with the maximum potential environmental impact of the 54 scenarios for each impact category (i.e., the base case scenario used varies for each impact category). In Figure C.7, the contributions of each biomass system's life cycle stages are shown with bars (positive values). The contributions of the alternative systems for each of the scenarios are shown with a geographic marker in line with their respective biomass system (negative value). The sum of the biomass system results and alternative system results corresponds to the base case scenario results shown in Figure 5.12 with geometric markers.

shows the primary contributing systems and biomass life cycle stages, while Table C.7 further specifies the substances that are the biggest contributors to each impact category.

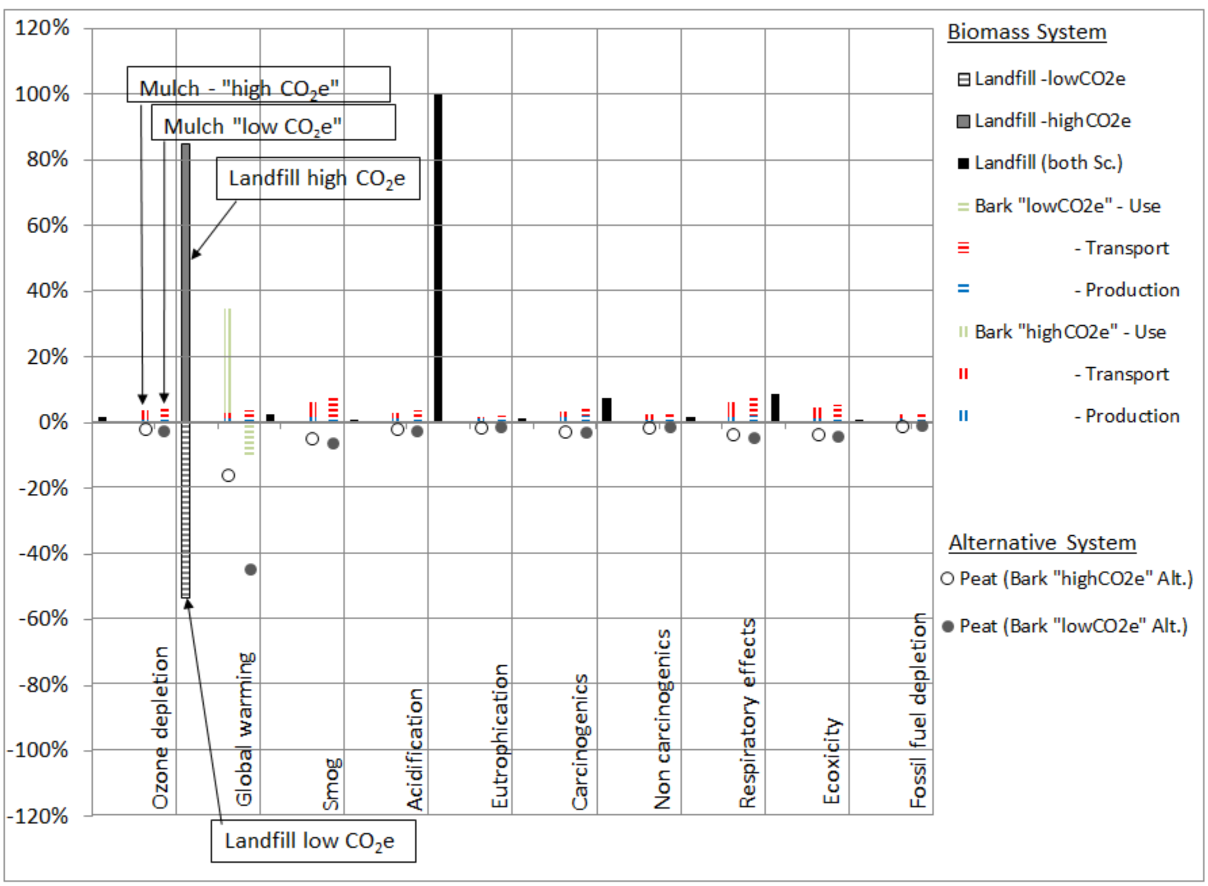


Figure C.7 Use as Horticultural Growing Media Pathway Biomass Systems Life Cycle Stage Contribution to Potential Environmental Impacts Normalized Against the Absolute Value of the Scenario with the Maximum Potential Environmental Impact of the 54 Scenarios for Each Impact Category [Bars represent biomass systems life cycle stage contribution while geometric markers represent alternative system contribution.]

Table C.7 Use as Horticultural Growing Media Pathway System – Contributing Substances for Impact Categories with Potential Environmental Impact of More than 20% of the Normalized Score

Impact Category	Biomass System		Alternative System	
	Biomass – life cycle stage	**Contributing substance**	**Alternative system – process**	**Contributing substance**
Ozone depletion				
Global warming	Bark_low CO_2e – Use	CO_2 stored and N_2O emitted to air during degradation	Peat (high CO_2 emissions) – Production and use	Carbon dioxide to air, and CH_4 and N_2O emitted to air during degradation
	Bark_highCO_2e – Use	CH_4 and N_2O emitted to air during degradation	Peat (low CO_2 emissions) – Production and use	Carbon dioxide to air, and CO_2 stored during degradation
Smog				
Acidification				
Eutrophication				
Carcinogens				
Non-carcinogens				
Respiratory effects				
Ecotoxicity				
Fossil fuel depletion				

APENDIX D

RESULTS OF THE SEMI-QUANTITATIVE UNCERTAINTY ASSESSMENT

D.1. Unconventional Use Pathway

Results are presented graphically and in tables to show the variations of the results and the impact score conclusions. For the graphical representation of the results, the distributions of results for each scenario (shown with an error bar on the graphs) must be either completely above or below the grey boxes representing impact category uncertainty in order to conclude that the impact score is different from zero.

