Fire with fire

REACHING THE PARIS TARGETS: PYROGENIC CARBON CAPTURE & STORAGE FOR COMBINED BIOCHAR & HEAT PRODUCTION IN THE CANADIAN NORTH

by

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to

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Abstract

Residents of Northwest Territories (NWT, Canada) are amongst the most affected by the climate crisis, with heating rates 2-3 times as high as the global average, affecting infrastructures and livelihoods. Despite good intentions, harsh environmental conditions make decarbonizing hot water and space heating a challenge due to solar-dark winters and limited options.

This thesis explores existing literature on Pyrogenic Carbon Capture and Storage (Pyro-CCS) in the NWT context and its influencing factors including feedstocks; biochar and its stability as a climate mitigation measure; post-fire forest dynamics; and briefly explores the inclusion of Indigenous and Traditional Knowledge into this suggested carbon-negative bioenergy source. This thesis then investigates the carbon footprint, land use, and broader sustainability of Pyro-CCS from wood pellets and locally-harvested fire-killed trees (FKT) as a low-carbon heat source in NWT. Biogenic emissions factors are employed in a high-level carbon footprint assessment methodology.

The results demonstrate that Pyro-CCS from FKT offers a remarkable environmental advantage over other common heating sources. With a carbon footprint of -10.3 g CO_2 eq. MJ^{-1} (from FKT), and 40.9 g CO_2 eq. MJ^{-1} (from imported wood pellets), Pyro-CCS outperforms heating oil (83.1 g), propane (89.9 g), natural gas (79.4 g), and biomass combustion (59.7 g) in terms of greenhouse gas emissions. Decarbonization scenarios are explored, showcasing the potential for the region to achieve carbon-negative space heating through the adoption of Pyro-CCS with FKT, using only a mere 2% of the annual fire-killed areas, and thus promising a sustainable and renewable biomass source.

This research underscores the potential economic feasibility of Pyro-CCS from FKT and calls for further federal, territorial, and municipal research and development support in order to deploy it at scale.

Résumé

Les résidents des Territoires du Nord-Ouest (TNO, Canada) sont parmi les plus touchés par la crise climatique, avec une augmentation des températures de 2 à 3 fois plus élevées que la moyenne mondiale, affectant le quotidien et les infrastructures. Malgré de bonnes intentions, les conditions environnementales font de la décarbonisation du chauffage (eau chaude et espaces) un défi en raison des hivers sombres et des alternatives qui sont limitées.

Cette thèse explore la littérature existante sur la capture et le stockage du carbone pyrogénique (Pyro-CCS) dans les TNO et ses facteurs d'influence, notamment des matières entrantes; le biocharbon et sa stabilité en tant que mesure d'atténuation des changements climatique; la dynamique des forêts après les incendies; et explore brièvement l'inclusion de savoirs traditionnels et autochtones dans cette source de bioénergie carbone-négative qui est explorée. Cette thèse étudie ensuite l'empreinte carbone, l'utilisation des terres et la durabilité de la Pyro-CCS à partir de granules de bois, et à partir d'arbres de feux de forêts (AFF) récoltés localement comme source de chaleur à faible teneur en carbone dans les TNO. Des facteurs d'émissions biogéniques sont utilisés dans une méthodologie d'analyse de cycle de vie (ACV) de haut niveau.

Les résultats démontrent un avantage remarquable de la Pyro-CCS à partir d'AFF par rapport à d'autres sources de chauffage courantes. Avec -10,3 g CO_2 eq. MJ^{-1} (à partir d'AFF), et 40,9 g CO_2 eq. MJ^{-1} (à partir de granules de bois importées), la Pyro-CCS surpasse le mazout (83,1 g), le propane (89,9 g), le gaz naturel (79,4 g) et la combustion de biomasse (59,7 g) en termes d'émissions de gaz à effet de serre. Des scénarios de décarbonisation sont proposés, mettant en évidence la possibilité de parvenir à un chauffage carbone-négatif dans la région grâce à l'adoption de la Pyro-CCS à partir d'AFF, en n'utilisant que 2 % des surfaces annuelles brûlées, promettant ainsi une source d'énergie renouvelable et durable.

Cette recherche souligne la faisabilité économique potentielle de la Pyro-CCS à partir d'AFF et appelle à un soutien supplémentaire pour de la recherche et du développement aux niveaux fédéral, territorial et municipal afin d'accélérer son déploiement à grande échelle.

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It is through exchanges and conversations that I decided to study biochar and climate mitigation— some were very short but sent me on the right path, others remain ongoing over text, video, or beer : Thomas Hoffman and colleagues at Carbofex (pasta-sausage-ketchup, that'll do!), Edvard Hamilton (he picked me up in the smallest train station in Sweden— probably one square meter— and drove me very fast in his electric car to his solar-and-biochar farm, where I stayed the night), Stockholm Vatten and Jonas Dahllöf, Dr Mikhail Smilovic (I remember Park Avenue and the Bixi station). Conversations with Dr Shiv Prasher and Dr Grant Clark at the MacDonald Campus informed my interests. Listening to the Métis National Council's Dane de Souza's stories opened my eyes about the climate- and wildfire-mitigation potential of Pyro-CCS.

Although we never met, it is somehow through Doug Richie's endowment fund that I learned about Pyro-CCS, and I extend this gratitude to loving-but-troublesome France Benoit— please make some space in your garden and rally up your neighbors for the first Pyro-CCS plant in Yellowknife— and Craig Scott. Also to Kristel Derkowski for participating and falling for the early Pyro-CCS schemes.

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Lastly, but more importantly I would like to recognize the McGill legacy over the last two centuries. It is humbling to be part of such a respected institution— it was an honor to be admitted to this program and I hope to have contributed to the furthering and elevation of McGill's name and legacy, and the partial repair of some of the historical wrongs. Once no longer a student, I will be a proud alumni.

Any omissions, errors and mistakes throughout this entire text remain entirely and exclusively mine.

Land acknowledgement

This work and the rationale behind it emerged through conversations with, and through time spent with and on the Lands of the Yellowknives Dene First Nation, and the Homelands of the North Slave Métis Alliance, since I relocated to Yellowknife, Northwest Territories in 2017. The writing of this thesis was also partly completed on the territory of the Ta'an Kwäch'än Council and the Kwanlin Dün First Nation (Whitehorse, Yukon).

McGill University (Tiohtiá:ke/Montreal) is situated on the traditional territory of the Kanien'kehà:ka, a place which has long served as a site of meeting and exchange amongst many First Nations including the Kanien'kehá:ka of the Haudenosaunee Confederacy, Huron/Wendat, Abenaki, and Anishinaabeg. I recognize and respect the Kanien'kehà:ka as the traditional custodians of the lands and waters on which McGill University sits today.

This thesis and the continuation of my work are my best-informed efforts at Reconciliation and Decolonization— here in Canada, and abroad— and my expression of commitment to the protection of our Lands, Water, Air and Climate.

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List of abbreviations

CAD — Canadian Dollar

CCS — Carbon Capture and Storage

CH_4 — Methane

CHP — Combined Heat and Power

DES — District Energy System

EUR — Euro

FKT — Fire-Killed Trees

GHG — Greenhouse Gas Emissions

GJ — Gigajoule

GNWT — Government of Northwest Territories

GoC — Government of Canada

GWP — Global Warming Potential

GWP_{bio} — Biogenic Global Warming Potential

IPCC — Intergovernmental Panel on Climate Change

kg — Kilogram

L — Liter

LCA — Life Cycle Analysis

LCI — Life Cycle Inventory

LCIA — Life Cycle Inventory Assessment

MJ — Megajoule

NET — Negative Emissions Technology

NT — Northwest Territories

NWT — Northwest Territories

PJ — Petajoule

Pyro-CCS — Pyrogenic Carbon Capture & Storage

QC — Quebec

UNFCCC — United Nations Framework Convention on Climate Change

USD — United States Dollar

Organization of thesis

This research is organized in the following fashion:

Chapter 1* — *Introduction highlights the impetus for this research and introduces the topics at hand.

***Chapter 2* —** *Literature review* presents the literature review and briefly discusses the topics involved in this research.

Chapter 3 — *Manuscript* presents the most important findings from this research in the format of a journal article.

***Chapter 4* —** *Discussion* expands on the meaning of the results and on influencing factors.

Supplementary Information presents additional information that might be useful to the reader to gain additional perspectives.

References are collected into a single bibliography at the end of the thesis, and numbering is continuous throughout the document. The information presented in this text follows the International System of Units (SI), and English Canadian spelling. Formatting style is based on McGill University's *Graduate and Postdoctoral Studies' Thesis Guidelines* but is adjusted by author for readability and accessibility.

Chapter 1 — Introduction

1. The climate emergency

Due to a phenomenon called polar warming amplification, the poles are seeing climate change progress at 2-3 times the rate of the global mean surface temperature (1). Whereas the planet has warmed by 1.2°C to date, Northwest Territories (NWT), a region in Canada's North, has observed on average 2.8°C of warming. It is felt the most intensely in the winter, where temperatures are on average 5.1°C warmer than 75 years ago (2). Residents of NWT (Northerners) are experiencing climate impacts more acutely than residents in other jurisdictions.

The 2014 *Summer of Smoke* was the worst wildfire season in at least three decades. Nearly 34,000 km^2 burned, leaving Northerners exposed to unabating wildfire smoke for 2.5 months, doubling emergency room asthma-related admissions (3, 4). Increased temperatures represent a shortening of the window of operation for ice roads, which is now a liability for Northerners dependent on those roads for the transport of food, fuel and building materials to otherwise fly-in-only communities (5) (Figure 1A). The boreal forest of NWT is becoming a net greenhouse gas source due to the increasing occurrence, severity and frequency of wildfire events (6): the 2014 wildfire (Figure 1B) burned through 34,000 km^2 of forest land (7). Inuvialuit in Aklavik, Northwest Territories reported a decline in beluga population (*Delphinapterus leucas*) (8) and Kugluktumiut (Kugluktut, Nunavut) have reported a decline in caribou herds (9)— which corroborates findings for climate change impacts on biodiversity loss (10). Thawing permafrost is causing roads, parking lots, and building foundations to shift and crack (11), with an estimated 40 to 75% of buildings in the Inuvik region at risk of foundation damage in coming decades (12) (Figure 1C). In the last years, Northerners have seen significant floods in the Deh Cho region (Figure 1D) and in Hay River (13), as well as several cars and trucks fell through ice roads (14). These impacts have led several residents to express feelings of solastalgia, or anxiety related to place-based environmental changes (15).

***1A:** Truck plunges through ice road in Déline̜, Northwest Territories in 2016 (16)*

***1B:** 2014 "Summer of Smoke" in Northwest Territories, Canada (17)*

***1C:** Coastal erosion in Tuktoyaktuk, Northwest Territories. After a heavy storm in 2019, one meter of shore was lost to the sea (18)*

***1D:** Aerial photo of the 2021 floods in Fort Simpson, Northwest Territories (19)*

Figure 1: Impacts of climate change in NWT communities.

Communities throughout the North are increasingly equipping themselves with clean air shelters (20), wildfire protection plans, all-weather roads and better drainage and flood management capacity to adapt to climate change. However, the speed of change is outpacing capacity to adapt (21). Although the various levels of government express intentions to decarbonize across sectors, current targets are not aligned with global efforts to keep global warming below 1.5 °C (22), and observed reductions in emissions fail to meet existing targets. This is not only due to a lack of political leadership— but also because of the high costs of decarbonizing cold, harsh environments. Northerners are in a bind, affected more than most by climate change but with the least avenues to act.

2. Decarbonizing Northern Canada

1.1. Current emissions profile in Northwest Territories

2.1.1. An economy heavily reliant on fossil fuels

Simultaneously to those climate impacts, Northerners are highly dependent on diesel for electricity production, heating oil for space heating and jet fuel for transportation, and they have the highest annual per capita greenhouse gas emissions of all Canadian Territories at 28.1 tons of carbon dioxide equivalents (CO_2 eq.). This positions them at the high end of average emissions for an affluent country, and 43 % above the national average (23).

Northerners depend heavily on mineral extraction for economic development. Forty-six percent of emissions in 2019 came from the industrial sector and 34 % from the transportation sector, which is heavily tied to the industrial sector. Space heating in NWT was responsible for 17 % of greenhouse gas emissions in 2013, with 253 kilotons of CO_2 eq.

2.1.2. Space and hot water heating are responsible for a third of emissions

Yellowknife, the capital of NWT, presents more than 8,000 heating degree-days, nearly double the requirements in “cold” cities like Montreal, Québec (24). Communities are powered primarily through electricity generators with limited throttle capacity— meaning that they generally consume the same amount of fuel even if the electrical demand is reduced. The Northwest Territories' grid carbon intensity decreased from 185 g per kWh in 2017 to 174 in 2021 (25), which is higher than the national average of 110 g per kWh (23). Quebec, on the other hand, produces electricity at 1.5 g per kWh (23). Yellowknife is considered a "hydro community" due to its access to hydroelectricity, but it relies heavily on diesel electricity from December to March. The Northwest Territories Power Corporation (NTPC) has been reducing the share of hydroelectricity generation in the Inuvik region and transitioning to liquefied natural gas (25). Biomass, mainly imported wood pellets, is increasingly used for space heating, with over 20 MW utilized in 2015 (26). However, heating oil is still the primary fuel source for most buildings in the Beaufort Delta and Sahtu regions (27).

The Government of Northwest Territories (GNWT) has committed to reducing their GHG emissions by 30 % below 2005 levels before 2030 (28)— about half the reduction needed to keep warming below 1.5 °C (22). The GNWT aims to meet these targets using bioenergy, but the carbon performance of these systems is unclear (29, 30). The GNWT has been actively promoting the production of low-carbon pellets in the territory to increase economic and energy independence (28), but many say it is mostly political posturing as an economic development opportunity.

1.2. Existing solutions technically feasible but financially prohibitive

Remoteness and harsh climatic conditions make it difficult to find climate-friendly alternatives to heating, electricity production and transportation in NWT and the Canadian North (31). Solar energy is a limited option during the winter— in Yellowknife, for example, the average solar irradiance in December is 0.14 kWh/m^2/day, while it climbs to 6.22 kWh/m^2/day in July (32).

The low amount of solar energy available in the wintertime would require larger systems to provide the same amount of energy or seasonal energy storage capacity. Wind is starting to be used by some communities, but faces delay and cost challenges (33).

2.2.1. All solutions still technically feasible, just at a cost premium

Various jurisdictions in Southern Canada are embracing the "electrify everything" motto, but electricity-based space heating poses challenges in NWT due to high electricity costs of 35 ¢ per kWh (34). In comparison, Quebec purchases electricity at 7 ¢ per kWh, while the average in Canada is 18 ¢ (35). Heat pumps become ineffective below -15 °C, limiting their use during the cold season (36). Additionally, electricity storage in lithium batteries is costly and faces seasonality issues due to limited solar availability in winter (31). Although models suggest compressed air energy storage (36) and hydrogen energy storage could be viable under Arctic conditions with a four-year payback (37), no real-life pilot studies have been conducted. Geothermal energy has garnered interest in NWT, but previous attempts were deemed expensive (38). Discussions on geothermal energy and district energy systems resurface regularly in municipal councils and working groups (39), but costs often hinder progress. Biodiesel remains unpopular in NWT due to lack of education, perceived environmental impacts, and cost premiums (40). Synthetic fuel production through direct air capture and electrolysis of water faces challenges in terms of pricing, energy requirements, and limited prototypes (41). Northerners need a cost-competitive, low-carbon energy production solution.

Eliminating greenhouse gas emissions is a moral obligation for Northerners, who also have a personal stake in it. The unique challenges they face call for innovative climate solutions tailored to the Arctic context (42). As we fall short of our climate targets, the need for negative emissions technologies becomes increasingly urgent alongside decarbonization efforts. Certain sectors, such as agriculture and aviation, may prove harder to decarbonize, potentially resulting in residual emissions that will need to be mitigated in net-zero 2050 scenarios (43, 44).

1.3. A potential solution: Pyrogenic Carbon Capture & Storage

During a personal research trip in 2019, I visited several Pyrogenic Carbon Capture and Storage (Pyro-CCS) projects in Tampere (Finland), in Stockholm and Hällekis (Sweden) and in Rehburg (Germany). I started wondering if Pyro-CCS could deliver on the promise of a viable low-carbon energy source in NWT. This trip became the impetus for this research.

Pyro-CCS works as follows: biomass is pyrolyzed in a low-oxygen environment, producing bio-oil, biogas and biochar. The bio-oil and biogas are burned to produce heat, which can be used for local or district heating. Some reactors are designed to let the bio-oil condense for underground carbon storage or future energy production (45). Other reactors burn the biogases generated immediately to produce additional heat

(46). The pyrolysis process itself is endothermic, meaning that the reaction requires a heat input. The combustion of the bio-oil and biogas produced provides the heat required for the reaction to continue— although this causes a release of greenhouse gas emissions.

Biochar— a product like charcoal— is collected and stored. It has a variety of uses and is lauded as a promising solution to the climate crisis for its ability to sequester carbon, to increase forest soil fertility, and to increase agriculture yields. Biochar characteristics are highly dependent on the feedstock properties and pyrolysis conditions; influencing environmental and agricultural factors such as nitrogen retention, crop yields and others (47). Heating rate, chamber temperature and residence time affect the quality and quantity of biochar, bio-oil and biogas produced (48-54). Biochar is not a new technology: Indigenous communities in the Amazon have used pyrolysis for centuries to increase the fertility of otherwise nutrient-poor soils (55).

Pyro-CCS can use any carbonaceous biomass as a feedstock. Those include but are not limited to hardwood, softwood, rice hulls, switchgrass (56), bagasse (57), straw (56), crop wastes (56), sewage sludge (58), short rotation woody energy crops (59), and manure (60).

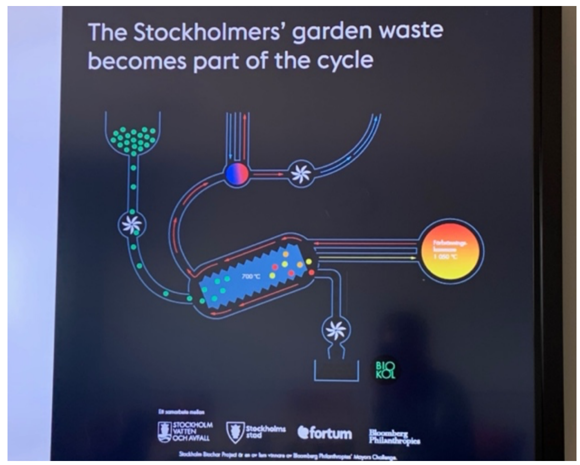
2A: *Biochar. With permission (61).*

2B: *Biochar-amended concrete block. Author photo.*

2C: *Sampo Tukiainen, then Carbofex CEO and Kim Lehiö, in Hiedanranta, Tampere, Finland. Author photo.*

2D: *Biochar bags stored outside next to a barn with a Pyro-CCS machine at the Hjelmsäters Egendom farm owned by Edvard Hamilton near Hällekis, Sweden. Author photo.*

2E: *Visiting the Stockholm Pyro-CCS project by Stockholm Vatten. Author photo.*



2F*: Infographic at Stockholm Biochar. Stockholmers are encouraged to bring garden waste and Christmas trees to the Pyro-CCS plant in exchange for a free bag of biochar. Author photo.*

Figure 2: Pyro-CCS projects in Finland and Sweden.

2.3.1. Pyro-CCS for space heating and climate mitigation

Space heating is one of the largest components of carbon footprint in the far north. Pyro-CCS is a promising technology that could provide low-carbon heating fuels and biochar as a valuable by-product. Conventional biomass is often used as a feedstock in Pyro-CCS, but harvesting these feedstocks can have unintended environmental consequences (62). Biomass from fire-killed trees (FKT) may provide a sustainable alternative to conventional biomass. There are immense reserves of FKT in NWT, with 34,000 km^2 burned during the 2014 *Summer of Smoke* alone (63).

Despite the huge opportunity of using FKTs as a feedstock in Pyro-CCS towards space heating, we still lack basic knowledge of the technical and economic feasibility of this technology in NWT.

3. Rationale and objectives of the research

Climate change presents the biggest health threat of the 21st century, and its effects are felt more deeply by Northerners. The climate crisis is not about polar bears in the Arctic in 2050— it is about Yellowknifers expecting another smoky summer and having difficulty breathing.

Despite those realities, it remains difficult for Northerners to decarbonize in a financially competitive way due to high heating needs and harsh environmental conditions.

Pyro-CCS appears to be a potentially cost-competitive heating source compared to currently used energy sources in NWT. However, a few unknowns remain— these are the questions that this thesis is aiming to answer:

- What is the carbon footprint of Pyro-CCS in Yellowknife, NT?
- To what extent can Pyro-CCS decarbonize space heating in NWT and what are the land use and financial implications of Pyro-CCS under various decarbonization scenarios?

To answer these questions we performed a carbon footprinting analysis as well as a land-use estimation and high-level financial assessment. These allowed us to determine the climate impact of Pyro-CCS in NWT, evaluate its sustainability and determine the barriers to its large-scale deployment.

Connecting text

Chapter 1 — *Introduction* presented the topic at hand (Pyrogenic Carbon Capture & Storage using fire-killed biomass as a feedstock in Northwest Territories) and highlights the objectives of the research (produce a carbon footprint analysis of this technology compared to currently used options) and the questions left to answer.

Chapter 2 — *Literature review* presents an overview of relevant topics regarding this technology and identifies literature gaps.

Chapter 2 — Literature review

Chapter overview

This chapters presents an overview of literature on Pyro-CCS, pyrolysis and its history, and the different products issued from pyrolysis. The carbon and energy contents of bio-oil, bio-gas and biochar are explored, with a deeper dive on the carbon sequestration potential of biochar and its stability as a climate solution. Then, the reader will learn about the factors influencing the outcome of the pyrolysis process, including temperature, residence time, feedstock selection, and others.

We then cover aspects of Life-Cycle Analysis and Carbon Footprinting, and consider how to include biogenic emissions from biomass, as well as how to select an appropriate accounting method.

Then, we look at wildfire and forestry trends including necromass and forest post-fire conditions, including potential climate mitigation strategies, inspired from Indigenous ways of living on and managing the Land.

Lastly, we identify the knowledge gaps that this research will pursue.

Summary of Relevant Findings

- Pyro-CCS uses biomass feedstock to produce biogas, bio-oil and biochar; (56)
- Researchers recommend using longer timeframes for life-cycle analysis for a better depiction of actual impacts (30, 64-66);
- A 100-year timeframe seems to be a reasonably conservative analysis period (64) since forests are expected to regrow in a shorter time frame (66);
- Biochar degrades very slowly once applied to soils (0.004 % per day) (67);
- There seems to be growing consensus on the need to include biogenic emissions in life-cycle analyses (68-73);
- Researchers recommend the use of a global warming potential (GWP) of somewhere between 0 and 0.7 for biogenic emissions (30) as opposed to 1 for fossil emissions;
- Forest fire severity and frequency is increasing;
- Biochar amendments to soils presents a climate mitigation opportunity (56, 74-76);

1. What is Pyrogenic Carbon Capture & Storage (Pyro-CCS)?

Pyro-CCS involves the heating of biomass under no- or low-oxygen conditions, causing it to break down and release volatile compounds. Feedstocks are mostly made of carbon, hydrogen and oxygen (77). The volatile gases that are a result of the pyrolysis process are burned for heat; the bio-oil generated in the process is kept for underground carbon storage, or for heat generation by combustion (48). Biochar is the material left over once the reaction is complete. Each by-product is covered in this section.

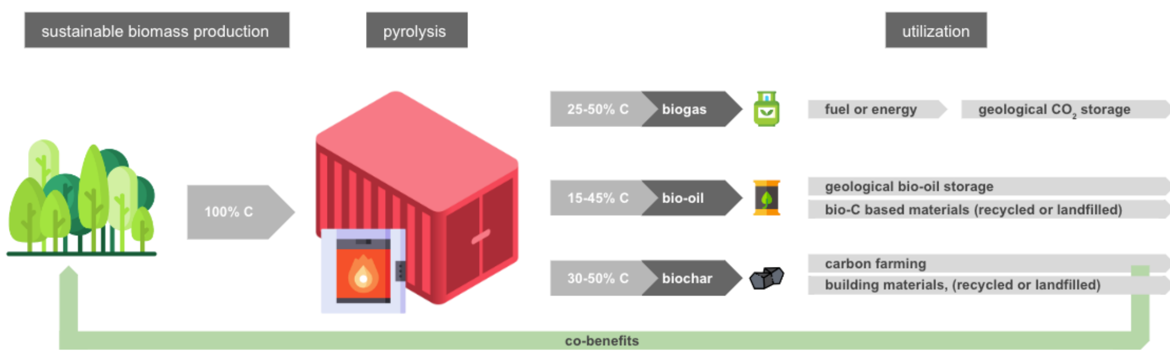


Figure 3: Carbon flow in the context of Pyro-CCS. Adapted from (48), icons by (78)

1.1 The three stages of the chemical process of pyrolysis

Pyrolysis typically occurs in three stages. It is a chemical process that involves the thermal decomposition of organic materials in the absence of oxygen (79). In the first stage, organic materials such as wood, agricultural waste, or plastics are heated to high temperatures, typically between 300°C and 900°C, in an environment with no or with limited[1] oxygen supply, and water and volatile organic compounds are released. In the second stage, the primary pyrolysis stage, the material decomposes into smaller molecules, including gases such as methane, carbon monoxide, and hydrogen, as well as liquid tar and bio-oil (48). In the final stage, the remaining biomass converts to char.

[1] Tests were conducted with oxygen contents ranging from 0 to 11% (80)— some found optimum biochar yield at 2.3% oxygen (81).

The composition and characteristics of the char depend on the feedstock and pyrolysis conditions (56). As a result, the material breaks down into smaller molecules, which includes gases, liquids, and solids. The specific products of pyrolysis depend on the temperature, heating rate, and residence time of the process (79).

1.2 History of pyrolysis

The word pyrolysis comes from the Greek words *pyro*, meaning fire, and *lysis*, meaning to break apart. It is not a new technology: it was used by the ancient Greeks and Romans to produce charcoal for heating and cooking, as well as for the production of iron and other metals (82). In the 18th and 19th centuries, pyrolysis was used as part of the process to produce town gas, a fuel made by heating coal in the absence of air, a process that starts with pyrolysis, followed by gasification (83). Pyrolysis transforms carbonaceous materials (like biomass) into gas, tar and char, also currently known as biogas, bio-oil and biochar, respectively. The further transformation of the outputs of biochar into gases is called gasification.

