REPORT

Greenhouse Gas Emissions Assessment
The Substitution of Fossil Fuels with Woody Biomass in the Northwest Territories

Prepared for Government of the Northwest Territories

Attention: Walters Tubua
Climate Change Specialist
Environment Division
Dept. of Environment and Natural Resources

By Anastassia Manuilova and Mark Johnston
Saskatchewan Research Council
Environment and Forestry

SRC Publication No. 13069-1C11

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EXECUTIVE SUMMARY

The use of bioenergy is expanding rapidly around the world due to rising oil prices and the introduction of climate change policies. Previous research on bioenergy production from perennial woody biomass has shown promise both in terms of net greenhouse gas (GHG) reductions and other environmental and socio-economic benefits, especially if woody biomass residues are utilized as feedstock and efficient energy conversion technologies such as combustion for heat or co-generation of heat and power are employed.

While bioenergy is often assumed to be carbon-neutral, the net reduction of GHG and other emissions and wastes is often significantly less than 100%. CO_2 of fossil origin as well as other air emissions may be emitted due to the use of transportation or biomass pre-treatment options. The amount of emissions and wastes released depends on various factors, such as efficiency of the equipment, pre-treatment methods applied, transportation distances, etc. Thus, an evaluation methodology based on life cycle thinking ("cradle-to-grave" approach) is considered the best approach to estimate the environmental impacts associated with existing and future deployment of biomass combustion projects.

Three scenarios were analyzed in this study:

Scenario 1: Forest bioenergy for home and district heating – production of thermal energy from locally-sourced woody biomass (firewood and woodchips) in the NWT.

Scenario 2: Pellet bioenergy for home and district heating – production of thermal energy from imported and locally produced wood pellets.

Scenario 3: Heating oil energy for home and district heating – production of thermal energy from imported heating oil.

Wood chips produced from locally sourced woody biomass showed the lowest GHG emissions over the full life cycle, followed by locally produced wood pellets and wood pellets imported from Alberta. Wood pellets imported from BC and locally produced firewood combusted in residential conventional technology stove have the highest GHG emissions after heating oil. Based on the life cycle results, we recommend local wood

chips and pellets production as one of the strategies for reduction of fossil GHG emissions.

We also conclude that harvesting biomass for bioenergy in the NWT is sustainable given the relatively low demand, which represents a small fraction of the territories' sustainable timber yield. In addition, sustainability will be achieved if best practices are followed regarding the values outlined in the CCFM Criteria: protection of biodiversity and water and soil quality; maintenance of forest health, productivity and carbon storage; and equitable distribution of benefits to local communities. However, there may be site-specific sustainability questions related to, for example, intensive willow harvesting in riparian areas and impacts of harvesting on caribou habitat.

Future research should include a full Life Cycle Assessment of bioenergy production, and a forest landscape carbon balance analysis using the Carbon Budget Model of the Canadian Forest Sector.

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ABBREVIATIONS

AEA	Arctic Energy Alliance
BAU	Business-as-usual
BC	Black Carbon
C	Carbon
C&I	Criteria and Indicators
CCAR	California Climate Action Registry
CCFM	Canadian Council of Forest Ministers
CDM	Clean Development Mechanism
CH_4	Methane
CO_2	Carbon Dioxide
CO_2e	Carbon dioxide equivalent
GHG	Greenhouse Gas
GNWT	The Government of the Northwest Territories
GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MCCS	Manomet Center for Conservation Sciences
N_2O	Nitrous Oxide
NFD	National Forestry Database
NWT	Northwest Territories
OC	Organic Carbon
PAS	Publicly Available Specification
U.S. DOE/EIA	United States Department of Energy/Energy Information Administration
U.S. EPA	United States Environmental Protection Agency
UNFCCC	United Nations Framework Convention on Climate Change
VCS	The Voluntary Carbon Standard
WBCSD	World Business Council for Sustainable Development
WRI	World Resource Institute

Fuels heating values

Wood pellets	19,700 MJ per tonne
Heating oil	38.4 MJ per litre
Firewood	16,400 MJ per tonne (18% moisture content)
Wood chips	15,200 MJ per tonne (20% moisture content)

1. INTRODUCTION

The use of bioenergy is expanding rapidly around the world due to rising oil prices and the introduction of climate change policies. Previous research on bioenergy production from perennial woody biomass has shown promise both in terms of net greenhouse gas (GHG) reductions and other environmental and socio-economic benefits, especially if woody biomass residues are utilized as feedstock and efficient energy conversion technologies such as combustion for heat or co-generation of heat and power are employed.

While bioenergy is often assumed to be carbon-neutral, the net reduction of GHG and other emissions and wastes is often significantly less than 100%. CO_2 of fossil origin as well as other air emissions may be emitted due to the use of transportation or biomass pre-treatment options. The amount of emissions and wastes released depends on various factors, such as efficiency of the equipment, pre-treatment methods applied, transportation distances, etc. Thus, an evaluation methodology based on life cycle thinking ("cradle-to-grave" approach) is considered the best approach to estimate the environmental impacts associated with existing and future deployment of biomass combustion projects.

The recent study of using forest wood for energy in Massachusetts, US (MCCS, 2010) showed that the situation with carbon-neutrality of bioenergy is even more complex. Using wood to produce energy results in an initial "carbon debt", because burning wood releases more CO_2 into the atmosphere per unit of energy than fossil fuels. However, when forests grow back and recapture CO_2 from the atmosphere, the "carbon dividend" is realized. The length of time it takes to get carbon dividends depends on the type of biomass used to produce energy, the fossil fuel that biomass replaces, the bioenergy combustion technology and the forest management practices. For example, using forest biomass in district heating in Massachusetts can provide carbon dividends within 10 to 20 years.

The Government of the Northwest Territories (NWT) is committed to increasing use of biomass energy to replace fossil fuels as outlined in the 2010 NWT Biomass Energy Strategy (NWT, 2010). The locally-sourced wood and imported wood pellets are increasingly being used for generation of thermal energy in home and district heating applications in the NWT. Biomass is a renewable source of energy if managed in the sustainable manner. However, the greenhouse gas implications of using biomass in home and district heating applications in the NWT should be studied from the life cycle perspective. Carbon footprints of fossil fuel energy need to be compared to carbon footprints of woody biomass energy to provide information on which energy planning decisions in the NWT will be based.

The goal of this study is to conduct a thorough comparison of the overall greenhouse gas emissions associated with the generation of thermal energy from different sources in the Northwest Territories.

The following questions are answered by the study:

1. What are the atmospheric greenhouse gas implications of shifting energy production in the Northwest Territories from heating oil to locally grown woody biomass or imported wood pellets?
2. What are the environmental benefits and drawbacks of different biomass combustion applications (such as home heating and district heating)?
3. What is the NWT forest carbon dynamics?
4. What monitoring and measurement programs need to be in place to ensure sustainability of local forests?

The study follows the LCA methodology defined in the ISO 14000 standards (ISO 14040 and 14044 standards, 2006) for the estimation of greenhouse gas emissions. The study also follows the PAS 2050 – Specification for GHG Emissions of Goods and Services (PAS 2050, 2008) greenhouse gas accounting protocol and takes into consideration the Greenhouse Gas Protocol Product / Supply Chain Initiative of World Resource Institute (WRI) and World Business Council for Sustainable Development (WBCSD) (WRI/WBCSD, 2010).

The report consists of the following parts:

Chapter 2 – Goal and scope definition;

Chapter 3 – Methodology;

Chapter 4 - Forest sustainability assessment;

Chapter 5 – Forest carbon modeling;

Chapter 6 – Greenhouse gas emissions assessment results;

Chapter 7 - Conclusions and recommendations.

2. STUDY GOAL AND SCOPE

This section of the report provides a general description of the system under study, definition of the system boundaries and functional unit. Data quality, assumptions and GHG assessment methodology including black carbon analysis are also discussed.

2.1 Objectives and intended application

The project has the following objectives:

- Using the "cradle-to-grave" approach, develop greenhouse gas emission inventories associated with thermal energy generation from heating oil, imported and locally grown wood pellets and locally-sourced forest wood in the Northwest Territories;
- Provide a comparative study results with recommendations on how to minimize the GHG emissions from woody biomass energy sources and fossil fuels in the Northwest Territories;
- Provide information on the Northwest Territories forest carbon dynamics and sustainability;
- Identify the mechanisms that the forest manager can use to present sustainability of forest use within the scope of internationally recognized standards.

The assessment of greenhouse gas emissions from three systems is conducted using the "cradle-to-grave" approach. The following scenarios are studied:

Scenario 1: Forest bioenergy for home and district heating– production of thermal energy from locally-sourced woody biomass in the NWT;

Scenario 2: Pellet bioenergy for home and district heating – production of thermal energy from imported and locally produced wood pellets;

Scenario 3: Heating oil energy for home and district heating – production of thermal energy from imported heating oil.

The study is intended to provide results specific to the Northwest Territories wood sources, biomass combustion technologies used for home and district heating, and the fossil fuel that forest biomass replaces (i.e. heating oil).

The results of this study are intended for the internal use by the Government of the NWT to improve understanding of the GHG implications associated with replacement of fossil fuels with biomass.

2.2 General description of the system

This section provides a general description of the system under study.

Scenario 1: Forest bioenergy

Biomass in the NWT is available from the following sources (NWT Biomass Energy Strategy, 2010; Lakusta, 2011):

- *Harvest of green wood from the merchantable forest.* Merchantable volume data are available from the NWT Forest Inventory and can be converted to biomass using the volume to biomass conversion factors from Boudewyn et al (2007).
- *Black wood from recent burns.* The National Forestry Database (NFD, 2011) provides estimates of area burned for NWT. It can be combined with volume estimates from the forest inventory and the conversion factors from Boudewyn et al. (2007) to determine how much biomass this represents.
- *Harvest of 20-40 year old willows from river flats.* This is a localized biomass resource that has not been quantified but may provide opportunities for a few communities.
- *Decked wood salvaged from incidental land uses, e.g. oil and gas activity, other land uses.* Note that in many cases there is no regeneration requirement for these areas and the carbon debt generated by using this material will remain negative.
- *Use of waste wood fibre from other processes, e.g. sawmill residues, wood in landfills.*

In this scenario two options are reviewed:

- *1A: Firewood bioenergy*. Green wood from the merchantable forest is harvested; split firewood is prepared in the forest and transported by truck to the customers. The current estimated market for firewood is approximately 15,000 m^3/year or 7,500 t/year[1] (Lakusta, 2011).
- *1B: Wood chips bioenergy.* In this option it is assumed that woody biomass from the sources described above is chipped on site by a mobile wood chipper. Wood chips are then transported by truck to the customers. No wood chips are used for heating purposes in the NWT now. However, it is expected that local wood chips will be used as a fuel in a number of proposed district heating systems.

[1] Average seasoned firewood density is assumed to be 500 kg/m^3.

Life cycle stages included in this scenario are woody biomass harvesting or collection, firewood preparation/ biomass size reduction by a mobile wood chipper, firewood/ wood chips transportation to a bioenergy facility, combustion and waste management (Figure 2.1).

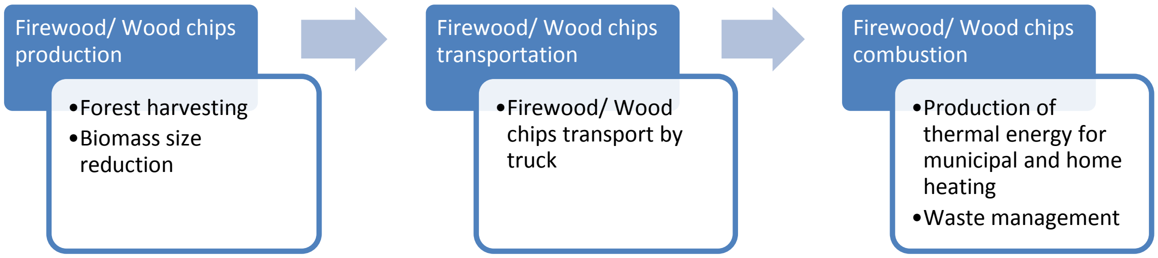

Figure 2.1 Schematic diagram of activities within the life cycle of generation of thermal energy from locally-sourced woody biomass.

Scenario 2: Pellet bioenergy

Wood pellets are usually made of residual materials such as sawmill residues (sawdust, planer shavings) and diseased and insect-killed trees and forest logging residues.

2A: Current scenario

Currently, the NWT wood pellets consumption is estimated at 12,000 – 13,000 tonnes per year[2] (La Crete, 2011; Pinnacle, 2011; Premium, 2011). Wood pellets are imported from the LaCrete pellet mill in Northern Alberta and from Pinnacle Pellet's mill and Premium Pellet mill in central BC (Table 2.1). Pellets from LaCrete are imported primarily in bulk form by truck to service institutional customers. The majority of Pinnacle and Premium pellets come in a bag form for home heating market. Residential houses are not designed for wood pellets fuel and homeowners have to use pellets in bagged form (FPInnovations, 2009).

[2] Data for 2010 received directly from the wood pellets suppliers.

Table 2.1 Wood pellets supply to the NWT.

Material	Location	Quantity, tpy (2010)	Mode of transport	Type of packaging	Distance, km	Source
Wood pellets	Le Crete pellet mill, Alberta	12,000	Super B-train trucks (payload 42 t, 8-axle)	90% Bulk 10% Bagged	824	La Crete, 2011
	Pinnacle and Premium pellet mills, BC	600 45	Freight trailer (payload 30 t and 45 t)	100% Bagged	1,800	Pinnacle, 2011 Premium, 2011

Note: Retail shops, such as Wal-Mart and Canadian Tire carry bagged pellets for residential use. These pellets come mainly from Pinnacle Pellet and Premium Pellet, BC. However, some originate from AB, MB and even US (Arctic, 2010).

The pellet bioenergy scenario life cycle activities include biomass harvesting, biomass transportation to a sawmill, sawmill operations, transportation to a pellet facility, pelletization, transportation of pellets to a combustion facility, combustion of pellets, and waste management (plastic and wood ash) (Figure 2.2).

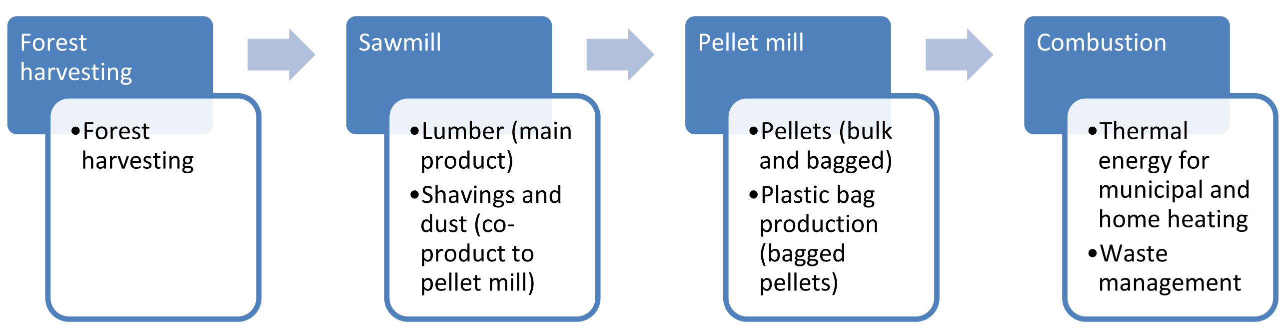

Figure 2.2 Schematic diagram of activities within the life cycle of generation of thermal energy from imported wood pellets.

It should be noted that the main output from sawmill is lumber; co-products are sawdust and shavings, bark and other wood residues. Shavings and sawdust are transported to the pellet mill for pellets production. In this study, allocation for products from sawmill (i.e. allocation of environmental impacts associated with main product and co-products production) is based on green mass.

Wood pellets at LaCrete (spruce) and Pinnacle mills (spruce, pine) are produced from clean, dry wood-waste fiber from neighbouring sawmills. A schematic of wood pelletization process is shown in Figure 2.3.

Figure 2.3 Schematic diagram of pelletization process.

The manufacture of wood pellet is a simple process. The raw material arrives to a pellet mill in a variety of partially processed states (i.e. chips, shavings, sawdust). The raw material is then dried and ground into a uniform size. It is subsequently compressed and formed into pellets. Pellets are then cooled to allow the natural bonding agents (resins in the wood) to set. Once the pellets have hardened, any loose material is screened out and fed back into the pelletization process. Pellets are then ready to be distributed to the market. Pellets are supplied to customers in bulk or bagged form (pellets are typically packaged in 40 lbs (18 kg) bags).

2B: Future scenario

In this scenario it is assumed that wood pellets will be produced from the locally sourced wood in the NWT in the near future. The local green wood will be harvested for this purpose. It is assumed that the green wood harvested for this purpose will go towards wood pellets production.

Scenario 3: Heating oil energy

Current thermal energy source in the NWT is #2 heating oil. This scenario is a business-as-usual scenario that is used to estimate GHG emissions reductions due to the use of bioenergy instead of fossil fuel. The heating oil energy scenario life cycle activities include crude oil extraction, crude oil transportation to the refinery, conversion into heating oil, heating oil transportation to a combustion facility, and combustion (Figure 2.4).

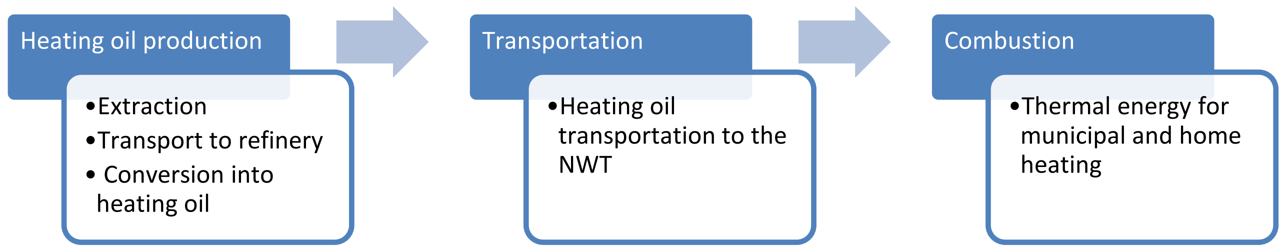

Figure 2.4 Schematic diagram of activities within the life cycle of generation of thermal energy from heating oil.

More information on scenarios described above can be found in Appendix B: Life Cycle Inventory Supporting Information.

2.3 Systems function and functional unit

The main function of the system under study is to produce thermal energy for home and district heating in the NWT. In order to compare carbon footprints of three scenarios a common functional unit should be selected – a unit that provides a reference to which the input and output data are normalized. Functional unit for this study is **1 MJ of thermal energy**[3] produced from the NWT locally-sources wood, imported pellets or heating oil.

2.4 System boundaries

The system boundary defines the unit processes to be included in the system. Temporal, geographical and technological boundaries are also defined here.

All life cycle activities from resource extraction (e.g., crude oil, wood) and production (e.g., pellets, wood chips, firewood, #2 heating oil production) through generation of thermal energy are included, as well as all transportation stages. Material and energy inputs needed for equipment manufacture, facility construction, and labour are not included in the study, except for the processes taken from Ecoinvent database, such as transportation and waste management (Ecoinvent Centre, 2009). Exclusion of these activities is common practice where it is expected that these processes have far smaller environmental implications than the operations of the facilities (Baumann and Tillman, 2004).

[3] Net thermal energy

Temporal and geographical boundaries

The thermal energy generation from pellets and heating oil pathways are relevant to the time frame 2009 to 2010, while the pathway utilizing locally-sourced biomass is relevant post-2012 but could be implemented prior to that time.

Most of the processes included in the system boundaries occur in the Northwest Territories, Alberta and British Columbia. However, some unit processes may occur in other Canadian provinces and the US.

Technological boundaries

There are several types of boiler technologies that are currently in use in the NWT. This study evaluates only the most frequently used technologies/configurations for generation of thermal energy.