Note that for the contribution analyses, all scores in the ozone depletion impact category were found to be too uncertain to warrant drawing conclusions. That said, the results for this impact category are shown in the graphs for transparency. Also, note that compiled results excluding the contribution of zinc to agricultural soil from wood ash spreading, which affects results for non-carcinogens.

D.1.1. Heat Production Pathway

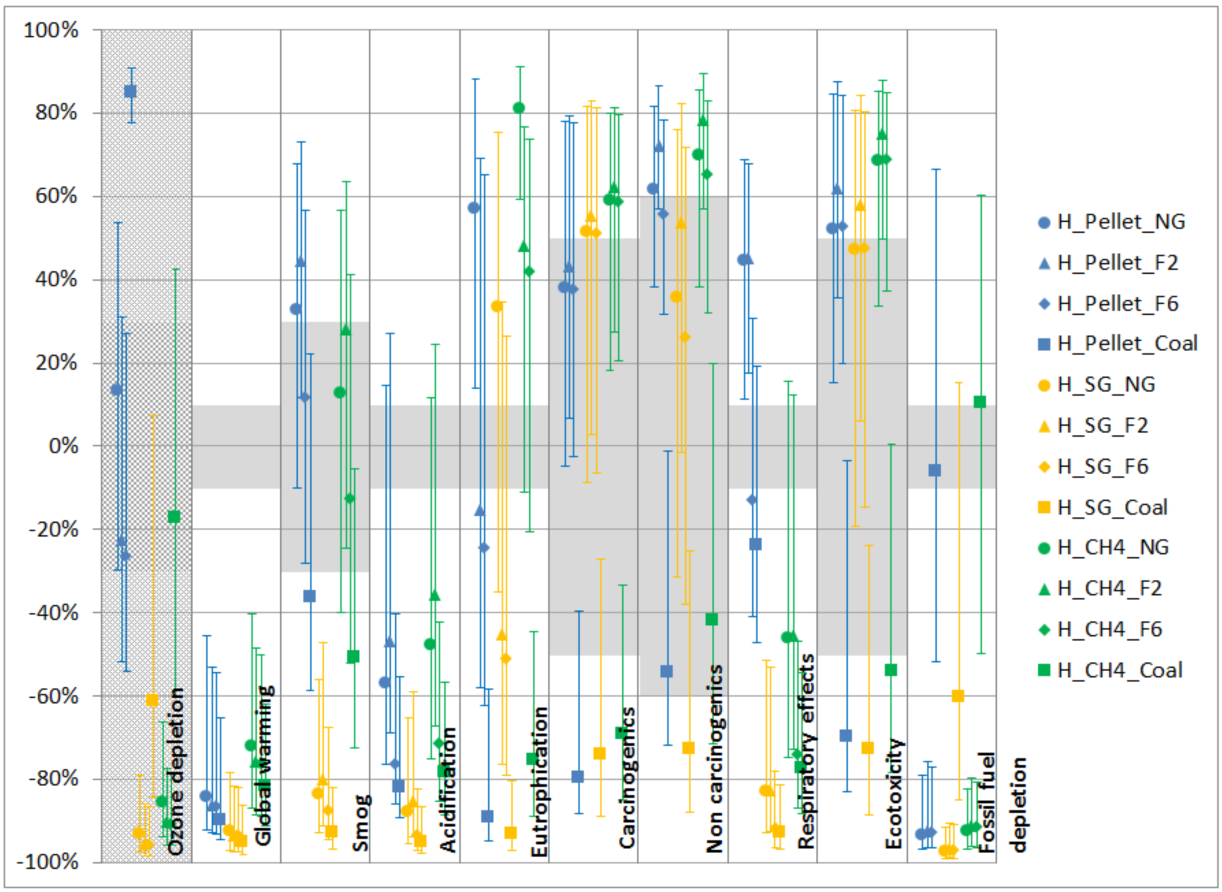


Figure D.1 Heat Pathway Scenarios Systems Differences Normalized with Maximum Absolute Value of Scenario System Impact Score [Geographic Marker Represents Base Case Scenarios, While Error Bars Represent Scenario Parameter and Efficiency Uncertainty. Grey Boxes Represent Impact Category Uncertainty.]

Table D. 1 Heat Pathway Scenarios Impact Score Result Considering Parameter and Efficiency Uncertainty

Pathway	Biomass system	Alternative system	Ozone depletion*	Global warming	Smog	Acidification	Eutrophication	Carcinogens	Non-carcinogens**	Respiratory effects	Ecotoxicity	Fossil fuel depletion	Number of Impact Categories with Impact Score: Lower than zero	Number of Impact Categories with Impact Score: Greater than zero	Number of Impact Categories with Impact Score: Neutral
Heat	Pellets	Natural gas											2	**2**	6
		No. 2 fuel oil											2	1	7
		No. 6 fuel oil											3	0	7
		Coal											3	0	7
	Syngas	Natural gas											**5**	0	5
		No. 2 fuel oil											**5**	0	5
		No. 6 fuel oil											**5**	0	5
		Coal											**5**	0	5
	Methane	Natural gas											2	1	7
		No. 2 fuel oil											2	0	8
		No. 6 fuel oil											4	0	6
		Coal											4	0	6

* Uncertainty relative to ozone depletion is considered too great to permit conclusions to be made.
** Scenario results compiled without potential impact of zinc emitted to agricultural soil.