During the 20th century, pyrolysis became an important part of the process for generation of the feedstocks for the production of synthetic rubber, plastics, and other petrochemical products (84). During World War II for example, it was used to produce synthetic rubber when natural rubber supplies were cut off (85). Since then, pyrolysis has been used to produce a wide range of feedstocks that are then used in the generation of biofuels, chemicals, and carbon black.

Pyrolysis is seen as a promising technology for converting waste materials such as biomass, plastics, and tires into biofuels and other valuable products, while also sequestering carbon in the resulting biochar (86) or offering lower-carbon alternative fuels (87). The last two decades have seen an acceleration of research and development surrounding pyrolysis (88).

1.3 Pyrolysis products

Research and industry experience has proven that the by-products of pyrolysis can be used in a myriad of ways (60, 82, 89-97). Figure 4 demonstrates the avenues for commercial utilization.

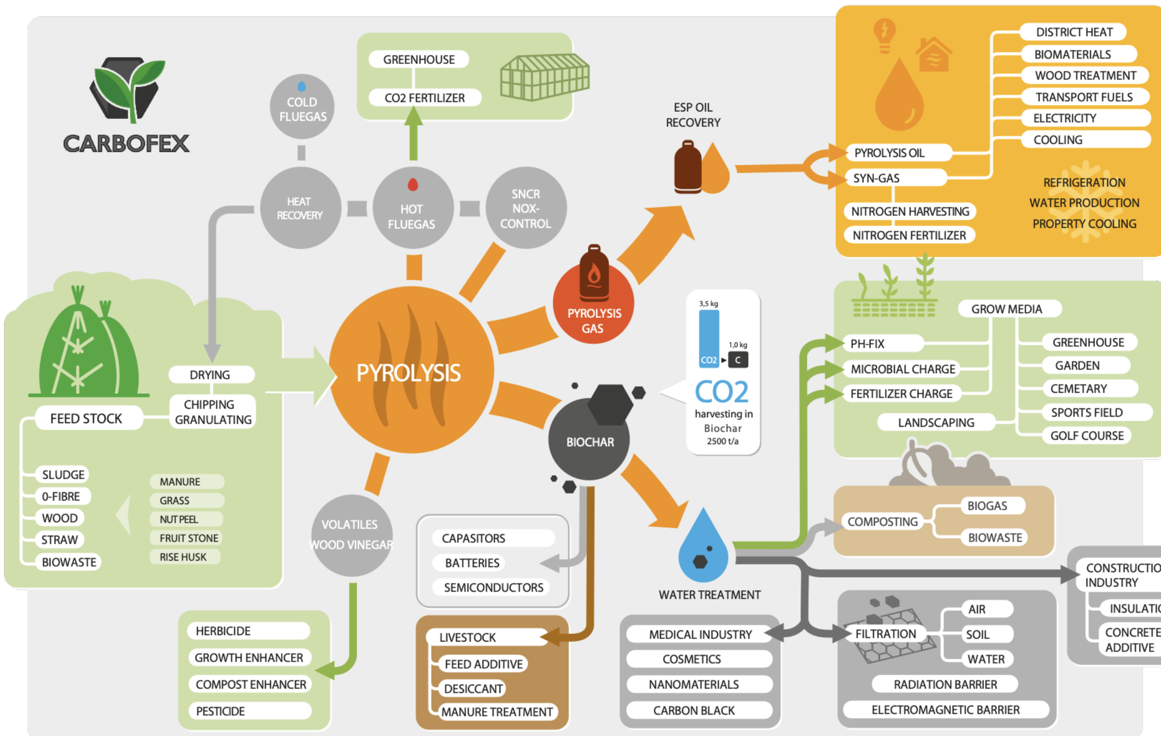


Figure 4: Pyrolysis Market Options and Potential Biochar Uses[2] (45)

1.3.1. Carbon and energy distribution of the products

Bio-oil typically contains around 25-50% of the carbon in the feedstock and can be used as a renewable fuel or as a feedstock for the production of chemicals and other high-value products (48). Biogas contains about 15-45% of the carbon in the feedstock, whereas biochar represents 30 to 50% of the total amount of carbon in the feedstock (Figure 3).

1.3.2. Carbon contents of outputs

The distribution of energy between the pyrolysis products is dependent on various factors, including the heating value of the feedstock, the efficiency of the pyrolysis process, and the quality of the products produced. Biochar typically has a low energy

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[2] Used with permission.

content and is not used as an energy source during or after the pyrolysis process. Table 1 depicts the energy distribution of biochar, biogas and bio-oil from the pyrolysis of different feedstocks.

1.3.3. Energy content of outputs

Table 1: Higher heating value (MJ/kg daf) of biomass and component pyrolysis products[3] (98)

	Higher heating value				Energy distribution (%)		
	Biomass	Char	Liquids	Gas[a]	Char	Liquids	Gas
Biomass							
Coir pith	19.5	25.0	18.7	16.1	37.9	28.3	33.9
Corn cob	16.1	28.6	23.8	05.2	35.6	49.4	15.0
Groundnut shell	19.8	27.4	23.6	10.0	37.5	44.7	17.9
Rice husk	20.0	44.2	22.5	07.4	38.3	46.2	15.5
Wood	20.0	24.1	24.9	16.6	23.4	28.3	48.3
De-ashed biomass							
Coir pith	-	26.2	22.3	9.9	42.1	41.4	16.6
Corn cob	-	26.4	24.2	5.0	21.2	65.2	13.7
Groundnut shell	-	29.8	21.8	6.2	41.2	50.5	08.3
Rice husk	-	31.0	19.5	6.6	37.9	56.1	06.0
Wood	-	24.2	28.5	11.3	16.5	57.3	26.2
Components							
Cellulose	11.7	32.4	16.2	01.3	30.8	64.6	04.5
Lignin	24.1	33.3	28.7	08.2	57.7	31.9	10.4
Xylan	30.4	32.3	22.5	37.6	22.0	30.0	48.0

[a]Gas yield and heating value obtained by difference

1.3.4. Biogas

Biogas produced from pyrolysis typically contains carbon monoxide, methane, carbon dioxide, water vapor, hydrogen and small amounts of other gases such as nitrogen oxides (48). It can be combusted for heating and electricity generation. Its combustion releases carbon dioxide and other gases; its carbon footprint is therefore influenced by the origin of the feedstock.

1.3.5. Bio-oil

Bio-oil is a dark brown, viscous liquid that contains a complex mixture of organic compounds. The exact composition of bio-oil depends on the type of feedstock that is

[3] Adapted from (98)

used and the conditions under which it is pyrolyzed. Typically, bio-oil contains several compounds that can be classified as follows (99):

- organic acids: may include acetic acid, formic acid, and levulinic acid;
- oxygenated compounds: aldehydes, ketones, and esters.
- hydrocarbons including alkanes, alkenes, and aromatics— these hydrocarbons contribute to the energy content of bio-oil;
- nitrogen-containing compounds: amines and amides.
- phenols and aromatic compounds: contributing to its color and aromatic properties.

Additionally, bio-oil may contain other minor components, including water, tars, and trace elements, which can further influence its characteristics. The composition of bio-oil is highly feedstock-dependent.

1.3.6. Energy content

Bio-oil has a high energy density and can be used as a fuel for heating (Figure 5) and electricity generation— the calorific density depends on several conditions and has been measured between 13 to 38 MJ/kg (100, 101). For comparison, diesel and natural gas have a calorific density of 45 MJ/kg (102) and 55 MJ/kg (102), respectively.

Analytical techniques of bio-oil contents

The composition of bio-oil can be analyzed using a variety of analytical techniques such as gas chromatography-mass spectrometry (GC-MS), Fourier transform infrared spectroscopy (FTIR), and nuclear magnetic resonance (NMR) spectroscopy (103). Understanding the composition of bio-oil is essential for optimizing the pyrolysis process and for developing applications for the resulting bio-oil, and optimizing marketability.

1.3.7. Bio-oil uses & limitations

However, its use is limited by its high acidity, high viscosity, and high water content. In some contexts, bio-oil is used for carbon sequestration and storage (90). Carbofex, the Finnish company visited by the author in 2019 has a history of collecting and storing bio-oil (Figure 6) for deep underground carbon storage. It is shipped from Finland to Kansas, United States where it is buried in depleted natural oil reservoirs (104).

Bio-oil is a complex mixture with a diverse range of compounds, and its composition can vary depending on the feedstock and pyrolysis conditions. It is challenging to handle and process (105), and precautions need to be taken during its utilization and refinement (106).

Figure 5: *Bio-oil combustion connected to a local district energy system (DES) in Hiedanranta, Tampere, Finland. Author photo.*

Figure 6: *Bio-oil containers at the Carbofex facility in Hiedanranta, Tampere, Finland. Author photo.*

1.3.8. Biochar

Biochar is a solid material that is produced during the pyrolysis of biomass. It is a porous, carbon-rich material that can be used as a soil amendment (60, 107-109).

It can be used in various sectors with more than 50 documented uses (89), including agriculture (109, 110), forestry, mining remediation (94, 97), and energy production (30), to reduce greenhouse gas emissions and improve soil health (97).

In agriculture, biochar can be used as a soil amendment to improve soil fertility, water holding capacity, and nutrient retention (60). It has been shown to increase crop yields and reduce fertilizer use (56, 60). The addition of biochar to soil can also enhance carbon sequestration, as it is a stable form of carbon that can remain in the soil for hundreds or even thousands of years (56, 67, 108-113).

In forestry, biochar can be used to improve forest health (114) and reduce the risk of wildfires through the use of “ladder fuels” as feedstock for its production (115). It can be applied to soils to increase water retention and alleviate droughts (96) and reduce soil erosion (116), as well as to mitigate greenhouse gas emissions by sequestering carbon.

Researchers at McGill have demonstrated biochar's ability to remove pollutants from water run-off and improve urban forestry (93, 117).

Biochar has been used for water treatment, where it can remove pollutants from water and soil including but not limited to mercury, zinc, lead, copper, cadmium, chromium, arsenic, magnesium (93, 118-121). It has been shown to be effective at removing phosphate and potassium from water, while the charged, value-added biochar acted as a fertilizer (94).

Biochar doesn't lack potential uses that could be deployed in NWT or our neighbour Alberta— but it might still be in early stages of development and might require additional investments before demand is high enough to insure financial viability of Pyro-CCS in Northwest Territories.

2. What is Biochar?

2.1. Terra Preta— not a new technology

Terra Preta is a type of dark, nutrient-rich soil found in the Amazon rainforest that has been used by Indigenous communities for thousands of years for agricultural purposes (55). The term "Terra Preta" means "black earth" in Portuguese, and the soil is characterized by its high levels of organic matter and carbon, as well as its ability to retain water and nutrients. The origin of Terra Preta is still not entirely clear, but it is believed to have been created by ancient Amazonian civilizations who enriched the soil with biochar, a type of charcoal produced by pyrolyzing organic materials such as plant waste and animal bones (55).

2.1.1. Physical properties of biochar

Biochar is a black, porous solid material produced by pyrolysis. Its physical characteristics depend on factors such as the feedstock used, pyrolysis conditions, and post-processing methods (48). Generally, it has a high surface area and porosity (122), which makes it effective for use in a variety of applications (89). It is primarily composed of carbon, minerals, and ash (123). The ash content of biochar can range from less than 1 % to over 50 %, with most of the ash consisting of minerals such as calcium, potassium, magnesium, and phosphorus. The carbon content of biochar is typically between 65 % and 90 %, and the chemical structure of the carbon can vary depending on the pyrolysis temperature and residence time (108, 124).

2.2. Biochar carbon sequestration potential

Biochar has gained interest amongst the climate community in the last two decades as a material that could be used in climate mitigation strategies (30, 56, 67, 74-76, 89, 91, 107, 108, 110, 125-129) . Researchers demonstrated that biochar amendment in boreal forests in Scandinavia does not cause a change in carbon dioxide effluxes from the soil, nor changes the native soil carbon stocks (114). They experimented with 0, 5 and 10 tons of biochar per hectare of boreal forest (114). Their final analysis suggest that the use of biochar amendment in boreal forests can be used as a climate mitigation tool (114).

2.2.1. Biochar is generally highly stable

Research suggests that wood-derived biochar decomposes at a rate of 0.004% per day, whereas crops-derived biochar decomposes at 0.025% per day (67). Higher pyrolysis temperatures (> 375°C) represent higher decomposition rates than lower pyrolysis temperatures (200-375°C) (67). The addition of biochar to soils can lead to positive priming (kickstarting respiration in soils) but generally still represents carbon sequestration— researchers reported that “apparently moderate biochar amendments do not cause large increases in soil respiration” (114). Ninety-seven per cent (97%) of biochar can persist in soils on a centennial scale, and oxygen depletion increases the mean residence time (MRT) of biochar in soils (67). Biochar degrades faster in water-unsaturated soils, or in alternating unsaturated-saturated soils than in saturated soils (67).

Biochar degrades very slowly into CO_2 in soils, and mostly remains as carbon, but producing biochars with high physical strengths can slow down their migration to other layers or their likelihood of becoming oxidized or degraded (125).

2.2.2. Lack of consistency or methodology for characterization

It is observed that there are currently no consistent methodology, protocol or index to measure biochar carbon stability in soils (130). This was also a concern shared by government researchers, although research, equipment capacity and funding capacity for the characterization of biochar has been increasing in recent years (131).

3. Pyrolysis characteristics

3.1 Fast Pyrolysis, Slow Pyrolysis

The main difference between fast and slow pyrolysis is the heating rate and the residence time of the feedstock in the pyrolysis reactor.

Fast pyrolysis is a high-temperature process (typically 450-550°C) that heats the feedstock rapidly, usually within seconds (0.5 to 5 seconds), to vaporize the organic material (132). The resulting vapors are then rapidly cooled to bio-oil, leaving behind a small amount of solid char and non-condensable gases such as methane, carbon monoxide, and hydrogen. Fast pyrolysis is typically used to produce bio-oil for biofuels or chemicals (133, 134).

Slow pyrolysis, on the other hand, can be a process happening at a lower temperature (typically 300-500°C) that heats the feedstock slowly, typically over several hours (5 to 80 K min^{-1}) (135). In slow pyrolysis, the organic material is thermally decomposed in the absence of oxygen, resulting in a higher yield of biochar and a lower yield of bio-oil. Slow pyrolysis is commonly used for soil improvement, as the resulting biochar has a high surface area and can be used as a soil amendment to improve water retention, nutrient availability, and microbial activity (56, 124, 125, 134).

3.2 Factors influencing the outcome of the pyrolysis process

The pyrolysis process can be affected by several factors, including temperature, particle size, residence time, and feedstock characteristics (48). These factors can impact the composition of the resulting bio-oil, biogas, and biochar (48).

Higher pyrolysis temperatures typically result in more biochar and less bio-oil and biogas. Low pyrolysis temperatures (350-450°C) produce the highest amount of biochar although with a lower carbon stability. Higher temperatures (700-850°C) produce larger amounts of pyrogas (48).

The size of the biomass particles can impact the pyrolysis process and the composition of the resulting products. Smaller particle sizes typically result in faster heating rates and higher yields of bio-oil and biogas. Larger particle sizes can result in more biochar and less bio-oil and biogas (48).

The residence time, or the amount of time that the biomass is exposed to heat during the pyrolysis process, can impact the composition of the resulting products. Longer residence times can result in more biochar and less bio-oil and biogas. Shorter residence times can result in more bio-oil and biogas and less biochar (48).

The characteristics of the feedstock, such as its moisture content, chemical composition, and density, can impact the pyrolysis process and the composition of the resulting products. Feedstocks with high moisture content can require more energy to dry, while feedstocks with high lignin content can result in higher yields of biochar.

Table 2: Influence of pyrolysis characteristics on the by-products

Factor	Outcome on biochar	Source
Lower temperatures	Higher yield	(49-51)
Higher temperatures	Higher stability	(52-54)
Higher particle size	Higher yield, higher stability	(49, 52)
Slower heating rate	Higher yield, higher stability	(48, 52)
Higher residence time	Higher yield, higher stability	(48, 52)
Higher lignin content	Higher yield, higher stability	(49, 52)

3.3 Feedstocks

There are many feedstock options for pyrolysis, and the feedstock selection is likely to impact the carbon footprint of the overall process.

Woody biomass can be used— this includes trees, shrubs, and woody plants (126). Woody biomass is often used in pyrolysis because it has a high energy density and is readily available.

Any agricultural residues can be used for pyrolysis. This includes straw and plant stalks, as well as animal waste such as poultry litter and manure (127) can be used. “Energy crops” such as switchgrass and miscanthus have a quick growth interval and therefore could demonstrate a more beneficial overall carbon footprint when used as part of a process of pyrolysis (56, 59).

Municipal and solid waste including household waste, commercial waste, and industrial waste can be used as a feedstock for Pyro-CCS (136). In the context of NWT where waste recycling is often left as an afterthought, or not done at all, this might present as a financially interesting option. Northerners produce on average 0.66 tons of waste per capita annually, and most of it is not recycled, with 0.62 tons per capita ending up in a landfill (137).

The feedstock selection influences the generation of by-products (heat, biochar, bio-oil and biogas) in pyrolysis. For example, feedstocks with high lignin content can result in higher yields of biochar. Humidity content plays a role: wet feedstocks can require more energy to dry, which can reduce the efficiency of the process and the amount of heat generated (138). The size of the biomass particles can impact the heating rate and the composition of the resulting products (139, 140). Smaller particle sizes can result in higher yields of bio-oil and biogas (141), whereas biochar yield increases with increasing particle size (142).

4. Carbon Footprinting and Life Cycle Assessment

The aim of this research is to evaluate if the carbon dioxide released by the combustion process will be offset by the carbon sequestration potential that the biochar represents.

4.1. Is Pyro-CCS a Negative Emission Technology (NET)?

As we have discussed in the previous section, biochar has potential climate mitigation benefits. It appears that Pyro-CCS could be a Negative Emission Technology (NET) depending on the feedstock and the end use of the biochar, the heat, and other by-products. A life-cycle analysis (LCA) is a multifactorial analysis tool to evaluate the environmental impacts of a product. This analysis focuses on the global warming potential (greenhouse gas emissions in CO_2 eq.) of Pyro-CCS.

The aim of a LCA in the Pyro-CCS context is to evaluate the environmental performance and to identify opportunities for environmental improvement. The LCA, in this case called “carbon footprinting” since it is limited to one variable (global warming potential, or CO_2 eq.) will be useful in answering the question: “Can Pyro-CCS be a carbon-negative form of heat production in NWT?”

4.2. Introduction to LCA method

4.2.1. What is a Life-Cycle Analysis

A life-cycle analysis (LCA) is a comprehensive approach for assessing the environmental impact of a product, process, or service throughout its entire life cycle (143). The LCA considers all stages of a product’s life, including raw material extraction, production, use, and end-of-life disposal. The goal of LCA is to identify the environmental impacts associated with each stage of the product’s life cycle and to evaluate potential ways to reduce these impacts (144). A carbon footprint exercise is similar to an LCA, but with a reduced scope, typically only analyzing for global warming factors (CO_2 eq.) and leaving out other variables like land use and water consumption (145).

4.2.2. What is a Life-Cycle Inventory Assessment

A life-cycle inventory assessment (LCIA) is a technique used in LCA that involves quantifying the inputs and outputs associated with each stage of a product's life cycle (143). The life-cycle inventory (LCI) provides a detailed inventory of the resources used, emissions generated, and waste produced throughout the life cycle. This information is used to assess the environmental impacts of the product and to identify opportunities for improving its performance.

4.2.3. Defining a functional unit

A functional unit is a key concept in LCA that defines the unit of analysis for assessing the environmental impact of a product or service. The functional unit is a measure of the product's performance or function, which can vary depending on the product type and intended use. By defining a consistent functional unit, different products can be compared and evaluated based on their environmental performance. In this case, it was observed that various life-cycle analyses for thermal heat or electricity production were defined in terms of grams of CO_2 eq. per MJ (146, 147). This functional unit will be used throughout this text.

4.2.4. The four (4) phases of an LCA

The four phases of an LCA in the contact of Pyro-CCS are:

1. <u>Goal and scope definition</u>: In this phase, the goals of the analysis are identified, and the scope of the analysis is defined. This includes identifying the system boundaries, determining the functional unit of analysis, and specifying the environmental impacts and resources to be considered for Pyro-CCS. For example: where and when do the boundaries start, and when do they stop?
2. <u>Inventory analysis</u>: In this phase, data is collected on the inputs and outputs of the Pyro-CCS system being analyzed. This includes data on the production of the Pyro-CCS plant, any transportation emissions, electricity consumed in the process, employee commute, travel emissions, feedstock emissions, and others.
3. <u>Impact assessment</u>: In this phase, the potential environmental impacts of the Pyro-CCS system being analyzed are evaluated. This includes identifying and quantifying the environmental impacts associated with the inputs and outputs of the Pyro-CCS system, such as greenhouse gas emissions, water use, and land use. The results of this phase are used to identify the key environmental hotspots in the Pyro-CCS system. Note that for the purpose of this thesis, the only metric evaluated is global warming impacts, or CO_2 equivalent. For simplicity, other impacts like water and land consumption are not considered— this exercise is called carbon footprinting.
4. <u>Interpretation</u>: In this phase, the results of the inventory analysis and impact assessment are interpreted to draw conclusions about the environmental performance of the Pyro-CCS system being analyzed. This includes identifying areas for improvement and making recommendations for reducing the environmental impacts of the Pyro-CCS system. The results of the analysis can be used to support decision-making and to communicate the environmental performance of the Pyro-CCS system to stakeholders.

Those four phases are mostly performed in ***Chapter 3 —*** *Manuscript*. Additional information is shared in ***Chapter 4 —*** *Discussion.*

4.2.5. Considerations regarding biogenic carbon in relation with carbon accounting

Carbon emissions from biomass are called *biogenic*, as opposed to *fossil* carbon emissions (from fossil fuels). The accounting of biogenic carbon emissions is disputed worldwide and has been the subject of various research papers. Currently, in Canada, biogenic emissions are counted as having a zero-sum impact on greenhouse gas emissions totals: "CO_2 emissions from biomass are currently not counted in the total (148)". Gunn et al. explain that there are five major global pools of carbon, presented here in decreasing order of volume: oceanic, geologic, pedologic, atmospheric and biogenic (149). Climate change is mostly caused by the transfer of carbon from the biogenic (biomass), geologic and pedologic layers (peat, permafrost thaw) to the atmospheric and oceanic carbon pools. They argue that the utilization of economic incentives for the use of our forests to reduce our dependence on fossil fuels must be carefully planned, depending on location and temporality (149). Should carbon from the biogenic carbon pool be considered the same way that fossil carbon is considered?

4.2.6. Suggested global warming potential values for biomass-related emissions

Although most jurisdictions are using a global warming potential (GWP) of zero (0) to account for biogenic emissions as "carbon-neutral", various researchers are suggesting this number should not be zero. Some suggest using different GWP_{bio} for different types of biomass feedstocks: those numbers are reported in Table 3. In contrast, the GWP for fossil fuels combustion is of 1.0 (30).

Table 3: Range of Global Warming Potential (GWP_{bio}) for different biomass sources[4] (30)

Source	GWP_{bio} range
Slow growing forest	0.34 to 0.62
Forest	0.3 to 0.7
Slow growing forest with unharvested biomass	0.21 to 0.32
Short rotation crops (eg, willow, poplar, caragna)	0.04
Slow growing forest with 25% of residues harvested	0.17 (Time horizon 500) to 1.40 (Time horizon 20)
Forest	-0.92 (with bioenergy with carbon emissions capture and storage) to 1.57

Albers et al. differentiate between short-lived (for bioenergy purposes) and long-lived (for wood for construction materials) products (150). In both cases, there seems to be a consensus on the need to include biogenic emissions in the overall carbon accounting to paint a more accurate environmental picture of the operations.

4.2.7. Consensus on the need to count biogenic emissions in the construction wood products industry

Various researchers agree on the need to account for biogenic emissions in the construction of the wood products industry in Canada as a climate mitigation strategy, and to depict a better picture of the positive environmental impacts (68-73). Aligning the bioenergy industry practices with those of the construction industry might lead to more accurate accounting.

Some argue that the incorporation of standing dead trees and decay factors in forest biomass accounting (for aboveground carbon) is necessary as it otherwise leads to overestimates in carbon sequestration in forest biomass (68).

Tellnes et al. argue that biogenic carbon must be reported in the total greenhouse gas emissions and removals over construction materials' life cycle— they also explain that the different carbon accounting approaches give different results and

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[4] Adapted from (30)

are time consuming for researchers and professionals, and that more sophisticated modelling of biogenic carbon in life-cycle analyses (LCA) is needed (69).

Not accounting for biogenic emissions in the utilization of wood products in construction overestimates climate impacts and is too conservative (69). They explain that carbon fluxes are modeled as a function of tree species, growing conditions, forest management practices, and others (151).

Garcia et al. argue for the accounting of biogenic emissions in wood products. The paper presents eight (8) biogenic carbon accounting methods the are presented and evaluated: Zero-GWP, Fixed GWP, ILCD, PAS 2050, GWPbio, DynLCA-p, DynLCA-r, and DynLCA-n (72). It appears that the GWP_{bio} method is the most conservative and should be used out of precaution (72).

Sgarbossa et al. argue that the use of whole trees from forest thinning operations present the highest environmental performance from a GWP, ODP POCP and HTP perspectives (73). They also repeat the importance of including biogenic emissions in the calculations in order to depict an accurate environmental impact (73).

Head et al. developed biogenic carbon profiles for cradle-to-grave wood products in Canada— and argues for the counting of biogenic emissions in this sector, as wood products harvesting in Canada are a climate mitigation strategy (71). This is in line with a previous paper by Head et al. which presents results that support the continuation of the current harvest rates— and argue that with the current wildfire rates, sustained wood harvests continue to deliver net carbon sequestration benefits (151).

There is less research in the field of bioenergy on the need to include biogenic carbon emissions in national carbon accounting; however, by extrapolation, it seems reasonable to include them for bioenergy purposes as well. This research will continue forward with this assumption.

4.2.8. Consensus on the need to consider larger time scales in biogenic carbon accounting

Various research papers produce evidence that the consideration of longer time scales in carbon accounting leads to more complete results (30, 64-66):

Levasseur et al. demonstrate that static LCAs over longer time horizons (100 years) show similar results to dynamic LCAs with similar time horizons. On the other hand, shorter time horizons tend to misrepresent environmental performance (64).

Jäppinen et al. use GWP_{100} on a 100 years time horizon, since it is assumed that forests in this experiment regrow in less than 100 years (66).

The GWP_{bio} depends on the time horizon utilized and the rotation time period for the biomass being harvested. Faster-growing forests tend to deliver a lower GWP_{bio}. Van Fan et al. suggests using a different GWP based on the time horizon used in the calculations: slow growing forest with 25% of residues harvested (0.17 for a 500 years time-horizon and 1.40 for a 20 years time-horizon) (30) (Table 3).