2.5 Life Cycle Inventory data quality, sources and assumptions

Data quality requirements specify the characteristics of the data needed for the study. Description of data quality, sources and assumptions is important to understand the reliability of the study results and properly interpret the outcome of the study (ISO, 2006).

Data sources and quality

Several different methods of data collection were available, such as questionnaires, personal interaction and both peer-reviewed and un-reviewed literature. Modelling a life cycle is a complex task involving several assumptions that are at the discretion of the analyst. To ensure proper LCA technique, the analyst should clearly document all employed data, sources, assumptions and supporting literature.

The majority of the data used in this project is specific to the Northwest Territories, Alberta and British Columbia in terms of process contribution. In the absence of the NWT data, information was drawn from western Canadian sources, followed by Canadian sources, North American sources and, finally, from pre-existing life cycle databases; most notably Ecoinvent v2.1. The Ecoinvent library is a European database considered to be the most comprehensive and up-to-date inventory currently available (Ecoinvent Centre, 2009). Canadian data was directly substituted into the Ecoinvent library where possible, and the default European data remained when Canadian data was unavailable.

Data used in this study is no older than 5 years from the onset of the analysis (2010). Sources of data include, but are not limited to: Intergovernmental Panel on Climate Change (IPCC), Environment Canada's National Greenhouse Gas Inventory (Environment Canada, 2008), GHGenius, and scientific publications. All data adheres to the specifications listed in the 2006 ISO 14040 and 14044 standards.

Data sources for main processes within system boundaries are presented in Table 2.2. More information on life cycle inventory data, assumptions and data sources can be found in Appendix B: Life Cycle Inventory Supporting Information.

Table 2.2 Data sources and assumptions for processes in the system boundaries.

Process	Assumptions	Source
Wood harvesting (forest road construction, forest harvesting and wood delivery to the forest product conversion facility)	Diesel consumption: 7.1 L/m^3 or 273 MJ/m^3 of wood	Sambo, 2002
Firewood processing (splitting)	Diesel consumption: 6.6 L/tonne firewood	Paul et al., 2003
Transport of firewood to customers	75 km; Truck 16 t payload	Pa, 2010 Swiss Centre for Life Cycle Inventories et al., 2008
Size reduction by mobile wood chipper	Diesel consumption: 1.7 L/tonne of biomass	Jones et al., 2010
Wood chips drying	10.3 kWh/m^3 of wood chips	Mikko, 2005
Transport of wood chips to customers	75 km; Truck 22.8 t payload	Swiss Centre for Life Cycle Inventories et al., 2008
Sawmill operations	Details provided in Appendix B, Table B.1	Nyboer and Jaccard, 2010 Pa, 2010
Pellet plant operations	Details provided in Appendix B, Table B.1	Pa, 2010
Plastic bag production	Bag weight: 63.5 g Polyethelene	Bulldog, 2011 Swiss Centre for Life Cycle Inventories et

Process	Assumptions	Source
		al., 2008
Transport of pellets from AB	824 km; Super B-train trucks (payload 42 t, 8-axle)	La Crete, 2011 Swiss Centre for Life Cycle Inventories et al., 2008
Transport of pellets from BC	1800 km, Freight trailer (payload 30 t and 45 t)	Pinnacle, 2011 Premium, 2011 Swiss Centre for Life Cycle Inventories et al., 2008
Locally produced wood pellets	Details provided in Appendix B, Table B.2	Zhang et al., 2010
Transport of locally produced pellets	150 km; Truck 22.8 t payload	Swiss Centre for Life Cycle Inventories et al., 2008
Heating oil upstream and combustion processes	Details provided in Appendix B, Table B.4	GHGenius, 2010
Firewood combustion	Details provided in Appendix B, Table B.5	SGA, 2000
Wood chips combustion	Details provided in Appendix B, Table B.6	Swiss Centre for Life Cycle Inventories et al., 2008
Wood pellets combustion	Details provided in Appendix B, Table B.7	Johansson et al., 2004 Swiss Centre for Life Cycle Inventories et al., 2008
Plastic bag waste management	Municipal landfill	Swiss Centre for Life Cycle Inventories et al., 2008
Wood ash waste management from institutional boilers	Municipal landfill	Swiss Centre for Life Cycle Inventories et al., 2008
NWT electricity production mix	Electricity mix: Diesel (51.27%), Hydro (32.16%), Natural gas (16.56%)	MKJA, 2011

2.6 Greenhouse gas assessment methodology

Emissions accounted for in this study are fossil and biogenic carbon dioxide (CO_2), fossil methane and biogenic methane (CH_4), nitrous oxide (N_2O) and black and organic carbon.

The goal of this study is to quantify the GHG emissions (e.g. Global Warming impact category) from three scenarios described above. The results are presented as carbon dioxide equivalents (CO_2-e). An attempt is made to include the black carbon (a product of incomplete combustion of heavy petroleum products and other sources such as biomass, etc.) emissions to the analysis.

The global warming effects were analyzed across 100 year time horizons with the 1996 and 2007 IPCC GWP factors. Table 2.3 shows the difference between GWP factors across time periods for carbon dioxide, methane and nitrous oxide.

Table 2.3 1996 and 2007 Intergovernmental Panel on Climate Change global warming potential factors across 100 year time horizon for carbon dioxide, methane and nitrous oxide.

	2007 Global warming potential factors	**1996 Global warming potential factors**
GHG	**100 year**	**100 year**
Carbon dioxide	1	1
Methane	25	21
Nitrous oxide	298	310

Source: IPCC, 1996 and IPCC, 2007.

2.7 Contribution and sensitivity analyses

In the final stage of the analysis, the results of the impact assessment phase are interpreted. Two major analyses are conducted in determining the validity of the results:

- Contribution analysis - a measure of the effect each process has on the complete environmental profile of the life cycle. The processes that make up the largest portions of the total impact assessment are then subjected to rigorous data quality checks and sensitivity analyses;

- Sensitivity analysis - determines the effect of changing parameters and assumptions on the final results. It is essential to determine whether the final results are resistant to small changes through the life cycle. If results fluctuate greatly during a sensitivity analysis, results are not reliable and the life cycle should be reassessed.

3. METHODOLOGY

3.1 Greenhouse gas emissions assessment or carbon footprint

Woody biomass is considered a renewable fuel compared to fossil fuels such as heating oil. Wood fuel is also considered to be carbon neutral if it originates from sustainably managed forests. However, as mentioned earlier, bioenergy production from woody biomass needs to be studied from the life cycle perspective to take into account carbon emissions from upstream and downstream life cycle stages (e.g. wood processing and transportation).

Life cycle assessment (LCA) methodology to estimate greenhouse gas emissions is used in this study. LCA is a method for examining the environmental effects of a product or process across its lifespan. It is a "cradle-to-grave" analysis in which complex systems are broken down into elementary flows. The flows are then grouped and categorized based on the effects they have on the environment. LCA studies must adhere to the principles set by the International Organization for Standardization (ISO); specifically ISO 14040 (ISO, 2006a) and ISO 14044 (ISO, 2006b). ISO regulations ensure that the limitations of LCA are both recognized and minimized. Furthermore, the standards certify that LCA results are presented in a concise and transparent manner.

Benefits include that LCA:

- Assesses not only the product or process itself, but also the upstream and downstream effects allowing for an investigation of the full life cycle. This life cycle approach also avoids shifting of burdens upstream or downstream that may be ignored in a more traditional analysis;
- Must adhere to the principles set by the International Organization for Standardization (ISO); specifically ISO 14040 and ISO 14044. ISO regulations ensure that the limitations of LCA are both recognized and minimized. Furthermore, the standards certify that LCA results are presented in a concise and transparent manner; and
- Assist with decision-making. For a company, LCA can facilitate in identifying low-hanging fruit to improve efficiencies, but may also help a company in demonstrating the "greenness" of their product over an alternative. For governments, LCA can assist in policy development.

SimaPro computer modeling software was used to conduct LCA. SimaPro is currently the most widely used and sophisticated LCA computer modelling system available. The software, which was developed in the Netherlands in 1990, includes thousands of processes and substances across several inventories, as well as methods for impact assessment.

In this study we quantify the GHG emissions (CO_2, CH_4 and N_2O) associated with local wood feedstock production, transportation, and use for home heating and district heating. We also compare GHG emissions associated with the substitution of local woody biomass feedstock or imported wood pellets for heating oil.

3.2 Greenhouse gas accounting protocol

There are a wide variety of GHG programs that include a role for forests and thus provide some guidance on forest GHG accounting. For example:

- National GHG Inventories under the United Nations Framework Convention on Climate Change (UNFCCC)
- Guidelines for National GHG Inventories by the Intergovernmental Panel on Climate Change (IPCC)
- Clean Development Mechanism (CDM) forest projects
- The Carbon Disclosure Project (CDP)
- The Voluntary Carbon Standard (VCS)
- U.S. EPA Climate Leaders
- U.S. DOE/EIA 1605b Voluntary GHG Reporting Program
- California Climate Action Registry (CCAR).

Major greenhouse gas protocols presume that biomass is inherently carbon neutral and carbon dioxide emitted in biomass combustion is automatically excluded from carbon footprints. Guidance from the World Business Council for Sustainable Development and the World Resource Institute (WRI at el., 2006) recognizes that there is problem with carbon neutrality of biomass. However, it still excludes biomass carbon-combustion emissions from its footprint definitions. Current guidance and practice are problematic since they defy common sense, contravene UNFCCC rules and ISO standards and ignore a large body of research. Thus, in this study will follow the PAS 2050 – Specification for GHG Emissions of Goods and Services greenhouse gas accounting protocol for estimation of emissions from all life cycle stages other than biomass combustion. Biomass combustion carbon footprint is evaluated using “carbon debt” - “carbon dividend” approached developed by the Massachusetts Department of Energy and Resources and Manomet Center for Conservation Sciences (MCCS, 2010). This approach takes into account an initial “carbon debt” when wood is used to produce energy. However, when forests grow back and recapture CO_2 from the atmosphere, the “carbon dividend” is realized. This study estimates the length of time it takes to get carbon dividends based on the type of biomass used to produce energy.

3.3 Sustainable Forest Management and Biomass Production

In addition to the impacts of bioenergy production, the sustainability of the biomass feedstock should be considered. This includes both the production or collection of biomass and the indirect effects such as land use change, impacts on biodiversity and impacts on soil and water quality. A range of biomass sources could be considered, including pellets, harvesting native forests and using existing sources of residue (e.g. from forest product harvesting or right-of-way clearing). This report provides guidance on the key questions and considerations required to assess the long-term sustainability of these feedstocks. This analysis is integrated with the bioenergy production LCA to provide a system-wide perspective on bioenergy sustainability. The Canadian Council of Forest Ministers Criteria and Indicators of Sustainable Forest Management (Canadian Council of Forest Ministers, 2003) is used to structure this component of the project.

3.4 Black Carbon

The incomplete combustion of hydrocarbons results in soot. Soot is mainly composed of black carbon and organic carbon, with smaller proportions of sulphur and other chemicals (Bachmann, 2009). There are instances where soot and black carbon have been interchangeable used to imply black carbon (Ramaswamy et al, 2001).

The major source of black carbon emissions and their percentage contributions are open biomass burning (including wild fires and intentional burning in agriculture) – 42%, coal and oil burned in industrial and mobile use - 40%, and biofuels for residential use – 18% (Bachmann, 2009).

Black carbon is rarely emitted alone, but with a mixture of other constituents. Its proportion with regards to the other elements influences soot’s global warming potentials due to the cooling potential of some other constituents. Hence, emissions from diesel combustion, which appear black because of the higher concentration of black carbon have a higher global warming potential than soot from open biomass burning which usually appears blue, brown or gray because of higher organic carbon particles content (Bachmann, 2009). The major black carbon sources and their respective warming potentials are presented in Figure 3.1.

It is generally accepted that black carbon to organic carbon ratio is more in fossil fuels compared to biomass fuels like wood which have a higher organic carbon to black carbon ratio (Bahner et al, 2007). Organic carbon can lead to reductions in temperature. Since it has been demonstrated that biomass emissions contain a higher organic carbon content than black carbon, there may actually be a net benefit to global warming by the use of biomass as fuel, particularly if improvements are made to even lower the black carbon emitted from their use.

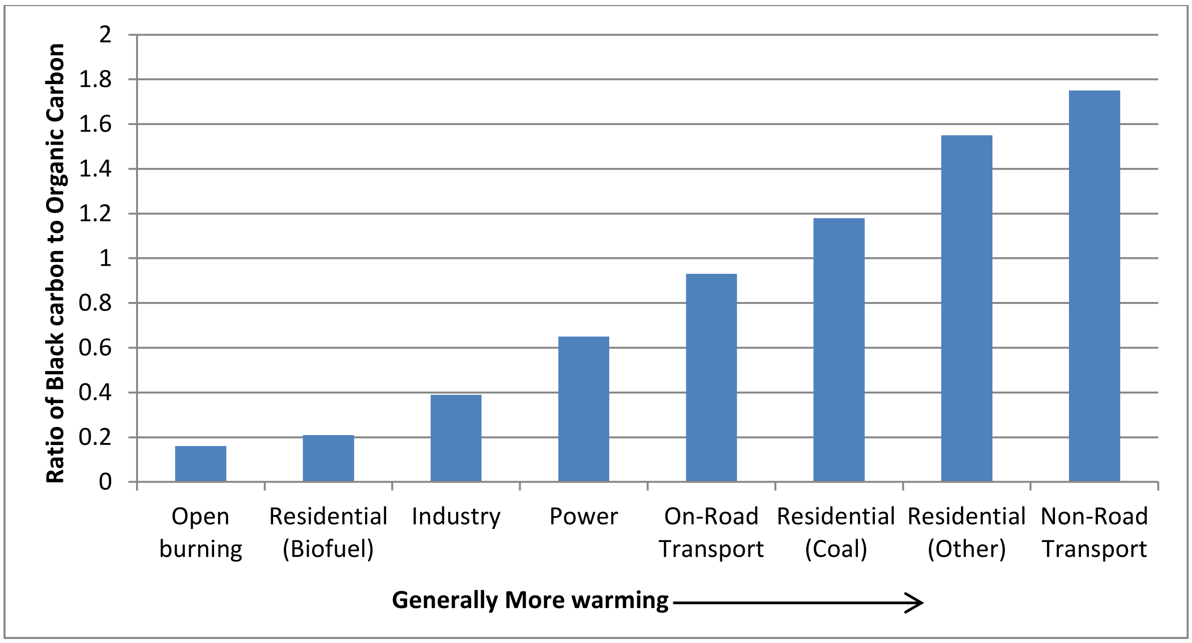

Figure 3.1 Black carbon sources and warming potentials (Bachmann, 2009).

It is difficult to say what the percentage of un-burnt carbon comes from biomass combustion. One major factor being that the efficiency of the combusting system or technology/configuration plays a vital part in the amount of soot released.

Nussbaumer et al (2008) have indicated that there is a high mass concentration of particle emissions in automatic wood boilers for natural wood chips (100 mg/m^3 at 13 vol.%) and even significantly higher for fuels such as bark. A well designed and operated automatic wood combustion system will yield mainly inorganic matter like salts, while those from wood stoves in poor operating conditions will largely result in soot and organic substances.

Even though the IPCC (1996) does recommend a value of 1% for unoxidized carbon for fossil fuels, the same may not necessarily apply to biomass. More so, it highlights that cases abound where there are variations even up to 10%. However, with appropriate technology, it is possible to curtail black carbon emissions substantially (Hill, 2009; Bond and Sun, 2005).

The black and organic carbon emissions from heavy fuel oil combustion and residential wood burning are presented in Table 3.1. These numbers are applied in this study.

Table 3.1 Black and organic carbon emissions from controlled combustion of heavy fuel oil and wood in residential applications.

Type of fuel	BC (g/kg)	OC (g/kg)	BC %	OC %
Heavy fuel oil	0.07	0.015	0.007	0.0015
Biofuel: Wood	0.3 - 1.4	1.7 -7.8	0.03 – 0.14	0.17 – 0.78

BC – black carbon; OC – organic carbon.

Source: Adapted from Bond et al. 2003.

The significance of soot (including black carbon) in influencing climate change has only recently being given much attention. Some authors hold the position that black carbon is second to CO_2 in terms of contribution to global warming (Ramanathan & Carmichael, 2008; Raffensperger, 2008).

Unlike other greenhouse gases that actually allow sunlight to pass through the atmosphere to the earth but only absorb the radiated component of heat energy and reemitting it in the air, soot particles absorb sunlight and warm the atmosphere by radiating the heat energy by conduction and radiation, making it a very potent warming agent (Bachmann, 2009).

One important distinction between the climate change potentials of soot/black carbon is that unlike GHGs whose emissions can have effects for the next hundred years, those from black carbon rarely last more than a few weeks (Moore, 2009). Another difference is that the black carbon effect/influence is much more local/regional unlike the global effect of traditional GHGs (Bahner et al, 2007).

A view held by some experts is that black carbon reduces the reflective coefficient of ice, resulting in an accelerated melting of the ice (Hansen & Nazarenko, 2004; Raffensperger, 2008). This school of thought also believes that up to 25% percent of observed global warming, particularly regarding melting ice is attributed to soot (Hansen & Nazarenko, 2004).

It is reckoned that on a mass basis, an ounce of black carbon particle can absorb more than a million times more radiant energy than an ounce of CO_2, however, because the concentrations of CO_2 are usually higher as well as possessing a lifetime more than 2500 times that of black carbon, CO_2 is still considered a greater threat (Jacobson, 2010)

Bond and Sun (2005) highlighted much uncertainty in estimating GWP. They however proffer that in terms of CO_2 equivalents, $GWP_{BC,100}$ ranges between 210 to 1500 and $GWP_{BC,20}$ ranges between 690 to 4700. The central value for $GWP_{BC,100}$ being 680. Findings from other researchers, presented by Hill (2009) are included in Table 3.2 as GWP for 20 and 100 years for both black carbon and organic carbon (the negative signs indicating a cooling effect).

Table 3.2 Black and organic carbon global warming potentials.

Author	GWP20		GWP100	
	BC CO_2-e	OC CO_2-e	BC CO_2-e	OC CO_2-e
	Global GWP			
Hansen et al, 2007	2000		500	
BC: Bond and Sun, 2005 OC: Bond et al, 2004	2200	-250	680	-75
Jacobson, 2007 (lower bound estimate)	4480		1500	
Reddy and Boucher, 2007			480	
Schulz et al, 2006	1600	-240	460	-69
	North America GWP			
Reddy and Boucher, 2007	1500		430	
Koch et al, 2007	1900	-150	550	-42
Naik et al, 2007	3200	-310	920	-88

BC – black carbon; OC – organic carbon. Negative signs indicate a cooling effect.

Source: Adapted from Hill, 2009

In this study, Koch et al, 2007 GWP factors are applied ($GWP_{BC,100}$ = 550 and $GWP_{OC,100}$ = -42). A sensitivity analysis is conducted and a range of results based on other GWP factors is given.

4. FOREST SUSTAINABILITY

4.1 Introduction

In addition to reductions in GHGs, other environmental considerations also play a role in a decision regarding the use of biomass for energy production. In the case of biomass harvested from existing forest stands, long-term sustainability is a key consideration. Forests provide multiple values for society, including forest products, wildlife habitat and contributing to clean water and productive soils. These values must be maintained while using forest biomass for energy production. In this project we use the Criteria and Indicators of Sustainable Forest Management (C&I) developed by the Canadian Council of Forest Ministers (CCFM) to characterize the values associated with forests in NWT and to assess needs for forest sustainability as plans for harvesting woody biomass for energy production are developed. The purpose of this report is to summarize the C&I and to use them as a framework for determining how harvesting of woody biomass for energy production can be done in a way that ensures long-term sustainability of forest values.