<u>Legend</u>
Impact Score Result:

- Impact scores less than zero
- Impact scores greater than zero
- Environmentally Neutral

D.1.2. Combined Heat and Power Pathway

D.1.2.1. CHP Maximized for Heat Production

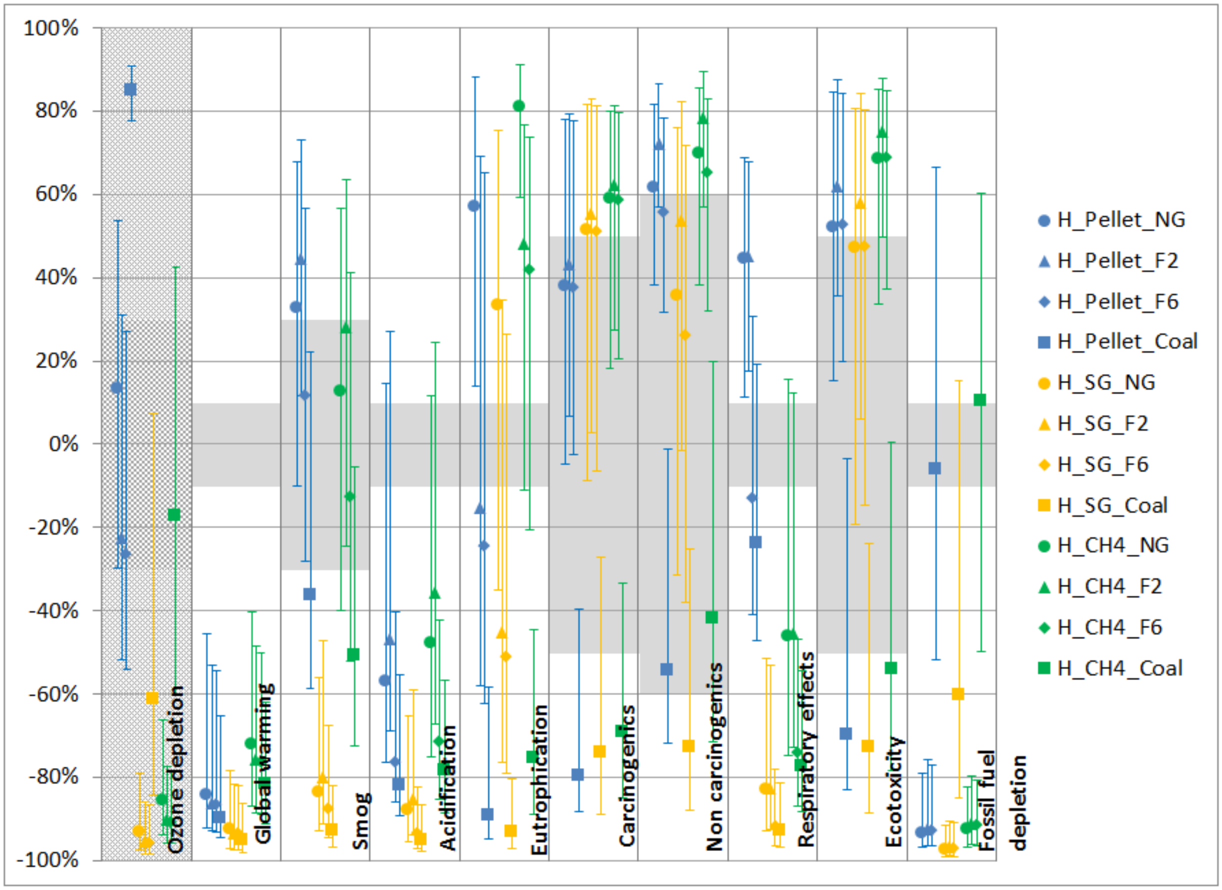


Figure D.2 **Heat Pathway Scenarios Systems Differences Normalized with Maximum Absolute Value of Scenario System Impact Score** [**Geographic** marker represents base case scenarios, while error bars represent scenario parameter and efficiency uncertainty**.** Grey boxes represent impact category uncertainty.]

Table D.2 Heat Pathway Scenarios Impact Score Result Considering Parameter and Efficiency Uncertainty

Pathway	Biomass system	Alternative system	Ozone depletion*	Global warming	Smog	Acidification	Eutrophication	Carcinogens	Non-carcinogens**	Respiratory effects	Ecotoxicity	Fossil fuel depletion	Number of Impact Categories with Impact Score		
													Lower than zero	Greater than zero	Neutral
Heat	Pellets	Natural gas											2	**2**	6
		No. 2 fuel oil											2	1	7
		No. 6 fuel oil											3	0	7
		Coal											3	0	7
	Syngas	Natural gas											**5**	0	5
		No. 2 fuel oil											**5**	0	5
		No. 6 fuel oil											**5**	0	5
		Coal											**5**	0	5
	Methane	Natural gas											2	1	7
		No. 2 fuel oil											2	0	8
		No. 6 fuel oil											4	0	6
		Coal											4	0	6

* Uncertainty relative to ozone depletion is considered too great to permit conclusions to be made.
** Scenario results compiled without potential impact of zinc emitted to agricultural soil.