Demertzi et al. argue that time frame selection influences the results of both dynamic (with variable time horizons) and static LCAs— as the time frames grow longer, both dLCA and LCA are getting closer in similarity (65).

4.2.9.Methods

Brandão et al. present six methods for carbon removal accounting (152). A cut-off of 100 years is depicted— delayed emissions beyond that number being considered "long-term" delayed emissions. Of all methods presented in this paper, not one is preferred as recommendations would be based on value judgements (152).

Downie et al. present three approaches to GHG accounting methods for biomass carbon: the biogenic method, the stock method and the simplified method. It is recommended that GHG abatement methodologies use the biogenic approach as emissions abatement is most appropriately calculated by the biogenic method (153).

This project will move forward with the assumption that the biogenic approach is best suited, and will continue using a static LCA of 100 years; this is also used by various other researchers in this field.

4.2.10. Carbon mass balance of fire-killed biomass

When determining the carbon mass balance in biomass destroyed by wildfire, the "burnt carbon" approach yields more accurate representations of carbon emissions over the "consumed biomass" approach— which can lead to a 9% overestimation (154). Pappas et al. argue that only about 9% of carbon ends up as aboveground biomass— at least for the Southern Boreal Forest, here studied in Saskatchewan, Canada. Below ground roots carbon has the lowest mean residence time (0.77 to 1.07 years), followed by forest floor carbon (15 to 40 years), followed by aboveground tree biomass with much lower renewal rates (several decades) (155). It is estimated that the boreal forest in NWT has the potential to store up to 75 kilograms of carbon per square meter (6). On the other hand, some studies suggest that a forest fire event could emit 1,000-2,000 g C per square meter (112). The amount of carbon that ends up as pyrogenic carbon is small compared to the amount of carbon released during a fire. The pyrogenic carbon might be re-burnt during subsequent fires or lost through other means.

The distribution of carbon in the different carbon stocks is estimated to be as follows: 45% of terrestrial carbon (861 ± 66 Pg C) in soils (44% of total storage), above and below ground live biomass (42%), deadwood (8%) and litter (5%) (156)". Disturbance events are the primary mechanism that shift ecosystems from carbon sinks to carbon sources.

4.2.11. Environmental impacts of wood pellets production and biomass feedstock selection

Melin et al. point to the use of stumps from dead forests as a carbon-intensive source of energy—with a carbon balance slightly worse than coal in the short term, but in favor of stumps combustion on the longer term (157). Jäppinen et al. investigated five power production systems (combined heat and power, condensing power production, torrefied pellets, gasification and pyrolysis oil production) with three feedstock types (harvesting residues, small-diameter energy wood, and stumps) and recommend replacing peat and coal combustion by biomass combustion as a climate mitigation strategy (66). It is suggested that pellet stoves present the lowest impacts for global warming and ozone formation compared to wood stoves and fireplaces, but present the worst impacts on all other categories (158). Decrease in distances traveled by feedstock lead to very small decrease in impacts— negligible (this was also observed in the preliminary carbon footprinting analysis for Pyro-CCS in NWT) (159).

Quinteiro et al. compare centralized and decentralized wood pellets production and suggest that the greatest impacts of the industrial pellet production mainly comes from high electricity and diesel consumption during the pelletization process (158). It is assumed that the raw material is already dry in the decentralized processes, therefore reducing the need for drying energy (158). Others argue that the use of whole trees from forest thinning operations present the highest environmental performance from a GWP, ODP POCP and HTP perspectives (73).

4.2.12. Biomass storage-related emissions

Some researchers suggest the inclusion of biomass storage emissions (methane, mostly) in order to depict an accurate picture of environmental impacts (160). They argue for biogenic emissions to be included in the calculations of bioenergy emissions: "the actual climate impact of bioenergy can only be assessed by accounting for the non-bioenergy uses of biomass feedstock and by including all climate forcers" (160).

Precaution is called for on the storage of biomass as the methane and nitrogen dioxide emissions lack experimental backing (66)— they recommend keeping biomass storage to a minimum to avoid decomposition emissions. Values in the range of 16-40 g CO_2 eq. MJ^{-1} woodchips have been proposed for composting systems (66), and 9.3 to 11.7 g CO_2 eq. MJ^{-1} for a 1-year storage duration on landfill sites (66). Because of the lack of experimental data, the forecasted shorter duration storage, and the protected environment in which the feedstock would be stored (sheltered from rain), biomass storage emissions are estimated to represent less than 5 g CO_2e MJ^{-1}— and therefore less than 10% of overall results— and are therefore outside the scope of this study.

4.3. Existing carbon footprinting studies for heating fuels of interest, and Pyro-CCS

Table 4: Existing carbon footprinting studies and carbon intensity result per energy source

Energy source	Carbon intensity (g CO_2 e/MJ)
Heating oil	70 (161), 72 (146) to 300 (162)
Natural gas	51.4, 56 (146) and 200 (163)
Pellets combustion	6-10 (164), 30 (162), and 92 (165)
Pyrolysis heat without CCS	16 (126), 25 (56), 29 (133) and 70

Table 4 depicts carbon intensity values for heat generation processes— this is for comparison.

Other researchers have estimated the carbon footprint of heat from pyrolysis without significant CCS as 16 (126), 25 (56), 29 (133) and 70 g CO_2e MJ^{-1}. One study considering heat production and carbon sequestration estimated 0 g CO_2 e MJ^{-1} (126). Other studies of carbon sequestration with pyrolysis reported near-zero or negative net emissions per unit of biochar produced (128) or per unit of land harvested (110).

Note that none of these studies considered the carbon impact of such technologies in remote, northern locations.

5. Forests: feedstocks, carbon flows and behaviour

Because feedstocks play a determining factor in the characteristics of biochar and in the overall greenhouse gas emissions of Pyro-CCS, a literature review on the topic was warranted. The proposed Pyro-CCS study involves two types of biomass feedstock: imported wood pellets from forest industry waste in Alberta, and locally-harvested FKT in Northwest Territories. Understanding forest carbon feedstocks dynamics might help us pick the most suitable feedstock for climate mitigation.

5.1. Trends: increase in wildfire intensity, frequency and severity

Research on forest carbon is sparse, and particularly limited for the context of NWT. Nonetheless, some trends are clear: fire-return intervals (years between forest fires) are decreasing, fire intensity and frequency is increasing, and legacy carbon is at risk of being consumed and released (166). As a result, various forests across the globe are shifting their regimes from carbon sinks to carbon sources, namely in NWT (6) and in Australia (167). Mitigation strategies need to be identified to stop this trend, and reverse it. Legacy carbon is defined as "organic-soil carbon that escaped burning in previous fires" (6).

5.2. Necromass: available bioresource increasing

Researchers have identified conflicts in the nomenclature of necromass (168). Necromass is also sometimes identified as dead wood, fine woody debris and organic matter. Maas et al. have proposed a terminology and size limit of necromass that is differentiated between aboveground and belowground. Aboveground includes non-woody and woody. Woody includes downed (coarse and fine) and standing (snags and stumps). Belowground includes coarse and fine roots (168). For the exercise of this research, we assume that “necromass” is inclusive of FKT in Northwest Territories, including fine and coarse branches, snags and stumps, trunks, and others.

5.3. Forest regimes changing from carbon sinks to carbon sources as fire-return time interval diminishes

In 2000, Chen et al. argued that Canadian forests were carbon sources from 1895-1910, large carbon sinks from 1930-1970, and moderate sinks from 1980-1996 (169). Walker et al argue that as the wildfire recurrence time in boreal forests becomes shorter because of anthropogenic global warming, younger forests are more likely to burn earlier than under normal conditions— causing a release of legacy carbon, which in turns shifts forests into net carbon sources rather than carbon sinks (6).

Dieleman et al. show that forest fires in the Southern Canadian boreal forest are increasing in “intensity, extent, and frequency” and that, by extension, northern boreal stands are at a high risk of holding less carbon under changing disturbance conditions (166). The situation is similar on the other side of the globe: Bowman et al. argue that increasing wildfires and droughts in Australian eucalyptus forests are leading to a reduction in carbon stocks, and call for more research on carbon storage mitigation strategies (167).

We are currently observing a carbon storage shift from aboveground and belowground biomass to atmospheric carbon— forests are turning from carbon sinks to carbon sources and releasing their carbon into the atmosphere. The trend is predicted to keep increasing as we approach the end of this century: “In the North America boreal forest, fire-induced carbon emissions were projected to be 2.5–4.4 times their current level by the end of this century [21st century] (170)”.

The average fire-return interval for northwestern boreal forests in North America is 70-130 years. Shorter fire-return intervals will lead to the depletion of legacy carbon in the soils— this indicates forests becoming carbon sources (170).

Harden argues that periods of droughts and wildfires are leading to boreal forests becoming carbon sources— droughts making the forests more likely to ignite (171).

Loehman et al. explain that wildfires are one of the main pathways for the movement of carbon from the biosphere to the atmosphere; or from the land surface to the atmosphere. Fires have the potential to change carbon sinks into carbon sources. The ecological drivers of wildfires are system drivers (weather, climate), behaviours (wildfire occurrence, spread, intensity) and resulting patterns (vegetation composition and structure, carbon emissions) (156).

For the purposes of developing a model from Pyro-CCS in NWT, it is critical to determine the fire-return interval for NWT forests, and the maturity year of forests.

5.4. Post-fire forest conditions

Researchers at the University of Arizona (2013) argued that although a peak in carbon emissions was expected in the years after a pine beetle infestation, the research demonstrated otherwise. Respiration from trees having disappeared, emissions were much lower, but regained speed after about 6-7 years after the initial event. This might prove a relevant time frame to harvest FKT in northern boreal forests (172).

Pukkala argues that, in simulations led for the fennoscandian forest (Finland, Sweden, Norway and the Western part of Russia), a better carbon balance was reached when trees were mostly left unharvested—unless those trees were used to store carbon on a long-term basis (173). Approximately only 20% of the carbon in harvested trees ends up as sawn wood. The author encourages the use of wood as a construction material and climate mitigation strategy (173).

Martinez et al. argue that tree snags (dead tree trunks) are emitting CH_4, but it is oxidized into CO_2 within the snags. The snags might be acting as conduits for soil-produced greenhouse gases to exit to the atmosphere. Their conditions are changing depending on types of salinity and hydrological conditions— and are said to be "unpredictable" (174).

5.5. Forest modeling and methods

The Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) can be used to determine tree species, age class, yield curves, areas, carbon stock, and region cases.

Prentice et al. present two models used to forecast wildfire and carbon modelling in boreal forests: GFED (Global Fire Emissions Database) and LFX (Land surface Processes and Exchanges) (175). Yang et al. present three methods for investigating global burned areas: ground-based inventory data interpolation, satellite observation and model simulations— parameters included burn severity (combustion completeness and forest mortality), both factors depend on local topography, weather, climate conditions and vegetation species (170). Higher precipitations in one season can lead to higher wildfire risk in the following year due to higher fuel load. Fire suppression policies in the early-to-mid 20th century might have led to an increase in fuel accumulation on the ground which caused higher fire emissions in the 21th century (170).

5.6. Wildfire mitigation and climate mitigation strategies

Wiechmann describes three types of thinning and controlled burns treatment in mixed-conifer forests as climate mitigation strategies. The [1] understory thin treatment quickly recovered the related carbon emissions, [2] the carbon released in the burn-only treatment was recovered within the fire-return interval; and [3] the combined thin and burn treatment, which was the most effective at reducing wildfire, was considered a carbon source since it led many FKT post-treatment. It appears that the understory thin treatment presents the best climate mitigation opportunity (176).

Along the same lines, some researchers suggest that restoring forest structure and surface fire regimes can prove to be a positive climate mitigation strategy— although upon treatment there is an initial larger increase in GHG emissions, but is evened out over time (177)

To this end, Pyro-CCS might contribute to re-establishing forest structures by increasing the quantity of carbon in the soils, thus mimicking the build-up of legacy carbon. Could the harvesting of FKT contribute to restoring the forest structure, and increase the quantity of “legacy” carbon present in soils?

Bennett et al. explain that high severity fires resulted in higher carbon losses and left more fine fuel loads to be consumed later, which would increase the risk and severity of future fires. On the other hand, low-severity fires contributed to growing carbon stocks locally (178). Charred material left onsite would increase the carbon stocks (pyrogenic carbon). To this end, active fire suppression in NWT coupled with biochar amendment might be a climate mitigation strategy.

Gouge et al. produce four scenarios: with and without biomass procurement for bioenergy, and with and without site preparation and planting— the scenario with biomass procurement for bioenergy and site preparation and planting yields the lowest greenhouse gas emissions per GJ of energy (179).

Based on this information, it is suggested that using biochar as a soil amendment to reduce droughts, restoring forest structures by harvesting FKT, and actively preparing the site before planting might be yielding the best environmental performance.

5.7. Mechanisms of carbon movement between reservoirs

How does carbon move between carbon reservoirs? Combustion is well known as a simple mechanism to transfer carbon from the biosphere to the atmosphere, and there are other mechanisms. There are different ways that soil carbon could decline; these ways include: absorption of oxygen, tree uprooting, gelifluction (downslope movement caused by seasonal freeze-thaw) and cryoturbation (mixing of soil by freezing and thawing of soils) (112). In Slovakian forests (mostly beech trees), although younger trees sequester less carbon than mature trees, they have a higher rate of contribution to the necromass flux (through fallen leaves and dead branches; which will ultimately be released to the atmosphere)— and their impact on the net carbon impact of land use should not be neglected (180). Tree mortality makes carbon more prone to release in subsequent forest fires (181). Mack et al. explain that following a fire, fast-growing deciduous broadleaf trees replace slow-growing black spruce. This has a net carbon storage increase (182).

5.8. Indigenous ways of wildfire management and fire-killed forest practices

The implied suggested deployment of a Pyro-CCS pilot project would take place in Northwest Territories, a territory with a majority Indigenous population. Honouring local culture and practice is key to implementing the 94 calls to action of the Truth and Reconciliation Commission (183), but also for the project to be successful. There is only very limited academic, western-type research on the Indigenous ways of wildfire management, and fire-killed forest practices. Adjacent topics like wildfire preparedness offer avenues for reflection as described below.

Asfaw et al. recommended pre-approved evacuation preparedness plans in order to avoid resistance to said plans when execution is necessary (184). By extension, climate mitigation plans should be passed by and pre-approved by the membership, and Chief and Council in order to secure buy-in by the communities, should biochar amendment in boreal forest soils be selected as a climate mitigation strategy, community members should take part in the decision process.

McGee et al. argue the need for safe havens to be constructed within a specific nation for members to feel comfortable evacuating the nation during a wildfire event—as opposed to evacuating to a nearby or remote site where people have less connections (184). By extension, should biochar be used as a forest soil amendment, the sites should be approved by the membership to reduce or eliminate resistance, but also to insure that Traditional Knowledge directs decisions regarding ecological impacts, and others.

6. Additional considerations

6.1 Formaldehyde creation during the pyrolysis process

Some authors have reported that formaldehyde formation can happen during the pyrolysis processes (185). Formaldehyde can have negative impacts on human health, including respiratory problems, skin irritation, cancers and others (186). Further investigation is needed in the Yellowknife Pyro-CCS project to ensure that formaldehyde is not created, or at least kept to manageable quantities. Industry experts have reported that at the temperatures that pyrolysis chambers are operating at, most VOCs are burned before they can exit (187).

6.2 Scaling up land use

Some studies on the land-use considerations of bioenergy highlight the importance of context-specific conditions for the evaluation of benefits, synergies and trade-offs (188) and that although emissions from land-use changes can be significant, the overall context must be considered in order to paint an accurate picture of the different climate mitigation solutions (189).

7. Knowledge gaps in the literature

From this literature review, to the best of my knowledge, it is understood that there are no or very limited studies about the following:

- carbon footprinting of Pyro-CCS in a Northern Canadian environment, or in any of the Canadian Territories;
- the carbon impacts of the use of fire-killed trees (FKT) as a feedstock for Pyro-CCS;
- the potential climate mitigation impacts of the large-scale use of FKT as Pyro-CCS feedstock in NWT;
- the large-scale impacts of biochar amendment to forest soils in Canada.

The following sections are meant to address those knowledge gaps.

Connecting Text

Chapter 2* — *Literature review presented an overview of Pyro-CCS, biochar, their influencing factors and feedstocks considerations, as well as concepts surrounding LCAs, carbon Footprinting and biogenic carbon.

Chapter 3 — *Manuscript* presents the results of a carbon footprinting analysis comparing the carbon intensity of heating oil, natural gas, propane, biomass combustion, Pyro-CCS from imported waste wood pellets, and Pyro-CCS from locally-harvested FKT.

It has been submitted for peer review and publication in the

Journal of Resources, Conservation & Recycling.

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Chapter 3 — Manuscript

Fighting Fire with Fire: Carbon-Negative Heat Production in Canada's North Using Pyrolysis of Fire-Killed Trees

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Highlights

- Fire-killed trees in NWT are an unexplored large-scale bioenergy resource;
- Carbon footprint model includes previously ignored post-wildfire carbon dynamics;
- Pyrogenic CCS of fire-killed trees produces carbon-negative heat;
- A carbon-negative bioenergy economy is possible without harvesting live trees;
- Biomass-based heating in NWT would require ~ 2% of the annual wildfire burn.

Keywords

Pyrolysis; decarbonization; Fire-Killed Trees (FKT); sub-arctic; energy; carbon sequestration; Pyrogenic Carbon Capture & Storage (Pyro-CCS); Northern Canada; Northwest Territories; Negative Emissions Technologies (NETs)

0. Abstract

Heating buildings in Northern communities is carbon intensive and existing low-carbon technologies are ill-suited for arctic conditions. Pyrogenic carbon capture and storage (Pyro-CCS), which heats biomass anoxically to produce fuels and biochar, could provide low-carbon fuels in this context. We calculate the carbon footprint of Pyro-CCS in Northwest Territories (NWT) using wood-pellets and a novel feedstock of fire-killed trees and compare these to conventional heat sources. We find that Pyro-CCS emits

40.9 CO_2 eq./MJ using wood-pellets and sequesters -10.3 CO_2 eq./MJ using fire-killed trees, compared to emissions of 59.7 CO_2 eq./MJ for wood-pellet combustion, and 79.4-89.9 CO_2 eq./MJ for fossil fuels. Scenarios suggest that widespread Pyro-CCS allows the heating sector in NWT to achieve 1.5°C-aligned emissions reductions targets using only 121 km^2 of burned forests annually (~ 2% of annual burn in NWT). We propose five policies to promote Pyro-CCS and transform NWT into a model for northern decarbonization.

1. Introduction

Millions of residents of the Arctic and Sub-Arctic are experiencing climate change firsthand. In Northwest Territories (NWT), the 2014 *Summer of Smoke* burned 34,000 square kilometres (km^2) of forest, doubling emergency room visits for asthma (3, 190). Unprecedented flooding, thawing permafrost, and coastal erosion are making communities uninhabitable and jeopardize natural and built infrastructures (13). Supply chain disruptions are increasingly frequent as trucks fall through thawing ice roads (14). Declining animal populations threaten traditional subsistence hunting and livelihoods (8).

Northern communities in Canada and elsewhere must urgently adapt to climate change while decarbonizing. These communities have some of the highest per capita emissions globally due to long and harsh winters, automobile dependence, and importing consumer goods by aircraft. Per capita emissions are 14.2 tons CO_2 equivalent (t CO_2 eq.) for Yukon Territory, 15.4 t CO_2 eq. for Nunavut, and 30.9 t CO_2 eq. for NWT compared to just below 5 t CO_2 eq. globally in 2021 (23, 191, 192). Heating (space and water) alone accounts for roughly 30% of energy use and emissions (23).

Heat in NWT is primarily from fossil fuels – natural gas, propane, heating oil– and biomass – wood pellets and firewood (23). Decarbonization strategies for milder climates, such as electric heating with photovoltaics or passive solar work poorly in arctic conditions (31). Current drop-in biofuels cannot meet demand, and their carbon benefits remain contested (147, 193-195). An emerging alternative to these technologies is pyrolysis.

1.1. Pyrogenic Carbon Capture & Storage

Pyrogenic carbon capture and storage (Pyro-CCS) heats solid biomass under low-oxygen conditions (48). Long-chain organic molecules in the biomass decompose to gaseous alkanes and hydrogen, also called pyro-gas, and bio-oils (129). The remaining biomass becomes biochar. The ratio of biochar (30-50% C), bio-oil (25-50% C), and biogas (15-45% C) varies by residence time, feedstock, particle size, oxygen levels, and pyrolysis temperature (48). For example, biochar production decreases with higher temperature (49-51).

Pyro-gas and bio-oil can be burned for heat or in a turbine for electricity. Pyro-CCS has been deployed for heating in Finland (196), Sweden (74), and Norway (75). Biochar is also combustible but is typically spread on soil as an amendment. Indigenous Peoples have mixed biochar with bone, broken pottery, and food waste for thousands of years as *Terra Preta* to enhance soils (92). The carbon in biochar is exceedingly stable (67)— buried, it remained 97% stable after 100 years (111). Burying biochar essentially moves carbon from the fast- (biospheric) to the slow-carbon (fossil) cycle. Bio-oil can also be buried to sequester additional carbon (90). The ability for Pyro-CCS to produce heat and stable carbon positions the technology as a low-carbon or potentially carbon-negative energy source.

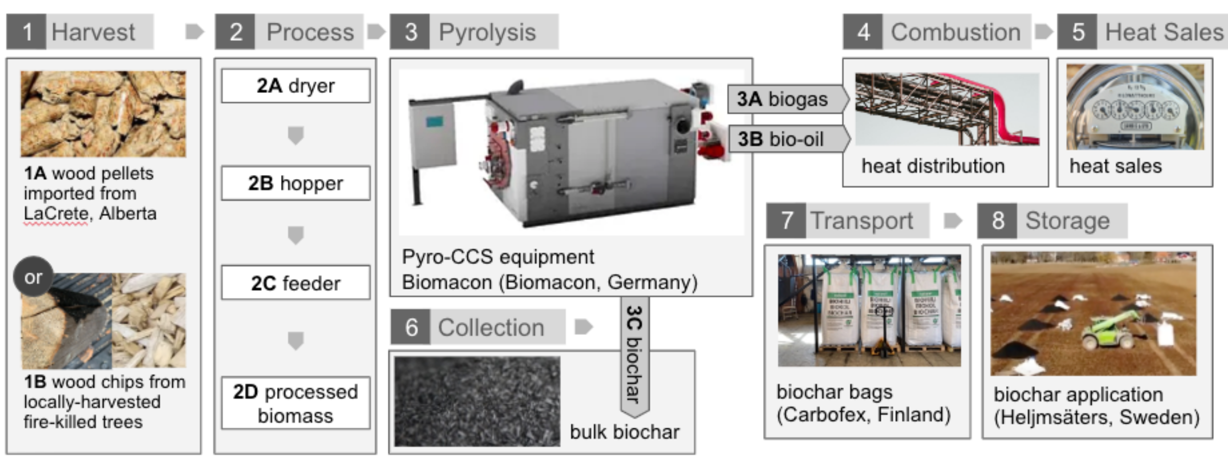


Figure 7: *Representation of the Pyro-CCS system. 1B, 7, author photo. 1A, 3, 4, 5, 6, 8 with permission.*

Most solid biomasses can be used as a feedstock in Pyro-CCS. Wood pellets, primarily imported from southern provinces, are a viable feedstock in the Canadian

North. A local alternative is dead biomass (necromass) in trees killed by wildfire. In NWT alone, this amounts to 6,000 km^2 annually(197). Harvesting necromass for energy through Pyro-CCS, and then returning the biochar to regenerating forests presents an opportunity for a local, sustainable, circular, carbon-negative energy economy.

However, key knowledge gaps remain. Despite its promise to overcome the limitations of other low-carbon energy technologies in the far-north, there has not been any analysis of Pyro-CCS in the region. Moreover, no studies explore the potential of FKT as a novel bioenergy feedstock (198-201). Previous studies suggest that the decarbonization potential of sustainable bioenergy with CCS is immense when residual biomass that does not compete with food crops is used (200) . Globally, the technology can contribute between 6% and 35% of the negative emissions needed to stabilize the climate (198). Numerous studies in China suggest that agricultural residues, forestry residues, and municipal waste can provide significant shares of local energy demands (202), albeit unevenly across the country (203). Spatial analysis shows that Pyro-CCS could supply 222 GW of power using 0.9 Gt biomass (50% agricultural residues) (201) and that CCS more broadly can offset sunk emissions in planned coal plants (199).

Others have explored the decarbonization potential of Pyro-CCS (198) and CCS (199, 200) more broadly— some with considerations for land use (201)— but the carbon footprint of Pyro-CCS using fire-killed trees (FKT) and its broader contributions to decarbonizing the North have not been explored.

We address this gap through a case study of Pyro-CCS in NWT. NWT covers 1,346 million km^2 in the Canadian Sub-Arctic with a population of 44,826 (2019). NWT typifies the many decarbonization challenges faced by similar northern communities. Thus, assessing Pyro-CCS in NWT contributes to broader knowledge on how to decarbonize the planet's most carbon-intensive communities.

Here, we estimate the carbon footprint of heat from fossil fuels, wood pellets combustion, and slow Pyro-CCS (600-800 °C) of imported wood pellets. We also provide the first carbon footprint estimate for Pyro-CCS with FKT. To properly estimate emissions from this previously unstudied feedstock, we develop a new model of post-wildfire forest-carbon dynamics. We then use scenario analysis in NWT to perform the first regional assessment in the far-north of the decarbonization potential of Pyro-CCS.

Results show that Pyro-CCS has a lower carbon footprint per unit heat delivered than wood pellets combustion and a much lower footprint than fossil fuels. When carbon sequestration is included, Pyro-CCS with FKT provides a sustainable, carbon-negative heating solution to help NWT meet its 2030 and 2050 climate targets. Although we only analyze NWT, we demonstrate for the first time the broader potential for Pyro-CCS to contribute to decarbonization in far-north communities in Canada and beyond. We conclude with policy recommendations for governments in the Canadian North to support this transition.

2. Methods

We estimated the carbon footprints of supplying heat using six technologies in the capital of NWT, Yellowknife. We included Scope 1 direct, on-site emissions (e.g. burning heating oil); Scope 2 direct, off-site emissions (e.g., electricity production); and Scope 3 indirect, off-site emissions (e.g. equipment manufacturing). Our analysis covered material extraction, manufacturing, and use stages of the life cycle. We also included disposal of fuel by-products but excluded disposal of heat distribution equipment and furnaces as they are assumed identical across systems. Below we describe the heating systems, data, assumptions and decarbonization scenarios.