4.2 Criteria and indicators of sustainable forest management

In the early 1990s an initiative was launched among temperate and boreal countries to develop and implement internationally agreed criteria and indicators for sustainable forest management. The Montréal Process began in June 1994, in Geneva, with the first meeting of the Working Group on Criteria and Indicators for the Conservation and Sustainable Management of Temperate and Boreal Forests. The Canadian Council of Forest Ministers released its first framework of C&I for Sustainable Forest Management in 1995, and subsequent reports in 1997 and 2000. In 2003, the CCFM released an updated C&I framework, and in 2006, the CCFM released its report on national progress toward sustainable forest management (CCFM 2011). The Canadian Criteria and Indicators Framework is a science-based framework used to define and measure Canada's progress in sustainable forest management. The criteria represent forest values that Canadians want to enhance or sustain, while the indicators identify scientific factors used to assess the state of the forests and measure progress over time. In this report we use the six Criteria to summarize the forest values and use the Criteria to identify sustainability requirements related to harvesting woody biomass for energy production in NWT. The more detailed Indicators can be used to measure progress toward sustainability, but we limit this discussion to the Criteria level since forest harvesting for bioenergy purposes has not yet been implemented on a large scale in NWT and local-level indicators remain to be identified.

The principles underlying the C&I framework include the following (CCFM 2003):

1. The need to manage forests as ecosystems in order to maintain their natural processes;
2. The recognition that forests simultaneously provide a wide range of environmental, economic, and social benefits to Canadians;
3. The view that an informed, aware, and participatory public is important in promoting sustainable forest management; and,
4. The need for forest management to evolve to reflect the best available knowledge and information.

4.3 The Criteria

The Criteria are made up of six aspects of forest ecosystems and management that are considered to be essential to ensuring sustainability (Table 4.1). In the following section the Criteria are reviewed with respect to how they can help ensure forest sustainability in the context of harvesting forest biomass for energy production in NWT.

Table 4.1. The six Criteria of Sustainable Forest Management (adapted from CCFM 2003)

Criterion	Explanation
1. Biological Diversity	Maintain ecosystem, species and genetic diversity
2. Ecosystem Condition and Productivity	Maintain forest health and capacity for growth
3. Soil and Water	Minimize soil disturbance and impacts to water quality and quantity
4. Role in Global Ecological Cycles	Maintain forests' ability to sequester carbon
5. Economic and Social Benefits	Maintain the value of both timber and non-timber forest products to local and national economies
6. Society's Responsibility	Maintain Aboriginal and treaty rights; maintain forest-based community well-being; use fair, effective and informed decision-making processes

4.3.1 Criterion 1: Biological Diversity

The conservation of biological diversity is a critical component of sustainable forest management regardless of forest use and forest type. Biological diversity as used in the C&I framework includes ecosystem diversity, species diversity and genetic diversity. Maintenance of the natural range of ecosystems, and the ability of their components to react to external forces and processes, provides the equilibrium required for the maintenance of species diversity. Changes in ecosystems necessarily cause changes in species populations and distribution. Knowing that certain species are vulnerable or threatened may suggest changes in forest management and other measures to restore biological diversity. Maintenance of genetic diversity ensures that species maintain viability through their capacity to evolve and adapt to change.

Natural resources management falls under the GNWT Sustainable Development Policy 52.05:

"The Government of the Northwest Territories shall promote economic development, which maintains harvestable resources at sustainable levels, essential ecological processes and natural diversity."(GNWT 2005a)

As indicated by this policy, biodiversity conservation will be promoted if harvesting is carried out at sustainable levels. For example, the Forest Resource Assessment for the Dehcho Region, Mackenzie River Lowlands (The Forestry Corp 2010) provides sustainable harvesting levels for fuelwood and sawlog/log home production. Considerations for protected areas and caribou habitat are also included in this assessment. This approach should be adopted in other areas that may be subject to biomass harvesting for bioenergy production, although further work will be required by GNWT to develop specific harvesting guidelines for the protection of caribou habitat. In addition, further consideration will need to be given to any species that fall within the Species at Risk Act. Finally, harvesting upland forests will be based on existing knowledge of these ecosystem's structure and function, e.g. the NWT Ecosystem Classification System[4]. However, harvesting for woody biomass in other areas, e.g. riparian willow stands, will require detailed knowledge of the role of these ecosystems in maintaining biodiversity, and how sustainable harvesting can be carried out.

Criterion 2: Ecological Condition and Productivity

This criterion is focused on maintaining the productivity of the forest and the extent of forest cover; reducing the area affected by insects and disease; and ensuring that all harvested areas are promptly regenerated. As mentioned above, resource assessments and forest management plans that focus on sustainable harvest levels and require prompt regeneration and a free-to-grow standard are an important tool in ensuring long-term productivity [under the Forest Management Act and Regulations, a regeneration plan is required for commercial timber harvesting licenses (GNWT 2004)]. Sustainability is also linked to the extent of insects and disease that reduce productivity and result in mortality. GNWT should review their existing forest pest monitoring program, particularly where forest biomass harvesting may occur in areas not previously considered for forest management.

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[4] The GNWT Ecosystem Classifications for the Taiga Plains, Taiga Shield and Cordillera Ecozones are available on-line: http://www.enr.gov.nt.ca/_live/pages/wpPages/Ecosystem_Classification.aspx.

This criterion also deals with reducing the area subject to forest fire disturbance. Given the relatively low population of NWT and the importance of fire as a natural ecological process, GNWT will determine the best mix of fire suppression and prescribed natural fire that will meet the sustainable development goals referred to above. According to Fire Management Policy 52.07 of GNWT, the following principles guide this decision making:

"(1) Fire should be recognized as a significant and natural phenomenon in the forests of the Northwest Territories and

(2) Fire management should strive to attain forest management and other land use objectives in a manner that considers environmental, social and economic criteria." (GNWT 2005b).

In addition, fire-killed timber should be considered as a source of bioenergy feedstock in areas where the logistics are reasonable (e.g. near communities) but only to the extent that dead and down woody material is not required for maintenance of biodiversity and ecosystem function. Research will likely be required to determine how much fire killed timber can be used as feedstock without compromising its ecological value, e.g. Donato et al. (2006).

Criterion 3: Soil and Water

Criterion 3 deals with conserving soil and water resources as forest management activities are implemented. This generally includes guidelines on minimizing impacts of road construction, skid trails and other access development; reducing the impacts of harvesting in riparian zones; and managing forest harvesting at the landscape scale to reduce impacts to watersheds and water supply. For bioenergy harvesting, normal operating guidelines under the Forest Management Regulations (GNWT 2004) and associated policies should be sufficient for upland forest stands. If harvesting is considered in riparian zones, e.g. in fast-growing willow stands, the impacts to adjacent water bodies need to be carefully regulated to avoid impacts to water quality, fish habitat etc.

Criterion 4: Role in Global Ecological Cycles

This criterion largely deals with maintaining the ability of the forest to continue sequestering carbon as a means of mitigating climate change. Key issues for this criterion are maintaining the health and productivity of the forest, prompt regeneration, and monitoring forest condition to determine potential impacts of dieback, insects, disease, fire etc. GNWT should also consider how to minimize the permanent loss of forest cover (i.e. deforestation) due to developments such as permanent roads and pipelines, notwithstanding the need for economic development. Analyses should be carried out of the impact of these developments on the landscape carbon balance in NWT forests. It will also be important to carry out a Life Cycle Assessment of bioenergy production (as included in this project) to determine the net impacts of substituting woody biomass for fossil fuels. Woody biomass is often assumed to be "carbon-neutral" but this depends on the details of the conversion technology used, the amount of transportation required, whether the biomass comes from forested areas that will be regenerated, and other factors. Once plans for use of forest biomass are more firmly developed, GNWT may be interested in using tools such as the Carbon Budget Model of the Canadian Forest Sector (freely available from the Canadian Forest Service) to determine the effects of natural disturbance and forest management activities, including harvesting for bioenergy, on the carbon balance of NWT forests.

Carbon accounting for bioenergy development needs to include both the role of the forest in sequestering carbon and the role of the bioenergy system in producing GHG emissions. When both the forest and the bioenergy system are included, the system as a whole may be nearly carbon-neutral relative to fossil fuel use, since the uptake of carbon by re-growing trees compensates for the emissions due to bioenergy production. A recent study in Massachusetts (MCCS 2010) developed the concepts of "carbon debt" and "carbon dividend". This describes the carbon balance of an integrated forest management-bioenergy system relative to the use of fossil fuels for energy production. In the forest-bioenergy system, the relative carbon balance is at first negative due to tree harvesting (a carbon debt) but becomes positive as the trees re-grow following harvest and begin to sequester increasing amounts of carbon. At some point, depending on species and growth rates, the system pays back the carbon debt through sequestration. After that point the system generates a carbon dividend as sequestration continues. Figure 4.1 shows a hypothetical example of the carbon balance and how it changes over time. In this example, the C debt has been recovered at about 35 years, and the system realizes a C dividend after that point (BAU refers to "business-as-usual" i.e. an unharvested stand).

It is important to note that this is a stand-level analysis. If harvesting for bioenergy is occurring across the landscape at different times, this kind of analysis would need to be integrated across time and space, similar to a traditional wood supply analysis. In addition, this analysis applies to stands that are replanted after harvest in a traditional sustainable forest management system. The C dividend will not occur in stands that are harvested but not replanted, e.g. those cleared for pipeline rights-of-way or road construction. In this scenario, the emissions associated with harvesting are not included because the harvesting is being done for a different reason. However, the offsets realized from replanting the forest are not available so that the system may remain more GHG-intensive than a fossil fuel-based system. Similarly, salvage harvesting for bioenergy in fire-killed stands will not realize the carbon dividend unless they are replanted following harvest. There may be an advantage to harvesting fast-growing willow stands since willow readily reproduces through coppicing, but GNWT should investigate what these re-growth rates will be to determine the extent and timing of the C dividend.

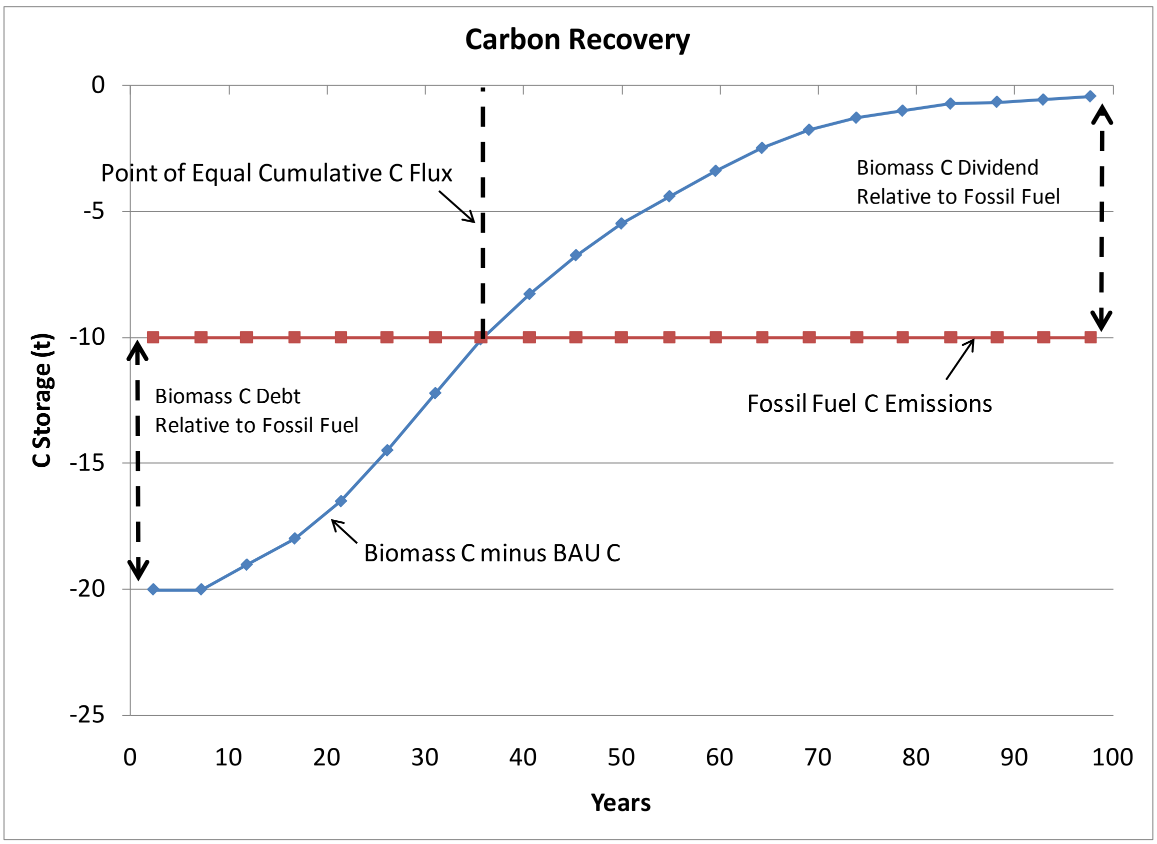


Figure 4.1 Carbon recovery in stands harvested for biomass, relative to emissions from fossil fuel. BAU, business-as-usual (adapted from MCCS 2010).

Criterion 5: Economic and Social Benefits

This criterion deals with economic and social benefits from the forest. These include economic values from timber production, value-added forest products, non-timber forest products and values from non-market products and services (where these can be quantified). For bioenergy harvesting, the net costs of the entire bioenergy production system, i.e. an integrated Life Cycle Cost Analysis needs to be completed to determine the overall economic benefits, rather than considering only the forest harvesting component. However, there are some harvesting scenarios in which costs of biomass harvesting and transport may render the entire system uneconomic. Studies of using post-harvest residues for bioenergy have found that in some jurisdictions transportation costs may be prohibitive beyond a haul distance of about 100 km (Bradley 2010), although this will vary depending on the details of location.

Criterion 6: Society's Responsibility

Criterion 6 is mainly concerned with ensuring that Aboriginal treaty rights are maintained as a cornerstone of forest management, and that forest-based communities (Aboriginal and non-aboriginal communities) participate in informed, fair and effective decision-making. GNWT has a long history of Aboriginal involvement in decision-making, and bioenergy development provides a number of opportunities for both Aboriginal and non-aboriginal communities. Replacing expensive fossil-fuel energy systems with bioenergy systems based on local biomass should reduce costs, and provide opportunities to residents through training and employment at these facilities. This will help in developing more resilient and self-sufficient communities.

5. FOREST CARBON MODELING

This section describes the analysis of bioenergy production under Scenario 1 (see Goal and Scope section of the report). In this scenario it is assumed that woody biomass from the sources described in Scenario 1 would be chipped on site by a mobile wood chipper. Wood chips are then transported by truck to the customers for thermal energy production.

Data used in the following calculations are shown in Table 5.1.

Table 5.1 Density, heat content and yield, and emissions per cubic metre of woody biomass.

	Units	Deciduous	Coniferous
Woody biomass	(m^3)	1	1
Wood density[1]	(kg m^{-3})	401	393
Heat Content[2]	(MJ kg^{-1})	20	20
Heat Content	(MJ)	8020	7860
Conversion Efficiency		0.8	0.8
Heat Yield	(MJ)	6416	6288
C Emissions[3]	(kg)	215.5	215.5
CO_2e Emissions[4]	(kg)	791	791

Notes:
[1] Wood density is on an oven-dry basis; values for deciduous are averages for aspen, poplar and birch; values for coniferous are averages for spruce and pine
[2] Heat content is on an oven-dry basis; data from US Department of Energy, Oak Ridge National Laboratory, Biomass Energy Data Book, http://cta.ornl.gov/bedb/index.shtml
[3] Data from MCCS 2010
[4] Calculated as C emissions X 3.667 (IPCC 2007)

Using the data in Table 5.1, the wood volumes required to satisfy the heating requirements for communities listed in the AEA Report (AEA 2010) were calculated (Table 5.2).

Table 5.2 Heating and wood volume requirements for communities listed in the AEA Report (AEA 2010).

Community[1]	Annual Heating Demand (MJ)	Wood Volume Required (m^3)[2]
All Weather Roads		
Enterprise	5,543,000	683
Kakisa	1,266,000	156
Fort Providence	14,120,000	1,739
Fort Resolution	12,588,000	1,550
Jean Marie River	2,944,000	363
Behchoko	27,196,000	3,349
Dettah	4,728,000	582
Fort Liard	7,871,000	969
Wrigley	2,092,000	258
Fort McPherson	14,892,000	1,834
Tsiigehtchic	5,533,000	681
Yellowknife	24,847,200	3,060
Subtotal	123,620,200	15,224
Ice Roads		
Trout Lake	1,590,000	196
What'i	8,546,000	1,052
Nahanni Butte	1,621,000	200
Gameti	2,716,000	334
Wekweeti	4,453,000	548

Community[1]	Annual Heating Demand (MJ)	Wood Volume Required (m^3)[2]
Tulita	7,711,000	950
Deline	10,921,000	1,345
Norman Wells	24,959,000	3,074
Fort Good Hope	6,277,000	773
Colville lake	944,000	116
Aklavik	16,168,000	1,991
Tuktoyaktuk	17,408,000	2,144
Subtotal	103,314,000	12,723
Grand total	**226,934,200**	**27,948**

Notes:
[1] Community data from AEA report (AEA, 2010) except Yellowknife which came from the North Slave Fire report.
[2] Based on 0.000123153 m^3 MJ^{-1}

These data area summarized in Table 5.3, along with the associated emissions. Revised demand refers to the increased wood volume required to compensate for the 80% conversion efficiency of the bioenergy technology assumed in the study.

Table 5.3 Summarized community bioenergy demand and associated emissions.

Annual fuelwood demand (m^3)	Conversion efficiency	Revised demand (m^3)	C emissions (kg m^3)	Total C emissions (kg)	Total C emissions (t)	Total C emissions (t CO_2e)[1]
27,948	0.8	34,934	215	7,528,22	7,528	27,629

Notes
[1] Calculated as C emissions X 3.667 (IPCC 2007)

It is beyond the scope of this study to carry out a formal wood supply analysis to determine the optimum location and timing of bioenergy harvesting for GNWT. The ideal tool for this purpose would be the Carbon Budget Model of the Canadian Forest Sector, freely available from the Canadian Forest Service (Kurz et al. 2009). In this report, data from the Forest Resource Assessment for the Dehcho Region (The Forestry Corp. 2010) was used to calculate an age-class-weighted mean volume per hectare (69 m^3 ha^{-1}). Using this value, a harvest area of approximately 500 ha per year would be required to supply these communities with 34,934 m^3 in perpetuity. Note that the sustainable annual allowable cut for the Dehcho region is 279,202 m^3, or approximately 8 times that required the level of bioenergy production shown in Table 5.3. In general, the sustainability of bioenergy feedstock from NWT forests does not appear to be in doubt. In addition, total NWT emissions for 2008 were 1,448,508 t CO_2e (Environment Canada 2010), while emissions from this level of bioenergy development would be approximately 27,629 t CO_2e, i.e. about 2% of overall emissions. However, location-specific issues may arise, for example the long-term sustainability of willow harvesting in some locations. In addition, the plans for harvesting fire-killed trees in the North Slave fire area for bioenergy production near Yellowknife will require some kind of forest renewal plan to ensure long-term sustainability.

The study from Massachusetts (MCCS 2010) shows how harvesting generates a "carbon debt" relative to fossil fuel use in the forest decades following harvest, but the debt is eventually recovered as the forest grows back and sequesters increasing amounts of carbon. For NWT, the best way to determine the rate of recovery of the carbon debt is to use yield curves. These show the rate of wood volume growth over time for each species or forest cover type (i.e. species groups that generally occur together on the landscape). The Forest Resource Assessment for the Dehcho Region (The Forestry Corp. 2010) provides yield curves for generalized conifer and deciduous species groups. These were converted into the equivalent amount of carbon (tonnes C ha^{-1}) using conversion factors in the IPCC Good Practice Guidance for Land Use, Land Use Change and Forestry (IPCC 2003). The curves are shown in Figure 5.1 (Table A1 in Appendix A shows the calculation results). According to these curves, the average rate of carbon sequestration is about 0.2 t C ha^{-1} yr^{-1}. Assuming that 500 ha are harvested annually, it would take about 70-75 years of regrowth to sequester the annual emissions from this level of bioenergy production. However, the use of faster growing planting stock and forest management practices may shorten this break-even point. In addition, once a large-scale harvest operation is in place, over time the landscape becomes a mosaic of forest patches of varying ages – some recently harvested and some older, depending on the harvest date. Over time the landscape-level carbon pool comes into a dynamic equilibrium so that there is always carbon on the landscape even though some areas are being harvested every year. Note also that this analysis only includes merchantable stem biomass, as the assumption in this report is that only stem wood would be harvested for bioenergy production.