Legend
Impact Score Result:

(green)	Impact scores less than zero
(yellow)	Impact scores greater than zero
(gray)	Environmentally Neutral

D.1.2.2. CHP Maximized for Electricity Production

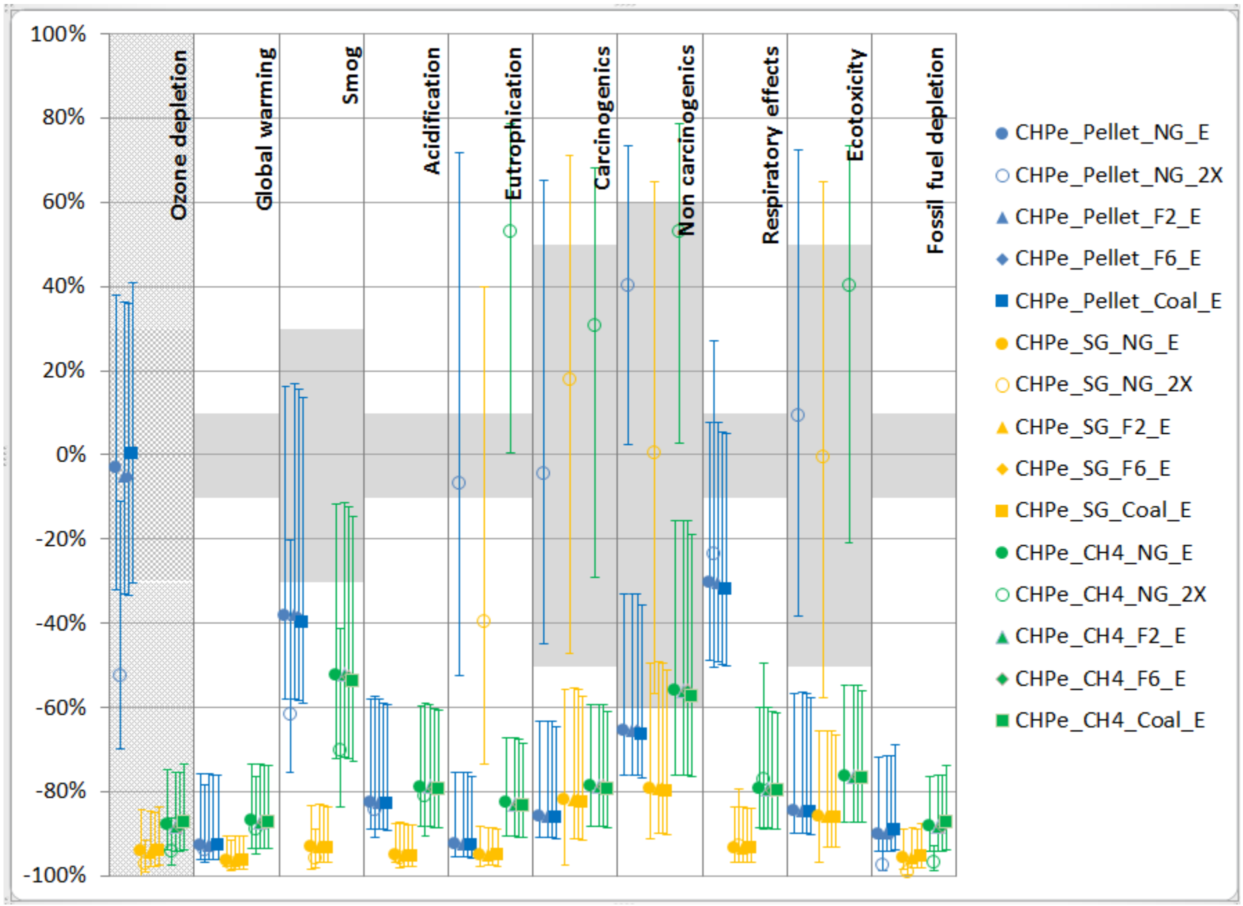


Figure D.3 **Combined Heat and Power Pathway Maximized for Electricity Production Scenarios Systems Differences Normalized with Maximum Absolute Value of Scenario System Impact Score** [**Geographic** marker represents base case scenarios, while error bars represent scenario parameter and efficiency uncertainty**.** Grey boxes represent impact category uncertainty.]

Table D.3 Combined Heat and Power Pathway Maximized for Electricity Production Scenarios Impact Score Result Considering Parameter and Efficiency Uncertainty