2.1. Unit of analysis, systems descriptions, and inventories

We analyzed for 1MJ of heat delivered at 98% reliability in a 160 kW boiler running 5,000 hours annually in Yellowknife (800 MWh total heat annually). We chose a 160 kW system to align with commercially-available Pyro-CCS units suitable for commercial, industrial and residential applications. We assessed six heating systems: Pyro-CCS using imported wood-pellets, Pyro-CCS with locally-harvested FKT (chipped), and combustion of heating oil, propane, natural gas, and wood pellets. All systems were analyzed over a 25-year timeframe, the common lifespan of a boiler. Below we describe each system. Figure 8 summarizes the inputs to our systems and Table 5 through Table 12 detail the Ecoinvent 3.8 processes in our OpenLCA model.

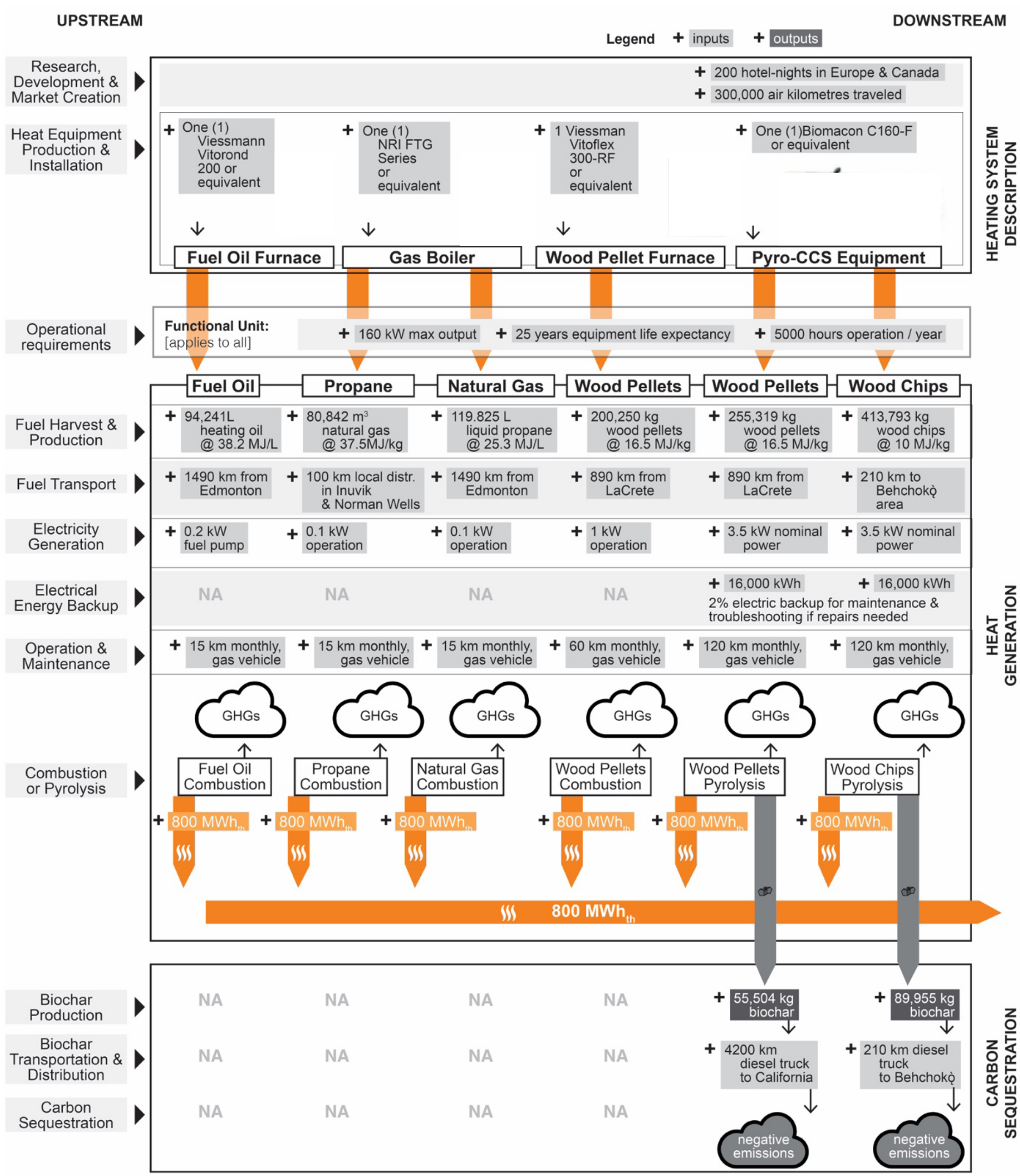


Figure 8: *Overview of inputs and outputs for the system. Original figure .*

2.2. Pyro-CCS With Wood Pellets from Alberta, Canada

This system uses wood pellets produced as a by-product of the forestry sector. Economic value is used to allocate carbon emissions between lumber and pellets. Pellets are produced in LaCrete, Alberta and shipped 890 km by diesel truck to Yellowknife, NWT, and fed into a *Biomacon C160-F* Pyro-CCS plant, a turnkey commercial-scale plant used in Northern Europe that is housed and operated inside a standard 45' shipping container (46). The system is shipped from Rehburg, Germany. We assumed that installing this novel system will necessitate in-person meetings resulting in 200 hotel-nights and 300,000 passenger-air kilometres (12 long-haul, and 40 short-haul flights).

Wood pellets are fed into the pyrolysis chamber via a feeding screw, and then heated under anaerobic conditions at 600-800°C for approximately 60 minutes. The residence time and pyrolysis temperatures are feedstock-dependent. Ninety-five kilograms of biomass can be processed hourly (46), transformed into biogas and combusted for heat, which is distributed to users by a hot water jacket system. Given a wood-pellet energy density of 16.5 MJ/kg (204) and an energy conversion of 86%, the system requires 255,319 kg of wood pellets and produces 55,504 kg of biochar annually. We assumed biochar is trucked 4,200 km from Yellowknife to California, United States for application to soils to provide a conservative estimate of environmental and economic performance. We tested the influence of this assumption on the results. We assumed daily visits by a technician travelling 4 km by car to operate the system and a nominal electrical power requirement of 3.5 kW, based on available industry data (46).

2.3. Local Pyro-CCS With Fire-Killed Trees

The only difference from the Pyro-CCS with wood pellets is feedstock. Assuming a 10 MJ/kg energy density (204), the system requires 413,793 kg of necromass annually. It is harvested from the 2014 wildfire area 30 km Southwest of Behchokǫ̀, NWT— approximately 130 km from Yellowknife— and chipped and sent to the same Pyro-CCS plant as above. As a result of the increased quantity of biomass fed into the unit, more biochar is also produced— 89,955 kg annually. The bark of the FKT is charred, but the interior is largely unburned biomass (author photographs in Figure 14). We assumed that 99% of the carbon in the necromass thermally decomposes during pyrolysis, with the remaining 1% already present as pyrogenic carbon. Fuel is processed, distributed, and used as above, but biochar is returned to the harvest site.

2.4. Combustion of Wood Pellets

As above, wood-pellets are produced in Alberta and shipped to Yellowknife. Assuming 85% thermal efficiency and a 16.5 MJ/kg energy density (204), 202,250 kg of wood pellets are required annually. Pellets are combusted in a 160 kW system (e.g. Viessman Vitoflex 300-RF 150, or equivalent) (205). The large volume of pellets necessitates a delivery truck and storage silos in Yellowknife. An automatic system feeds pellets to the furnace. Ash (approximately 1% by mass) is regularly removed from the furnace and landfilled. We assume a technician travels 15 km once a week for maintenance.

2.5. Fossil Fuel Systems

We modeled three fossil fuel systems, each with a typical efficiency; natural gas (95%) (206), heating oil (80%) (207), and propane (95%) (206). Heating oil and propane are extracted and refined in Alberta, Canada and then transported to Yellowknife (1,500 km) by truck for storage in outdoor tanks. Natural gas is assumed to be extracted in NWT (Beaufort Delta and Norman Wells) and distributed locally by truck. For our unit of analysis, we need either 92,241 L of heating oil, 80,842 m^3 natural gas, or 119,825 L of propane. All three are combusted in 160 kW furnaces. The heating oil furnace is fed by a 200 W pump, while the natural gas and propane systems use a 100 W pump.

2.6. Accounting for biogenic carbon

We calculated biogenic carbon emissions using a mass balance method similar to Brassard et al (208). This method takes emissions from the combustion of pyrolysis products and subtracts emissions from a counterfactual situation where the feedstock decays or is used elsewhere. We advance previous work by incorporating forest-carbon dynamics, both for necromass decay and biochar application. Equation 1 outlines the general approach.

(Equation 1) $C_{flux} = \left[C_{case} - C_{counterfactual}\right] * GWP_{bio} * 3.67$

C_{flux} is the net biogenic carbon flux (emissions or sequestration) for Pyro-CCS. C_{case} represents biogenic emissions from operating Pyro-CCS and $C_{counterfactual}$ represents emissions that would have occurred had the biomass not been used for Pyro-CCS (subtracted because these emissions are avoided). A factor of 3.67 converts carbon to CO_2. GWP_{bio} converts CO_2 to CO_2 eq. and varies by feedstock; 0.3 for wood-pellets from fast-growing managed forests and 0.55 for necromass from slow-growing forests in NWT (29, 30, 209, 210).

We use (Equation 2 to determine C_{case}, where m_{in} is the mass of feedstock required for our functional unit and χ_{fs} is the carbon content of the feedstock. We then subtract the carbon that remains as stable biochar, taken as the product of $\gamma_{biochar}$ —the biochar yield, $\chi_{biochar}$ —the carbon content of biochar (assumed 85% carbon) (211), and $\rho_{biochar}$ —the percentage of undegraded biochar after 100 years (67).

(Equation 2) $C_{case} = m_{in} * \chi_{fs}[1 - \gamma_{biochar} * \chi_{biochar} * \rho_{biochar}]$

To determine m_{in}, we use Equation 3. Here, E_{in} is our functional unit,1 MJ, η_f is the furnace efficiency (assumed 85 (212)), and ρ_{fs} is the heating value of the feedstock (204).

(Equation 3) $m_{in} = E_{in} * \frac{1}{\eta_f} * \frac{1}{\rho_{fs}}$

Equations 4 and 5 determine counterfactual emissions for FKT and wood pellets as feedstocks, respectively. In both instances, the mass of carbon in the feedstock is multiplied by the most likely outcome. For wood-pellets, the counterfactual is combustion whereby all carbon goes to CO_2 except for the percentage that becomes ash, χ_{ash}. The counterfactual for necromass is natural decomposition. Given the paucity of data on decomposition rates of necromass in the far-north, we assumed 90% natural decomposition, η_{decay}, over 100 years due to the cold climate (213).

(Equation 4) $C_{counterfactual,necromass} = m_{in} * \chi_{fs} * \eta_{decay}$

(Equation 5) $C_{counterfactual,wood-pellets} = m_{in} * \chi_{fs} * [1 - \chi_{ash}]$

Net biogenic carbon flux is then combined with other carbon emissions as calculated in OpenLCA. Table 14 in the supplementary information shows these calculations in more detail.

2.7. Scaling up: Decarbonization Scenarios for Northwest Territories

Total emissions in NWT were 1.40 MT in 2020, and energy use was 20.8 PJ in 2019, of which 94% was from fossil fuels (23). NWT does not publish energy statistics by end use (i.e. heat vs electricity), but it does provide sectoral use. In 2019, 44% was used by industry, 40% for transport, 10% for commercial, and 6% for residential. Excluding electricity, which is seldom used for heating in NWT, and transport, there remains 9.7 PJ for industrial, commercial, and residential uses. Given the paucity of data, we assumed that between 22% (23) and 28% (6 PJ) (214) are used for heat— resulting with a baseline assumption of 0.308 MT for 2020 from the space heating sector. Despite considerations for population growth and an increase in energy needs, global warming is also expected to reduce the number of heating degree days— therefore it was assumed that the energy demand would remain stable, for lack of better modelling. We charted the decarbonization of the heating sector in NWT to remain below the 1.5°C target of the Paris Agreement of 45% below 2010 levels before 2030, and net-zero before 2050 (22). We also tested how much further NWT could go into decarbonization and how much the heating sector could sequester annually. It models deep decarbonization by replacing existing heating systems and converting significant portions to wood-pellet boilers or to Pyro-CCS with FKT. A conversion rate is used: for example, a 30% conversion rate represents a 30% conversion to Pyro-CCS, and 70% to wood pellets combustion, to insure a smooth transition and support with current government policies and investments. Our model assumes that the carbon intensity performance of Pyro-CCS improves by 5% every year, a conservative assumption considering that several clean tech sectors have been growing at 10% or more per year (215-218) and that a significant share of those emissions, related to transportation, are forecasted to see drastic emissions reductions in the next decade (219).

Table 13 in the Supplementary Information provides detail on conversion and replacements rates under each scenario.

2.8. Parameter Uncertainty

To assess the impact of parameter uncertainty on the results, we first determined the reasonable maximum and minimum values of parameters with high uncertainty and significant contributions to baseline results. We then tested the cumulative effects of the impacts of the results of having these parameters all at their maximum or minimum values. The key parameters were:

- Fraction of biochar sequestered in soil: 80% to 100%— researchers refer to up to 20% loss after 100 years (208);
- Furnace efficiencies: between 50% to 95% efficiency (212);
- Fuel production upstream emissions: assuming reported emissions are more optimistic and adding 20% for fugitive or unaccounted for emissions, lacking better data (220);
- Fuel and biochar transportation: 25% of baseline emissions intensity for transportation electrification, and 150% for winter conditions, delays, remoteness, idling.;
- GWP_{bio}: from 0.1 to 0.5 for imported pellets, and 0.4 to 0.7 for fire-killed wood chips (30);
- Electricity production: allocating 10% or 1000% of the reference value depending on project location in a hydroelectrical community (lower emissions), or in a diesel-community with frequent system failure (23);
- Travel and accommodation: allowing for 5 times the referenced amount of travel and accommodation allocated (up to 500 hotel guest-nights, 200 short-haul flights and 40 long-haul flights) (221);
- Equipment lifetime (years): allowing for boilers lasting from 5 years to 50 years (221);
- Operation & Maintenance (passenger-km/day): allocating for only 20% and 300% of the referenced required trips;
- Fire-killed biomass decay rates: from 80% to 98% decayed biomass in 100 years (213).

3. Results

Results show that Pyro-CCS outperforms any combustion heating technology. Scenario analysis of ambitious substitution of Pyro-CCS into NWT heating portfolio suggests that the technology significantly helps NWT and other northern regions decarbonize. Below, we present our findings in detail.

3.1. Carbon footprint of different heating systems

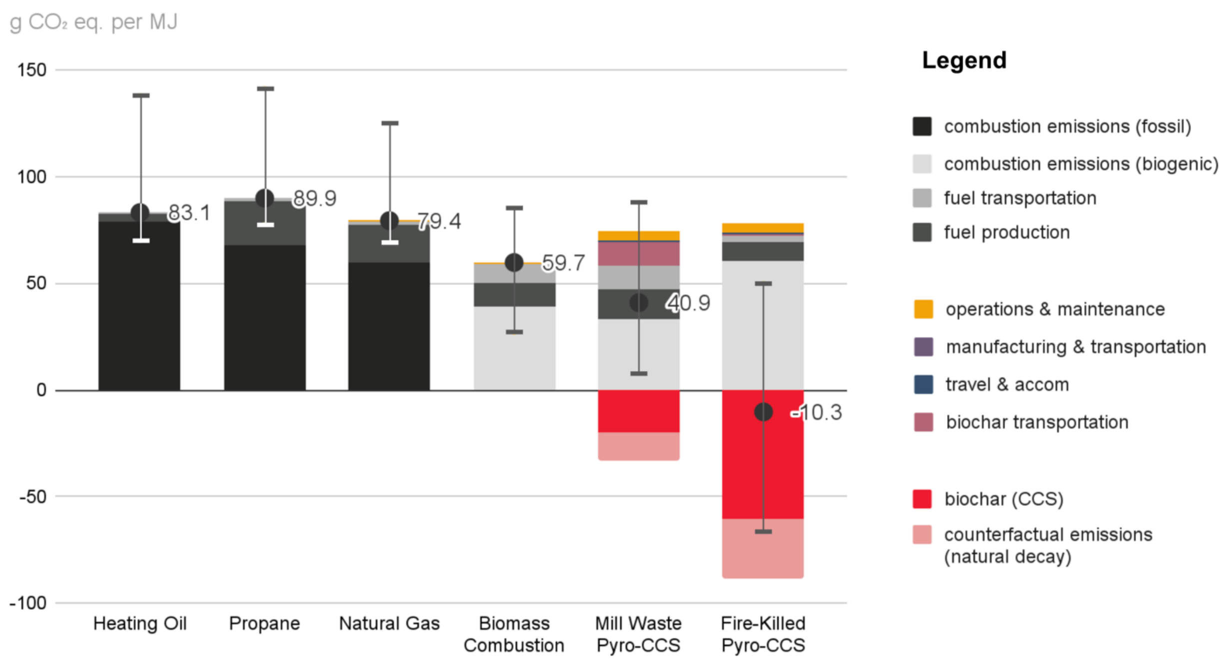


Figure 9: *Carbon intensity of heat in Yellowknife, NT.*

Carbon intensity in grams CO2e per MJ for six heating systems in NWT. Error bars represent the range of values given uncertainty in modeling parameters.

Figure 9 shows the carbon footprints of the different heating systems and the largest contributing processes in grams of CO_2e per MJ heat (g CO_2e MJ^{-1}). Propane has the highest emissions, at 89.9 g CO_2e MJ^{-1} (77.8 g to 141.5 g CO_2e MJ^{-1}), followed by heating oil at 83.1 g CO_2e MJ^{-1} (69.09 g to 138.2 g CO_2e MJ^{-1}) and natural gas at 79.4 g CO_2e MJ^{-1} (68.6 g to 125.1 g CO_2e MJ^{-1}). Wood-pellet combustion emissions are significantly lower, at 59.7 g CO_2e MJ^{-1} (26.6 g to 85.3 g CO_2e MJ^{-1}). Emissions from Pyro-CCS of pellets are 40.9 g CO_2e MJ^{-1} (7.6 g to 88.1 g CO_2e MJ). The carbon footprint of Pyro-CCS of FKT is -10.3 g CO_2e MJ^{-1}, but ranges from -66.3 g CO_2e MJ^{-1} to 50.1 g CO_2e MJ^{-1} with our assumptions.

Our results agree with similar carbon footprint studies. The carbon footprint of natural gas heat production is between 51.4, 56 g (146) and 200 g CO_2e MJ^{-1} (163) compared to 79.4 g CO_2e MJ^{-1} here. For heating oil, estimates range between 70 g (161), 72 (146) to 300 g of CO_2e MJ^{-1} (162), in line with our results (83.1 CO_2e MJ^{-1}), although studies use different system boundaries which hinder direct comparisons. Our results agree with literature values for emissions from wood pellet combustion, 59.7 g CO_2e MJ^{-1} here compared to 6 to 10 (164), 30 (162), and 92 g CO_2e MJ^{-1} (165). This suggests that combusting biomass residues in NWT is favorable to fossil fuels for heat.

A paucity of studies of Pyro-CCS for heat hinders direct comparisons, but others estimate the carbon footprint of heat from pyrolysis without significant CCS as 16 (126), 25 (56), 29 (133) and 70 g CO_2e MJ^{-1}, which aligns with our results when excluding carbon sequestration. One study considering heat production and carbon sequestration estimated 0 g CO_2e MJ^{-1} (126). Other studies of carbon sequestration with pyrolysis reported near-zero or negative net emissions per unit of biochar produced (128) or per unit of land harvested (110), which supports our finding of net negative emissions for Pyro-CCS.

3.2. Sources of Emissions

Combustion is the largest driver of emissions for all systems. Naturally, fossil fuel systems have particularly high combustion emissions (75-95% of total). The only other major contributor (>1%) for the fossil fuels systems is fuel production which accounts for 4% in the fuel oil system, and 23% in the propane and natural gas systems.

For the biomass systems, combustion is the largest emissions driver; 65.2% for burning wood-pellets, 44.4% for Pyro-CCS from wood pellets, and 77.4% from Pyro-CCS from FKT. Fuel production is the second largest source of emissions for combustion (18.8%) and pyrolysis (19.3%) of wood-pellets, and for Pyro-CCS of FKT (12.0%). Emissions from fuel transport are more significant for the biomass systems (5.2%-18.0%) than the fossil fuel systems (0.7% to 1.8%) because of the lower energy density of these fuels (204). Operations and maintenance emissions, primarily from electricity, are visible on the wood-pellet (5.4%) and FKT (5.1%) Pyro-CCS systems but barely visible for biomass combustion (1.5%) and <1% for fossil fuel systems. System manufacturing and installation is barely visible on the graphs for the biomass systems, even when significant employee travel for installation are included.

Carbon sequestered as biochar is represented as negative bars in Figure 9. Sequestered carbon is -20.2 g CO_2e MJ^{-1} for the pellets feedstock, and -60.1 g CO_2e MJ^{-1} for the chipped FKT, resulting in low and net-negative emissions, respectively. However, the transport of biochar is an important source of emissions. For CCS with wood pellets, where biochar is sent to California, biochar transport is the second largest emissions source (15.0%). This suggests that local biochar markets are needed to maximize the benefits of CCS— the local distribution of biochar only represents 1.2% of emissions.

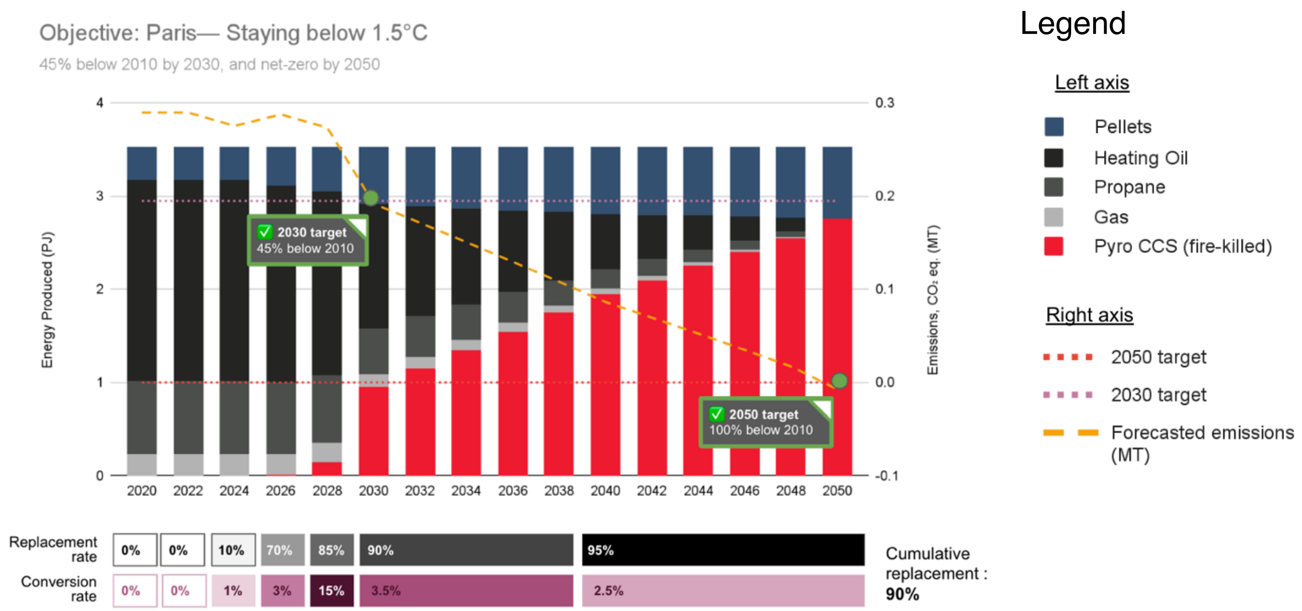
3.3. Decarbonization Scenarios

We ran a scenario to test if the 1.5°C Paris Agreement target could be achieved. Results suggest that Pyro-CCS can play an important role in meeting these targets, at least in the heating sector.

Figure 4 shows projected decarbonization pathways and required annual heating system replacement rates and rates of conversion to biomass systems. Reducing emissions by 45% emissions by 2030 based on 2010 levels and 100% by 2050 means replacing 103% of heating sources in the next 27 years. Of those, 90% are converted to Pyro-CCS. Meeting this target requires a significant phase out of fossil fuels-based heating, from 90% in 2020 to 56% and 0% in 2030 and 2050, respectively, for biomass-based based heating (either combustion or Pyro-CCS).

Our model shows that this transition need not happen overnight. On average, 3.7% of heating capacity must be replaced annually in NWT. However, accelerated rates are needed in the next 7 years (average 5.4%) to meet the 2030 target, with particularly high rates in 2028-30 (15%), to level off to 3.5% in the 2030s, and to 2.5% in the 2040s. Required conversion rates to Pyro-CCS start at 10% in 2024-25 (1% replacement rate), then to 70% in 2026-27 (3% replacement rate) and finally at 85% in 2028-29 (15% replacement rate). Government innovation investment support is needed to catalyze that level of Pyro-CCS adoption.

A second scenario is depicted where post-2030, a decision is made to increase carbon capture and storage capacity in the heating sector. The years leading to 2030 are kept unchanged from the previous scenario, but the replacement rate in the 2030s and 2040s is kept steady at 4% per year. This leads to a total replacement of 115% of all heating systems in NWT— which is a likely scenario considering their lifetime of approximately 25 years. With this scenario, the heating sector in the territory can achieve a 112% emissions reduction from 2010 levels by 2050.



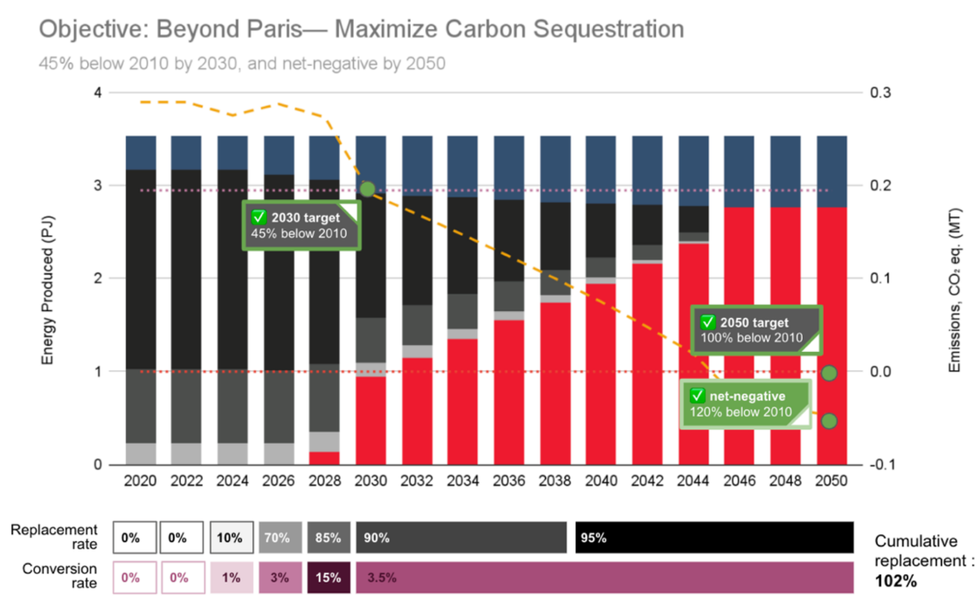


***Figure 10**: Decarbonization forecasts for Northwest Territories, Canada.*

The 1.5°C scenario requires heavy innovation investments to spur rapid conversion rates this decade followed by very high replacement rates next decade (A). The "Sequester" scenario is similar but keeps a higher pace throughout the 2030s and 2040s, to become carbon-negative by 2044.