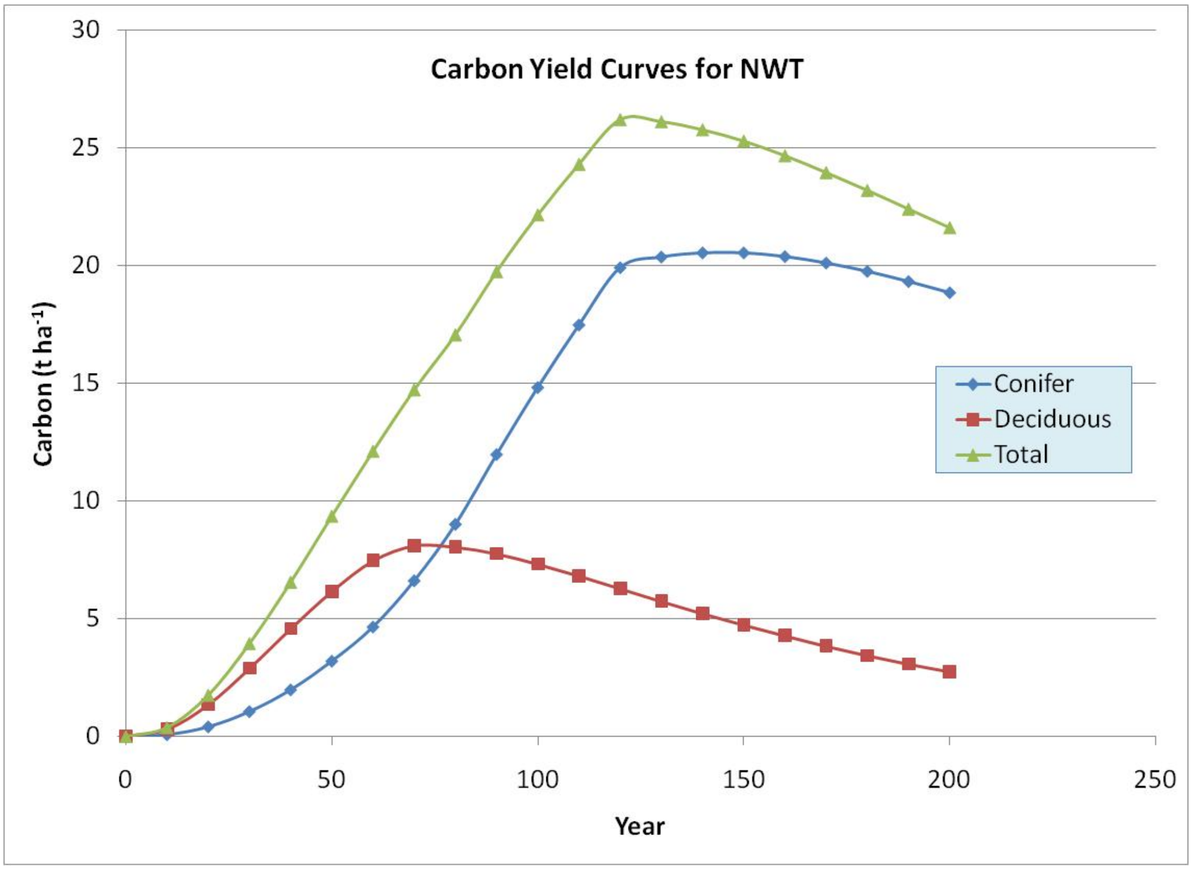


Figure 5.1 Carbon "yield curve" based on data in the Forest Resource Assessment for the Dehcho Region and using conversion factors from IPCC (2003).

6. GREENHOUSE GAS EMISSIONS ASSESSMENT RESULTS

6.1 Life Cycle Inventory

Life cycle inventory models have been developed to quantify and compare GHG emissions for the following scenarios. These scenarios are described in details in the Goal and Scope session of the report.

Scenario 1: Forest bioenergy for home and district heating– production of thermal energy from locally-sourced woody biomass in the NWT.

- 1A: Firewood bioenergy;
- 1B: Wood chips bioenergy.

Scenario 2: Pellet bioenergy for home and district heating – production of thermal energy from imported and locally produced wood pellets.

- 2A: Imported wood pellets bioenergy;
- 2B: Locally produced wood pellet bioenergy.

Scenario 3: Heating oil energy for home and district heating – production of thermal energy from imported heating oil.

Detailed description of the life cycle inventory data used in this study is presented in Appendix B: Life Cycle Inventory Supporting Information.

6.2 Results

All results are presented per MJ of net thermal energy produced.

Analysis of fossil greenhouse gas emissions[5]

Figure 6.1 presents overall comparison of all studied scenarios (please also see Figure D.1 in Appendix D). As it can be seen from the Figure 6.1, wood chips produced from locally sourced woody biomass have the lowest GHG emissions, followed by locally produced wood pellets, wood pellets imported from Alberta and locally produced firewood. Wood pellets imported from BC and firewood combusted in residential conventional technology stove have the highest GHG emissions after heating oil. A summary of global warming impacts is also given in Appendix D.

[5] It should be noted that only GHG emissions of fossil origin are presented here. This also includes biogenic methane emissions in line with greenhouse gas accounting protocols and standards.

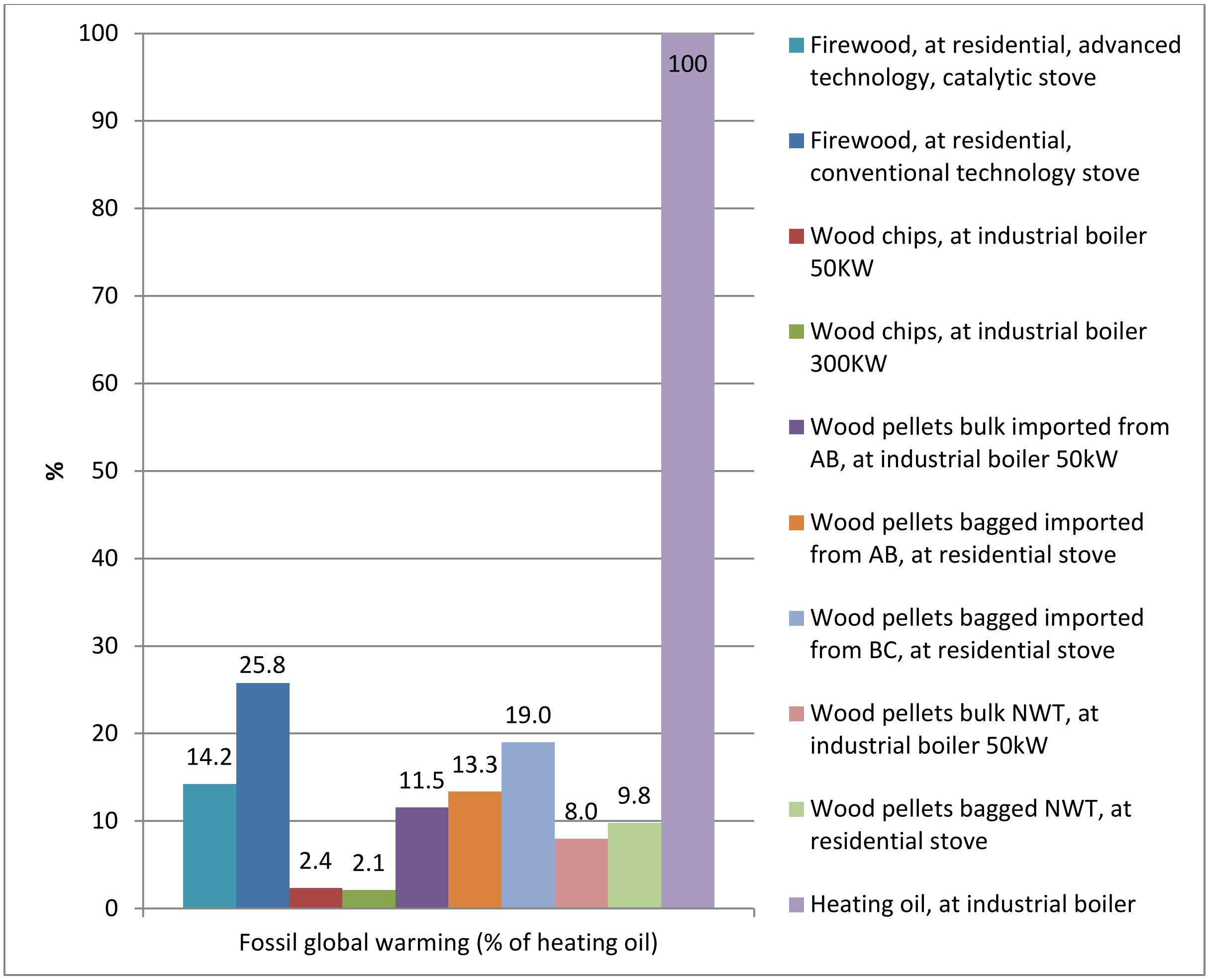


Figure 6.1 Comparison of all scenarios under study.

Contribution analysis: Scenario 1

The comparison of GHG emissions from bioenergy production from firewood and wood chips is presented in Figure 6.2. Two technologies for residential combustion of firewood were compared. These are advanced technology catalytic stove and conventional technology stove. Fossil GHG emissions from these technologies are shown in Figure 6.2. The detailed results are presented in Appendix D. Conventional technology stove has higher emissions from combustion stage due to lower efficiency compared to advanced technology stove.

Combustion of wood chips in two industrial boilers (50kW and 300kW) was modeled. The GHG emissions from 50kW boiler are slightly higher than that of the 300kW boiler (see Figure 6.2 and Appendix D). It should be noted that most institutional boilers in the NWT range from 300kW to 1.5MW.

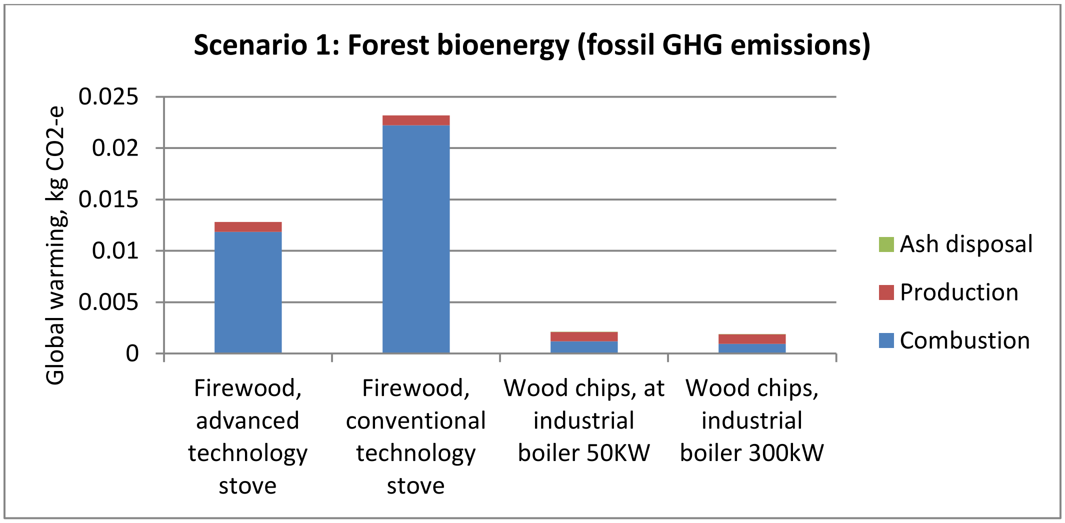


Figure 6.2 Contribution analysis of Scenario 1.

Fossil GHG emissions originate mainly from combustion of firewood or wood chips. Ash disposal stage contributes to less than 1% of global warming impact.

Wood chips resulted in much lower GHG emissions compared to firewood due to lower emissions from the combustion stage. The production stage of firewood and wood chips resulted in similar amounts of GHG emissions.

The impact from the combustion of firewood is much higher compared to the impact from combustion of wood chips. This is mainly due to the efficiencies of the combustion process. Firewood is assumed to be combusted in the residential stove, while wood chips – in a high efficiency industrial boiler.

<u>Contribution analysis: Scenario 2</u>

GHG assessment of locally produced wood pellets and wood pellets imported from AB and BC is presented in Figure 6.3. Most of the GHG emissions for imported pellets originate from pellets production and transportation stages. Transportation of wood pellets from AB and BC contribute to approximately half of the global warming impact from wood pellets life cycle. Since transportation has such a significant impact on global warming, sensitivity analysis on transportation distance was conducted. Results are presented in Figure 6.4.

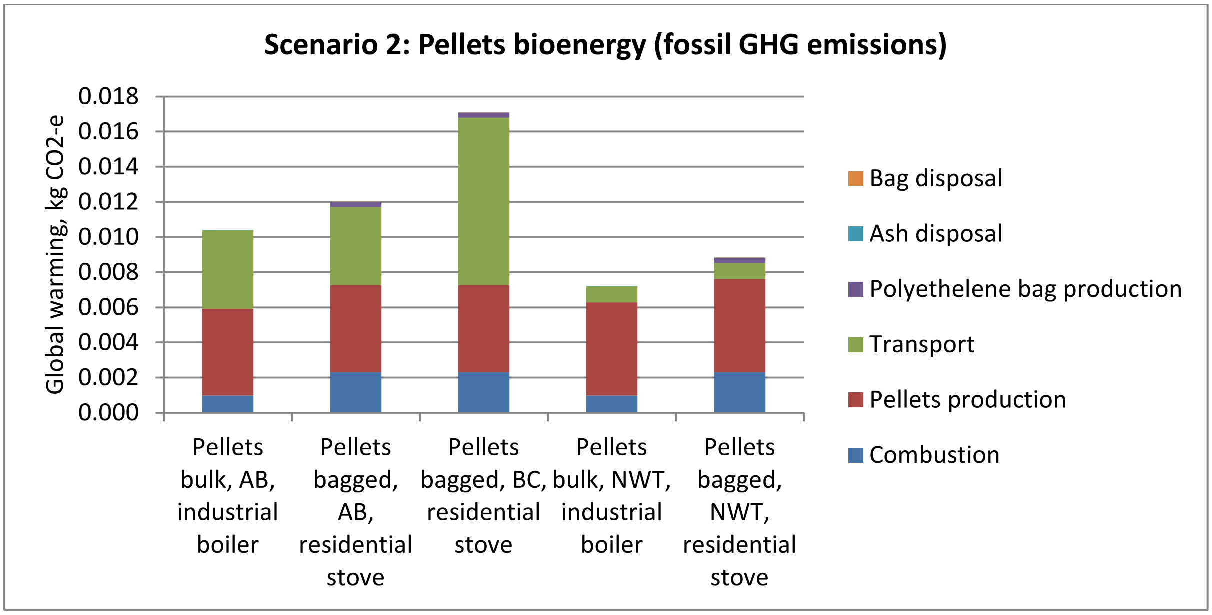


Figure 6.3 Contribution analysis of Scenario 2.

Polyethylene bag production, ash disposal and polyethylene bad disposal life cycle stages contribute to less than 1% of the total life cycle impact.

GHG emissions from combustion stage of wood pellets are slightly lower compare to firewood and wood chips combustion emissions. This is due to higher heating value of wood pellets (19,700 MJ/tonne pellets). Combustion of wood pellets in residential stoves is also less efficient than combustion in institutional boilers, resulting in higher GHG emissions.

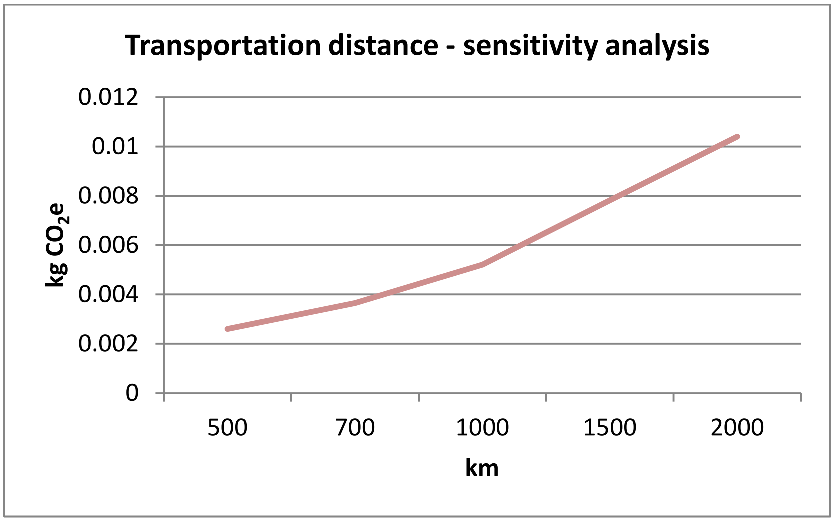


Figure 6.4 Sensitivity analysis of transportation distance.

Contribution analysis: Scenario 3

Scenario 3 describes the production of thermal energy from imported heating oil. The contribution analysis results are presented in Figure 6.5. As it can be seen from the figure, GHG emissions come mainly from the heating oil combustion stage. Upstream GHG emissions include GHG emissions from heating oil production and transportation to the NWT.

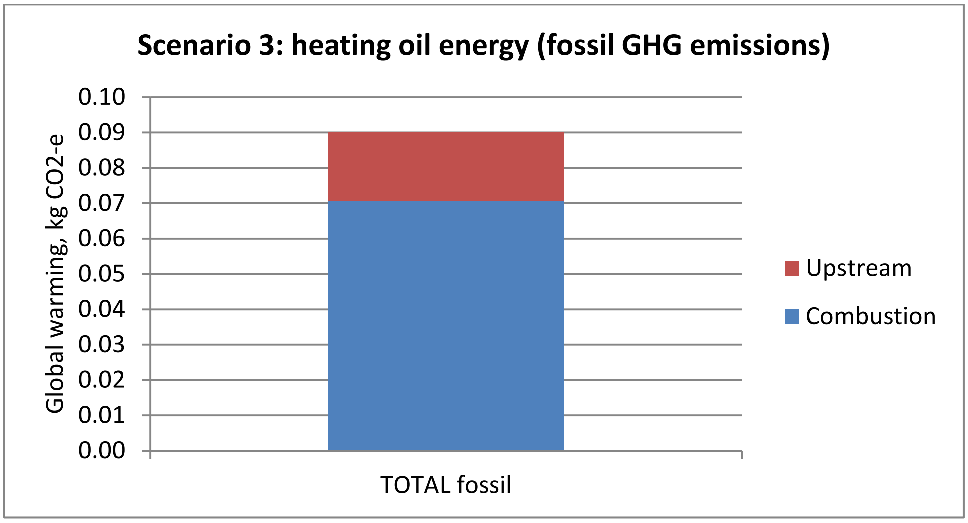


Figure 6.5 Contribution analysis of Scenario 3.

Analysis of biogenic greenhouse gas emissions

According to greenhouse gas accounting protocols and standards, CO_2 biogenic emissions should be reported separately. CO_2 biogenic emissions for scenarios 1 and 2 are presented in Figures 6.6 and 6.7 and in Appendix D.

In both scenarios, biogenic CO_2 emissions originate mainly from combustion of biomass. Since some biomass is used during pellets production (e.g. drying operations), a small amount of CO_2 biogenic emissions originates from pellets production stage.