Pathway	Biomass system	Alternative system (heat/electricity)	Ozone depletion*	Global warming	Smog	Acidification	Eutrophication	Carcinogens	Non-carcinogens**	Respiratory effects	Ecotoxicity	Fossil fuel depletion	Number of Impact Categories with Impact Score: Lower than zero	Greater than zero	Neutral
Combined Heat and Power Maximized for Electricity Production *CHPe)	Pellets	Natural gas/Grid	Gray	Green	Gray	Green	Green	Green	Gray	Gray	Green	Green	6	0	4
		Natural gas/NG	Gray	Green	Gray	Green	Gray	Gray	Gray	Gray	Gray	Green	3	0	7
		No. 2 fuel oil/Grid	Gray	Green	Gray	Green	Green	Green	Gray	Gray	Green	Green	6	0	4
		No. 6 fuel oil/Grid	Gray	Green	Gray	Green	Green	Green	Gray	Gray	Green	Green	6	0	4
		Coal/Grid	Gray	Green	Gray	Green	Green	Green	Gray	Gray	Green	Green	6	0	4
	Syngas	Natural gas/Grid	Gray	Green	Green	Green	Green	Green	Gray	Green	Green	Green	**8**	0	2
		Natural gas/NG	Gray	Green	Green	Green	Gray	Gray	Gray	Green	Gray	Green	5	0	5
		No. 2 fuel oil/Grid	Gray	Green	Green	Green	Green	Green	Gray	Green	Green	Green	**8**	0	2
		No. 6 fuel oil/Grid	Gray	Green	Green	Green	Green	Green	Gray	Green	Green	Green	**8**	0	2
		Coal/Grid	Gray	Green	Green	Green	Green	Green	Gray	Green	Green	Green	**8**	0	2
	Methane	Natural gas/Grid	Gray	Green	Gray	Green	Green	Green	Gray	Green	Green	Green	7	0	3
		Natural gas/NG	Gray	Green	Green	Green	Gray	Gray	Gray	Green	Gray	Green	5	0	5
		No. 2 fuel oil/Grid	Gray	Green	Gray	Green	Green	Green	Gray	Green	Green	Green	7	0	3
		No. 6 fuel oil/Grid	Gray	Green	Gray	Green	Green	Green	Gray	Green	Green	Green	7	0	3
		Coal/Grid	Gray	Green	Gray	Green	Green	Green	Gray	Green	Green	Green	7	0	3

* Uncertainty relative to ozone depletion is considered too great to allow conclusions to be made.
** Scenario results compiled without potential impact of zinc emitted to agricultural soil.

Legend

Impact Score Result	Green: Impact scores less than zero	Yellow: Impact scores greater than zero	Gray: Environmentally Neutral

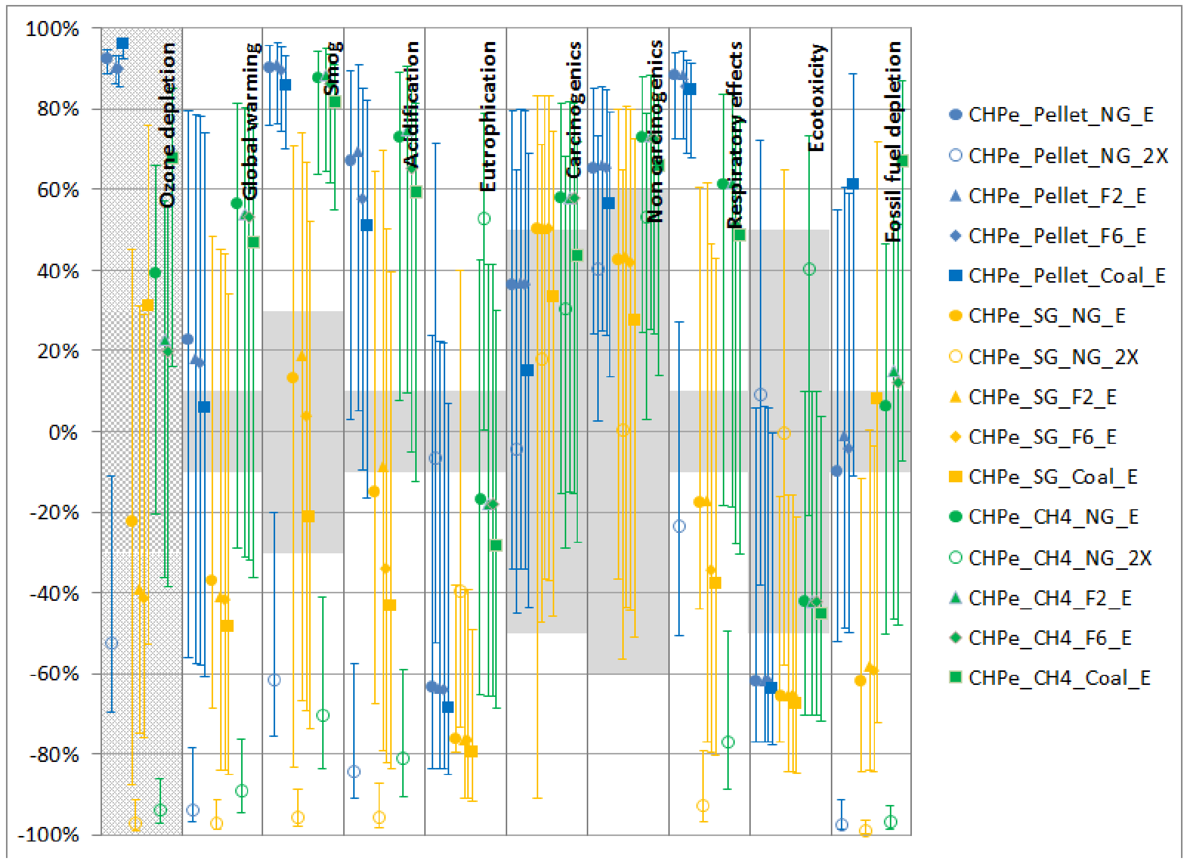


Figure D4 Combined Heat and Power Pathway Maximized for Electricity Production Scenarios Systems Differences Normalized with Maximum Absolute Value of Scenario System Impact Score [Geographic marker represents scenarios with Quebec grid mix, while error bars represent scenario parameter and efficiency uncertainty. Grey boxes represent impact category uncertainty.]