Figure 11 shows the area of FKT to support Pyro-CCS in the *Sequester* scenario. Historical annual area burned is shown in grey and the historical annual average of 6,000 km^2 (197) is projected in yellow to 2050. Our model suggests that only 121 km^2 annually are needed for our ambitious scenario in 2050 under the most aggressive decarbonization scenario; just above 2% of annual forest-fire area in NWT. Annual area of FKT is projected to grow as forest fires increase in severity and frequency under climate change (222). Hypothetically, the 6,000 km^2 of area burned yearly could support the annual heating needs of 2 million Canadians and promote sustainable economic growth in NWT— making Pyro-CCS a sustainable technology for the 45,000 residents of NWT.

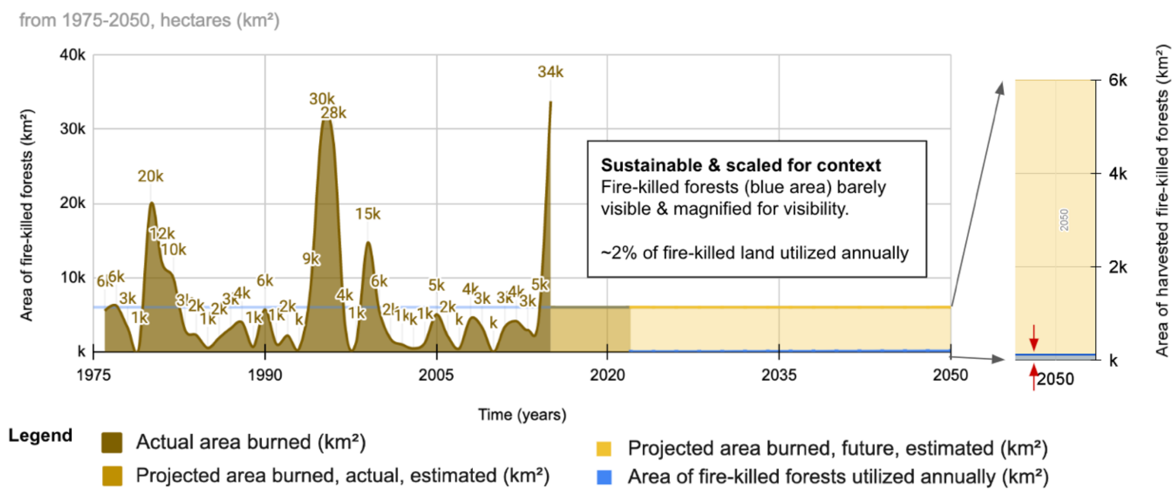


Figure 11: *Forest area killed by wildfire and fire-killed forest area utilized for energy purposes for the "Sequester" scenario.*

4. Discussion

We believe that Pyro-CCS with wood-pellets or FKT is a low- or negative-emissions heat source that can help NWT and similar regions decarbonize. Below we discuss its implementation and future research needs.

4.1. Policy Recommendations

We suggest four policies for Pyro-CCS implementation in NWT: [1] innovation investments, [2] improved data and monitoring, [3] incentivizing district energy, and [4] working with local stakeholders; they are discussed below.

Policy 1: Innovation investments with mandated phase-out of fossil fuel heating

Meeting decarbonization goals necessitates quickly converting old furnaces to low-carbon technologies. However, Pyro-CCS must first be technically and commercially feasible in NWT. The Government of Northwest Territories (GNWT) and the Government of Canada (GC) can provide grants funding to support local Pyro-CCS research and demonstration projects. To avoid carbon-lock in (223), innovation investments must happen quickly so that Pyro-CCS is a viable alternative to fossil fuels when policies to boost replacement rates are introduced.

To accelerate replacements and conversions, the government could mandate a cap of 120 g CO_2e MJ^{-1} for new installations in 2023. This cap could decrease by 5 g CO_2e MJ^{-1} annually, effectively eliminating new fossil fuel installations by 2030 and biomass combustion in the mid-2030s. A progressive carbon price will further incentivize retrofits by penalizing late adopters. GNWT should lead by example by adopting these rules for public buildings 3-5 years earlier.

Decarbonizing heating requires 3-15% annual replacement rates, far above those of other Canadian jurisdictions (224). GNWT can take inspiration from Ireland which aims to retrofit 8% of its homes annually (225). GNWT can use carbon tax revenues to catalyze decarbonization by creating a fund to offset longer payback periods of energy retrofits and to support a green jobs initiative. Figure 12 shows that modest carbon taxes will provide payback for decarbonizing heat in NWT, in the order of approximately $150M by 2050 in NWT only.

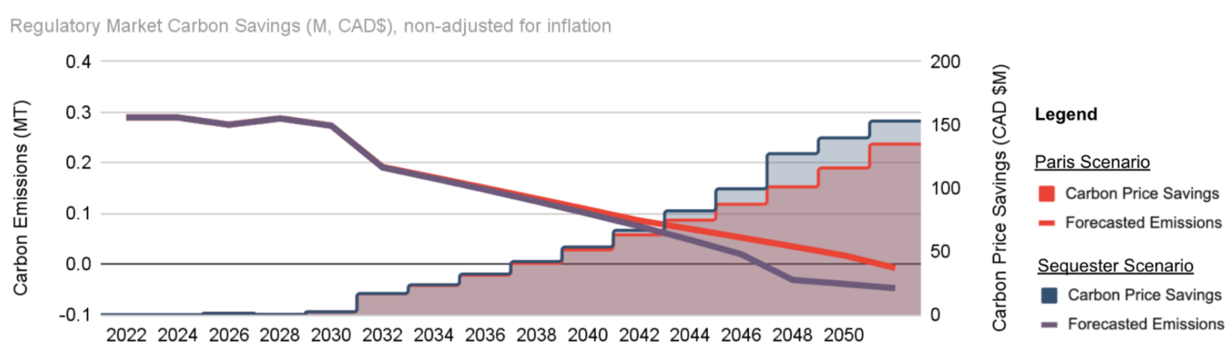


Figure 12: *Cumulative Savings for Pyro-CCS in NWT (CAD $M) from 2022 to 2050*

More than $150M could be saved annually by the territory. These prices are all in 2022 dollars and represent regulatory market savings from avoided carbon taxes. Carbon tax rate increases of $15/year (226) is assumed sustained post-2030.

Considerations for financial viability

Carbon pricing is only one revenue stream to make this technology financially feasible in NWT— alongside heat and biochar sales. Heating costs in NWT fluctuate between $0.10 to $0.16 per kWh for biomass combustion and fossil fuels combustion. Pricing for bulk biochar is between USD $571 and USD $2,200 (88), although higher-end, smaller quantities consumer products can go as high as CAD $60k per tonne (88, 227-229). Wok is ongoing regarding the creation of a viable business case on Pyro-CCS in NWT. With further work and innovation investments, we believe it can price-match currently available technologies.

Policy 2: Improved energy and emissions data

Existing data on energy and emissions in NWT are unavailable at the community level, by fuel type, or by end use (23). The GNWT and the GC must provide these data in a barrier-free, open-access, and user-friendly form. The United States Energy Information Administration's Energy Atlas provides a template for this (230). Private energy providers can assist by publishing anonymized consumption data.

Plugging data gaps will help green businesses and residents identify opportunities for district energy, Pyro-CCS, and community energy hubs. Robust emissions data can support further research, including detailed forecasts of decarbonization pathways across sectors. Transparent, up-to-date data will also motivate GNWT to stop missing its decarbonization targets (231).

Policy 3: Promote district heating

Results show that decarbonization is maximized if replacement rates ramp up after Pyro-CCS is widely available to supplant fossil fuels. District energy systems (DES) can help convert swathes of homes and business to low-carbon heat once Pyro-CCS or another low-carbon technology is established in NWT. DESs have been deployed successfully in northern communities including Yellowknife (232). Hybrid-DES could combine heat pumps (for days above -15°C) with low-carbon or carbon-negative technologies like biomass combustion or Pyro-CCS for the cold winter months when heat pumps are ineffective (233). DES can simplify decarbonization for the customer, as it is handled privately (234). Establishing an energy governance structure, leading public engagement, and developing legal frameworks can eliminate barriers for low-carbon energy adoption (235).

Policy 4: Include local stakeholders

NWT and the two other Canadian territories house a large Indigenous population (236). Deploying Pyro-CCS using FKT at scale demands 121 km^2 of land annually. Indigenous stakeholders should lead any project harvesting FKT to honour and put forward Traditional Knowledge on sustainable land management. For example, First Nations and Métis communities have long practiced controlled burns (237, 238), which are likely to enhance soil carbon. Indigenous communities leave fire-killed areas in fallow for 7 years prior to harvesting the biomass to allow the Land to gain maximum benefits from the wildfire— other Indigenous or Métis practices continue to be utilized today (239). These and other practices can be incorporated into NWT's future bioenergy economy.

4.2. Future Research

Additional research is needed to better understand the potential of Pyro-CCS. One challenge is accounting for post-fire carbon-pool dynamics in forests. Equations 1 through (Equation 4 show that sequestered carbon depends on emission from decaying FKT and regenerative carbon uptake (accounted using the biogenic emission factor) (30). There exists only a handful of studies on post-fire carbon dynamics in boreal forests (213, 240, 241), none of which are in the Canadian far-north. Using conservative values (slow decay and uptake) in our uncertainty analysis can cause Pyro-CCS with FKT to be a net emitter, yet less than fossil fuels. Studies of carbon-pool dynamics in NWT and other far-north regions would reduce this source of uncertainty in future carbon footprint studies.

Relatedly, better data are needed on carbon uptake from biochar in northern regions as most research has focused on southern climates (67, 92, 111). All studies point towards high stability of biochar in soil (51-54, 67, 92, 111, 123). However, research on soil-carbon dynamics in circumpolar regions could reduce uncertainty and determine if biochar produces knock-on carbon benefits through enhanced primary production immediately after fires. Another outstanding question surrounding biochar is its application at large scales. Solutions for local markets need to be identified as they are essential to financial viability (242, 243). Potential uses include filler for local roads (91) or for mining remediation (94, 97). If it is spread on land, technologies to do this at immense scales are needed (e.g. drones, airplanes). Additional work should investigate when biochar should be applied to minimize effects on forest albedo and local warming (76).

The pyrolysis system we modeled produced a specific ratio of biochar to fuel. Given the ample surplus of FKT in NWT an alternative is to tune the pyrolysis process to produce less pyro-gas and more biochar. Future work should study how seasonal shifts in pyrolysis outputs could align with heating demands. For instance, in the summer biochar and bio-oil could be maximized assuming a healthy market exists to use these products, or for carbon storage— carbon dioxide removal credits allowing for increased revenues.

Future analysis should consider a broader portfolio of heating technologies. For instance, air-source heat pumps, which we excluded in our model, can offer heating and cooling when temperatures are mild and provide strategic redundancy, and energy and carbon optimisation to energy systems (233). Studies should look at complementing Pyro-CCS and biomass combustion with heat pumps powered by photovoltaics in summer months. Electric resistance heating should also be considered in models, as it might be part of the solution for jurisdictions with lower electricity prices than NWT— Yukon, for example.

Lastly, further research is needed to develop small-scale Pyro-CCS. Systems below 40 kW are not commercially available yet. Connecting this to multiple homes ramps up complexity and hinders adoption. A 5 to 10kW system would be more appropriate for individual homes— although likely less carbon-efficient— and would present an opportunity for a just workforce transition through maintenance requirements. The innovation funding suggested above could support this research.

5. Conclusions

NWT and other northern communities urgently need to decarbonize. These communities are at the front-line of climate change and have some of the highest per-capita emissions globally. Local conditions make it challenging to decarbonize in the same manner as communities in milder climates. The “electrify everything” mantra is simply not financially feasible. Heating is a major energy use and source of emissions in northern communities. Decarbonizing this carbon-intensive sector will require creative solutions.

This study suggests that using Pyro-CCS to produce heat and bury carbon is one such solution. We demonstrated this through an analysis of Pyro-CCS of a previously unstudied feedstock that incorporates forest carbon dynamics that are often ignored in bioenergy studies. Under our modeling scenarios, Pyro-CCS is the lowest currently-available technology on the market. Even under conservative modeling assumptions, it provides significant carbon savings over fossil fuels. Policies supporting Pyro-CCS could move NWT towards a carbon-negative, sustainable, circular bioenergy economy, under Indigenous leadership. This is the first study to consider this possibility in the far-north. At scale, the technology could make significant contributions to economy-wide decarbonization and provide a useful outlet for the billions of trees that will inevitably be killed as the planet heats and forest fires ravage the northern boreal forests.

6. Supplementary information

For reading clarity, the supplementary information that was initially submitted with this manuscript has been located in an additional section in this document. Jump to page 109 to find the Supplementary Information

It is broken down by section:

1 OpenLCA inputs, ouputs and results per fuel type

3 Decarbonization scenarios, conversion & replacement rates

4 Fire-killed trees image

5 Detailed results, carbon footprint

Connecting text

Chapter 3 — *Manuscript* presented the results of the carbon footprinting analysis, and demonstrated that Pyro-CCS in Northwest Territories from FKT is likely to be carbon-negative, and highly likely to offer significant emissions reduction achievements compared to other sources of heat that are currently utilized in Northwest Territories.

Chapter 4 **—** *Discussion* expands on the technological, economic and policy implications of the large-scale deployment of Pyro-CCS in Northwest Territories, and highlights additional work required for the technology to take off in the territory.

Chapter 4 — Discussion

1. Results review

The results from this research are summarized below. We start with the carbon flow (answering the question: “where does the carbon go?”), followed by the LCA and carbon footprinting results, and following with systems growth and the potential for large-scale carbon sequestration in Northwest Territories.

1.1. Carbon flow

The flow of carbon from its biospheric form to the atmosphere is expressed in Figure 13 below— note the difference between carbon C and its carbon dioxide equivalent on the right hand side of the figure.

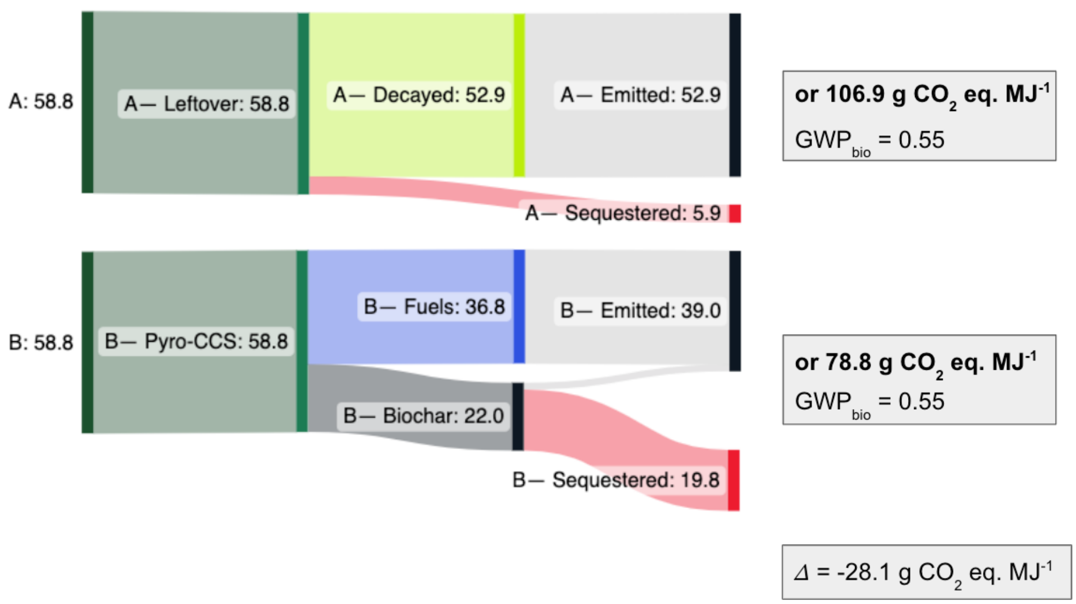


Figure 13: *Sankey Diagram of Scenario A (Counterfactual, untouched) vs Scenario B (Pyro-CCS, proposed) with the use of FKT.*

The diagram demonstrates a reduction in emissions of 28.1 g of CO2 eq. per MJ of energy produced.

Figure 13 answers the question: “Where does the carbon go?”.

In scenario A, 58.8 g of carbon (C) is considered as the quantity of carbon required to produce 1MJ of heat. It is left untouched in the forest. After 100 years, 52.9 g have decayed and been emitted back to the atmosphere. The rest (5.9 g) has been sequestered by the surroundings— either as pyrogenic carbon, or as others forms of biomass.

Instead of being left undisturbed, it is fed through a Pyro-CCS plant. Out of the 58.8 g of carbon, 36.8 g end up transformed as either bio-oil or biogas, and both are combusted for heat, and emitted. The pyrolysis process also created 22.0 g of carbon under the form of biochar. Out of those 22.0 g, a small portion (2.2 g) ends up decaying back into the atmosphere.

Overall, system A emits 106.9 g of CO_2 eq. System B emits 78.8 g CO_2 eq. These are avoided emissions of 28.1 g CO_2 eq. per MJ of energy produced. Note that a GWP_{bio} of 0.55 is used in this case. Its determination is estimated based on currently-available literature (30, 125) and would be more accurate with hands-on experiments, but remains outside the scope of this research.

Table 15 and Table 16 (Supplementary Information) represent carbon flow depictions for both locally-harvested necromass feedstock, and imported wood pellets feedstock.

1.2. LCA results

The results from the carbon footprinting exercise are presented in the manuscript— the reader can refer back to the text below Figure 9 for a textual description of the results. They are summarized as such: With a carbon footprint of -10.3 g CO_2 eq. MJ^{-1} (from FKT), and 40.9 g CO_2 eq. MJ^{-1} (from imported wood pellets), Pyro-CCS outperforms heating oil (83.1 g), propane (89.9 g), natural gas (79.4 g), and biomass combustion (59.7 g) in terms of greenhouse gas emissions.

2. Towards a broader low-carbon energy portfolio in NWT

Other heating systems could have been considered for this paper but were excluded for simplicity and local reasoning: heat pumps, although generating a larger interest particularly for shoulder seasons (Spring, Fall) decarbonization and rise in cooling needs, have been excluded because the current technology is not effective at temperatures below -15°C and as such cannot be used as a primary heat source (233); electrical resistance heat in Northwest Territories is financially uninteresting because of high electricity prices (37¢/kWh) (23) and very dark winters where energy needs are highest; geothermal has been investigated in NWT (38, 244) but with only limited uptake due to local conditions making it expensive (Canadian Shield); and firewood is assumed to be less convenient but similar to wood pellets combustion and although used widely in the territory, its carbon intensity varies widely depending on stove efficiency and the related energy data is extremely hard to quantify with certainty because of its unregulated economy, often driven by self-harvest.

Emissions from the shipment of fuels to smaller communities have been excluded from the Northwest-Territories-wide scenario forecasting for simplicity; the scenarios being too multi-factorial, we estimate that added emissions cannot be higher than 10%. In some cases, locally-available bioresource might drive down overall emissions.

We imagine northern-made District Energy Systems powered on heat pumps from community solar during the shoulder seasons, and Pyro-CCS during cold months. This would provide comfortable redundancy, and a large thermal mass to buffer solar availability; effectively reducing the need for battery-electric energy storage, which has a high financial and carbon entry cost.

3. Economic implications: carbon pricing & mitigation financing

The financial viability of Pyro-CCS as a business opportunity in NWT relies upon the additional revenue streams created by this innovative technology— namely, the production of carbon dioxide removal credits, which some call carbon offsets, and the sale of the biochar by-product. A high national or global price on carbon would make the technology only more appealing financially— understanding the financial environment is crucial for this project.

Some groups are opposed to carbon markets as they supposedly allow for the continued exploitation of fossil fuels (245); others argue that carbon offsets should not be used due to concerns about their non permanence, additionality, conflicts of interest and other factors (246). The author estimates that Pyro-CCS in Northwest Territories would be cost-competitive with other currently-available heat sources ($0.12/kWh) at a carbon price of $150 per ton, and a bulk biochar price of $1,500 per ton. Detail to follow.

3.1. Creating a revenue-positive business in Northwest Territories

Although government grants should be sought after, this technology has a higher likelihood of deployment at a large scale if it does not depend on government grants. It is likely to necessitate grants to get it started, but revenue streams appear to be favorable for Pyro-CCS to take place in Canada.

There are three important potential revenue streams for Pyro-CCS in NWT: heat sales, biochar sales, and carbon dioxide removal sales. Likely additional revenue streams could be created but for the sake of this exercise, we limit it to those three, to see if it would be a business able to sustain itself:

3.1.1. First potential revenue stream: heat sales

Selling heat from the Pyro-CCS process is trivial and is likely to present as a good business opportunity if the heat produced from biochar can be sold at a lower price than currently-available heat sources. Currently, heating costs in Northwest Territories are about $0.13 per kWh for heating oil, $0.16 per kWh for propane, $0.12 per kWh for natural gas, $0.11 per kWh for biomass combustion, and $0.37 for electrical resistance heating. Heat pump costs would be around $0.15 per kWh but would require auxiliary heating in temperatures colder than -15°C.

3.1.2. Second potential revenue stream: biochar sales

Biochar pricing on the market seems to be emergent and volatile. Researchers in California highlight a price of USD $571 and $1,455 per ton (90% probability) (229). The International Biochar Initiative's *State of the Biochar Industry 2014* reports a global average value of biochar of USD $2,060 per tonne (88), in line with other values of USD $2,200 used by other for mine remediation projects (228). It is possible to buy biochar online directly from the manufacturer at a price of CAD $1,300 (247). Michigan State University suggests that the current price of biochar on the market is between USD $4,000 to USD $20,000 per tonne (227). Consumer pricing for smaller quantities (i.e. indoor potted plants amendments) are detailed at about CAD $40,000 and $60,000 per tonne.

3.1.3. Third revenue stream: carbon pricing

Carbon pricing acts in two ways to make this technology financially interesting: on penalizing the carbon-intensive alternatives, but also in rewarding Pyro-CCS for its carbon storage capacity with the national carbon price, and voluntary carbon markets, respectively. Carbon pricing does not make a large difference in the overall financial viability, and as such the technology would still be viable even without it. However, the Government of Canada has established a price on carbon in 2019, which started at $20 CAD per tonne of CO_2 equivalent, and which is set to increase gradually to $170 CAD per tonne in 2030 (248). At the time of writing this text, carbon was valued at $65 CAD per tonne. Even if the global price on carbon was to raise to very high values, its influence on the financial viability of this technology is likely to make up less than 5% of total revenues— other Pyro-CCS businesses also experienced similar financial situations: in the first days of Carbofex, carbon dioxide removal credits were not contributing to their revenues and they could continue to function (104).

3.2. Voluntary carbon markets and possible projects

In Tampere, Finland, Pyro-CCS entrepreneur and operator Carbofex is selling CORCs (CO_2 removal certificates) at 270€ (CAD $390) per metric tonne of CO_2 equivalent— it is a significant portion of the revenues of the company. Large businesses have invested in this technology (Shopify, Microsoft), reportedly for the long lives and trustability of the CORCs that were created (249).

3.4.1. Could carbon pricing support Reconciliation?

Nonetheless, it appears that carbon offsets could help further some of the 94 Calls to Action in the Truth and Reconciliation Commission Report, namely through *Indigenous Protected and Conserved Areas:* “For the most part, however, Indigenous-led conservation—such as Indigenous Protected and Conserved Areas (IPCAs)— and climate initiatives—such as carbon offsets credits—are proceeding separately from one another (183). In principle, both initiatives are complementary, yet in practice this is unknown. In part, this is because their linkages have been insufficiently studied (250).”

For this reason, a deeper dive in instruments for revenue-generation from carbon offsets is of interest to this project.

3.4.2. Biogenic emissions not accounted for globally

Biogenic emissions (from biomass combustion, as opposed to fossil emissions) in Canada and around the world are currently not counted towards our Paris Agreement commitments and *Nationally Determined Contributions*, but various researchers argue that they should be, as it would depict more accurate carbon footprinting of products, projects and processes. Additionally, the use of dynamic LCAs, or at least the integration of longer time scales in static LCAs is preferable as a way to represent the environmental impacts more accurately. The counting of biogenic emissions is likely to make Pyro-CCS a more promising technology from an emissions point of view.

4. Policy implications

4.1. Conversion rate: risk of carbon lock-in

The Government of Northwest Territories (GNWT) should mandate a territory-wide replacement and conversion rate. The Federal Government of Canada (GoC) and the GNWT should invest immediately in Pyro-CCS demonstration projects in NWT— and offer an innovation grant fund of at least $1M in year 2023 to support a demonstration project. This purpose of the innovation fund will be to rapidly increase the conversion rate in the years 2024-2026 so that we can gain confidence in the maturity of the technology before scaling it up.

As expressed in the results section, carbon lock-in can be a concern especially if a low conversion rate is coupled with a high replacement rate in early years. It might prove more financially responsible to slowly ramp up the replacement rate, while heavily investing in innovation at the onset to implement, pilot, commission and improve Pyro-CCS in NWT. It is best to avoid a high replacement rate coupled with a low conversion rate as that might lead to the carbon lock-in of biomass combustion systems— good, but with missed opportunities for carbon sequestration.

4.2. Replacement rate

This is two-fold. Both new installs and retrofits should be limited by a carbon intensity metric capped at 115 g CO_2 eq. per MJ in 2023, reducing by 5 g CO_2 eq. per MJ per year, effectively eliminating the possibility of new fossil fuel installations as early as 2025, and biomass combustion by 2040. A progressive price on carbon will also incentivize retrofits by providing a retrofit fund, but also by penalizing late adopters. GNWT should lead by example by imposing on itself the same rules, but 3 years earlier.