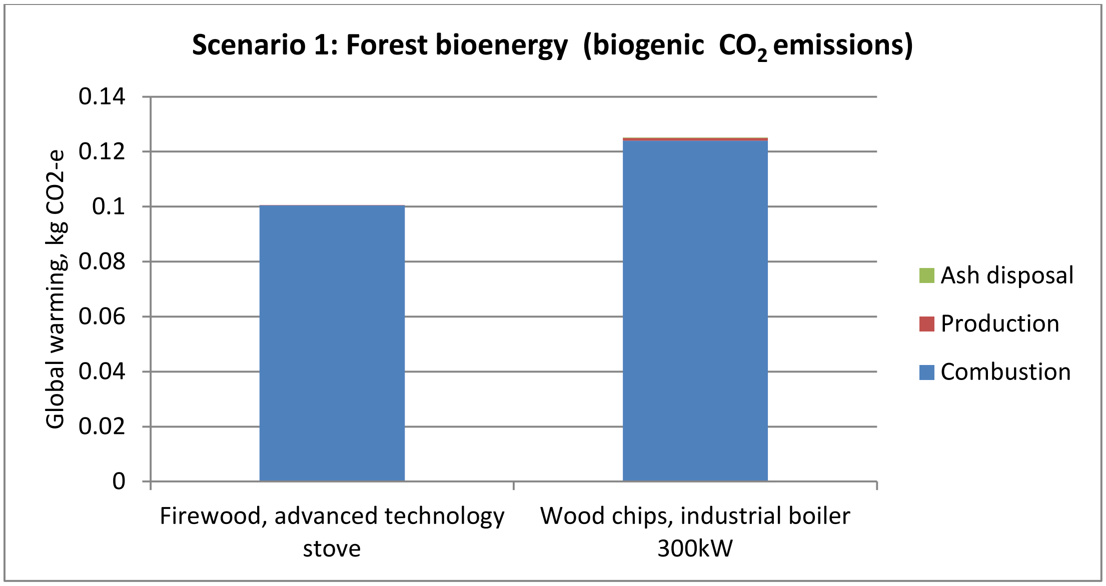


Figure 6.6 Scenario 1: Biogenic CO_2 emissions.

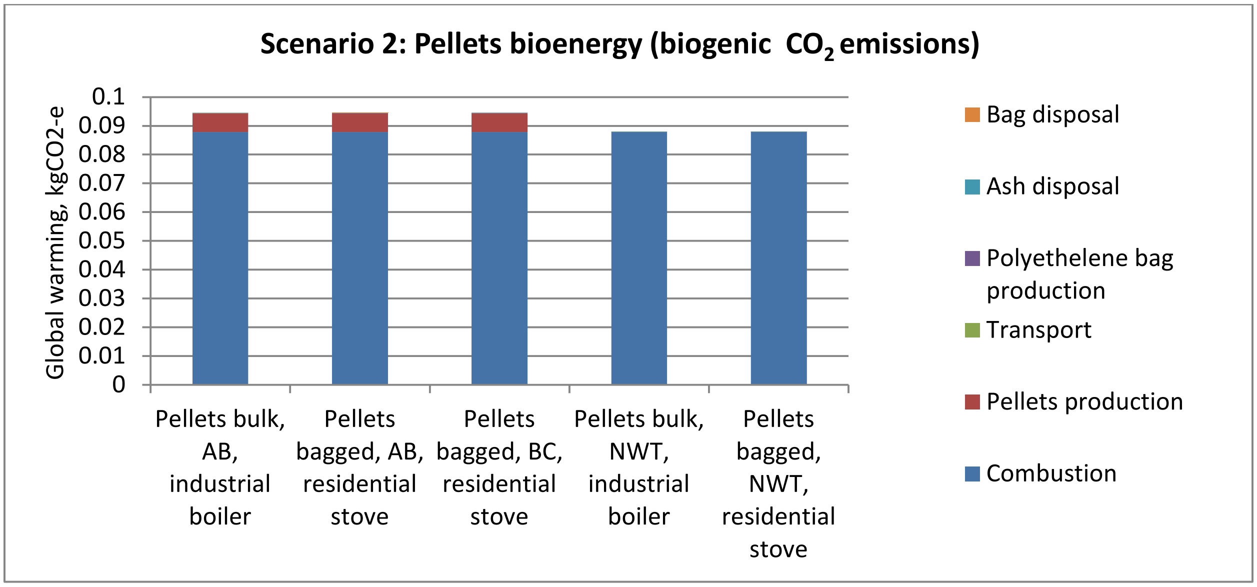


Figure 6.7 Scenario 2: Biogenic CO_2 emissions.

Both fossil and biogenic GHG emissions for all scenarios under study are presented in Figure 6.8. It should be noted that according to current GHG accounting guidance, CO_2 biogenic emissions should be accounted separately from all other GHG emissions. The graph presents contribution of fossil and biogenic emissions to the total GHG emissions from the life cycle of different fuels.

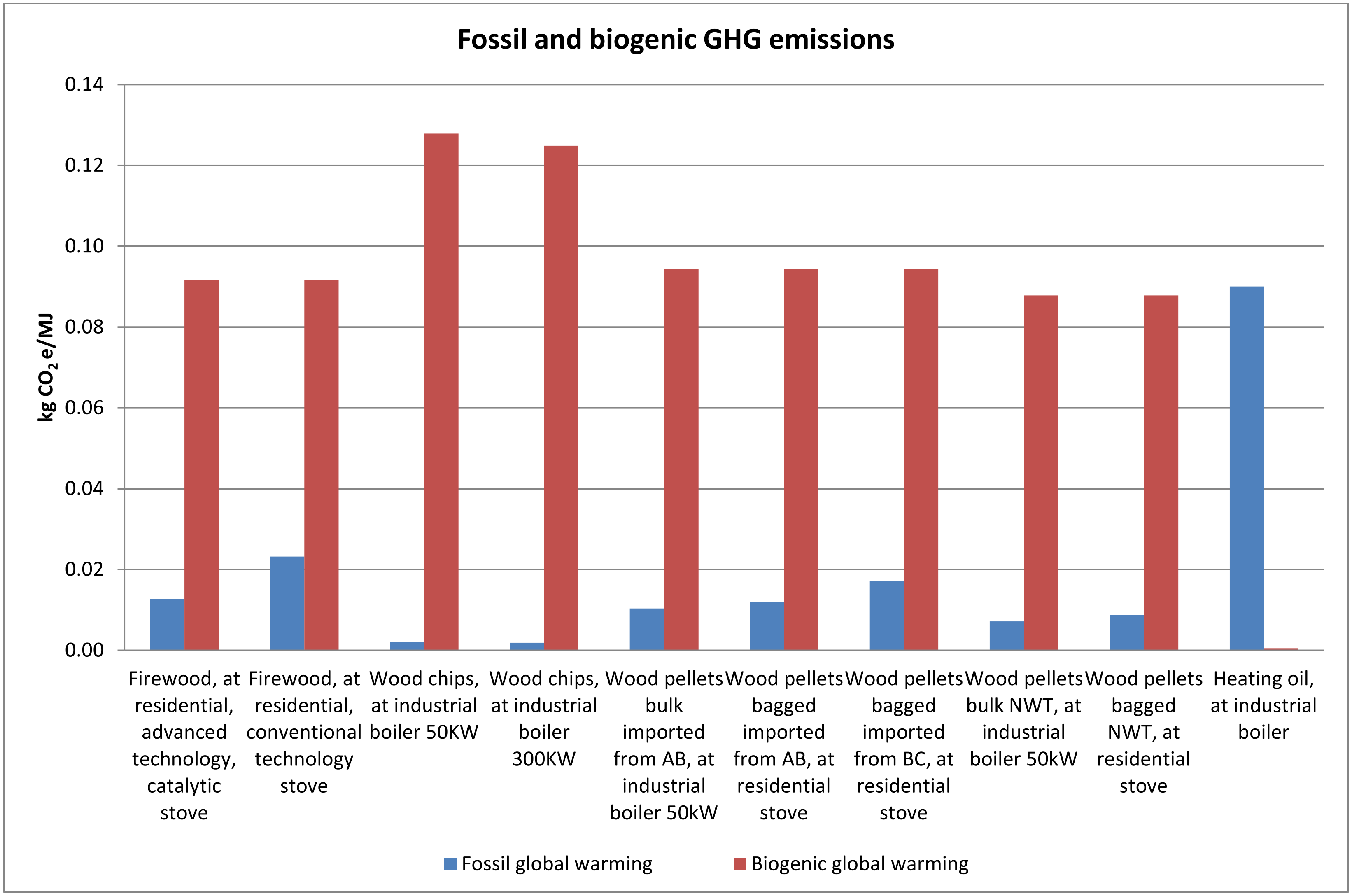


Figure 6.8 Fossil and biogenic GHG emissions – comparison of all scenarios under study.

Black and organic carbon assessment results

Emissions factors in Table 6.1 were used to estimate black and organic carbon emissions from firewood, wood chips, pellets and heating oil.

Table 6.1 Black and organic carbon emissions from controlled combustion of heavy fuel oil and wood in residential applications.

Type of fuel	BC (g/kg)	OC (g/kg)
Heavy fuel oil	0.07	0.015
Biofuel: Wood	0.3 - 1.4	1.7 -7.8

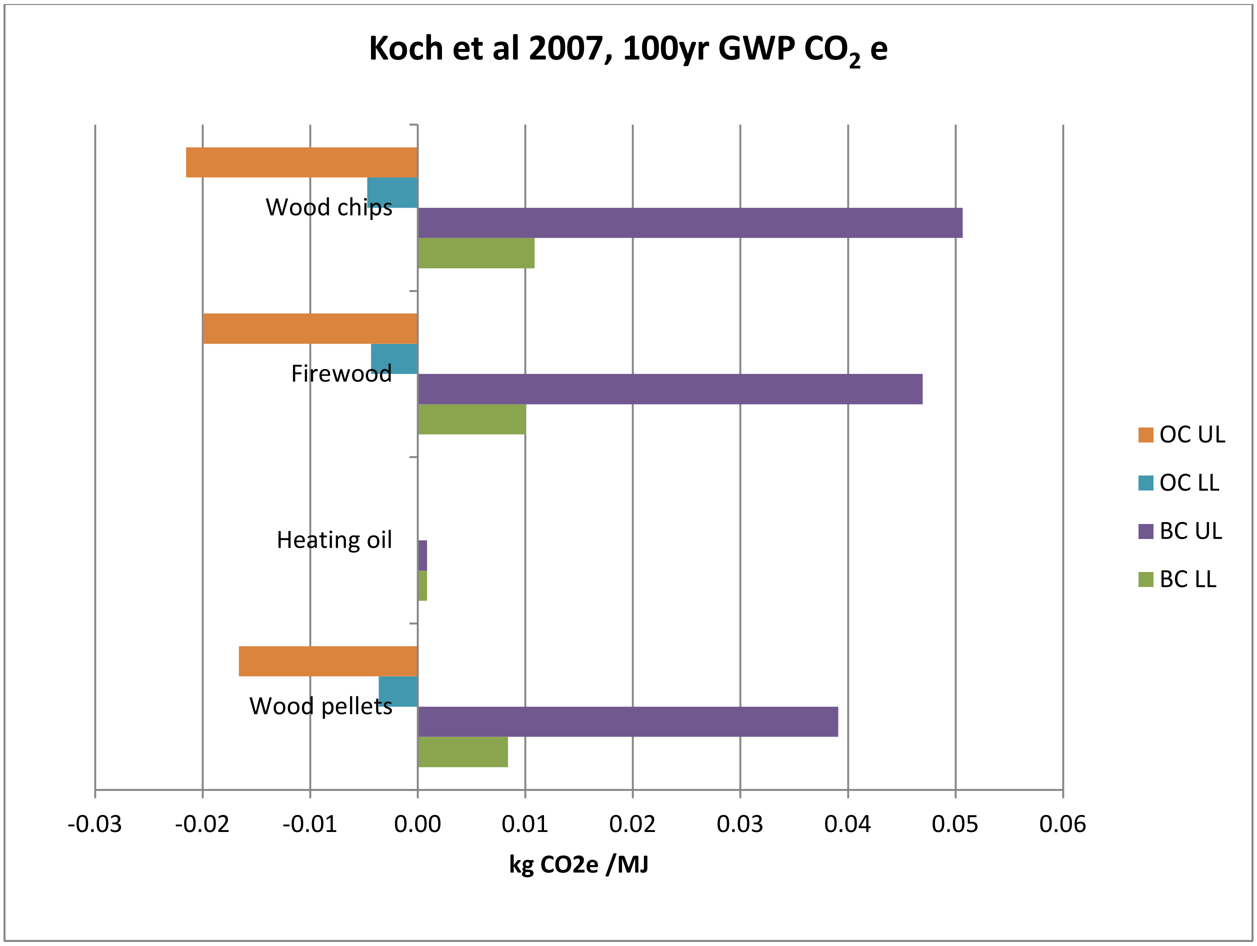
BC – black carbon; OC – organic carbon.

Source: Adapted from Bond et al. 2003.

Koch et al., 2007 GWP factors were applied ($GWP_{BC,100}$ = 550 and $GWP_{OC,100}$ = -42) to calculate global warming impact (Figure 6.9). A sensitivity analysis was conducted and a range of results based on GWP factors from other authors is presented in Figures 6.10-6.13. GWP factors obtained from Naik et al, 2007, Schulz et al, 2006, Bond and Sun, 2005 (BC), and Bond et al, 2004 (OC) studies were used to conduct the sensitivity analysis (see Table 3.2).

Applying a lower limit for black carbon estimation, the contribution of black carbon emissions to total GHG emissions from combustion range from 7.5 to 9.6% depending on the wood fuel type. If organic carbon emissions are subtracted from black carbon emissions, this results in 4-6% of black carbon emissions.

There is a huge uncertainty with calculation of black carbon emissions from biomass combustion using lower and upper limits that resulted in the wide spread of results for black and organic carbon. In our opinion, lower limit values are more applicable in this study since the combustion occurs in the controlled environment. For more information on black carbon results, please see Appendix D. It should be noted that contribution of black carbon emissions from biomass combustion can be significant. Further research in this area is recommended.



Note: OC (organic carbon), BC (black carbon), UL (upper limit), LL (lower limit).

Figure 6.9 Global warming potential ranges for black and organic carbon emitted from combustion of wood chips, firewood, wood pellets and heating oil.

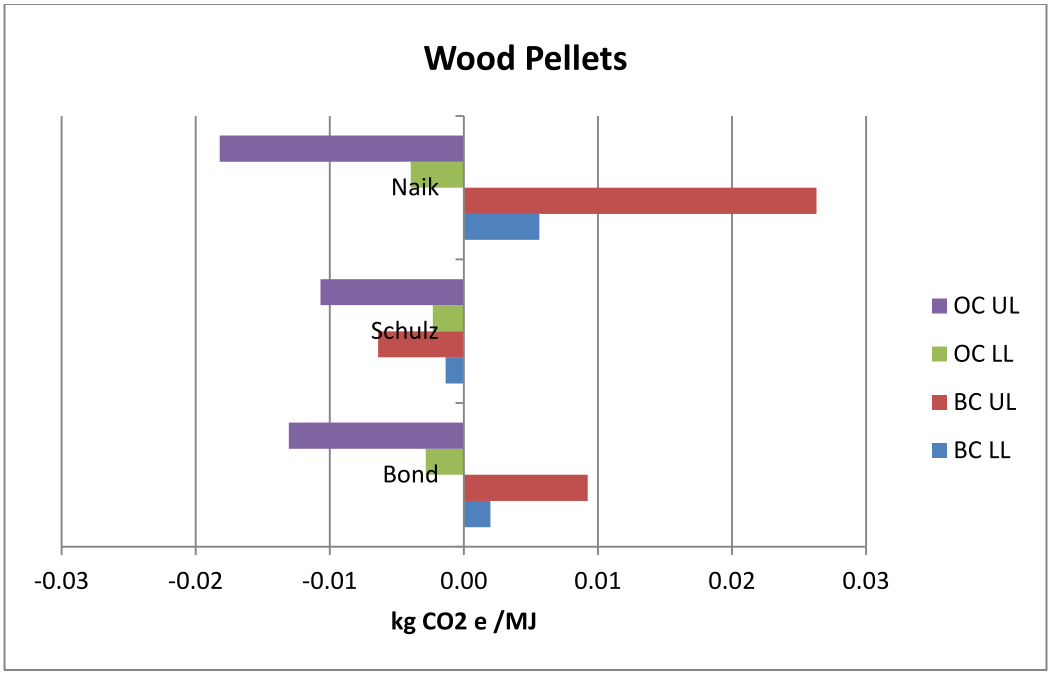


Figure 6.10 Sensitivity analysis for wood pellets: global warming potential ranges for black and organic carbon emitted from combustion of wood chips, firewood, wood pellets and heating oil.

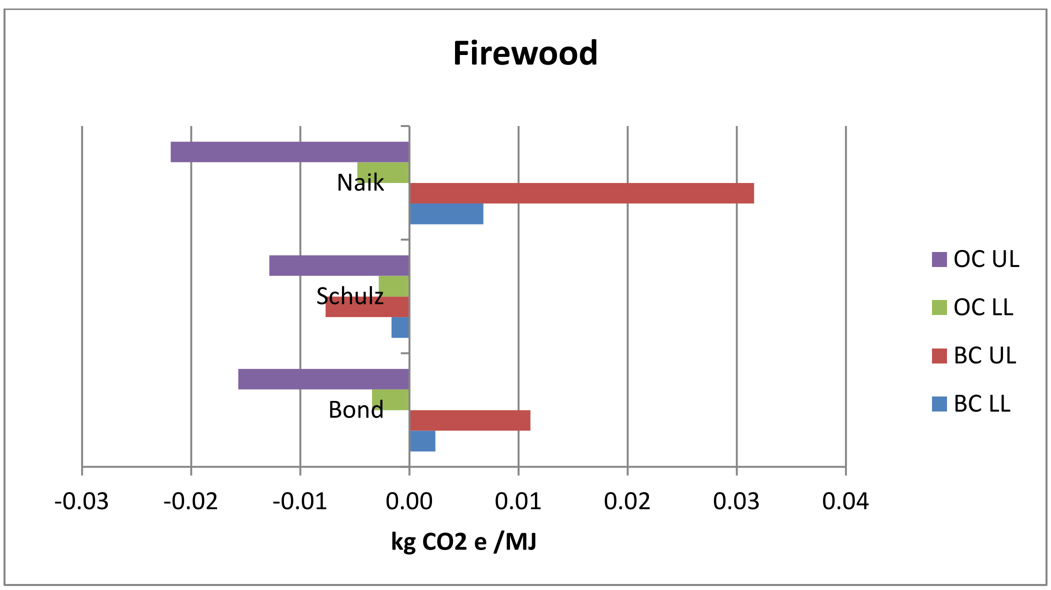


Figure 6.11 Sensitivity analysis for firewood: global warming potential ranges for black and organic carbon emitted from combustion of wood chips, firewood, wood pellets and heating oil.