Table D.4 Combined Heat and Power Pathway Maximized for Electricity Production Scenarios Impact Score Result with Quebec Grid Mix Considering Parameter and Efficiency Uncertainty

Pathway	Biomass system	Alternative system (heat/electricity)	Ozone depletion*	Global warming	Smog	Acidification	Eutrophication	Carcinogens	Non-carcinogens**	Respiratory effects	Ecotoxicity	Fossil fuel depletion	Number of Impact Categories with Impact Score: Lower than zero	Greater than zero	Neutral
Combined Heat and Power Maximized for Electricity Production *CHPe)	Pellets	Natural gas/Grid	Neutral	Neutral	Loss …	Neutral	Neutral	Neutral	Neutral	Loss …	Neutral	Neutral	0	2	8
		Natural gas/NG	Neutral	Gain	Neutral	Gain	Neutral	Neutral	Neutral	Neutral	Neutral	Gain	3	0	7
		No. 2 fuel oil/Grid	Neutral	Neutral	Loss	Neutral	Neutral	Neutral	Neutral	Loss	Neutral	Neutral	0	2	8
		No. 6 fuel oil/Grid	Neutral	Neutral	Loss	Neutral	Neutral	Neutral	Neutral	Loss	Neutral	Neutral	0	2	8
		Coal/Grid	Neutral	Neutral	Loss	Neutral	Neutral	Neutral	Neutral	Loss	Neutral	Neutral	0	2	8
	Syngas	Natural gas/Grid	Neutral	Neutral	Neutral	Neutral	Gain	Neutral	Neutral	Neutral	Neutral	Gain	2	0	8
		Natural gas/NG	Neutral	Gain	Gain	Gain	Neutral	Neutral	Neutral	Gain	Neutral	Gain	**5**	0	5
		No. 2 fuel oil/Grid	Neutral	Neutral	Neutral	Neutral	Gain	Neutral	Neutral	Neutral	Neutral	Neutral	1	0	9
		No. 6 fuel oil/Grid	Neutral	Neutral	Neutral	Neutral	Gain	Neutral	Neutral	Neutral	Neutral	Neutral	1	0	9
		Coal/Grid	Neutral	Neutral	Neutral	Neutral	Gain	Neutral	Neutral	Neutral	Neutral	Neutral	1	0	9
	Methane	Natural gas/Grid	Neutral	Neutral	Loss	Neutral	Neutral	Neutral	Neutral	Neutral	Neutral	Neutral	0	1	9
		Natural gas/NG	Neutral	Gain	Gain	Gain	Neutral	Neutral	Neutral	Gain	Neutral	Gain	**5**	0	5
		No. 2 fuel oil/Grid	Neutral	Neutral	Loss	Neutral	Neutral	Neutral	Neutral	Neutral	Neutral	Neutral	0	1	9
		No. 6 fuel oil/Grid	Neutral	Neutral	Loss	Neutral	Neutral	Neutral	Neutral	Neutral	Neutral	Neutral	0	1	9
		Coal/Grid	Neutral	Neutral	Loss	Neutral	Neutral	Neutral	Neutral	Neutral	Neutral	Neutral	0	1	9

* Uncertainty relative to ozone depletion is considered too great to allow conclusions to be made.
** Scenario results compiled without potential impact of zinc emitted to agricultural soil.

Legend

Impact Score Result	Environmental Gain (green)	Environmental Loss (yellow)	Environmentally Neutral (grey)