Both the carbon intensity metric and the price on carbon should be high enough to effectively follow the replacement and conversion rates highlighted in Figure 10. Infrastructure replacements are usually unplanned (failure during winter usually warrants an immediate call to a repair professional for a same-day replacement), and when the opportunity passes then we are witnessing carbon lock-in. Both barriers and incentives must be put in place to prevent the conversion and carbon lock-in to fossil fuels.

Our emissions forecasting model assumes that heating systems convert to either biomass combustion or pyrolysis— but there remains a very important risk that residents could convert to natural gas or propane from heating oil, or even stick with heating oil. Both federal and territorial governments need to make immediate significant investments in innovation, research and development in order to make the capital expenditure cost of Pyro-CCS and other low-carbon technologies cheaper than the current status quo options.

4.3. How this compares to other large-scale retrofit efforts: Yukon, and Ireland

The Government of Yukon released an action plan in 2020 for the replacement of 1,300 heating systems in the territory by 2030 (251). The total number of heating systems is not disclosed, but assuming 10,000 heating systems, this provides a replacement rate of less than 2% per year— the Government of Northwest Territories would need to take inspiration from the Government of Yukon but largely expand on those efforts to reach 3 to 15% replacements annually. This can be tied to a territory-wide job creation initiative in the global context of fossil fuel projects closures. This scale of ambition is not unlike the retrofit of 1.6M homes (80%, or 8% per year) and installation of 600,000 heat pumps in Ireland in this decade (225).

4.4. Mandate & support availability & access to fuel consumption, emissions & energy data

A large barrier for the development of this research was the availability of emissions and energy data in Northwest Territories communities, and in other territories. On government data sources, there is no geographical breakdown of data (grouped for the entire territory) nor by fuel type (grouped as "Refined Petroleum Products"). "Privacy" barriers on energy data are unhelpful in accelerating the transition to carbon-neutrality. Community groups have asked for energy consumption availability in the territory (40, 252)— an open-access, user-friendly, barrier-free access to energy consumption data in NWT with neighbourhood-scale and fuel-type breakdowns would accelerate the development of new energy alternative options offered by private businesses (i.e. district energy systems, Pyro-CCS, community solar, community storage, etc.) This data exists in the hands of fuel distributers and must be made available to municipalities and businesses interested in deploying decarbonization solutions.

4.5. Highly incentivize district energy systems, a "no-regrets" strategy

As suggested in the first policy, we might be able to achieve a higher carbon sequestration capacity if the conversion rate can be maximized prior to increasing the replacement rate so as to avoid carbon lock-in. The installation of district energy systems (DESs)— even if limited to the installation of buried thermal pipe in initial phases— is likely to accelerate the deployment of Pyro-CCS once the initial innovation and testing phases are completed. This no-regret strategy is likely to benefit other forms of renewable energies as well, should a new technology emerge and steal sail winds from Pyro-CCS. DESs could be used in hybrid systems with community-scale heat pumps to eliminate shoulder season carbon emissions (> -15°C average temperature), topped up with biomass combustion during winter nights. DESs can simplify decarbonization for the customer, as it is handled privately. Establishing an energy governance structure at the community level is critical to remove future energy deployment barriers for Pyro-CCS or other renewables.

4.6. Emissions reductions forecasting

Although the governments have set 2030 (federal, territorial) and 2050 (federal only) targets, it remains imperative to set interim targets to keep track of progress. The proposed decarbonization models are assuming a linear trend between 2022 and 2030, and between 2030 and 2050. Although some could argue that waiting a few years to develop carbon-negative infrastructure, and subsequently ramping up replacements could be strategic, it must be tied to a legislated plan. The governments of Canada and Northwest Territories have failed on all greenhouse gas emissions targets they set for themselves and additional accountability mechanisms must be put in place.

5. Incorporating Indigenous & Traditional Knowledge

First Nations, Métis and Inuit practices

This thesis was written by a cis white male from French-Canadian descent. My worldviews are narrow as per my euro-centric education, culture and employment backgrounds. In various informal discussions with First Nations and Métis, the author learned of the importance of fire on forested lands. A practice that has surfaced in the research is the retainment of FKT on-site for 7 years after the burn event, in various First Nations and Métis communities in so-called Canada. The pyrogenic carbon is said to have beneficial impacts in the forest regrowth— as expressed by the growth of fireweed in fire-killed areas post-fire. Low-intensity burns is a cultural practice often observed amongst Métis and First Nations groups that is said to enhance carbon sequestration in soils. The use of FKT from high-intensity burn areas for Pyro-CCS and ultimately Land[5] regrowth seems to be of interest amongst the people we interacted with. My work and relationship-building continues.

[5] Land is capitalized to reflect its cultural importance and significance (253).

6. Future work and remaining knowledge gaps

This section depicts several additional research opportunities that were outside the scope of this research but that could help accelerate the deployment of Pyro-CCS in NWT and in Canada. Most of those are tied to the increase of territorial and federal investments and ambitions.

6.1. Optimizing for carbon capture and storage

There are various variables that could be optimized to improve the carbon footprint and sequestration potential of Pyro-CCS, and as a result improve the business case as well. Although currently, carbon credits revenues are not likely to tip the balance in a significant way, reducing emissions from the operations as currently presented would make the process less emissions intensive. The following activities could be part of a future research and development program to further increase the CCS capacity of Pyro-CCS— this is a non-exhaustive list:

- Wildfire-related feedstock selection: Forest thinning operations and prescribed burns are suggested to reduce overall emissions from wildfire (254)— could emissions reduction from wildfire mitigation initiatives be claimed towards Pyro-CCS?;
- Slowing wildfire return with biochar: Could the dissemination of biochar on drought-prone forests retain additional water that would slow down wildfire return, and could these efforts be claimed as an optimization of carbon storage?
- Transportation electrification: The electrification of the harvest and transportation equipment would likely reduce emissions from those sectors significantly— fuel production, transportation and biochar transportation make up 56% and 25% in the wood pellets and FKT scenarios. Assuming an emissions reduction potential of at least 60% (conversative) for the electrification of transportation and harvesting equipment, we could further reduce emissions by up to 21 g CO_2 eq. MJ^{-1} which is very considerable;
- Seasonal programming for delayed heat utilization: Modifying operating characteristics of the chosen Pyro-CCS equipment for it to produce a lower

amount of heat in the warmer months in favor of more biochar production; or storing bio-oil in the summer for heat production in the winter, or shipping the bio-oil to remote locations for deep underground storage (Kansas, for example). Some Pyro-CCS equipment allow for the separation of bio-oil and for its subsequent storage. The German technology (*Biomacon*) explored in this research does not allow for this, but the Finnish one (Carbofex) has already demonstrate additional CCS capacity through a deep burial storage partnership in Kansas. The interest in bio-oil storage is two-fold: for summer production which can be used during the cold season, or off-site in more conventional equipment; but also in additional capacity for carbon capture and storage. Federal funding could help investigate the local capacity for bio-oil storage in underground reservoirs in the territory or in former oil wells in neighbouring Alberta.

- Local biochar market creation: Finding local biochar uses would allow for a significant reduction in transportation emissions, in addition to creating local economic opportunities;
- Improved forest performance: The biochar produced could be used to accelerate the growth rate of new or existing forests, increasing the carbon sequestration potential of the technology;
- Seasonal programming for increased biochar production: Running in summer months on high biochar output, low or no energy output: The Pyro-CCS systems can be modified to run on a higher energy, lower biochar output, or higher biochar output and lower energy output. Two operating regimes could be determined in collaboration with the product manufacturer in order to determine the best cold-months and warm-months biochar and heat production capacities. This might increase the financial viability of the technology, particularly if biochar can be sold at high prices. For this to happen, a demonstration project must be put in place in Yellowknife.

- Amending untouched forests: Because of the already high presence of pyrogenic carbon in burnt forests, spreading biochar in live forests might be a better strategy for greenhouse gas emissions reduction;

6.2. Developing a biochar market, dissemination methods and smaller size units

6.2.1. Current biochar market prices

Although fairly unknown to the general public, the biochar market is growing. The carbon footprinting performed in this work included the shipment of biochar back to California after production in Yellowknife— this was done mostly to insure the financial viability of the project. However, there is evidence that biochar is growing in popularity, and the creation of a local market is highly likely. Various industry reports demonstrate continued growth in the sector: the biochar market was estimated at $1.45B USD in 2018, and forecasted to grow then at a compound annual growth rate (CAGR) of 9.1% to reach $3,23B USD in 2026 (255). Although the COVID—19 pandemic slowed down the growth, another industry analyst in 2021 rose the forecasted CAGR to 12.3% for 2022-2027 (256). Some papers describe an acceleration of research on biochar in the last two decades (109).

Tailings ponds remediation in the oil sands present a large opportunity for water remediation, bioremediation and heavy metals decontamination; and similarly for mine remeditation projects in Northwest Territories. The large agricultural sector in Alberta and emerging little sibling in Northwest Territories also present opportunities. The forestry industry in the Western provinces as well as in Northwest Territories are another clear potential buyer.

6.2.2. Creating a local biochar market

The implementation of Pyro-CCS in Yellowknife and its financial viability is partially dependent on the technology proponents' capacity to sell biochar on local, national or international markets. Local uses (within 200 km of Yellowknife) include but are not limited to mine remediation, agricultural amendments, municipal landscaping amendments, residential landscaping amendments, filling, burial, or others. The determination of biochar uses and the creation of a biochar market in Yellowknife is outside the scope of this research but it is assumed that it is financially viable and demand can be generated— biochar research publications have grown 6-folds in the last 10 years (257) (88). Various national stakeholders are interested in the purchase of biochar— notably tailings ponds remediation in Alberta, for example, or agricultural amendments in the Prairies. This paper included an option to ship biochar to Californian markets if geographically closer customers cannot be found, but we believe that a local demand can be created with the help of federal economic development investments.

6.2.3. Disseminating large amounts of biochar on vast areas

Pyro-CCS projects in Europe are, at least partly, financially dependent on the biochar sales. The by-product is lesser known in Canada— the financial return of Pyro-CCS is partly tied to its market cost. To do so, it must at least be established as a viable soil amendment for agricultural and forestry sites. Additionally, research into the mechanical dissemination of biochar on large swaths of land (agriculture, post-fire revegetation, etc.) There has been anecdotal evidence for the dissemination of biochar with tractors in Sweden (258), and some suggested it could be disseminated with air-dropped “seed balls” during revitalization efforts. In larger decarbonization schemes, biochar could be used as a filler material to build logging roads to access fire-killed areas; and could later on be further spread into the land with other mechanical efforts. A particular attention to snow fall timings should be observed, as some experiments demonstrate that the change in land albedo resulting from the dissemination of biochar can change the global warming potential benefits by up to 22%. This could be avoided by either using biochar in deep mine remediation projects, or by timing biochar dissemination with snow falls so as to minimize climate forcings.

6.2.4. Pyro-CCS unit sizing for single family homes

Pyro-CCS equipment designed to produce heat to be used for space or domestic hot water heating right now is limited to bigger heat loads. Biomacon (Rehburg, Germany) produces devices that are as small as 60 kW and that remains too big for use in an individual family home, for example. The creation of local small-scale district energy systems even between four family houses poses an additional level of complexity which slows down the adoption of Pyro-CCS. A 10kW system would be more appropriate for individual homes, although likely less carbon-efficient. Smaller systems would reduce the failure risk and the improvement-iteration rate would be increased. Federal research investments are needed.

6.3. Impacts on the ecosystems

6.3.1. Land restoration through biochar amendment

Although a carbon analysis has been performed for the emissions related to the counterfactual case (the "do-nothing" scenario) for both FKT and imported wood pellets, there was no analysis done of the potential ecosystem impacts of disseminating biochar on forested land. Could the application of biochar accelerate forest regrowth and improve the carbon impact of the technology? This was tested by some researchers and they reported that biochar "did not have a clear and consistent effect on CO_2 effluxes in boreal Scots pine forests (114)". What about different types of forests? What about fire-killed forests?

Although albedo changes following biochar dissemination are a concern in terms of cancelling the climate mitigation intents of the project, its magnitude does not pose a threat to this technology, and could be remediated by proper timing with snow falls (76).

Additional questions that emerge include: does removing pyrokill from the land has negative impacts? Is there an equilibrium to reach?

Conversely, could the application of biochar to certain areas become so appealing that it could accelerate the development of the technology? Could biochar be applied in peatlands and muskegs that are prone to floods and droughts? Its water holding capacity is sometimes presented as an opportunity to increase soil resilience to a changing climate and its physical properties seem to be improve soil structure, which can alleviate drought conditions (96, 259, 260).

Biochar has been demonstrated to increased yields in crops (60, 95) but that there was diminishing returns at application rates higher than 15 and 30 tons per hectare (respectively).

6.3.2. Does Pyro-CCS present health concerns for the community?

Some papers point to the presence of formaldehyde in the Pyro-CCS outputs, as well as other VOCs. The literature points to VOC destruction efficiency of at least 90% when the temperature is of at least 200°C (261)— and likely to reach an efficiency of nearly 99% when passing through the pyrolysis chamber at 600°C. Pyrolysis presents an advantage over biomass combustion: experiments demonstrate the total particulate matter emissions becoming negligible with pyrolysis temperatures over 400°C (262).

6.4. Small size units for residential deployment

The size of Pyro-CCS machines makes it difficult for individuals to introduce this technology at home. The smallest size that Biomacon offers is a 40 kW system, which could largely provide space and hot water heating for three houses in Yellowknife. There is a barrier in establishing partnerships with neighbours or through a Home Owners Association, or in convincing a board of a City Council to take on such a project. The creation of small-scale equipment for an individual homeowner might strongly accelerate this market. Currently, farmers (through the presence of multiple buildings on site), small and medium businesses and neighbourhood-scale utilities are a great target audience for Pyro-CCS. There is evidence to show that solar panels are contagious; citizens are more likely to install solar energy on their roof if their neighbours have already done it (263).

A Pyro-CCS market targeted to homeowners might come with services associated with the technology, including but not limited to maintenance, biomass delivery and biochar collection services. Homeowners might not have a need or run out of garden beds to amend with biochar and might be interested in a regulated service that could provide them with a cost reduction to their heating systems through the sale of the carbon dioxide removal services that they are effectively providing.

Conclusion and Recommendations

1. Summary of Recommendations

Policies to Support Pyro-CCS in NWT

We suggest three policies for Pyro-CCS implementation in NWT: (1) innovation investments, (2) improved accessibility to data on energy and emissions, (3) and incentives for the installation of district energy systems. Combined, these policies will foster a business environment for Pyro-CCS to thrive, remove perverse incentives that maintain fossil-fuel lock-in, and track decarbonization. We summarize each policy in turn below.

1.1. Policy Recommendations for the City of Yellowknife

1.1.1. Install District Energy Systems—

District Energy Systems will remove barriers into the deployment of Pyro-CCS at scale— particularly because the consumer end will be partly blind to the change of systems, and thus removing a layer of complexity. The City of Yellowknife is already a national leader in the deployment of DESs— and this work should be pushed further. Street renovations should automatically trigger the installation of heat pipes.

1.1.2. Make space and invest for Innovative Decarbonization Options—

Various municipal buildings and planned projects present great opportunities for the piloting of a carbon-negative heat source. Buildings or clusters of buildings with large heat requirements present great decarbonization opportunities. The City of Yellowknife should make space for at least one innovation project to test the operability of Pyro-CCS in the Northwest Territories.

1.2. Policy Recommendations for the Government of Northwest Territories

1.2.1. Support District Energy Systems Deployment in NWT—

Support upfront investments in DESs by providing guidance and supporting infrastructure such as best management practices, and funding.

1.2.2. Make detailed energy data available to the public

A large barrier in the development of this work is the lack of fuel consumption data— it is currently not broken down by community nor by fuel, and as such it is difficult to prioritize carbon-intensive street corners and neighbourhoods. Shifting to open-access in a more user-friendly way will provide businesses the confidence that their investments would bear fruit.

1.3. Policy Recommendations for the Government of Canada

1.3.1. Invest more heavily in innovation and decarbonization

The Government of Canada has already demonstrated leadership in the creation of funding programs that are intended to spur innovation and accelerate the scaling up of decarbonized practices (i.e. Clean Energy in Rural and Remote Communities— CERRC— and others). Those programs often are oversubscribed, which speaks to the community interest in decarbonizing operations and saving operational costs. Large federal investments are necessary to fast track innovation of Pyro-CCS so that system operators can become comfortable with their operation in Canadian jurisdictions.

1.3.2. Mandate the phasing-out of fossil-based heating systems

The Government of Canada already has influence on fuel efficiency standards for vehicles— and this should be extended to heating systems. An emissions cap should be introduced in such a way to phase out new fossil fuel systems by 2025. A cap of 120 g CO_2e MJ^{-1} for new installations in 2023 should be set in place, and could decrease by 5 g CO_2e MJ^{-1} annually, effectively eliminating new fossil fuel installations before 2030 and biomass combustion in the mid-2030s. A progressive carbon price will further incentivize retrofits by penalizing late adopters. Both the GC and the GNWT should lead by example by adopting these rules for public buildings 3-5 years earlier.

1.3.3. Install annual emissions reduction targets

Although Canada is expressing global leadership on emissions reduction by the installation of a net-zero target for 2050, we must demonstrate better results. Canada has a history of broken climate targets. We must introduce annual climate targets, to build credibility in our national climate plan.

2. Conclusion

Northerners are too acutely aware of the impacts of the climate crisis on their livelihoods: thawing permafrost leads to cracked infrastructure foundations, weakened ice roads; smoky summers lead to reduced quality of life; wildfires are a threat to infrastructure and the loss of natural environment and traditional hunting practices is leading to solastalgia and anxiety, amongst others. Yet, Northerners, in these harsh environmental conditions and solar-dark winters, are the least well equipped to decarbonize their way of life. Pyrogenic Carbon Capture and Storage (Pyro-CCS) is explored as a way to generate heat from fire-killed trees (FKTs) in a carbon-negative fashion. This research aims to answer the following questions: what is the carbon footprint of Pyro-CCS of imported wood pellets, and of locally-harvested fire-killed trees? What are the land-use implications of a large-scale transition to Pyro-CCS from locally-harvested necromass, would it be sustainable, and would it help to align the Territory with the Paris Agreement net-zero commitments by 2050?

An initial literature review was pursued on Pyro-CCS and its influencing factors; Life-Cycle Assessments (LCAs) and carbon footprinting; concepts for the accounting of biogenic carbon, forest behaviours in relation to feedstocks and carbon flows, and other topics relevant to the piloting of a Pyro-CCS plant with fire-killed trees in Northwest Territories. Through this literature review, it was not possible to find carbon footprint analyses for Pyro-CCS in a Northern Canadian environment, and neither for Pyro-CCS from FKTs.

This research then pursues a carbon footprinting analysis for Pyro-CCS from imported saw mill wood pellets, and from locally-harvested FKTs and finds a carbon intensity of 40.9 and -10.3 g CO_2 eq. MJ^{-1}, respectively. The results are compared with other types of heating sources that are utilized locally, including fossil fuels (heating oil at 83.1, propane at 89.9, natural gas at 79.4) and biomass combustion at 59.7 g CO_2 eq. MJ^{-1}. The research then purses a land-use assessment for the large-scale deployment of Pyro-CCS from FKTs and demonstrates that even under very ambitious scenarios, the resource utilization in Northwest Territories would be close to 2% of annual fire-killed land, meaning that the technology would be environmentally sustainable under static models. We also demonstrate promising financial returns in the order of approximately $CAD 150M per year in 2050 from carbon pricing savings only. This research is the first to consider biogenic emissions in the context of Northern Canadian heat production from biomass-based systems.

We then discuss some technological, economic and policy implications for Pyro-CCS in NWT. Notably, that Pyro-CCS presents some solutions that other currently-available heating systems do not offer (winter reliability, low- or negative-emissions) but that current financial environment presents high risk for the introduction of a new technology, untested in the Northern Canadian context. Nonetheless, we make a high-level business feasibility analysis to demonstrate that Pyro-CCS could present a comfortable profit margin for business operators. Some barriers need to be further defined and mitigated, notably the creation of a local purchasing market for biochar (in NWT or Alberta), identify large-scale biochar dissemination impacts and techniques in Northern boreal forests for increased carbon storage and accelerated forest growth; and the synchronization of conversion and replacement rates in order to avoid carbon lock-in. We believe that Pyro-CCS presents an opportunity for Reconciliation and Decolonization through Land-based nature-based solutions, either through *Indigenous Protected and Conserved Areas*, or *Land Guardian Programs*. A pilot project should be explored with Knowledge Holders and Land Experts in order to determine the most favorable locations for the incorporation of biochar in existing Lands, and to avoid unintended consequences.

We believe that Pyro-CCS presents significant emissions reduction capabilities compared to all other heating systems in Northwest Territories used at scale, and will perform better from an emissions point of view than heating oil, propane, natural gas, and biomass combustion. We believe that Pyro-CCS will be able to compete financially with currently utilized technologies, and will help the territory achieve net-zero emissions in its space- and hot water heating sector by 2050.

Municipal, territorial and federal governments must step in in various ways in order to support innovation efforts for Pyro-CCS, and bring the technology to a point of development where consumers will be confident that its installation will not represent any reduced operability compared to other heating systems. Pyro-CCS is a technology worth pursuing efforts for, to give Northerners a northern-made solution for decarbonization and climate mitigation.

Thank you for reading.

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Supplementary Information

1. OpenLCA inputs, ouputs and results per fuel type

Table 5: OpenLCA global references

Global Parameters		
Name	**Value**	**Description**
biochar_chips_production_annual	89955	kg, total amount of biochar produced by the operation of the system, per year
biochar_production_annual	55504	kg, total amount of biochar produced by the operation of the system, per year
biochar_to_CO2_factor	3.5	multiplication factor to convert kg of biochar into kg of CO2 sequestered
biomass_chips_consumption_annual	413793	kg, total amount of biomass (wood chips) consumed per year
biomass_combustion_consumption_anr	200250	kg, total amount of biomass consumed in one year
biomass_consumption_annual	255319	kg, total amount of biomass consumed per year
carbon_content_biochar	0.75	%, carbon content of biochar per weight
carbon_content_biomass	0.5	%, carbon content of biomass, per weight
carbon_price_federal_average_2024	150	CAD$, average price of carbon, national market, starting in 2024, 25 years out, conservative, minimum
carbon_price_market_average	30	CAD$, price of carbon on the offsets market, 2024 onwards, conservative, minimum
distance_lacrete_to_yk	900	km, distance from LaCrete AB to Yellowknife NT
distance_montreal_to_yellowknife	5500	km, distance from Montreal to Yellowknife by roads for transportation of the PyCCS machine delivered from Germany
distance_Port_Amsterdam_to_Port_Mo	6200	km, marine distance from Port of Amsterdam to Port of Montreal (estimated most likely trajectory)
distance_Rehburg_to_Amsterdam	400	km, distance from production facility to Port of Amsterdam for shipment
distance_yeg_yzf_road	1500	km, distance from Edmonton to Yellowknife by road, assuming transportation by truck
distance_yellowknife_to_san_francisco	4200	km, distance from Yellowknife to California by road
distance_yk_to_firekilled	210	km, distance from Yellowknife to Behchokǫ̀, NT
energy_production_annual	800000	kWh, total amount of energy produced per year by the machine
gross_energy_consumption_annual_die	100000	kWh consumed per year for diesel (gross value, before furnace efficiency)
gross_energy_consumption_annual_nat	842105	kWh consumed in one year (gross) before boiler efficiency
Heat_production_capacity	160	kW, Capacity of the machine to produce heat-- based on 160 kW for PyCCS Biomacon machine.
kWh_per_L_diesel	10	1:10 -- 1L of diesel for 10 kWh
life_expectancy_ashp	25	years, life expectancy of the air-source heat pump
life_expectancy_combustion	25	years, life expectancy of the biomass combustion boiler
life_expectancy_electric_heater	25	years, life expectancy, electric heater
life_expectancy_gshp	25	years, life expectancy of the ground source heat pump
life_expectancy_heating_oil_boiler	25	years, life expectancy of the heating oil boiler
life_expectancy_nat_gas_boiler	25	Life expectancy of the natural gas boiler
life_expectancy_pellet_stove	25	years, life expectancy of the pellet stove
life_expectancy_PyCCS_machine	25	years, expected length of operation of the PyCCS reactor
market_price_biochar	200	CAD$ per tonne, market price of biochar per tonne
market_price_energy_sales	0.1	CAD$ per kWh, market price for energy sale in Yellowknife starting in 2024, conservative, minimum
market_price_wood_pellets	337	$CAD per tonne, price of wood pellets per tonne, starting in 2024, minimum, conservative
nat_gas_heating_value_weight	42	42 MJ per kg of natural gas, https://world-nuclear.org/information-library/facts-and-figures/heat-values-of-various-fuels.aspx
operation_hours_per_year	5000	h, total amount of operation hours for the machine
system_reliability	0.98	%, percentage of the time the system will be operational and able to deliver (1-system_reliability = failure rate)
weight_per_L_diesel	0.85	kg, weight per L of diesel
weight_total_biomass_stove	500	kg, total weight of biomass stove
weight_total_heating_oil_boiler	500	kg, total weight of the heating oil boiler
weight_total_natgas_boiler	500	kg, total weight, natural gas boiler
weight_total_PyCCS_machine	1500	kg, weight of the PyCCS machine selected including seacan