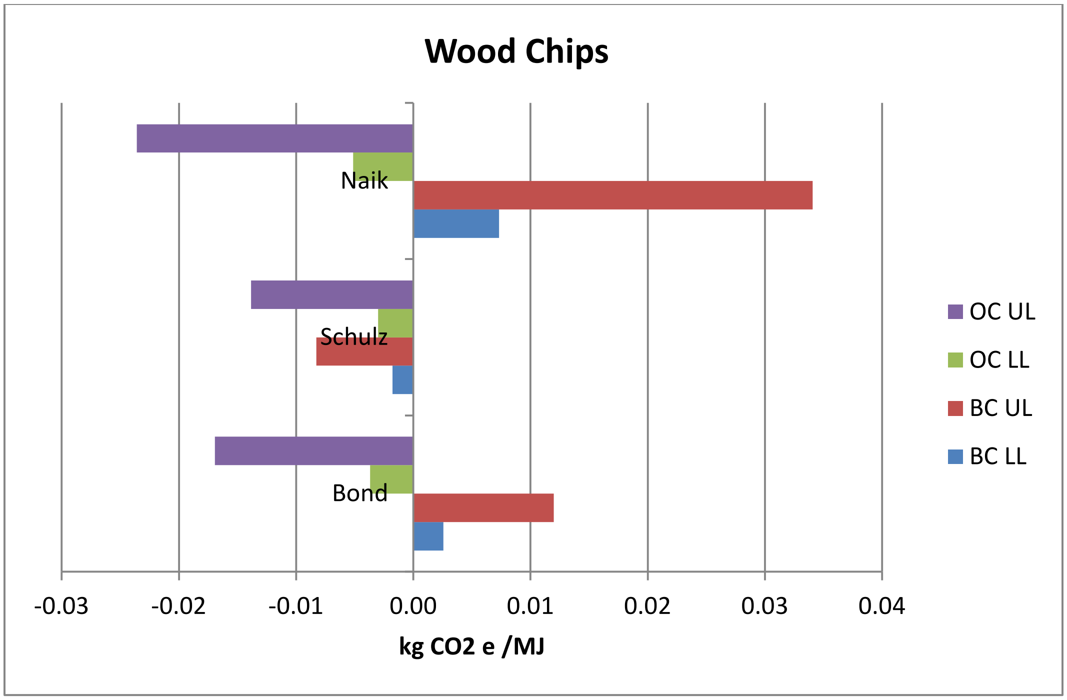


Figure 6.12 Sensitivity analysis for wood chips: global warming potential ranges for black and organic carbon emitted from combustion of wood chips, firewood, wood pellets and heating oil.

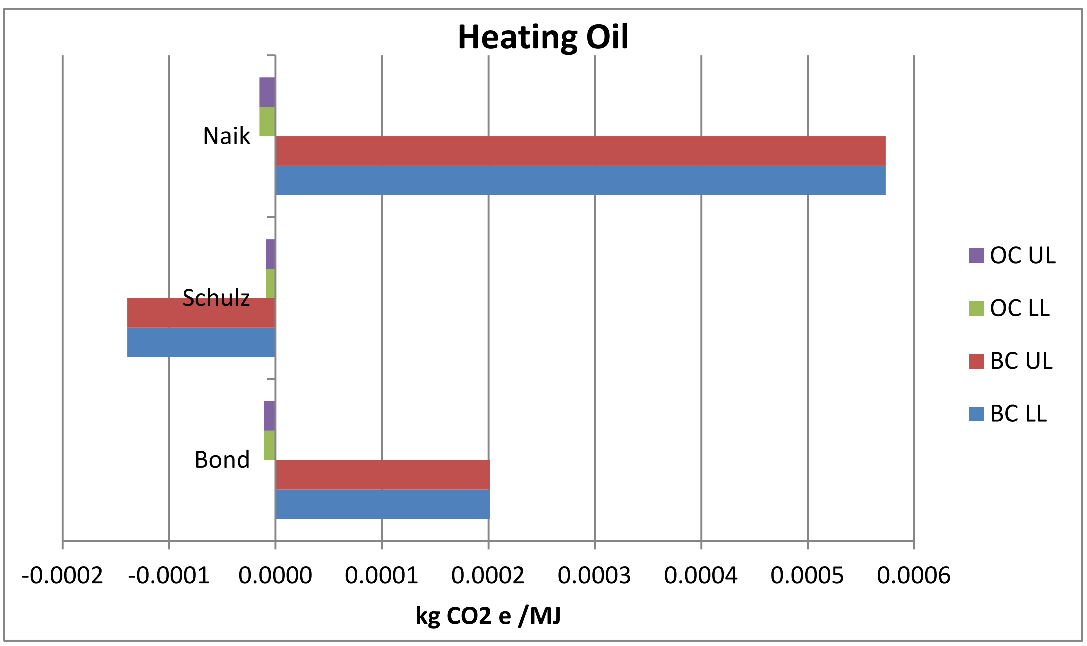


Figure 6.13 Sensitivity analysis for heating oil: global warming potential ranges for black and organic carbon emitted from combustion of wood chips, firewood, wood pellets and heating oil.

7. CONCLUSIONS AND RECOMMENDATIONS

1. Three scenarios were analyzed in this study:
   a. Scenario 1: Forest bioenergy for home and district heating – production of thermal energy from locally-sourced woody biomass (firewood and woodchips) in the NWT.
   b. Scenario 2: Pellet bioenergy for home and district heating – production of thermal energy from imported and locally produced wood pellets.
   c. Scenario 3: Heating oil energy for home and district heating – production of thermal energy from imported heating oil.
2. The study followed the LCA methodology defined in the ISO 14000 standards for the estimation of greenhouse gas emissions. It also followed the PAS 2050 and the WRI /WBCSD greenhouse gas accounting protocols.
3. The full life cycle of firewood, wood chips, pellets and heating oil starting from harvesting of wood in the forest/extraction of crude oil through production of the product to combustion and final disposal of wastes was evaluated.
4. Wood chips produced from locally sourced woody biomass showed the lowest GHG emissions over the full life cycle, followed by locally produced wood pellets, wood pellets imported from Alberta and locally produced firewood. Wood pellets imported from BC and firewood combusted in residential conventional technology stove have the highest GHG emissions after heating oil.
5. Transportation of wood pellets from AB and BC contribute to approximately half of the global warming impact from wood pellets life cycle.
6. Based on the life cycle results, local wood chips and pellets production may be recommended as one of the strategies for reduction of fossil GHG emissions.
7. Advanced technology catalytic stove and conventional technology stove used for residential combustion of wood were compared. Conventional technology stove has higher GHG emissions from combustion stage due to lower efficiency compared to advanced technology stove.

8. Residential stoves have lower efficiencies compared to institutional boilers. This resulted in higher GHG emissions from combustion of different type of wood fuels in residential applications.
9. Fossil GHG emissions and biogenic CO_2 emissions were presented separately, as required by international GHG protocols and standards (e.g. PAS 2050). Biogenic CO_2 emissions originate mainly from combustion of biomass.
10. The Criteria and Indicators of Sustainable Forest Management developed by the Canadian Council of Forest Ministers was used to assess the sustainability of biomass harvesting. In general, we conclude that harvesting biomass for bioenergy in the NWT is sustainable given the relatively low demand, which represents a small fraction of the territories' sustainable timber yield. In addition, sustainability will be achieved if best practices are followed regarding the values outlined in the CCFM Criteria: protection of biodiversity and water and soil quality; maintenance of forest health, productivity and carbon storage; and equitable distribution of benefits to local communities. However, there may be site-specific sustainability questions related to, for example, intensive willow harvesting in riparian areas and impacts of harvesting on caribou habitat. GNWT should undertake more detailed site assessments in areas where these concerns are likely to arise, and also revise forest pest monitoring plans to include new biomass harvesting areas. If fire-killed trees are harvested for bioenergy production, a forest renewal program for these areas should be developed before harvesting is implemented. Finally, a more detailed analysis of the impacts of biomass harvesting on landscape-level carbon storage should be undertaken before large-scale harvesting is implemented. The Carbon Budget Model of the Canadian Forest Sector is ideal for this purpose and is freely available from the Canadian Forest Service.
11. Black and organic carbon emissions from combustion of firewood, wood chips, pellets and heating oil were evaluated. Applying a lower limit for black carbon estimation, the contribution of these emissions to total GHG emissions from combustion range from 4 to 6% depending on the wood fuel type. There is a huge uncertainty with calculation of black carbon emissions from biomass combustion using lower and upper limits that resulted in the wide spread of results for black and organic carbon. Lower limit values would be more applicable in this study since the combustion occurs in the controlled

environment. The contribution of black carbon emissions from biomass combustion can be significant. Further research in this area is recommended.

12. This study was limited to GHG emissions only. More research is necessary to investigate other environmental effects. This would allow for a more complete and true comparison of different scenarios. As an example, typical flue gas from combustion of fuels contains considerable amounts of nitrogen oxides (NO_x), sulphur dioxide (SO_2) and particulate matter, three compounds related to air pollution. If the life cycle of carbon approach is used these compounds are neglected, as they do not contribute to climate change. Thus, it makes sense to include relevant non-greenhouse gas emissions, such as air pollutants (e.g. NO_x, particles, SO_x), especially when comparing different fuels (e.g. biomass, heating oil) for use in combustion applications. The full Life Cycle Assessment (LCA) study is recommended. The following impact categories in addition to global warming would be assessed if the full LCA is conducted: respiratory effects, aquatic acidification, aquatic eutrophication, terrestrial acidification and nitrification, land occupation, non-renewable energy, mineral extraction, human toxicity, ionizing radiation, ozone layer depletion, photochemical oxidation, aquatic ecotoxicity, and terrestrial ecotoxicity. Biomass use in combined heat and power application or for co-generation should also be evaluated. We also recommend an analysis of the forest landscape carbon balance using the Carbon Budget Model of the Canadian Forest Sector. This model uses traditional forest inventory data (or other data if inventory is not available) and determines the annual carbon balance of the forest under any number of user-defined scenarios. These may include the effects of fire, insect outbreaks and harvesting for forest products or bioenergy. The model is freely available from the Canadian Forest Service, Pacific Forestry Centre.

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APPENDIX A

FOREST CARBON MODELING RESULTS

Table A.1 Carbon yield curves calculated from data in The Forestry Corp. (2010).

	Carbon in merchantable biomass (tC ha^{-1})		
Stand Age	**Conifer**	**Deciduous**	**Total**
0	0.0	0.0	0.0
10	0.1	0.3	0.4
20	0.4	1.3	1.8
30	1.1	2.9	3.9
40	2.0	4.6	6.6
50	3.2	6.2	9.4
60	4.7	7.5	12.1
70	6.6	8.1	14.7
80	9.0	8.0	17.1
90	12.0	7.8	19.7
100	14.8	7.3	22.2
110	17.5	6.8	24.3
120	19.9	6.3	26.2
130	20.4	5.7	26.1
140	20.6	5.2	25.8
150	20.6	4.7	25.3
160	20.4	4.3	24.7
170	20.1	3.8	24.0
180	19.8	3.4	23.2
190	19.3	3.1	22.4
200	18.9	2.7	21.6

APPENDIX B

LIFE CYCLE INVENTORY – SUPPORTING INFORMATION

B.1 Woody biomass harvesting operations

Harvesting wood for wood pellets production

In this study, the wood for imported pellet production is supplied from sustainably managed forests in western Canada (mainly in AB and BC). The main species of wood used for pellets production are spruce and pine.

Forest harvesting data which includes forest road construction, forest harvesting and wood delivery to the forest product conversion facility (here sawmill) was obtained from Sambo 2002 and Pa 2010. The data is based on the survey of the Forest Engineering Research Institute of Canada (FERIC) member companies (Sambo 2002). Wood in western Canada is harvested by four ground-based harvesting systems: full-tree (53%); cut-to-length at roadside (7%), cut-to-length at-the-stump (8%); and cut-to-length with harvesters and forwarders (14%). An average harvested area of 24 ha has a merchantable timber volume of 244 m^3/ha (or volume of 5,856 m^3). An average one-way haul distance is approximately 100 km. An estimated diesel fuel consumption to deliver 1 m^3 of wood to the sawmill in western Canada is 7.1 L/m^3 or 273 MJ/m^3, from which hauling operations use 51% of all fuel consumed (Sambo 2002).

Pa 2010 recalculated diesel fuel consumption from MJ/m^3 of wood to MJ/tonne of pellets produced from the sawmill by-products (e.g. chips, shavings, sawdust). The recalculated energy consumption in MJ/tonne of pellets and corresponding GHG emissions from harvesting operations are presented in Table B.1.

Harvesting wood for firewood production

The local wood is harvested for firewood in this scenario. A number of small size businesses produce firewood in the NWT. Several businesses were contacted, however, they could not provide data on diesel consumption for firewood harvesting and processing. Thus, the data from the literature was used.

The density of the green wood with the moisture content of 50% is assumed to be 840 kg/m^3. Using Sambo (2002) estimate of 3.5L of diesel or 134 MJ for the production of 1 m^3 of green timber (note: hauling is not included), 6.8L of diesel or 262 MJ is required to produce 1 tonne of firewood with 18% of moisture content. The green lumber is transported over 5 km to the log processing facility where it is allowed to dry and then processed. Diesel consumption for processing the wood was assumed to be 6.6 L/tonne (Paul et al., 2003). The seasoned firewood is then delivered to customers by a small truck. An average transportation distance (recommended distance) of 75 km was assumed (Pa, 2010).

<u>Harvesting wood for wood chips production</u>

The local wood is harvested and chopped by a mobile wood chipper in this scenario. Wood may come from different sources (green wood from the merchantable forest, black wood from recent burns, 20-40 year old willows from river flats). However, here it is assumed that all wood in this scenario comes from the merchantable forest. This green biomass typically has a moisture content of 50% and is allowed to air dry to 30% moisture content prior to grinding and hauling offsite (Jones et al., 2010). An average hauling distance of 100 km is assumed (Sambo, 2002). Estimated diesel fuel consumption to harvest and haul 1 m^3 of wood is 7.1 L/m^3 or 273 MJ/m^3 (Sambo 2002) or 325 MJ/tonne of wood chips (8.5L/tonne of wood chips). Size reduction occurs in the forest by a mobile wood chipper. Diesel consumption for grinding biomass was assumed at 1.7 L/tonne of biomass or 65.37 MJ/tonne of biomass (Jones et al., 2010). The moisture content of the wood influences the energy content of the fuel. Wood chips need to be dried to 20% moisture content before combustion. Electricity consumption for wood chips drying to 20% moisture content was estimated at 10.3 kWh/m^3 of wood chips (Mikko, 2005). Using the bulk density of wood chips of 350 kg/m^3, it amounts to 29.43 kWh/tonne of wood chips. It is assumed that heat for drying comes from woody biomass combustion. Wood chips are then transported via a distance of 75 km to customers by five axle tractor-trailers, each with a 22.8 tonne payload.

B.2 Sawmill operations

<u>Imported wood pellets</u>

The data on energy consumption for sawmill operations is based on Nyboer and Jaccard 2010 and Pa 2010. Production of lumber at the sawmill involves the following steps: wood preparation, sawing, kiln drying, planning and trimming. Wood residues such as bark, sawdust, shavings and wood chips are generated during these processing stages. Some of the residues are also used onsite as a hog fuel. The recalculated energy consumption (MJ/tonne of pellets) and associated GHG emissions (kg/tonne of pellets) from sawmill operations are given in Table B.1.

Table B.1 Energy consumption and GHG emissions for harvesting, sawmill and pellet plant operations.

	Harvesting	Sawmill	Pellet plant
Energy consumption, MJ/tonne of pellets			
Electricity	-	186	490
Natural gas	-	135	-
Heavy fuel oil	-	14.57	-
Diesel	689	42.86	23.49
Propane	-	3.68	6.16
Steam	-	47.55	-
Wood waste	-	271	1059
Gasoline	-	-	-
Emissions, kg/tonne of pellets			
	Harvesting	**Sawmill**	**Pellet plant**
CO_2, fossil	62.40	19.70	8.33
CO_2, biogenic	0.427	26.70	102.0
CH_4	0.0894	0.0446	0.0506
CH_4, biogenic	-	0.00255	0.00981
N_2O	0.00777	0.00228	0.00640

Source: Adapted from Pa 2010.

B.3 Pellet plant operations

Imported wood pellets

Pa 2010 in cooperation with Wood Pellet Association of Canada conducted a pellet mills survey in western Canada. The results of the surveys are used in this study. Transportation to and from pellet mills is not included in the data for pellet mill energy consumption and GHG emissions (Table B.1). It is assumed that sawmill is located in the near proximity of the pellet mill. The average transportation distance between sawmill and pellet mill is 25.6 km (Pa 2010). Sawdust and shavings are transported to the pellet mill by truck (15 tonnes payload).

Pellets are supplied to the customers in the NWT in bulk and bagged form. Production of plastic bag (material: polyethelene; weight: 0.14 lb or 63.5 g) manufactured by Bulldog Bag Ltd. is taken into account in this study (Bulldog, 2011). The dataset from the EcoInvent database is used for the production of plastic bag.

Locally produced wood pellets

Local green wood is used to produce wood pellets in this scenario. The whole tree is assumed to be used for pellets production. The data for pellets production originates from Zhang et al., 2010 (Table B.2). Wood pellets are transported to customers by truck. An average transportation distance is assumed to be 150 km.

Table B.2 Parameters for biomass pelletization.

Process	Energy or materials consumption
Grinding of biomass, kWh/t biomass	3.75
Biomass for drying, t biomass/t pellets	0.18
Other pelletization stages (hammer mill, drying, compression, and cooling and sieving), kWh/t pellets	140

Source: Adapted from Zhang et al., 2010.

B.4 Transportation of pellets to the NWT

Wood pellets currently used in the NWT come primarily from the LaCrete pellet mill in La Crete, Northern Alberta. The remainder comes from BC pellet mills, Premium Pellet and Pinnacle Pellet (Table B.3). Pellets from LaCrete are trucked as there is no rail access in La Crete (La Crete, 2011). The transportation distance for LaCrete pellets is estimated at 824 km (Google maps). The majority of Pinnacle pellets come in a bag form for home heating market. All bagged pellets from BC are also transported by truck. Bagged pellets are placed on wooden pallets and transported in standard freight trailers. The transportation distance for pellets imported from BC is estimated at 1,800 km.

Table B.3 Wood pellets supply to the NWT.

Material	**Location**	**Quantity, tpy (2010)**	**Mode of transport**	**Type of packaging**	**Distance, km**	**Source**
Wood pellets	Le Crete pellet mill, Alberta	12,000	Super B-train trucks (payload 42 t, 8-axle)	90% Bulk 10% Bagged	824	La Crete, 2011
	Pinnacle and Premium pellet mills, BC	600 45	Freight trailer (payload 30 t and 45 t)	100% Bagged	1,800	Pinnacle, 2011 Premium, 2011

Note: Retail shops, such as Wal-Mart and Canadian Tire carry bagged pellets for residential use. These pellets come mainly from Pinnacle Pellet and Premium Pellet, BC. However, some originate from AB, MB and even US (Arctic, 2010).

B.5 Wood consumption for municipal and residential heating in the NWT

Community energy profiles prepared by the Arctic Energy Alliance[6] were used to calculate wood consumption for residential heating. Both firewood and wood pellets consumption was combined in the energy profiles (Lakusta, 2011). The estimated amount of wood (firewood and

[6] http://www.aea.nt.ca/resources/map/

wood pellets) used for residential heating in the NWT in 2007-2008 was approximately 10,000 tonnes (Appendix C, Table C.1). The current estimated market for firewood in the NWT is about 7,500 t/year (Lakusta, 2011). Bagged wood pellets consumption in 2010 was approximately 1,845 t/yr (Table B.3). This value does not include wood pellets purchased at the retail stores such as Wal-Mart and Canadian Tire.

B.6 Heating oil production and transportation to the NWT

Heating oil is commonly delivered by tank truck to residential, commercial and municipal buildings and stored in above-ground storage tanks. Heating oil comes to NWT from the US and Alberta. It is delivered to the NWT by rail and truck; by ocean tanker or rail and then, distributed by tug and barge. Heating oil production and combustion data originates from the GHGenius (GHGenius, 2010). The upstream emissions include emissions from all transportation activities involved (Table B.4).

Table B.4 Total emissions over the life cycle of heating oil, per unit of energy delivered to end users, by pollutant (kg/MJ).

Emission	Total emission, kg/MJ	Upstream emissions, kg/MJ	Combustion emissions, kg/MJ
Carbon dioxide (CO_2), fossil	0.0862	0.0157	0.0705
Carbon dioxide (CO_2), biogenic	0.000475	0.000475	0
Methane (CH_4)	0.000122	0.000120	0.00000282
Nitrous oxide (N_2O)	0.000000977	0.000000667	0.00000031

Source: Adapted from GHGenius, 2010.