D.1.3. Transport Fuel Use Pathway

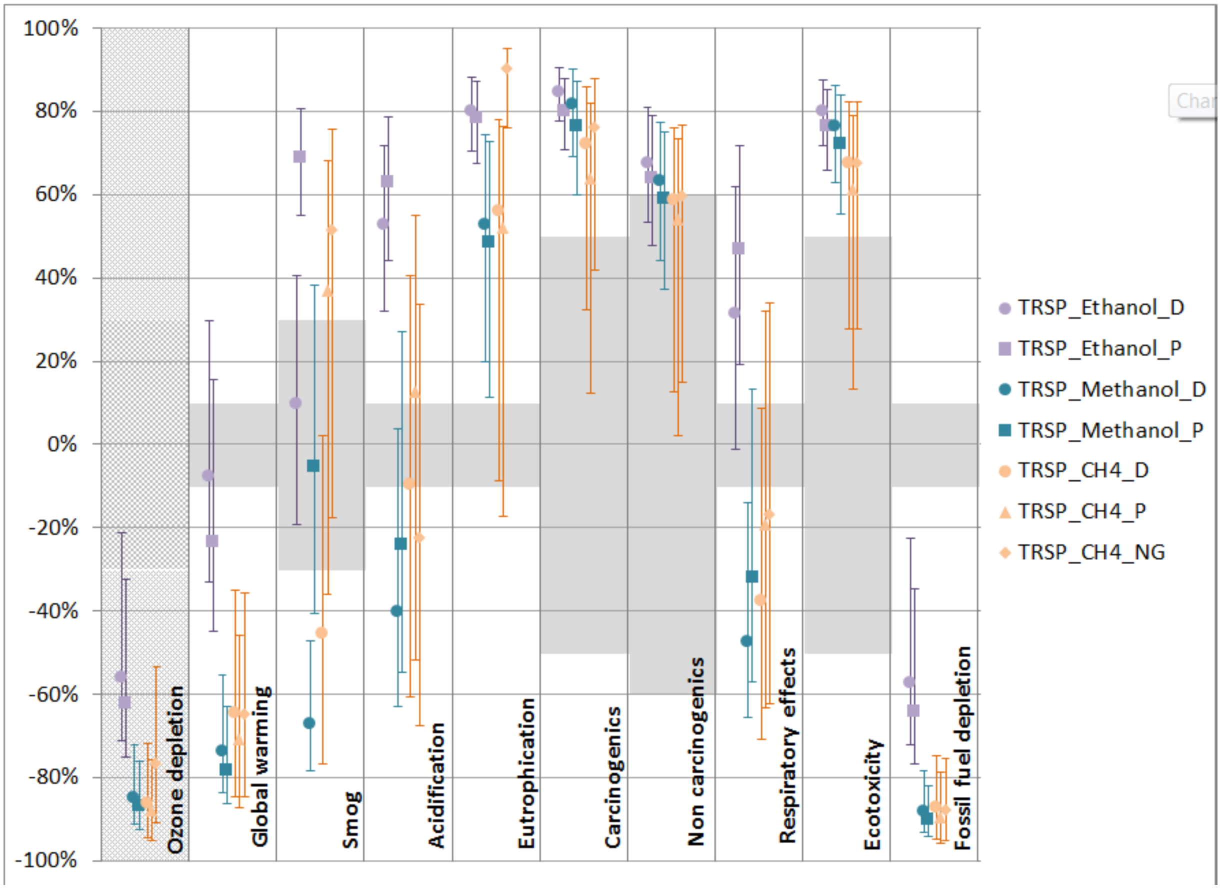


Figure D. 5 **Transport Use Pathway Scenarios Systems Differences Normalized with Maximum Absolute Value of Scenario System Impact Scor**e [**Geographic** marker represents base case scenarios, while error bars represent scenario parameter and efficiency uncertainty**.** Grey boxes represent impact category uncertainty.]

Table D.5 Transport Use Pathway Scenarios Impact Score Result Considering Parameter and Efficiency Uncertainty

Pathway	Biomass system	Alternative system	Ozone depletion*	Global warming	Smog	Acidification	Eutrophication	Carcinogens	Non-carcinogens**	Respiratory effects	Ecotoxicity	Fossil fuel depletion	Number of Impact Categories with Impact Score: Lower than zero	Greater than zero	Neutral
Transport Use	Ethanol	**Diesel**	Gray	Gray	Gray	Yellow	Yellow	Yellow	Gray	Gray	Yellow	Green	1	4	5
		Gasoline	Gray	Gray	Yellow	Yellow	Yellow	Yellow	Gray	Yellow	Yellow	Green	1	**6**	3
	Methanol	**Diesel**	Gray	Green	Green	Gray	Yellow	Yellow	Gray	Green	Yellow	Green	**4**	3	3
		Gasoline	Gray	Green	Gray	Gray	Yellow	Yellow	Gray	Gray	Yellow	Green	2	3	5
	Methane	**Diesel**	Gray	Green	Gray	Gray	Gray	Gray	Gray	Gray	Gray	Green	2	0	8
		Gasoline	Gray	Green	Gray	Gray	Gray	Gray	Gray	Gray	Gray	Green	2	0	8
		Natural Gas	Gray	Green	Gray	Gray	Yellow	Gray	Gray	Gray	Gray	Green	2	1	7

* Uncertainty relative to ozone depletion is considered too great to allow conclusions to be made.
** Scenario results compiled without potential impact of zinc emitted to agricultural soil.

Legend

Impact Score Result	Green: Impact scores less than zero	Yellow: Impact scores greater than zero	Gray: Environmentally Neutral

D.1.4. Use in Metallurgy Pathway

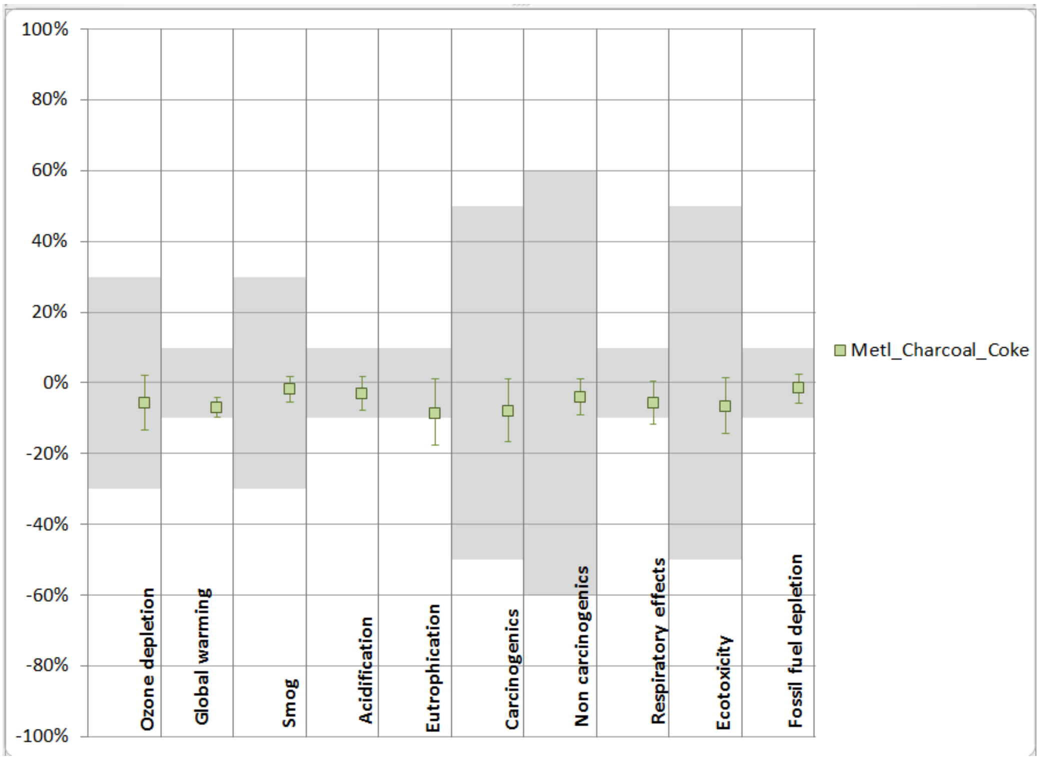


Figure D.6 Use in Metallurgy Pathway Scenarios Systems Differences Normalized with Maximum Absolute Value of Scenario System Impact Score [Geographic marker represents base case scenarios, while error bars represent scenario parameter and efficiency uncertainty**.** Grey boxes represent impact category uncertainty.]