Table 6: OpenLCA heating oil results, inputs and outputs

Heating Oil					
Results					
Contribution	**Process**	**Amount**	**Unit**		
100.00%	heating oil— main - CA-NT	0.08313	kg CO2 eq		
94.97%	heating oil— F : heat production emissions	0.07895	kg CO2 eq		
4.07%	heating oil— D : fuel production	0.00339	kg CO2 eq		
0.73%	heating oil— B : transport, fuel	0.00061	kg CO2 eq		
0.14%	heating oil— electricity use	0.00011	kg CO2 eq		
0.06%	heating oil— E : equipment manufacturing	4.63E-05	kg CO2 eq		
0.03%	heating oil— C : transport, employee commute	2.10E-05	kg CO2 eq		
Inputs— main process (all unspecified processes are 1:1 input:output)					
Flow	**Amount**	**Provider**	**Unit**	**Description**	
heating oil— B : transport, fuel	distance_yeg_yzf_road*life_expectancy_heating_oil_boiler*gross_energy_consumption_annual_diesel/kWh_per_L_diesel*weight_per_L_diesel/1000	heating oil— B : transport, fuel	t*km	Land transportation from Edmonton, AB to Yellowknife, NT	
heating oil— C : transport, employee commute	life_expectancy_heating_oil_boiler*15*12	heating oil— C : transport, employee commute	p*km	15 km driven monthly in a combustion engine vehicle for maintenance & operation	
heating oil— D : fuel production	energy_production_annual*life_expectancy_heating_oil_boiler	heating oil— D : fuel production	MJ	Quantity of fuel produced.	
heating oil— E : equipment manufacturing	1	heating oil— E : equipment manufacturing	Item(s)	Manufacturing of boiler, chimney, fuel tank.	
heating oil— electricity use	0.2/160*energy_production_annual*life_expectancy_heating_oil_boiler	heating oil— electricity use	kWh	200 W electric allowance for heating oil combustion furnace process (fuel pump, etc.)— please note that heat distribution system is excluded, for all systems	
heating oil— F : heat production emissions	energy_production_annual*life_expectancy_heating_oil_boiler	heating oil— F : heat production emissions	kWh	Emissions from the combustion of heating oil.	
Inputs— D: fuel production					
Flow	**Category**	**Amount**	**Unit**	**Provider**	**Description**
light fuel oil	C:Manufacturing/19:Manufacture of coke and refined petroleum products/192:Manufacture of refined petroleum products/1920:Manufacture of refined petroleum products	1.51E-04	kg	market for light fuel oil | light fuel oil | Cutoff, U - CO	Literature
light fuel oil	C:Manufacturing/19:Manufacture of coke and refined petroleum products/192:Manufacture of refined petroleum products/1920:Manufacture of refined petroleum products	2.03E-04	kg	market for light fuel oil | light fuel oil | Cutoff, U - ZA	Literature
light fuel oil	C:Manufacturing/19:Manufacture of coke and refined petroleum products/192:Manufacture of refined petroleum products/1920:Manufacture of refined petroleum products	1.40E-04	kg	market for light fuel oil | light fuel oil | Cutoff, U - PE	Literature
light fuel oil	C:Manufacturing/19:Manufacture of coke and refined petroleum products/192:Manufacture of refined petroleum products/1920:Manufacture of refined petroleum products	0.02126458452	kg	market for light fuel oil | light fuel oil | Cutoff, U - RoW	Literature
light fuel oil	C:Manufacturing/19:Manufacture of coke and refined petroleum products/192:Manufacture of refined petroleum products/1920:Manufacture of refined petroleum products	0.001045802411	kg	market for light fuel oil | light fuel oil | Cutoff, U - BR	Literature
light fuel oil	C:Manufacturing/19:Manufacture of coke and refined petroleum products/192:Manufacture of refined petroleum products/1920:Manufacture of refined petroleum products	0.002110678315	kg	market for light fuel oil | light fuel oil | Cutoff, U - IN	Literature
Inputs— E: equipment					
Flow	**Category**	**Amount**	**Unit**	**Provider**	**Description**
chimney	F:Construction/43:Specialized construction activities/439:Other specialized construction activities/4390:Other specialized construction activities	6	m	market for chimney | chimney | Cutoff, U - GLO	Calculated
oil boiler, 100kW	C:Manufacturing/28:Manufacture of machinery and equipment n.e.c./281:Manufacture of general-purpose machinery/2815:Manufacture of ovens, furnaces and furnace burners	1	Item(s)	market for oil boiler, 100kW | oil boiler, 100kW | Cutoff, U - GLO	Estimation 2100h use per year
oil storage, 3000l	C:Manufacturing/25:Manufacture of fabricated metal products, except machinery and equipment/251:Manufacture of structural metal products, tanks, reservoirs and steam generators/2512:Manufacture of tanks, reservoirs and containers of metal	1	Item(s)	market for oil storage, 3000l | oil storage, 3000l | Cutoff, U - GLO	EcoSpold01Location=CH
Outputs— main (all unspecified processes are 1:1 input:output)					
Flow	**Amount**	**Unit**			
heat, heating oil	energy_production_annual*life_expectancy_heating_oil_boiler	kWh			
Outputs— F: heat production					
Flow	**Category**	**Amount**	**Unit**	**Description**	
Acetone	Elementary flows/Emission to air/high population density	5.32E-08	kg	Literature, basic uncertainity estimated = 6	
Acrolein	Elementary flows/Emission to air/high population density	1.22E-08	kg	Literature, basic uncertainity estimated = 6	
Benzaldehyde	Elementary flows/Emission to air/high population density	6.38E-09	kg	Literature, basic uncertainity estimated = 6	
Benzene	Elementary flows/Emission to air/high population density	2.13E-08	kg	Literature, basic uncertainity estimated = 6	
Butane	Elementary flows/Emission to air/high population density	1.60E-07	kg	Literature, basic uncertainity estimated = 6	
Carbon dioxide, fossil	Elementary flows/Emission to air/high population density	0.07872340426	kg	Literature	
Carbon monoxide, fossil	Elementary flows/Emission to air/high population density	7.98E-06	kg	Deviation calculated	
Copper	Elementary flows/Emission to air/high population density	7.45E-10	kg	Literature	
Dinitrogen monoxide	Elementary flows/Emission to air/high population density	7.45E-07	kg	Literature, basic uncertainty estimated = 4	
Ethane	Elementary flows/Emission to air/high population density	2.13E-08	kg	Literature, basic uncertainity estimated = 6	
Ethene	Elementary flows/Emission to air/high population density	5.32E-08	kg	Literature, basic uncertainity estimated = 6	
Ethyne	Elementary flows/Emission to air/high population density	1.06E-08	kg	Literature, basic uncertainity estimated = 6	
Formaldehyde	Elementary flows/Emission to air/high population density	6.38E-09	kg	Literature, basic uncertainity estimated = 6	
heating oil— F : heat production emissions		1	MJ		
Hydrocarbons, aliphatic, alkanes, unspecified	Elementary flows/Emission to air/high population density	2.66E-07	kg	Literature, basic uncertainity estimated = 6	
Hydrocarbons, aliphatic, unsaturated	Elementary flows/Emission to air/high population density	2.13E-08	kg	Literature, basic uncertainity estimated = 6	
Hydrocarbons, aromatic	Elementary flows/Emission to air/high population density	2.13E-08	kg	Literature, basic uncertainity estimated = 6	
Hydrogen chloride	Elementary flows/Emission to air/high population density	1.00E-07	kg	Literature	
Hydrogen fluoride	Elementary flows/Emission to air/high population density	9.57E-09	kg	Literature	
Mercury	Elementary flows/Emission to air/high population density	5.32E-10	kg	Literature	
Methane, fossil	Elementary flows/Emission to air/high population density	2.13E-07	kg	Literature, basic uncertainity estimated = 6	
Nitrogen oxides	Elementary flows/Emission to air/high population density	2.93E-05	kg	Deviation calculated	
PAH, polycyclic aromatic hydrocarbons	Elementary flows/Emission to air/high population density	4.89E-10	kg	Literature	
Particulates, < 2.5 um	Elementary flows/Emission to air/high population density	5.32E-07	kg	Literature, basic uncertainty estimated = 3	
Pentane	Elementary flows/Emission to air/high population density	1.06E-07	kg	Literature, basic uncertainity estimated = 6	
Propanal	Elementary flows/Emission to air/high population density	6.38E-09	kg	Literature, basic uncertainity estimated = 6	
Propane	Elementary flows/Emission to air/high population density	3.19E-08	kg	Literature, basic uncertainity estimated = 6	
Propene	Elementary flows/Emission to air/high population density	2.13E-08	kg	Literature, basic uncertainity estimated = 6	
Sulfur dioxide	Elementary flows/Emission to air/high population density	4.98E-05	kg	Calculated	
Toluene	Elementary flows/Emission to air/high population density	1.06E-08	kg	Literature, basic uncertainity estimated = 6	
Zinc	Elementary flows/Emission to air/high population density	7.45E-10	kg	Literature	

Table 7: OpenLCA natural gas results, inputs and outputs

Supplementary Information 1 : OpenLCA Model inputs, outputs, and results per fuel type						
Natural Gas						
Results						
	Contribution	**Amount**	**Unit**	**Process**		
	100.00%	0.07935	kg CO2 eq	natural gas— main		
	75.10%	0.05959	kg CO2 eq	natural gas— F : heat production emissions		
	22.87%	0.01815	kg CO2 eq	natural gas— D : fuel production		
	1.81%	0.00144	kg CO2 eq	natural gas— B : transport, fuel		
	0.18%	0.00015	kg CO2 eq	natural gas— A : electricity use		
	0.03%	2.10E-05	kg CO2 eq	natural gas— C : transport, employee commute		
	0.01%	7.01E-06	kg CO2 eq	natural gas— E : equipment manufacturing		
Inputs— main process (all unspecified processes are 1:1 input:output)						
Amount			**Unit**	**Flow**	**Provider**	**Description**
distance_yeg_yzf_road*life_expectancy_nat_gas_boiler*gross_energy_consumption_annual_i			t*km	natural gas— B : transport, fuel	natural gas— B : transport, fuel	
life_expectancy_nat_gas_boiler*15*12			p*km	natural gas— C : transport, employee comm	natural gas— C : transport, employee c	15 km driven monthly in a combustion engine vehicle for mai
1			Item(s)	natural gas— E : equipment manufacturing	natural gas— E : equipment manufacturing	
energy_production_annual*life_expectancy_nat_gas_boiler			kWh	natural gas— F : heat production emissions	natural gas— F : heat production emissions	
0.1/160*energy_production_annual*life_expectancy_nat_gas_boiler			kWh	natural gas— A : electricity use	natural gas— A : electricity use	100 W electric allowance for natural gas combustion furnace
energy_production_annual*life_expectancy_nat_gas_boiler			kWh	natural gas— D : fuel production	natural gas— D : fuel production	
Inputs— D: fuel production						
Flow		**Amount**	**Unit**	**Provider**	**Description**	**Category**
natural gas, low pressure		2.92E-02	m3	market for natural gas, low pressure | natural gas, low pressure | Cutoff, U - RoW	CH module used for RER	D:Electricity, gas, steam and air conditioning supply/35:Electricity, gas, steam and air conditioning supply/352:Manufacture of gas; distribution of gaseous fuels through mains/3520:Manufacture of gas; distribution of gaseous fuels through mains
Inputs— E: equipment manufacturing						
Flow		**Amount**	**Unit**	**Provider**	**Description**	**Category**
industrial furnace, natural gas		1	Item(s)	market for industrial furnace, natural gas | in	Uncertainty of life time and extrapolatic	C:Manufacturing/28:Manufacture of machinery and equipmer
Outputs— main (all unspecified processes are 1:1 input:output)						
Amount			**Unit**	**Flow**		
energy_production_annual*life_expectancy_nat_gas_boiler			kWh	natural gas— main		
Outputs— F: heat production emissions						
		Amount	**Unit**	**Flow**	**Category**	**Description**
		1.06E-09	kg	Acetaldehyde	Elementary flows/Emission to air/high p	rough estimate, high uncertainty
		1.59E-07	kg	Acetic acid	Elementary flows/Emission to air/high p	rough estimate, high uncertainty
		4.24E-07	kg	Benzene	Elementary flows/Emission to air/high p	rough estimate, high uncertainty
		1.06E-11	kg	Benzo(a)pyrene	Elementary flows/Emission to air/high p	rough estimate, high uncertainty
		7.42E-07	kg	Butane	Elementary flows/Emission to air/high p	rough estimate, high uncertainty
		5.94E-02	kg	Carbon dioxide, fossil	Elementary flows/Emission to air/high p	composition of natural gas
		3.18E-06	kg	Carbon monoxide, fossil	Elementary flows/Emission to air/high p	calculated based on (SVGW 2002)
		5.30E-07	kg	Dinitrogen monoxide	Elementary flows/Emission to air/high p	rough estimate, high uncertainty
		1.06E-07	kg	Formaldehyde	Elementary flows/Emission to air/high p	rough estimate, high uncertainty
		3.18E-11	kg	Mercury	Elementary flows/Emission to air/high p	trace element in natural gas
		2.12E-06	kg	Methane, fossil	Elementary flows/Emission to air/high p	rough estimate, high uncertainty
		1.00E+00	MJ	natural gas— F : heat production emissions		
		1.80E-05	kg	Nitrogen oxides	Elementary flows/Emission to air/high p	calculated based on (SVGW 2002)
		1.06E-08	kg	PAH, polycyclic aromatic hydrocarbons	Elementary flows/Emission to air/high p	rough estimate, high uncertainty
		1.06E-07	kg	Particulates, < 2.5 um	Elementary flows/Emission to air/high p	literature
		1.27E-06	kg	Pentane	Elementary flows/Emission to air/high p	rough estimate, high uncertainty
		2.12E-07	kg	Propane	Elementary flows/Emission to air/high p	rough estimate, high uncertainty
		2.12E-08	kg	Propionic acid	Elementary flows/Emission to air/high p	rough estimate, high uncertainty
		5.83E-07	kg	Sulfur dioxide	Elementary flows/Emission to air/high p	composition of natural gas
		2.12E-07	kg	Toluene	Elementary flows/Emission to air/high population density	rough estimate, high uncertainty

Table 8: OpenLCA propane results, inputs and outputs

Propane						
Results						
	Contribution	**Amount**	**Unit**	**Process**		
	100.00%	0.08988	kg CO2 eq	propane— main		
	75.58%	0.06794	kg CO2 eq	propane— F : heat production emissions		
	22.53%	0.02025	kg CO2 eq	propane— D : fuel production		
	1.60%	0.00144	kg CO2 eq	propane— B : transport, fuel		
	0.20%	0.00018	kg CO2 eq	propane— E : equipment manufacturing		
	0.06%	5.71E-05	kg CO2 eq	propane— A : electricity use		
	0.02%	2.10E-05	kg CO2 eq	propane— C : transport, employee		
Inputs— main process (all unspecified processes are 1:1 input:output)						
Amount			**Unit**	**Flow**	**Provider**	**Description**
0.1/160*energy_production_annual*life_expectancy_nat_gas_boiler			kWh	propane— A : electricity use	propane— A : electricity use	100 W electric allowance for propane gas furnace process (computer, etc.)— please note that heat distribution system is excluded, for all systems
distance_yeg_yzf_road*life_expectancy_nat_gas_boiler*gross_energy_consumption_annual_			t*km	propane— B : transport, fuel	propane— B : transport, fuel	Land transportation from Edmonton, AB to Yellowknife, NT
life_expectancy_nat_gas_boiler*15*12			p*km	propane— C : transport, employee	propane— C : transport, employee	15 km driven monthly in a combustion engine vehicle for maintenance & operation
energy_production_annual*life_expectancy_nat_gas_boiler			kWh	propane— D : fuel production	propane— D : fuel production	Quantity of fuel produced.
energy_production_annual*life_expectancy_nat_gas_boiler			kWh	propane— F : heat production emissions	propane— F : heat production emissions	Emissions produced by the combustion of fuel.
1			Item(s)	propane— E : equipment manufacturing	propane— E : equipment manufacturing	Emissions related to the manufacturing of the propane boiler and related equipment.
Inputs— D: fuel production						
Flow		**Amount**	**Unit**	**Provider**	**Description**	**Category**
propane		2.27E-02	kg	market for propane | propane | Cutoff, U - GLO	Calculated based on fuel use and net heating value.	B:Mining and quarrying/06:Extraction of crude petroleum and natural gas/062:Extraction of natural gas/0620:Extraction of natural gas
Inputs— E: equipment manufacturing						
Flow		**Amount**	**Unit**	**Provider**	**Description**	**Category**
industrial furnace, natural gas		1	Item(s)	market for industrial furnace, natural gas | industrial furnace, natural gas | Cutoff, U - GLO	Uncertainty of life time and extrapolation to range of capacity", as cited in ecoinvent v3.0 dataset "heat production, natural gas, at industrial furnace >100kW, GLO 2000".	C:Manufacturing/28:Manufacture of machinery and equipment n.e.c./281:Manufacture of general-purpose machinery/2815:Manufacture of ovens, furnaces and furnace burners
Outputs— main (all unspecified processes are 1:1 input:output)						
Amount			**Unit**	**Flow**		
energy_production_annual*life_expectancy_nat_gas_boiler			kWh	propane heating		
Outputs— F: heat production emissions						
		Amount	**Unit**	**Flow**	**Category**	**Description**
		1.05E-09	kg	Acetaldehyde	Elementary flows/Emission to air/high population density	Rough estimate, high uncertainty", as cited in ecoinvent v3.0 dataset "heat production, natural gas, at industrial furnace, GLO 2000".
		1.58E-07	kg	Acetic acid	Elementary flows/Emission to air/high population density	Rough estimate, high uncertainty", as cited in ecoinvent v3.0 dataset "heat production, natural gas, at industrial furnace, GLO 2000".
		4.21E-07	kg	Benzene	Elementary flows/Emission to air/high population density	Rough estimate, high uncertainty", as cited in ecoinvent v3.0 dataset "heat production, natural gas, at industrial furnace, GLO 2000".
		1.05E-11	kg	Benzo(a)pyrene	Elementary flows/Emission to air/high population density	Rough estimate, high uncertainty", as cited in ecoinvent v3.0 dataset "heat production, natural gas, at industrial furnace, GLO 2000".
		7.37E-07	kg	Butane	Elementary flows/Emission to air/high population density	Rough estimate, high uncertainty", as cited in ecoinvent v3.0 dataset "heat production, natural gas, at industrial furnace, GLO 2000".
		6.78E-02	kg	Carbon dioxide, fossil	Elementary flows/Emission to air/high population density	Stoechiometric calculation, based on carbon content.
		2.21E-06	kg	Carbon monoxide, fossil	Elementary flows/Emission to air/high population density	Calculated based on (SVGW 2002)", as cited in ecoinvent v3.0 dataset "heat production, natural gas, at industrial furnace >100kW, GLO 2000".
		1.05E-07	kg	Dinitrogen monoxide	Elementary flows/Emission to air/high population density	Rough estimate, high uncertainty", as cited in ecoinvent v3.0 dataset "heat production, natural gas, at industrial furnace, GLO 2000".
		1.05E-07	kg	Formaldehyde	Elementary flows/Emission to air/high population density	Rough estimate, high uncertainty", as cited in ecoinvent v3.0 dataset "heat production, natural gas, at industrial furnace, GLO 2000".
		3.16E-11	kg	Mercury	Elementary flows/Emission to air/high population density	Trace element in natural gas", as cited in ecoinvent v3.0 dataset "heat production, natural gas, at industrial furnace, GLO 2000".
		2.11E-06	kg	Methane, fossil	Elementary flows/Emission to air/high population density	Rough estimate, high uncertainty", as cited in ecoinvent v3.0 dataset "heat production, natural gas, at industrial furnace, GLO 2000".
		2.83E-05	kg	Nitrogen oxides	Elementary flows/Emission to air/high population density	see Parameters.
		1.05E-08	kg	PAH, polycyclic aromatic hydrocarbons	Elementary flows/Emission to air/high	Rough estimate, high uncertainty", as cited in ecoinvent v3.0 dataset "heat production, natural gas, at industrial furnace, GLO 2000".
		2.11E-07	kg	Particulates, < 2.5 um	Elementary flows/Emission to air/high	Literature", as cited in ecoinvent v3.0 dataset "heat production, natural gas, at industrial furnace, GLO 2000".
		1.26E-06	kg	Pentane	Elementary flows/Emission to air/high	Rough estimate, high uncertainty", as cited in ecoinvent v3.0 dataset "heat production, natural gas, at industrial furnace, GLO 2000".
		2.11E-07	kg	Propane	Elementary flows/Emission to air/high	Rough estimate, high uncertainty", as cited in ecoinvent v3.0 dataset "heat production, natural gas, at industrial furnace, GLO 2000".
		1	MJ	propane— F : heat production emissions		
		2.11E-08	kg	Propionic acid	Elementary flows/Emission to air/high	Rough estimate, high uncertainty", as cited in ecoinvent v3.0 dataset "heat production, natural gas, at industrial furnace, GLO 2000".
		2.27E-06	kg	Sulfur dioxide	Elementary flows/Emission to air/high	Stoechiometric calculation, based on sulfur content.
		2.11E-07	kg	Toluene	Elementary flows/Emission to air/high population density	Rough estimate, high uncertainty", as cited in ecoinvent v3.0 dataset "heat production, natural gas, at industrial furnace, GLO 2000".

Table 9: OpenLCA biomass combustion results, inputs and outputs

Supplementary Information 1 : OpenLCA Model inputs, outputs, and results per fuel type						
Biomass						
Results						
	Contribution	**Amount**	**Unit**	**Process**		
	Contribution	Amount	Unit	Process		
	100.00%	0.15063	kg CO2 eq	combustion— main - CA-NT		
	86.22%	0.12987	kg CO2 eq	combustion— F : heat production combustion		
	7.47%	0.01125	kg CO2 eq	combustion— D : fuel production		
	5.72%	0.00862	kg CO2 eq	combustion— B : transport, fuel		
	0.38%	0.00057	kg CO2 eq	combustion— A : electricity use		
	0.14%	0.00021	kg CO2 eq	combustion— E : equipment manufacturing		
	0.06%	8.38E-05	kg CO2 eq	combustion— C : transport, employee commute		
	0.02%	3.08E-05	kg CO2 eq	market for wood ash mixture, pure | wood ash mixture, pure | Cutoff, U - Europe without Switzerland		
Inputs— main process (all unspecified processes are 1:1 input:output)						
Amount			**Unit**	**Flow**	**Provider**	**Description**
1/160*life_expectancy_pellet_stove*energy_production_annual			kWh	combustion— A : electricity use	combustion— A : electricity use	
distance_lacrete_to_yk*biomass_combustion_consumption_annual*life_expectancy_pellet_st			t*km	combustion— B : transport, fuel	combustion— B : transport, fuel	
life_expectancy_pellet_stove*60*12			p*km	combustion— C : transport, employee comm	combustion— C : transport, employee commute	
biomass_combustion_consumption_annual*life_expectancy_pellet_stove			kg	combustion— D : fuel production	combustion— D : fuel production	
1			Item(s)	combustion— E : equipment manufacturing	combustion— E : equipment manufacturing	
energy_production_annual*life_expectancy_pellet_stove			kWh	combustion— F : combustion emissions only	none	
Inputs— D: fuel production						
Flow		**Amount**	**Unit**	**Provider**	**Description**	**Category**
wood pellet, measured as dry mass		1.00E+00	kg	market for wood pellet, measured as dry mass | wood pellet, measured as dry mass | Cutoff, U - RoW		C:Manufacturing/16:Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials/161:Sawmilling and planing of wood/1610:Sawmilling and planing of wood
Inputs— E: equipment manufacturing						
Flow		**Amount**	**Unit**	**Provider**	**Description**	**Category**
furnace, pellets, with silo, 300kW		1	Item(s)			C:Manufacturing/28:Manufacture of machinery and equipmer
Outputs— main (all unspecified processes are 1:1 input:output)						
Amount			**Unit**	**Flow**	**Category**	
energy_production_annual*life_expectancy_pellet_stove			kWh	LaCrete wood pellets		
biomass_combustion_consumption_annual*0.03*life_expectancy_pellet_stove			kg	wood ash mixture, pure	E:Water supply; sewerage, waste management and remediation activities/38:Waste collection, treatr	
Outputs— F: heat production emissions						
Category		**Amount**	**Unit**	**Flow**	**Description**	**Provider**
Elementary flows/Emission to air/high population density		2.31E-06	kg	Ammonia	extrapolation, based on measuring data of other emissions Amount was scaled to the amount of refe	
Elementary flows/Emission to air/high population density		1.33E-09	kg	Arsenic	extrapolation, based on measuring data of other emissions Amount was scaled to the amount of refe	
Elementary flows/Emission to air/high population density		1.21E-06	kg	Benzene	extrapolation, based on measuring data of other emissions Amount was scaled to the amount of refe	
Elementary flows/Emission to air/high population density		4.00E-08	kg	Benzene, ethyl-	extrapolation, based on measuring data of other emissions Amount was scaled to the amount of refe	
Elementary flows/Emission to air/high population density		9.60E-15	kg	Benzene, hexachloro-	extrapolation, based on measuring data of other emissions Amount was scaled to the amount of refe	
Elementary flows/Emission to air/high population density		6.67E-10	kg	Benzo(a)pyrene	extrapolation, based on measuring data of other emissions Amount was scaled to the amount of refe	
Elementary flows/Emission to air/high population density		8.00E-08	kg	Bromine	extrapolation, based on measuring data of other emissions Amount was scaled to the amount of refe	
Elementary flows/Emission to air/high population density		9.33E-10	kg	Cadmium	extrapolation, based on measuring data of other emissions Amount was scaled to the amount of refe	
Elementary flows/Emission to air/high population density		7.80E-06	kg	Calcium	extrapolation, based on measuring data of other emissions Amount was scaled to the amount of refe	
Elementary flows/Emission to air/high population density		1.29E-01	kg	Carbon dioxide, fossil		
Elementary flows/Emission to air/high population density		0.12867*0	kg	Carbon dioxide, non-fossil		
Elementary flows/Emission to air/high population density		2.67E-04	kg	Carbon monoxide, non-fossil	estimation	
Elementary flows/Emission to air/high population density		2.40E-07	kg	Chlorine	extrapolation, based on measuring data of other emissions Amount was scaled to the amount of refe	
Elementary flows/Emission to air/high population density		5.28E-09	kg	Chromium	extrapolation, based on measuring data of other emissions Amount was scaled to the amount of refe	
Elementary flows/Emission to air/high population density		5.33E-11	kg	Chromium VI	range of data Amount was scaled to the amount of reference product.	
		1	MJ	combustion— F : combustion emissions only		
Elementary flows/Emission to air/high population density		2.93E-08	kg	Copper	extrapolation, based on measuring data of other emissions Amount was scaled to the amount of refe	
Elementary flows/Emission to air/high population density		3.33E-06	kg	Dinitrogen monoxide	extrapolation, based on measuring data of other emissions Amount was scaled to the amount of refe	
Elementary flows/Emission to air/high population density		4.13E-14	kg	Dioxins, measured as 2,3,7,8-tetrachlorodibe	extrapolation, based on measuring data of other emissions Amount was scaled to the amount of refe	
Elementary flows/Emission to air/high population density		6.67E-08	kg	Fluorine	extrapolation, based on measuring data of other emissions Amount was scaled to the amount of refe	
Elementary flows/Emission to air/high population density		1.73E-07	kg	Formaldehyde	extrapolation, based on measuring data of other emissions Amount was scaled to the amount of refe	
Elementary flows/Emission to air/high population density		1.21E-06	kg	Hydrocarbons, aliphatic, alkanes, unspecified	extrapolation, based on measuring data of other emissions Amount was scaled to the amount of refe	
Elementary flows/Emission to air/high population density		4.13E-06	kg	Hydrocarbons, aliphatic, unsaturated	extrapolation, based on measuring data of other emissions Amount was scaled to the amount of refe	
Elementary flows/Emission to air/high population density		3.33E-08	kg	Lead	extrapolation, based on measuring data of other emissions Amount was scaled to the amount of refe	
Elementary flows/Emission to air/high population density		1.60E-07	kg	m-Xylene	extrapolation, based on measuring data of other emissions Amount was scaled to the amount of refe	
Elementary flows/Emission to air/high population density		4.80E-07	kg	Magnesium	extrapolation, based on measuring data of other emissions Amount was scaled to the amount of refe	
Elementary flows/Emission to air/high population density		2.27E-07	kg	Manganese	extrapolation, based on measuring data of other emissions Amount was scaled to the amount of refe	
Elementary flows/Emission to air/high population density		4.00E-10	kg	Mercury	extrapolation, based on measuring data of other emissions Amount was scaled to the amount of refe	
Elementary flows/Emission to air/high population density		6.00E-06	kg	Methane, non-fossil	extrapolation, based on measuring data of other emissions Amount was scaled to the amount of refe	
Elementary flows/Emission to air/high population density		8.00E-09	kg	Nickel	extrapolation, based on measuring data of other emissions Amount was scaled to the amount of refe	
Elementary flows/Emission to air/high population density		8.00E-05	kg	Nitrogen oxides	estimation	
Elementary flows/Emission to air/high population density		1.40E-05	kg	NMVOC, non-methane volatile organic compounds, unspecified origin	estimation	
Elementary flows/Emission to air/high population density		1.48E-08	kg	PAH, polycyclic aromatic hydrocarbons	extrapolation, based on measuring data of other emissions Amount was scaled to the amount of refe	
Elementary flows/Emission to air/high population density		6.00E-05	kg	Particulates, < 2.5 um	estimation	
Elementary flows/Emission to air/high population density		3.33E-06	kg	Particulates, > 2.5 um, and < 10um	estimation	
Elementary flows/Emission to air/high population density		1.08E-11	kg	Phenol, pentachloro-	extrapolation, based on measuring data of other emissions Amount was scaled to the amount of refe	
Elementary flows/Emission to air/high population density		4.00E-07	kg	Phosphorus	extrapolation, based on measuring data of other emissions Amount was scaled to the amount of refe	
Elementary flows/Emission to air/high population density		3.12E-05	kg	Potassium	extrapolation, based on measuring data of other emissions Amount was scaled to the amount of refe	
Elementary flows/Emission to air/high population density		1.73E-06	kg	Sodium	extrapolation, based on measuring data of other emissions Amount was scaled to the amount of refe	