B.7 Production of thermal energy

Institutional buildings heating

The wood pellet systems installed in the NWT currently range from 300kW to 1.5MW (Arctic, 2010). The most common types of wood boilers are KOB and BINDER with efficiencies of up to 92%. There are plans to install district heating systems in some NWT communities that initially can use imported wood pellets before a locally harvested biomass supply in a form of wood chips is established.

The following energy content of heating fuels was used in this study:

Wood pellets 19,700 MJ per tonne,

Heating oil 38.4 MJ per litre,

Firewood 16,400 MJ per tonne (18% moisture content),

Wood chips 15,200 MJ per tonne (20% moisture content).

Residential building heating

Wood and pellets stoves and furnaces are used for residential buildings heating.

Tables B.5-B.7 summarize the combustion emission factors of the various types of boilers and furnaces.

Table B.5 Combustion emission factors for firewood, kg/tonne.

		CO_2, biogenic	CH_4, biogenic	N_2O
Wood stove, residential	Advanced technology or catalytic control	1503 (0.0917 kg/MJ)	6.9 (0.000421 kg/MJ)	0.16 (0.0000097 kg/MJ)
	Conventional	1503 (0.0917 kg/MJ)	15 (0.000915 kg/MJ)	0.16 (0.0000097 kg/MJ)
	Source	*Based on carbon and moisture content of firewood*	*SGA, 2000*	*SGA, 2000*

Table B.6 Combustion emission factors for wood chips, kg/MJ of useful energy.

		CO_2, biogenic	CH_4, biogenic	N_2O
Boiler, industrial	50kW	0.127	8.75E-7	3.75E-6
	300kW	0.124	4.88E-7	3.05E-6
	Source	*Swiss Centre for Life Cycle Inventories et al., 2008*	*Swiss Centre for Life Cycle Inventories et al., 2008*	*Swiss Centre for Life Cycle Inventories et al., 2008*

Table B.7 Combustion emission factors for wood pellets, kg/tonne.

		CO_2, biogenic	CH_4, biogenic	N_2O
Boiler, industrial	50kW	1731 (0.0878 kg/MJ)	0.078 (0.0000039 kg/MJ)	0.058 (0.0000029 kg/MJ)
Pellet stove, residential		1731 (0.0878 kg/MJ)	1.11 (0.000056 kg/MJ)	0.071 (0.0000037 kg/MJ)
	Source	*Based on carbon and moisture content of wood pellets*	*Johansson et al., 2004*	*Swiss Centre for Life Cycle Inventories et al., 2008*

B.8 Waste management

The only solid waste from wood combustion is ash. Currently, ash from institutional boilers is deposited at the municipal landfill. Residential consumers usually spread ash in their gardens.

There are two grades of pellets, Premium and Standard. Standard grade pellets produce less than 3% ash, while Premium pellets produce less than 1% ash (Arctic, 2010). Most pellets produced in western Canada exceed the Premium standard.

In this study, it is assumed that 1% ash is produced from pellets combustion. The amount of ash from firewood and wood chips combustion is also assumed to be 1%. All ash from institutional boilers is deposited to the municipal landfill. Dataset for disposal of wood ash to the municipal landfill originates from the Ecoinvent database (Swiss Centre for Life Cycle Inventories et al., 2008).

Plastic bags from bagged pellets for residential use are not recycled at the moment. It is assumed that all plastic bags end up at the municipal landfill. The disposal of plastic bags to the municipal landfill dataset is taken from the Ecoinvent database (Swiss Centre for Life Cycle Inventories et al., 2008).

APPENDIX C

BIOENERGY AND FOSSIL FUEL ENERGY DATA

Location/city	Total amount of energy	Wood	Fuel oil	Wood	Fuel oil	Wood Pellets	Fuel oil
[7]	(MJ)	% of Energy		Energy (MJ)		Tonnes	Million Liters
Wekweti	**19,000,000**	**9**	**36**	**1,710,000**	**684,000,000**	**86.80**	**18**
Homes		100	40	1,710,000	273,600,000	86.80	7
Other Buildings		0	60	0	410,400,000	0.00	11
Sachs Harbour	**31,000,000**	**0**	**46**	**0**	**1,426,000,000**	**0.00**	**37**
Homes			40	0	570,400,000	0.00	15
Other Buildings			60	0	855,600,000	0.00	22
Ulukhaktok	**70,000,000**	**0**	**51**	**0**	**3,570,000,000**	**0.00**	**93**
Homes		0	45	0	1,606,500,000	0.00	42
Other Buildings			55	0	1,963,500,000	0.00	51
Paulatuk	**39,000,000**	**0**	**59**	**0**	**2,301,000,000**	**0.00**	**60**
Homes		0	40	0	920,400,000	0.00	24
Other Buildings			60	0	1,380,600,000	0.00	36
Tuktoyaktuk	**190,000,000**	**2**	**25**	**3,800,000**	**4,750,000,000**	**192.89**	**124**
Homes		100	50	3,800,000	2,375,000,000	192.89	62
Other Buildings		0	50	0	2,375,000,000	0.00	62
Tsiigehtchic	**29,000,000**	**4**	**46**	**1,160,000**	**1,334,000,000**	**58.88**	**35**
Homes		100	40	1,160,000	533,600,000	58.88	14
Other Buildings		0	60	0	800,400,000	0.00	21

[7]Energy profiles of communities from the Arctic Energy Alliance Resource map http://www.aea.nt.ca/resources/map/. Energy content of heating oil = 38.4 MJ per liter, Heat content of wood pellets = 19,700 MJ per tonne.

Location/city	**Total amount of energy**	**Wood**	**Fuel oil**	**Wood**	**Fuel oil**	**Wood Pellets**	**Fuel oil**
[7]	**(MJ)**	**% of Energy**		**Energy (MJ)**		**Tonnes**	**Million Liters**
Colville Lake	**17,000,000**	**15**	**20**	**2,550,000**	**340,000,000**	**129.44**	**9**
Homes		100	45	2,550,000	153,000,000	129.44	4
Other Buildings		0	55	0	187,000,000	0.00	5
Fort Good Hope	**100,000,000**	**8**	**36**	**8,000,000**	**3,600,000,000**	**406.09**	**94**
Home		100	45	8,000,000	1,620,000,000	406.09	42
Other buildings		0	55	0	1,980,000,000	0.00	52
INUVIK	**1,000,000,000**	**2**	**9**	**20,000,000**	**9,000,000,000**	**1,015.23**	**234**
Homes		100	60	20,000,000	5,400,000,000	1,015.23	141
Other Buildings		0	40	0	3,600,000,000	0.00	94
AKLAVIK	**100,000,000**	**1**	**46**	**1,000,000**	**4,600,000,000**	**50.76**	**120**
Homes		100	50	1,000,000	2,300,000,000	50.76	60
Other Buildings		0	50	0	2,300,000,000	0.00	60
FORT McPHERSON	**310,000,000**	**1**	**70**	**3,100,000**	**21,700,000,000**	**157.36**	**565**
Homes		100	50	3,100,000	10,850,000,000	157.36	283
Other Buildings		0	60	0	13,020,000,000	0.00	339
Norman wells	**370,000,000**	**3**	**5**	**11,100,000**	**1,850,000,000**	**563.45**	**48**
Homes		100	100	11,100,000	1,850,000,000	563.45	48
Other Buildings		0	0	0	0	0.00	0

Location/city	**Total amount of energy**	**Wood**	**Fuel oil**	**Wood**	**Fuel oil**	**Wood Pellets**	**Fuel oil**
[7]	**(MJ)**	**% of Energy**		**Energy (MJ)**		**Tonnes**	**Million Liters**
Tutlita	**96,000,000**	**5**	**39**	**4,800,000**	**3,744,000,000**	**243.65**	**98**
Homes		100	45	4,800,000	1,684,800,000	243.65	44
Other Buildings		0	55	0	2,059,200,000	0.00	54
Deline	**96,000,000**	**6**	**38**	**5,760,000**	**3,648,000,000**	**292.39**	**95**
Homes		100	45	5,760,000	1,641,600,000	292.39	43
Other Buildings		0	55	0	2,006,400,000	0.00	52
GAMETI	**34,000,000**	**10**	**37**	**3,400,000**	**1,258,000,000**	**172.59**	**33**
Homes		100	45	3,400,000	566,100,000	172.59	15
Other Buildings		0	55	0	691,900,000	0.00	18
WRIGLEY	**27,000,000**	**11**	**29**	**2,970,000**	**783,000,000**	**150.76**	**20**
Homes		100	50	2,970,000	391,500,000	150.76	10
Other Buildings		0	50	0	391,500,000	0.00	10
WHA TI	**47,000,000**	**10**	**33**	**4,700,000**	**1,551,000,000**	**238.58**	**40**
Homes		100	45	4,700,000	697,950,000	238.58	18
Other Buildings		0	55	0	853,050,000	0.00	22
BEHCHOKO	**250,000,000**	**6**	**41**	**15,000,000**	**10,250,000,000**	**761.42**	**267**
Homes		100	50	15,000,000	5,125,000,000	761.42	133
Other Buildings		0	50	0	5,125,000,000	0.00	133
FORT SIMPSON	**450,000,000**	**4**	**32**	**18,000,000**	**14,400,000,000**	**913.71**	**375**

Location/city	Total amount of energy	Wood	Fuel oil	Wood	Fuel oil	Wood Pellets	Fuel oil
[7]	(MJ)	% of Energy		Energy (MJ)		Tonnes	Million Liters
Homes		99	26	17,820,000	3,744,000,000	904.57	98
Other Buildings		1	74	180,000	10,656,000,000	9.14	278
DETTAH	**27,000,000**	**11**	**27**	**2,970,000**	**729,000,000**	**150.76**	**19**
Homes		100	60	2,970,000	437,400,000	150.76	11
Other Buildings		0	40	0	291,600,000	0.00	8
LUTSELK'E	**50,000,000**	**6**	**39**	**3,000,000**	**1,950,000,000**	**152.28**	**51**
Homes		100	47	3,000,000	916,500,000	152.28	24
Other Buildings		0	53	0	1,033,500,000	0.00	27
FORT RESOLUTION	**75,000,000**	**7**	**52**	**5,250,000**	**3,900,000,000**	**266.50**	**102**
Homes		100	72	5,250,000	2,808,000,000	266.50	73
Other Buildings		0	28	0	1,092,000,000	0.00	28
FORTH PROVIDENCE	**122,000,000**	**8**	**26**	**9,760,000**	**3,172,000,000**	**495.43**	**83**
Homes		100	60	9,760,000	1,903,200,000	495.43	50
Other Buildings		0	40	0	1,268,800,000	0.00	33
JEAN MARIE RIVER	**13,000,000**	**9**	**25**	**1,170,000**	**325,000,000**	**59.39**	**8**
Homes		100	50	1,170,000	162,500,000	59.39	4
Other Buildings		0	50	0	162,500,000	0.00	4

Location/city [7]	**Total amount of energy**	**Wood**	**Fuel oil**	**Wood**	**Fuel oil**	**Wood Pellets**	**Fuel oil**
	(MJ)	**% of Energy**		**Energy (MJ)**		**Tonnes**	**Million Liters**
NAHANNI BUTTE	**18,000,000**	**14**	**22**	**2,520,000**	**396,000,000**	**127.92**	**10**
Homes		100	49	2,520,000	194,040,000	127.92	5
Other Buildings		0	51	0	201,960,000	0.00	5
KAKISA	**9,000,000**	**13**	**28**	**1,170,000**	**252,000,000**	**59.39**	**7**
Homes		100	58	1,170,000	146,160,000	59.39	4
Other Buildings		0	42	0	105,840,000	0.00	3
HAY RIVER	**840,000,000**	**5**	**19**	**42,000,000**	**15,960,000,000**	**2,131.98**	**416**
Homes		100	75	42,000,000	11,970,000,000	2,131.98	312
Other Buildings		0	25	0	3,990,000,000	0.00	104
FORT LIARD	**75,000,000**	**11**	**9**	**8,250,000**	**675,000,000**	**418.78**	**18**
Homes		100	58	8,250,000	391,500,000	418.78	10
Other Buildings		0	42	0	283,500,000	0.00	7
TROUT LAKE	**17,000,000**	**15**	**22**	**2,550,000**	**374,000,000**	**129.44**	**10**
Homes		100	45	2,550,000	168,300,000	129.44	4
Other Buildings		0	55	0	205,700,000	0.00	5
ENTERPRISE	**18,000,000**	**7**	**58**	**1,260,000**	**1,044,000,000**	**63.96**	**27**
Homes		100	60	1,260,000	626,400,000	63.96	16
Other Buildings		0	40	0	417,600,000	0.00	11

Location/city	**Total amount of energy**	**Wood**	**Fuel oil**	**Wood**	**Fuel oil**	**Wood Pellets**	**Fuel oil**
[7]	**(MJ)**	**% of Energy**		**Energy (MJ)**		**Tonnes**	**Million Liters**
FORT SMITH	**530,000,000**	**5**	**54**	**26,500,000**	**28,620,000,000**	**1,345.18**	**745**
Homes		100	50	26,500,000	14,310,000,000	1,345.18	373
Other Buildings		0	50	0	14,310,000,000	0.00	373
Totals for regions outside Yellowknife				**213,450,000**	**148,186,000,000**	**10,835.03**	**3859**
Total for homes outside Yellowknife				**213,270,000**	**76,337,450,000**	**10,825.89**	**1988**
Totals for other building outside Yellowknife				**180,000**	**71,848,550,000**	**9.14**	**1871**

APPENDIX D

GHG ASSESSMENT RESULTS

Table D.1 GHG assessment results for firewood at residential, advanced technology, catalytic stove.

	GWP, 1996, kg CO_2-e			GWP, 2007, kg CO_2-e		
Residential						
	Total	***Combustion***	***Firewood production***	***Total***	***Combustion***	***Firewood production***
Carbon dioxide, biogenic	9.17E-02	9.17E-02	3.41E-06	9.17E-02	9.17E-02	3.41E-06
Carbon dioxide, fossil	8.65E-04	0.00E+00	8.65E-04	8.65E-04	0.00E+00	8.65E-04
Methane, biogenic	8.84E-03	8.84E-03	3.99E-08	1.05E-02	1.05E-02	4.75E-08
Methane, fossil	7.92E-05	0.00E+00	7.92E-05	9.43E-05	0.00E+00	9.43E-05
Nitrous oxide	3.02E-03	3.01E-03	1.70E-05	2.91E-03	2.89E-03	1.63E-05
TOTAL	**1.05E-01**	**1.04E-01**	**9.65E-04**	**1.06E-01**	**1.05E-01**	**9.79E-04**
TOTAL biogenic CO_2	**9.17E-02**	**9.17E-02**	**3.41E-06**	**9.17E-02**	**9.17E-02**	**3.41E-06**
TOTAL fossil[8]	**1.28E-02**	**1.18E-02**	**9.61E-04**	**1.44E-02**	**1.34E-02**	**9.76E-04**

Table D.2 GHG assessment results for firewood at residential, conventional technology stove.

	GWP, 1996, kg CO_2-e			GWP, 2007, kg CO_2-e		
	Total	***Combustion***	***Firewood production***	***Total***	***Combustion***	***Firewood production***
Carbon dioxide, biogenic	9.17E-02	9.17E-02	3.41E-06	9.17E-02	9.17E-02	3.41E-06
Carbon dioxide, fossil	8.65E-04	0.00E+00	8.65E-04	8.65E-04	0.00E+00	8.65E-04
Methane, biogenic	1.92E-02	1.92E-02	3.99E-08	2.29E-02	2.29E-02	4.75E-08
Methane, fossil	7.92E-05	0.00E+00	7.92E-05	9.43E-05	0.00E+00	9.43E-05
Nitrous oxide	3.02E-03	3.01E-03	1.70E-05	2.91E-03	2.89E-03	1.63E-05
TOTAL	**1.15E-01**	**1.14E-01**	**9.65E-04**	**1.18E-01**	**1.17E-01**	**9.79E-04**
TOTAL biogenic CO_2	**9.17E-02**	**9.17E-02**	**3.41E-06**	**9.17E-02**	**9.17E-02**	**3.41E-06**
TOTAL fossil	**2.32E-02**	**2.22E-02**	**9.61E-04**	**2.67E-02**	**2.58E-02**	**9.76E-04**

[8] Total fossil category includes biogenic methane emissions.

Table D.3 GHG assessment results for wood chips at industrial boiler 50KW.

	GWP, 1996, kg CO_2-e				GWP, 2007, kg CO_2-e			
	Total	***Combustion***	***Wood chips production***	***Ash disposal***	***Total***	***Combustion***	***Wood chips production***	***Ash disposal***
Carbon dioxide, biogenic	1.28E-01	1.27E-01	8.93E-04	1.10E-06	1.28E-01	1.27E-01	8.93E-04	1.10E-06
Carbon dioxide, fossil	8.41E-04	0.00E+00	8.33E-04	7.87E-06	8.41E-04	0.00E+00	8.33E-04	7.87E-06
Methane, biogenic	2.17E-05	1.84E-05	1.91E-07	3.17E-06	2.59E-05	2.19E-05	2.27E-07	3.78E-06
Methane, fossil	6.64E-05	0.00E+00	6.64E-05	0.00E+00	7.90E-05	0.00E+00	7.90E-05	0.00E+00
Nitrous oxide	1.19E-03	1.16E-03	2.60E-05	5.77E-08	1.14E-03	1.12E-03	2.50E-05	5.54E-08
TOTAL	**1.30E-01**	**1.28E-01**	**1.82E-03**	**1.22E-05**	**1.30E-01**	**1.28E-01**	**1.83E-03**	**1.28E-05**
TOTAL biogenic CO_2	**1.28E-01**	**1.27E-01**	**8.93E-04**	**1.10E-06**	**1.28E-01**	**1.27E-01**	**8.93E-04**	**1.10E-06**
TOTAL fossil	**2.12E-03**	**1.18E-03**	**9.26E-04**	**1.11E-05**	**2.09E-03**	**1.14E-03**	**9.37E-04**	**1.17E-05**

Table D.4 GHG assessment results for wood chips at industrial boiler 300KW.

	GWP, 1996, kg CO_2-e				GWP, 2007, kg CO_2-e			
	Total	***Combustion***	***Wood chips production***	***Ash disposal***	***Total***	***Combustion***	***Wood chips production***	***Ash disposal***
Carbon dioxide, biogenic	1.25E-01	1.24E-01	8.93E-04	1.10E-06	1.25E-01	1.24E-01	8.93E-04	1.10E-06
Carbon dioxide, fossil	8.41E-04	0.00E+00	8.33E-04	7.87E-06	8.41E-04	0.00E+00	8.33E-04	7.87E-06
Methane, biogenic	1.36E-05	1.02E-05	1.91E-07	3.17E-06	1.62E-05	1.22E-05	2.27E-07	3.78E-06
Methane, fossil	6.64E-05	0.00E+00	6.64E-05	0.00E+00	7.90E-05	0.00E+00	7.90E-05	0.00E+00
Nitrous oxide	9.72E-04	9.46E-04	2.60E-05	5.77E-08	9.34E-04	9.09E-04	2.50E-05	5.54E-08
TOTAL	**1.27E-01**	**1.25E-01**	**1.82E-03**	**1.22E-05**	**1.27E-01**	**1.25E-01**	**1.83E-03**	**1.28E-05**
TOTAL biogenic CO_2	**1.25E-01**	**1.24E-01**	**8.93E-04**	**1.10E-06**	**1.25E-01**	**1.24E-01**	**8.93E-04**	**1.10E-06**
TOTAL fossil	**1.89E-03**	**9.56E-04**	**9.26E-04**	**1.11E-05**	**1.87E-03**	**9.21E-04**	**9.37E-04**	**1.17E-05**

Table D.5 GHG assessment results for wood pellets bulk imported from AB, at industrial boiler 50kW.