Table D.6 Use in Metallurgy Pathway Scenarios Impact Score Result Considering Parameter and Efficiency Uncertainty

Pathway	**Biomass system**	**Alternative system**	**Ozone depletion***	**Global warming**	**Smog**	**Acidification**	**Eutrophication**	**Carcinogens**	**Non-carcinogens****	**Respiratory effects**	**Ecotoxicity**	**Fossil fuel depletion**	**Number of Impact Categories with Impact Score**		
													Lower than	**Greater than**	**Neutral**
Use in Metallurgy	**Charcoal**	**Coke**											0	0	10

* Uncertainty relative to ozone depletion is considered too great to allow conclusions to be made.
** Scenario results compiled without potential impact of zinc emitted to agricultural soil.

Legend

Impact Score Result	Impact scores less than zero (green)	Impact scores greater than zero (yellow)	Environmentally Neutral (grey)

D.1.5. Use as Horticultural Growing Media Pathway

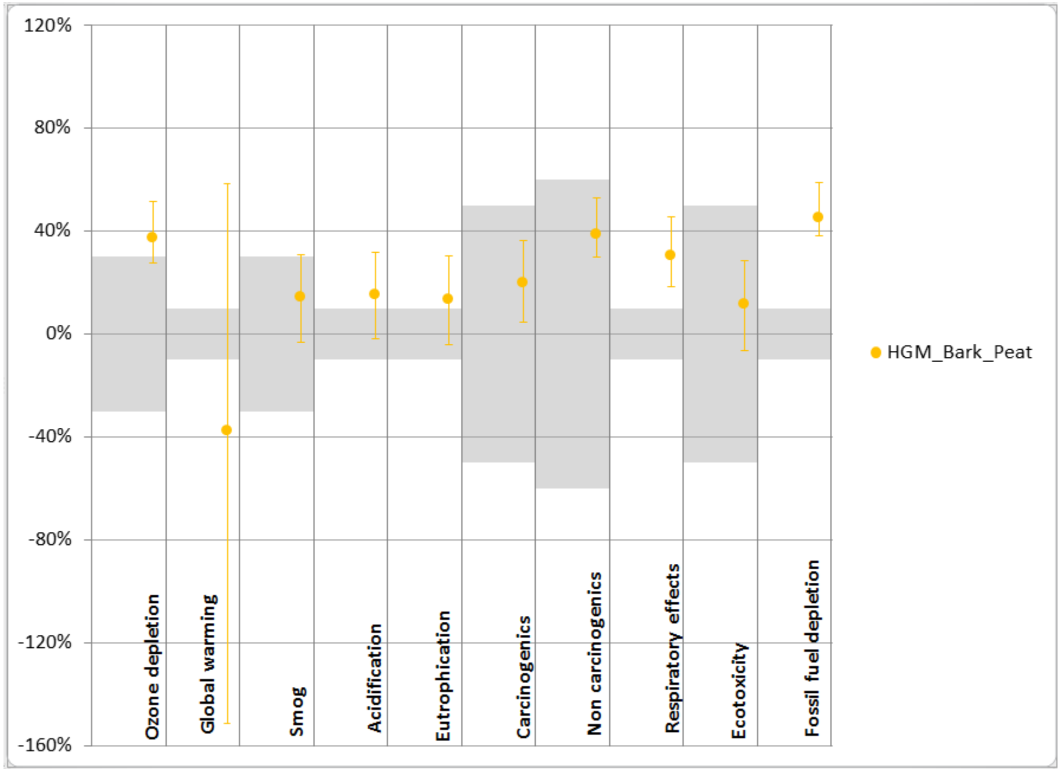


Figure D.7 **Use as Horticultural Growing Media Pathway Scenarios Systems Differences Normalized with Maximum Absolute Value of Scenario System Impact Score [Geographic** marker represents base case scenarios, while error bars represent scenario parameter and efficiency uncertainty**.** Grey boxes represent impact category uncertainty.]

Table D.7 Use as Horticultural Growing Media Pathway Scenarios Impact Score Result Considering Parameter and Efficiency Uncertainty

Pathway	Biomass system	Alternative system	Ozone depletion*	Global warming	Smog	Acidification	Eutrophication	Carcinogens	Non-carcinogens**	Respiratory effects	Ecotoxicity	Fossil fuel depletion	Number of Impact Categories with Impact Score		
													Lower than zero	Greater than zero	Neutral
Use as Horticultural Growing Media	Bark	Peat											0	2	8

* Uncertainty relative to ozone depletion is considered too great to allow conclusions to be made.
** Scenario results compiled without potential impact of zinc emitted to agricultural soil.

Legend

Impact Score Result	Impact scores less than zero	Impact scores greater than zero	Environmentally Neutral