	GWP, 1996, kg CO_2-e					**GWP, 2007, kg CO_2-e**				
	Total	***Combustion***	***Wood pellets production, bulk***	***Transport***	***Ash disposal***	***Total***	***Combustion***	***Wood pellets production, bulk***	***Transport***	***Ash disposal***
Carbon dioxide, biogenic	9.44E-02	8.78E-02	6.55E-03	1.29E-05	8.44E-07	9.44E-02	8.78E-02	6.55E-03	1.29E-05	8.44E-07
Carbon dioxide, fossil	1.14E-02	0.00E+00	4.58E-03	4.40E-03	6.07E-06	1.14E-02	0.00E+00	4.58E-03	4.40E-03	6.07E-06
Methane, biogenic	9.81E-05	8.19E-05	1.32E-05	3.89E-07	2.46E-06	1.17E-04	9.75E-05	1.57E-05	4.64E-07	2.93E-06
Methane, fossil	1.99E-04	0.00E+00	1.97E-04	2.81E-06	0.00E+00	1.99E-04	0.00E+00	2.34E-04	3.35E-06	0.00E+00
Nitrous oxide	1.14E-03	8.99E-04	1.58E-04	4.67E-05	4.43E-08	1.10E-03	8.64E-04	1.52E-04	4.48E-05	4.26E-08
TOTAL	**1.07E-01**	**8.88E-02**	**1.15E-02**	**4.46E-03**	**9.42E-06**	**1.07E-01**	**8.88E-02**	**1.15E-02**	**4.46E-03**	**9.88E-06**
TOTAL biogenic CO_2	**9.44E-02**	**8.78E-02**	**6.55E-03**	**1.29E-05**	**8.44E-07**	**9.44E-02**	**8.78E-02**	**6.55E-03**	**1.29E-05**	**8.44E-07**
TOTAL fossil	**1.28E-02**	**9.81E-04**	**4.95E-03**	**4.45E-03**	**8.57E-06**	**1.28E-02**	**9.62E-04**	**4.98E-03**	**4.45E-03**	**9.04E-06**

Table D.6 GHG assessment results for wood pellets bagged imported from AB, at residential stove.

	GWP, 1996, kg CO_2-e						
	Total	***Combustion***	***Wood pellets production, bagged***	***Transport***	***Polyethelene bag production***	***Ash disposal***	***Bag disposal***
Carbon dioxide, biogenic	9.44E-02	8.78E-02	6.55E-03	1.29E-05	2.30E-06	8.44E-07	1.87E-08
Carbon dioxide, fossil	9.27E-03	0.00E+00	4.58E-03	4.40E-03	2.80E-04	6.07E-06	5.84E-06
Methane, biogenic	1.19E-03	1.18E-03	1.32E-05	3.89E-07	3.70E-07	2.46E-06	2.35E-10
Methane, fossil	1.99E-04	0.00E+00	1.97E-04	2.81E-06	0.00E+00	0.00E+00	0.00E+00
Nitrous oxide	1.35E-03	1.15E-03	1.58E-04	4.67E-05	4.37E-09	4.43E-08	1.94E-08
TOTAL	**1.06E-01**	**9.01E-02**	**1.15E-02**	**4.46E-03**	**2.83E-04**	**9.42E-06**	**5.88E-06**
TOTAL biogenic CO_2	**9.44E-02**	**8.78E-02**	**6.55E-03**	**1.29E-05**	**2.30E-06**	**8.44E-07**	**1.87E-08**
TOTAL fossil	**1.20E-02**	**2.32E-03**	**4.95E-03**	**4.45E-03**	**2.80E-04**	**8.57E-06**	**5.86E-06**

Table D.7 GHG assessment results for wood pellets bagged imported from AB, at residential stove.

	GWP, 2007, kg CO_2-e						
	Total	*Combustion*	*Wood pellets production, bulk*	*Transport*	*Polyethelene bag production*	*Ash disposal*	*Bag disposal*
Carbon dioxide, biogenic	9.44E-02	8.78E-02	6.55E-03	1.29E-05	2.30E-06	8.44E-07	1.87E-08
Carbon dioxide, fossil	9.27E-03	0.00E+00	4.58E-03	4.40E-03	2.80E-04	6.07E-06	5.84E-06
Methane, biogenic	1.42E-03	1.40E-03	1.57E-05	4.64E-07	4.40E-07	2.93E-06	2.80E-10
Methane, fossil	2.37E-04	0.00E+00	2.34E-04	3.35E-06	0.00E+00	0.00E+00	0.00E+00
Nitrous oxide	1.30E-03	1.10E-03	1.52E-04	4.48E-05	4.20E-09	4.26E-08	1.87E-08
TOTAL	**1.07E-01**	**9.03E-02**	**1.15E-02**	**4.46E-03**	**2.83E-04**	**9.88E-06**	**5.88E-06**
TOTAL biogenic CO_2	**9.44E-02**	**8.78E-02**	**6.55E-03**	**1.29E-05**	**2.30E-06**	**8.44E-07**	**1.87E-08**
TOTAL fossil	**1.22E-02**	**2.50E-03**	**4.98E-03**	**4.45E-03**	**2.80E-04**	**9.04E-06**	**5.86E-06**

Table D.8 GHG assessment results for wood pellets bagged imported from BC, at residential stove.

GWP, 1996, kg CO_2-e							
	Total	***Combustion***	***Wood pellets production, bagged***	***Transport***	***Polyethelene bag production***	***Ash disposal***	***Bag disposal***
Carbon dioxide, biogenic	9.44E-02	8.78E-02	6.55E-03	2.77E-05	2.30E-06	8.44E-07	1.87E-08
Carbon dioxide, fossil	1.43E-02	0.00E+00	4.58E-03	9.43E-03	2.80E-04	6.07E-06	5.84E-06
Methane, biogenic	1.19E-03	1.18E-03	1.32E-05	8.38E-07	3.70E-07	2.46E-06	2.35E-10
Methane, fossil	1.99E-04	0.00E+00	1.97E-04	2.81E-06	0.00E+00	0.00E+00	0.00E+00
Nitrous oxide	1.40E-03	1.15E-03	1.58E-04	9.69E-05	4.37E-09	4.43E-08	1.94E-08
TOTAL	**1.11E-01**	**9.01E-02**	**1.15E-02**	**9.56E-03**	**2.83E-04**	**9.42E-06**	**5.88E-06**
TOTAL biogenic CO_2	**9.44E-02**	**8.78E-02**	**6.55E-03**	**2.77E-05**	**2.30E-06**	**8.44E-07**	**1.87E-08**
TOTAL fossil	**1.71E-02**	**2.32E-03**	**4.95E-03**	**9.53E-03**	**2.80E-04**	**8.57E-06**	**5.86E-06**

Table D.9 GHG assessment results for wood pellets bagged imported from BC, at residential stove.

GWP, 2007, kg CO_2-e							
	Total	***Combustion***	***Wood pellets production, bulk***	***Transport***	***Polyethelene bag production***	***Ash disposal***	***Bag disposal***
Carbon dioxide, biogenic	9.44E-02	8.78E-02	6.55E-03	2.77E-05	2.30E-06	8.44E-07	1.87E-08
Carbon dioxide, fossil	1.43E-02	0.00E+00	4.58E-03	9.43E-03	2.80E-04	6.07E-06	5.84E-06
Methane, biogenic	1.42E-03	1.40E-03	1.57E-05	9.98E-07	4.40E-07	2.93E-06	2.80E-10
Methane, fossil	2.37E-04	0.00E+00	2.34E-04	3.35E-06	0.00E+00	0.00E+00	0.00E+00
Nitrous oxide	1.35E-03	1.10E-03	1.52E-04	9.31E-05	4.20E-09	4.26E-08	1.87E-08
TOTAL	**9.44E-02**	**8.78E-02**	**6.55E-03**	**2.77E-05**	**2.30E-06**	**8.44E-07**	**1.87E-08**
TOTAL biogenic CO_2	**9.58E-02**	**8.92E-02**	**6.57E-03**	**2.87E-05**	**2.74E-06**	**3.77E-06**	**1.90E-08**
TOTAL fossil	**1.73E-02**	**2.50E-03**	**4.98E-03**	**9.53E-03**	**2.80E-04**	**9.04E-06**	**5.86E-06**

Table D.10 GHG assessment results for heating oil, at industrial boiler.

	GWP, 1996, kg CO_2-e			GWP, 2007, kg CO_2-e		
	Total	***Combustion***	***Upstream***	***Total***	***Combustion***	***Upstream***
Carbon dioxide, biogenic	4.99E-04	0.00E+00	4.99E-04	4.99E-04	0.00E+00	4.99E-04
Carbon dioxide, fossil	8.70E-02	7.05E-02	1.65E-02	8.70E-02	7.05E-02	1.65E-02
Methane, biogenic	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Methane, fossil	2.71E-03	5.92E-05	2.65E-03	3.22E-03	7.05E-05	3.15E-03
Nitrous oxide	3.13E-04	9.61E-05	2.17E-04	3.01E-04	9.24E-05	2.09E-04
TOTAL	**9.05E-02**	**7.07E-02**	**1.99E-02**	**9.10E-02**	**7.07E-02**	**2.04E-02**
TOTAL biogenic CO_2	**4.99E-04**	**0.00E+00**	**4.99E-04**	**4.99E-04**	**0.00E+00**	**4.99E-04**
TOTAL fossil	**9.00E-02**	**7.07E-02**	**1.94E-02**	**9.05E-02**	**7.07E-02**	**1.99E-02**

Table D.11 GHG assessment results for wood pellets bulk NWT, at industrial boiler 50kW.

GWP, 1996, kg CO_2-e						
	Total	***Combustion***	***Wood harvesting***	***Transport***	***Wood pellet production (electricity)***	***Ash disposal***
Carbon dioxide, biogenic	8.78E-02	8.78E-02	1.13E-06	2.44E-06	3.14E-06	8.44E-07
Carbon dioxide, fossil	5.97E-03	0.00E+00	1.76E-04	8.97E-04	4.89E-03	6.07E-06
Methane, biogenic	8.44E-05	8.19E-05	0.00E+00	4.61E-08	1.48E-06	2.46E-06
Methane, fossil	2.21E-04	0.00E+00	4.20E-05	2.75E-06	1.77E-04	0.00E+00
Nitrous oxide	9.22E-04	8.99E-04	3.72E-07	1.21E-05	1.06E-05	4.43E-08
TOTAL	**9.50E-02**	**8.88E-02**	**2.20E-04**	**9.14E-04**	**5.08E-03**	**9.42E-06**
TOTAL biogenic CO_2	**8.78E-02**	**8.78E-02**	**1.13E-06**	**2.44E-06**	**3.14E-06**	**8.44E-07**
TOTAL fossil	**7.19E-03**	**9.81E-04**	**2.18E-04**	**9.12E-04**	**5.08E-03**	**8.57E-06**

Table D.12 GHG assessment results for wood pellets bulk NWT, at industrial boiler 50kW.

GWP, 2007, kg CO_2-e						
	Total	***Combustion***	***Wood harvesting***	***Transport***	***Wood pellet production (electricity)***	***Ash disposal***
Carbon dioxide, biogenic	8.78E-02	8.78E-02	1.13E-06	2.44E-06	3.14E-06	8.44E-07
Carbon dioxide, fossil	5.97E-03	0.00E+00	1.76E-04	8.97E-04	4.89E-03	6.07E-06
Methane, biogenic	1.00E-04	9.75E-05	0.00E+00	5.49E-08	1.76E-06	2.93E-06
Methane, fossil	2.63E-04	0.00E+00	5.00E-05	3.28E-06	2.10E-04	0.00E+00
Nitrous oxide	8.86E-04	8.64E-04	3.58E-07	1.17E-05	1.02E-05	4.26E-08
TOTAL	**9.50E-02**	**8.88E-02**	**2.27E-04**	**9.14E-04**	**5.12E-03**	**9.88E-06**
TOTAL biogenic CO_2	**8.78E-02**	**8.78E-02**	**1.13E-06**	**2.44E-06**	**3.14E-06**	**8.44E-07**
TOTAL fossil	**7.22E-03**	**9.62E-04**	**2.26E-04**	**9.12E-04**	**5.11E-03**	**9.04E-06**

Table D.13 GHG assessment results for wood pellets bagged NWT, at residential stove.

GWP, 1996, kg CO_2-e										
	Total	***Combustion***	***Wood harvesting***	***Transport***	***Polyethelene bag production***	***Wood pellet production (electricity)***	***Ash disposal***	***Bag disposal***	***Ash disposal***	***Bag disposal***
Carbon dioxide, biogenic	8.78E-02	8.78E-02	1.13E-06	2.44E-06	2.30E-06	3.14E-06	8.44E-07	1.87E-08	8.44E-07	1.87E-08
Carbon dioxide, fossil	6.25E-03	0.00E+00	1.76E-04	8.97E-04	2.80E-04	4.89E-03	6.07E-06	5.84E-06	6.07E-06	5.84E-06
Methane, biogenic	1.18E-03	1.18E-03	0.00E+00	4.55E-08	3.70E-07	1.48E-09	2.46E-06	2.35E-10	2.93E-06	2.80E-10
Methane, fossil	2.21E-04	0.00E+00	4.20E-05	2.75E-06	0.00E+00	1.77E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Nitrous oxide	1.17E-03	1.15E-03	3.72E-07	1.21E-05	4.37E-09	1.06E-05	4.43E-08	1.94E-08	4.26E-08	1.87E-08
TOTAL	**9.66E-02**	**9.01E-02**	**2.20E-04**	**9.14E-04**	**2.83E-04**	**5.08E-03**	**9.42E-06**	**5.88E-06**	**9.88E-06**	**5.88E-06**
TOTAL biogenic CO_2	**8.78E-02**	**8.78E-02**	**1.13E-06**	**2.44E-06**	**2.30E-06**	**3.14E-06**	**8.44E-07**	**1.87E-08**	**8.44E-07**	**1.87E-08**
TOTAL fossil	**8.82E-03**	**2.32E-03**	**2.18E-04**	**9.12E-04**	**2.80E-04**	**5.08E-03**	**8.57E-06**	**5.86E-06**	**8.82E-03**	**2.32E-03**

Table D.14 GHG assessment results for wood pellets bagged NWT, at residential stove.

GWP, 2007, kg CO_2-e								
	Total	***Combustion***	***Wood harvesting***	***Transport***	***Polyethelene bag production***	***Wood pellet production (electricity)***	***Ash disposal***	***Bag disposal***
Carbon dioxide, biogenic	8.78E-02	8.78E-02	1.13E-06	2.44E-06	2.30E-06	3.14E-06	8.44E-07	1.87E-08
Carbon dioxide, fossil	6.25E-03	0.00E+00	1.76E-04	8.97E-04	2.80E-04	4.89E-03	6.07E-06	5.84E-06
Methane, biogenic	1.40E-03	1.40E-03	0.00E+00	5.42E-08	4.40E-07	1.76E-09	2.93E-06	2.80E-10
Methane, fossil	2.63E-04	0.00E+00	5.00E-05	3.28E-06	0.00E+00	2.10E-04	0.00E+00	0.00E+00
Nitrous oxide	1.12E-03	1.10E-03	3.58E-07	1.17E-05	4.20E-09	1.02E-05	4.26E-08	1.87E-08
TOTAL	**9.69E-02**	**9.03E-02**	**2.27E-04**	**9.14E-04**	**2.83E-04**	**5.11E-03**	**9.88E-06**	**5.88E-06**
TOTAL biogenic CO_2	**8.78E-02**	**8.78E-02**	**1.13E-06**	**2.44E-06**	**2.30E-06**	**3.14E-06**	**8.44E-07**	**1.87E-08**
TOTAL fossil	**9.04E-03**	**2.50E-03**	**2.26E-04**	**9.12E-04**	**2.80E-04**	**5.11E-03**	**9.04E-06**	**5.86E-06**

Table D.15 Black and organic carbon assessment results for Koch et al, 2007.

	kg CO_2 e /MJ			
	BC LL	**BC UL**	**OC LL**	**OC UL**
Wood pellets	0.00838	0.03909	-0.00362	-0.01663
Heating oil	0.00085	0.00085	-0.00001	-0.00001
Firewood	0.01006	0.04695	-0.00435	-0.01998
Wood chips	0.01086	0.05066	-0.00470	-0.02155

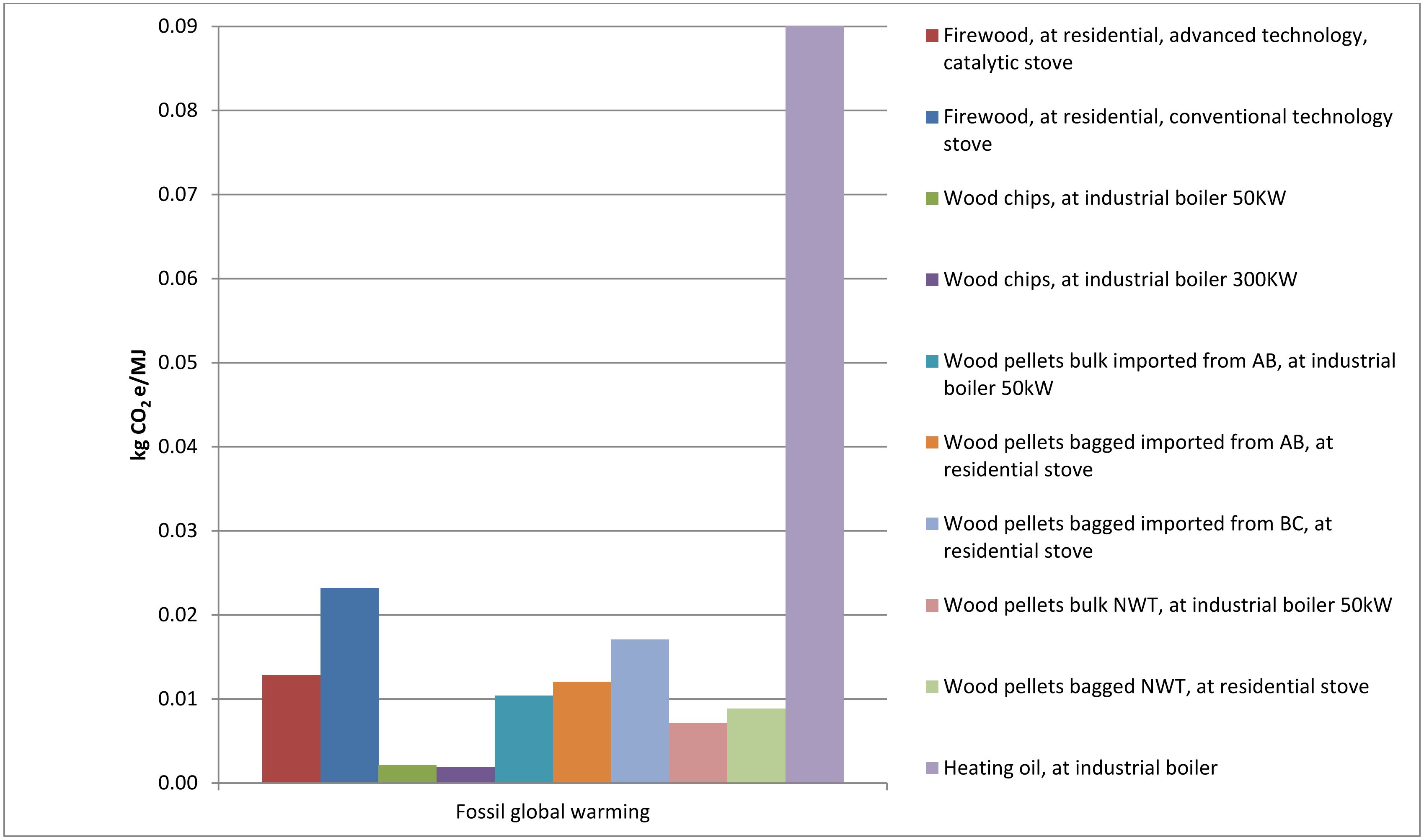

Figure D.1 Comparison of all scenarios under study.