Table 10: OpenLCA biomass combustion results, inputs and outputs (continued)

<table>
<tr><td>Elementary flows/Emission to air/high population density</td><td></td><td>3.33E-06</td><td>kg</td><td>Sulfur dioxide</td><td>extrapolation, based on measuring data of other emissions Amount was scaled to the amount of refe</td><td></td></tr>
<tr><td>Elementary flows/Emission to air/high population density</td><td></td><td>4.00E-07</td><td>kg</td><td>Toluene</td><td>extrapolation, based on measuring data of other emissions Amount was scaled to the amount of refe</td><td></td></tr>
<tr><td>Elementary flows/Emission to air/high population density</td><td></td><td>7.12E-05</td><td>m3</td><td>Water</td><td>calculated value, supposed to ensure correct water balance</td><td></td></tr>
<tr><td>E:Water supply; sewerage, waste management and remediation activities/38:Waste collection, treatment and disposal activities; materials recovery/382:Waste treatment and disposal/3821:Treatment and disposal of non-hazardous waste</td><td></td><td>2.14E-04</td><td>kg</td><td>wood ash mixture, pure</td><td>homogeneous fuel Amount was scaled to the amount of reference product.</td><td>market for wood ash mixture, pure | wood ash mixture, pure | Cutoff, U - RoW</td></tr>
<tr><td>E:Water supply; sewerage, waste management and remediation activities/38:Waste collection, treatment and disposal activities; materials recovery/382:Waste treatment and disposal/3821:Treatment and disposal of non-hazardous waste</td><td></td><td>1.03E-04</td><td>kg</td><td>wood ash mixture, pure</td><td>homogeneous fuel Amount was scaled to the amount of reference product.</td><td>market for wood ash mixture, pure | wood ash mixture, pure | Cutoff, U - Europe without Switzerland</td></tr>
<tr><td>Elementary flows/Emission to air/high population density</td><td></td><td>4.00E-07</td><td>kg</td><td>Zinc</td><td>extrapolation, based on measuring data of other emissions Amount was scaled to the amount of refe</td><td></td></tr>
</table>

Table 11: OpenLCA imported wood pellets Pyro-CCS results, inputs and outputs

Pyro-CCS— Imported Wood Pellets						
Results						
	Contribution	**Amount**	**Unit**	**Process**		
	100.00%	0.21837	kg CO2 eq	PyCCS— main - CA-NT		
	50.20%	0.10963	kg CO2 eq	PyCCS— B : heat production emissions		
	30.89%	0.06745	kg CO2 eq	PyCCS— A: biochar		
	6.57%	0.01434	kg CO2 eq	PyCCS— D : fuel production		
	5.11%	0.01115	kg CO2 eq	PyCCS— F : biochar transportation		
	5.03%	0.01099	kg CO2 eq	PyCCS— E : fuel transportation		
	0.91%	0.002	kg CO2 eq	PyCCS— G : electricity use		
	0.84%	0.00183	kg CO2 eq	PyCCS— H : electricity backup		
	0.19%	0.00041	kg CO2 eq	PyCCS— I : travel		
	0.14%	0.00032	kg CO2 eq	PyCCS— K : boiler manufacturing & transportation		
	0.08%	0.00017	kg CO2 eq	PyCCS— L : employee commute		
	0.04%	8.00E-05	kg CO2 eq	PyCCS : J : accom		
Inputs— main process (all unspecified processes are 1:1 input:output)						
Amount			**Unit**	**Flow**	**Provider**	**Description**
(biomass_consumption_annual*carbon_content_biomass-biochar_production_annual*carbon_			kg	PyCCS— B : heat production emissions	PyCCS— B : heat production emissions	
biomass_consumption_annual*life_expectancy_PyCCS_machine			kg	PyCCS— D : fuel production	PyCCS— D : fuel production	
distance_lacrete_to_yk*biomass_consumption_annual*life_expectancy_PyCCS_machine/100			t*km	PyCCS— E : fuel transportation	PyCCS— E : fuel transportation	
biochar_production_annual*distance_yellowknife_to_san_francisco*life_expectancy_PyCCS_			t*km	PyCCS— F : biochar transportation	PyCCS— F : biochar transportation	
3.5/160*life_expectancy_PyCCS_machine*energy_production_annual			kWh	PyCCS— G : electricity use	PyCCS— G : electricity use	
0.02*life_expectancy_PyCCS_machine*energy_production_annual			kWh	PyCCS— H : electricity backup	PyCCS— H : electricity backup	
20*4500*2+6*10000*2			p*km	PyCCS— I : travel	PyCCS— I : travel	
4*10*2+10*6*2			guest night	PyCCS— J : accom	PyCCS : J : accom	
1			Item(s)	PyCCS— K : boiler manufacturing & transpo	PyCCS— K : boiler manufacturing & transportation	
120*12*life_expectancy_PyCCS_machine			p*km	PyCCS— L : employee commute	PyCCS— L : employee commute	
biochar_production_annual*life_expectancy_PyCCS_machine			kg	PyCCS— A: biochar	none	
Inputs— I : travel						
Flow		**Amount**	**Unit**	**Provider**	**Description**	**Category**
transport, passenger aircraft, long haul		6*10000*2	p*km	market for transport, passenger aircraft, long haul | transport, passenger aircraft, long haul | Cutoff, U - GLO	Allowing for 6 overseas trips from Berlin to Yellowknife, with layovers in Amsterdam, Montreal, Calgary and Edmonton	H:Transportation and storage/51:Air transport/511:Passenger air transport/5110:Passenger air transport
transport, passenger aircraft, medium haul		20*4500*2	p*km	market for transport, passenger aircraft, medium haul | transport, passenger aircraft, medium haul | Cutoff, U - GLO	Allowing for 10 return trips from Yellowknife to Montreal for research and business development.	H:Transportation and storage/51:Air transport/511:Passenger air transport/5110:Passenger air transport
Inputs—J : accommodation						
Flow		**Amount**	**Unit**	**Provider**	**Description**	**Category**
building operation, luxury hotel		10*6*2	guest night	market for building operation, luxury hotel | building operation, luxury hotel | Cutoff, U - GLO	Allowing for 10 nights for overseas travelers (x6 person-trips)	I:Accommodation and food service activities/55:Accommodation/551:Short term accommodation activities/5510:Short term accommodation activities
building operation, luxury hotel		4*10*2	guest night	market for building operation, luxury hotel | building operation, luxury hotel | Cutoff, U - GLO	Allowing for 4 nights for domestic travelers per trip (x 10 person-trips)	I:Accommodation and food service activities/55:Accommodation/551:Short term accommodation activities/5510:Short term accommodation activities
Inputs—K : boiler manufacturing &						
Flow		**Amount**	**Unit**	**Provider**	**Description**	**Category**
hot rolling, steel		weight_total_PyCCS_machine	kg	hot rolling, steel | hot rolling, steel | Cutoff, U - RoW	Assuming 1 ton of steel is used	C:Manufacturing/24:Manufacture of basic metals/241:Manufacture of basic iron and steel/2410:Manufacture of basic iron and steel
hot rolling, steel		0.3*weight_total_PyCCS_machine	kg	hot rolling, steel | hot rolling, steel | Cutoff, U - RoW	30% accounting for factory emissions post steel production	C:Manufacturing/24:Manufacture of basic metals/241:Manufacture of basic iron and steel/2410:Manufacture of basic iron and steel
intermodal shipping container, 45-foot, high-cube		1	Item(s)	market for intermodal shipping container, 45-foot, high-cube | intermodal shipping container, 45-foot, high-cube | Cutoff, U - GLO		C:Manufacturing/29:Manufacture of motor vehicles, trailers and semi-trailers/292:Manufacture of bodies (coachwork) for motor vehicles; manufacture of trailers and semi-trailers/2920:Manufacture of bodies (coachwork) for motor vehicles; manufacture of traile
transport, freight, lorry, unspecified		weight_total_PyCCS_machine*distance_montreal_to_yellowknife	kg*km	market for transport, freight, lorry, unspecified | transport, freight, lorry, unspecified | Cutoff, U - RoW		H:Transportation and storage/49:Land transport and transport via pipelines/492:Other land transport/4923:Freight transport by road
transport, freight, lorry, unspecified		weight_total_PyCCS_machine*distance_Rehburg_to_Amsterdam	kg*km	market for transport, freight, lorry, unspecified | transport, freight, lorry, unspecified | Cutoff, U - RoW	Land transport from New York to Yellowknife	H:Transportation and storage/49:Land transport and transport via pipelines/492:Other land transport/4923:Freight transport by road
transport, freight, sea, container ship		weight_total_PyCCS_machine*distance_Port_Amsterdam_to_Port_Montreal	kg*km	market for transport, freight, sea, container ship | transport, freight, sea, container ship | Cutoff, U - GLO	Maritime transport from Germany to Canada	H:Transportation and storage/50:Water transport/501:Sea and coastal water transport/5012:Sea and coastal freight water transport
Outputs— main (all unspecified processes are 1:1 input:output)						
Amount			**Unit**	**Flow**		
life_expectancy_PyCCS_machine*energy_production_annual			kWh	100 PyCCS		
Outputs— A: biochar						
		Amount	**Unit**	**Flow**	**Category**	**Description**
biochar_to_CO2_factor			kg	Elementary flows/Emission to air/high popula	Carbon dioxide, fossil	
1			kg		PyCCS— A: biochar	
Outputs— B: heat production emissions						
		Amount	**Unit**	**Flow**	**Category**	**Description**
		3.67E+00	kg	Carbon dioxide, fossil	Elementary flows/Emission to air/high population density	
		1.00E+00	kg	PyCCS— B : heat production emissions		

Table 12: OpenLCA locally-harvested fire-killed Pyro-CCS results, inputs and outputs

Pyro-CCS— Imported Wood Pellets								
Results								
	Contribution	**Amount**	**Unit**	**Process**				
	100.00%	2.37E-01	kg CO2 eq	PyCCS local— main - CA-NT				
	46.34%	1.10E-01	kg CO2 eq	PyCCS local— B : heat production emissions				
	46.21%	1.09E-01	kg CO2 eq	PyCCS local— A: biochar				
	3.95%	9.35E-03	kg CO2 eq	PyCCS local— D : fuel production				
	1.08%	2.57E-03	kg CO2 eq	PyCCS local— E : fuel transportation				
	0.84%	2.00E-03	kg CO2 eq	PyCCS local— G : electricity use				
	0.77%	1.83E-03	kg CO2 eq	PyCCS local— H : electricity backup				
	0.38%	9.00E-04	kg CO2 eq	PyCCS local— F : biochar transportation				
	0.18%	4.10E-04	kg CO2 eq	PyCCS local— I : travel				
	0.13%	3.20E-04	kg CO2 eq	PyCCS local— K : boiler manufacturing & transportation				
	0.07%	1.70E-04	kg CO2 eq	PyCCS local— L : employee commute				
	0.03%	8.00E-05	kg CO2 eq	PyCCS local— J : accom				
Inputs— main process (all unspecified processes are 1:1 input:output)								
Amount			**Unit**	**Flow**	**Provider**	**Description**		
(biomass_consumption_annual*carbon_content_biomass-biochar_production_annual*carbon_			kg	PyCCS— B : heat production emissions	PyCCS local— B : heat production emissions			
biomass_chips_consumption_annual*life_expectancy_PyCCS_machine			kg	PyCCS— D : fuel production	PyCCS local— D : fuel production			
distance_yk_to_firekilled*biomass_consumption_annual*life_expectancy_PyCCS_machine/10			t*km	PyCCS— E : fuel transportation	PyCCS local— E : fuel transportation			
biochar_chips_production_annual*distance_yk_to_firekilled*life_expectancy_PyCCS_machine			t*km	PyCCS— F : biochar transportation	PyCCS local— F : biochar transportation			
3.5/160*life_expectancy_PyCCS_machine*energy_production_annual			kWh	PyCCS— G : electricity use	PyCCS local— G : electricity use			
0.02*life_expectancy_PyCCS_machine*energy_production_annual			kWh	PyCCS— H : electricity backup	PyCCS local— H : electricity backup			
20*4500*2+6*10000*2			p*km	PyCCS— I : travel	PyCCS local— I : travel			
4*10*2+10*6*2			guest night	PyCCS— J : accom	PyCCS local— J : accom			
1			Item(s)	PyCCS— K : boiler manufacturing & transpo	PyCCS local— K : boiler manufacturing & transportation			
120*12*life_expectancy_PyCCS_machine			p*km	PyCCS— L : employee commute	PyCCS local— L : employee commute			
biochar_chips_production_annual*life_expectancy_PyCCS_machine			kg	PyCCS— A: biochar	PyCCS local— A: biochar			
Inputs—D: fuel production								
Flow		**Amount**	**Unit**	**Provider**	**Description**	**Category**		
bundle, energy wood, measured as dry mass		1	kg	softwood forestry, pine, sustainable forest management | bundle, energy wood, mea		A:Agriculture, forestry and fishing/02:Forestry and logging/022:Logging/0220:Logging		
wood chipping, industrial residual wood, stationary electric chipper		1	kg	wood chipping, industrial residual wood, stationary electric chipper | wood chipping,		C:Manufacturing/16:Manufacture of wood and of products of wood and cork, except furniture; m		
Inputs— I : travel								
Flow		**Amount**	**Unit**	**Provider**	**Description**	**Category**		
transport, passenger aircraft, long haul		6*10000*2	p*km	market for transport, passenger aircraft, long	Allowing for 6 overseas trips from Berli	H:Transportation and storage/51:Air transport/511:Passenger air transport/5110:Passenger air t		
transport, passenger aircraft, medium haul		20*4500*2	p*km	market for transport, passenger aircraft, med	Allowing for 10 return trips from Yellow	H:Transportation and storage/51:Air transport/511:Passenger air transport/5110:Passenger air t		
Inputs—J : accommodation								
Flow		**Amount**	**Unit**	**Provider**	**Description**	**Category**		
building operation, luxury hotel		10*6*2	guest night	market for building operation, luxury hotel | b	Allowing for 10 nights for overseas trav	I:Accommodation and food service activities/55:Accommodation/551:Short term accommodatio		
building operation, luxury hotel		4*10*2	guest night	market for building operation, luxury hotel | b	Allowing for 4 nights for domestic trave	I:Accommodation and food service activities/55:Accommodation/551:Short term accommodatio		
Inputs—K : boiler manufacturing &								
Amount			**Unit**	**Provider**	**Description**	**Category**	**Flow**	
6			m	chimney production | chimney | Cutoff, U - RoW		F:Construction/43:Specialized construction activities/439:Oth	chimney	
weight_total_PyCCS_machine			kg	hot rolling, steel | hot rolling, steel | Cutoff, U	Assuming 1 ton of steel is used	C:Manufacturing/24:Manufacture of basic metals/241:Manufa	hot rolling, steel	
0.3*weight_total_PyCCS_machine			kg	hot rolling, steel | hot rolling, steel | Cutoff, U	30% accounting for factory emissions p	C:Manufacturing/24:Manufacture of basic metals/241:Manufa	hot rolling, steel	
1			Item(s)	market for intermodal shipping container, 45-foot, high-cube | intermodal shipping cc		C:Manufacturing/29:Manufacture of motor vehicles, trailers ar	intermodal shipping container, 45-foot, high-cube	
weight_total_PyCCS_machine*distance_montreal_to_yellowknife			kg*km	market for transport, freight, lorry, unspecified | transport, freight, lorry, unspecified |		H:Transportation and storage/49:Land transport and transpor	transport, freight, lorry, unspecified	
weight_total_PyCCS_machine*distance_Rehburg_to_Amsterdam			kg*km	market for transport, freight, lorry, unspecifie	Land transport from New York to Yellov	H:Transportation and storage/49:Land transport and transpor	transport, freight, lorry, unspecified	
weight_total_PyCCS_machine*distance_Port_Amsterdam_to_Port_Montreal			kg*km	market for transport, freight, sea, container ship | transport, freight, sea, container ship | Cutoff, U - GLO	Maritime transport from Germany to Canada	H:Transportation and storage/50:Water transport/501:Sea and coastal water transport/5012:Sea and coastal freight water transport	transport, freight, sea, container ship	
Outputs— main (all unspecified processes are 1:1 input:output)								
Amount			**Unit**	**Flow**				
life_expectancy_PyCCS_machine*energy_production_annual			kWh	100 PyCCS				
Outputs— A: biochar								
Amount			**Unit**	**Flow**	**Category**	**Description**		
biochar_to_CO2_factor			kg	Carbon dioxide, fossil	Elementary flows/Emission to air/high	population density		
1			kg	PyCCS— A: biochar				
Outputs— B: heat production emissions								
		Amount	**Unit**	**Flow**	**Category**	**Description**		
		3.67E+00	kg	Carbon dioxide, fossil	Elementary flows/Emission to air/high	population density		
		1.00E+00	kg	PyCCS— B : heat production emissions				

3. Decarbonization scenarios, conversion & replacement rates

Table 13: Emissions forecasting, scenarios A and B

Supplementary Information 2 : Decarbonization Scenarios Forecasting

A : IPCC Ambitious Scenario (60% below 2005 before 2030, 120% by 2050)

								Heating Oil		Propane		Gas		Pellets		Pyro CCS (fire-killed)							
								Energy	CO2	Energy	CO2	Energy	CO2	Energy	CO2	Energy	CO2						
				3,631,311,977				**2,148,923,373**	**0.179**	**788,161,994**	**0.071**	**232,892,250**	**0.018**	**461,334,360**	**0.022**	**0**	**0.000**						
Emissions intensity (g per MJ)								**83.1**		**89.9**		**79.4**		**46.7**		**-37.9**							
Initial share								58.00%		23.00%		6.00%		7.00%		0							
	Target Emissions (MT)	Forecasted emissions (MT)	Target check	Total energy production (should remain equal, not accounting for demand growth)	Conversion rate (yearly, per year)	Replacement rate (yearly, per year)		**Heating Oil**		**Propane**		**Gas**		**Pellets**		**Pyro CCS (fire-killed)**		**2030 target**	**2050 target**	**Carbon price**	**Carbon price savings**	**Biomass consumption (kg)**	**Fire-killed consumption**
2020	0.308	0.290	✅	3,631,311,977	0%	0.00%	0.000	2,148,923,373	0.179	788,161,993.77	0.071	232,892,249.53	0.018	461,334,360.42	0.022	0	0.000	0.160	-0.080	30	CA$ -	32,077,204.87	0.00
2022	0.278	0.290	❌	3,631,311,977	0%	0.00%	0.000	2,148,923,373	0.179	788,161,994	0.071	232,892,250	0.018	461,334,360	0.022	0	0.000	0.160	-0.080	50	CA$ -	32,077,204.87	0.00
2024	0.249	0.288	❌	3,631,311,977	30%	0.05%	0.000	2,148,923,373	0.177	788,161,994	0.071	232,892,250	0.018	461,334,360	0.022	0	0.000	0.160	-0.080	80	CA$ 157,203	32,077,204.87	0.00
2026	0.219	0.289	❌	3,631,311,977	60%	0.50%	0.003	2,146,774,450	0.178	787,373,832	0.071	232,659,357	0.018	463,553,345	0.022	950,993	0.000	0.160	-0.080	110	CA$ 22,035	32,231,493.86	136,636.97
2028	0.190	0.287	❌	3,631,311,977	90%	5.00%	0.045	2,125,285,216	0.177	779,492,212	0.070	230,330,435	0.018	476,233,255	0.022	19,970,859	-0.001	0.160	-0.080	140	CA$ 421,197	33,113,145.27	2,869,376.29
2030	0.160	0.250	❌	3,631,311,977	97%	10.00%	0.097	1,910,392,879	0.159	700,676,012	0.063	207,041,210	0.016	507,933,031	0.024	305,268,844	-0.012	0.160	-0.080	170	CA$6,654,025	35,317,273.77	43,860,466.16
2032	0.136	0.174	❌	3,631,311,977	97%	10.00%	0.097	1,480,608,204	0.123	543,043,614	0.049	160,462,760	0.013	526,952,897	0.025	920,244,502	-0.035	0.160	-0.080	197	CA$ 22,648,868	36,639,750.87	132,219,037.65
2034	0.112	0.098	✅	3,631,311,977	97%	10.00%	0.097	1,050,823,529	0.087	385,411,215	0.035	113,884,310	0.009	545,972,763	0.026	1,535,220,160	-0.058	0.160	-0.080	225	CA$ 43,062,405	37,962,227.98	220,577,609.14
2036	0.088	0.022	✅	3,631,311,977	97%	10.00%	0.097	621,038,855	0.052	227,778,816	0.020	67,305,860	0.005	564,992,628	0.026	2,150,195,817	-0.082	0.160	-0.080	254	CA$ 67,820,080	39,284,705.08	308,936,180.63
2038	0.064	-0.054	✅	3,631,311,977	97%	0.60%	0.006	191,254,180	0.016	70,146,417	0.006	20,727,410	0.002	584,012,494	0.027	2,765,171,475	-0.105	0.160	-0.080	282	CA$ 96,921,892	40,607,182.18	397,294,752.12
2040	0.040	-0.058	✅	3,631,311,977	97%	0.60%	0.006	165,467,100	0.014	60,688,474	0.005	17,932,703	0.001	585,153,686	0.027	2,802,070,014	-0.106	0.160	-0.080	311	CA$ 108,146,85	40,686,530.81	402,596,266.40
2042	0.016	-0.063	✅	3,631,311,977	97%	0.60%	0.006	139,680,019	0.012	51,230,530	0.005	15,137,996	0.001	586,294,878	0.027	2,838,968,554	-0.108	0.160	-0.080	340	CA$ 119,632,46	40,765,879.44	407,897,780.69
2044	-0.008	-0.067	✅	3,631,311,977	97%	0.60%	0.006	113,892,939	0.009	41,772,586	0.004	12,343,289	0.001	587,436,070	0.027	2,875,867,093	-0.109	0.160	-0.080	368	CA$ 131,378,71	40,845,228.06	413,199,294.98
2046	-0.032	-0.072	✅	3,631,311,977	97%	0.60%	0.006	88,105,858	0.007	32,314,642	0.003	9,548,582	0.001	588,577,262	0.028	2,912,765,633	-0.110	0.160	-0.080	397	CA$ 143,385,62	40,924,576.69	418,500,809.27
2048	-0.056	-0.077	✅	3,631,311,977	97%	0.60%	0.006	62,318,778	0.005	22,856,698	0.002	6,753,875	0.001	589,718,454	0.028	2,949,664,172	-0.112	0.160	-0.080	425	CA$ 155,653,17	41,003,925.32	423,802,323.56
2050	-0.080	-0.081	✅	3,631,311,977	97%	0.60%	0.006	36,531,697	0.003	13,398,754	0.001	3,959,168	0.000	590,859,646	0.028	2,986,562,711	-0.113	0.160	-0.080	454	CA$ 168,181,38	41,083,273.94	429,103,837.85
Total						99.50%	95.38%																
						Total	Cumulative																

Supplementary Information 2 : Decarbonization Scenarios Forecasting

A : IPCC Ambitious Scenario (60% below 2005 before 2030, 120% by 2050)

								Heating Oil		Propane		Gas		Pellets		Pyro CCS (fire-killed)					
								Energy	CO2	Energy	CO2	Energy	CO2	Energy	CO2	Energy	CO2				
Energy produced (MJ)				3,631,311,977				**2,148,923,373**	**0.179**	**788,161,994**	**0.071**	**232,892,250**	**0.018**	**461,334,360**	**0.022**	**0**	**0.000**				
Emissions intensity (g per MJ)								**83.1**		**89.9**		**79.4**		**46.7**		**-37.9**					
Initial share								58.00%		23.00%		6.00%		7.00%		0					
	Target Emissions (MT)	Forecasted emissions (MT)	Target check	Total energy production (should remain equal, not accounting for demand growth)	Conversion rate (yearly, per year)	Replacement rate (yearly, per year)		**Heating Oil**		**Propane**		**Gas**		**Pellets**		**Pyro CCS (fire-killed)**		**2030 target**	**2050 target**	**Carbon price**	**Carbon price savings**
2020	0.308	0.290	✅	3,631,311,977	0%	0%	0.000	2,148,923,373	0.179	788161993.769	0.071	232892249.527	0.018	461334360.423	0.022	0	0.000	0.220	0.000	30	CA$ -
2022	0.290	0.290	✅	3,631,311,977	0%	0%	0.000	2,148,923,373	0.179	788,161,994	0.071	232,892,250	0.018	461,334,360	0.022	0	0.000	0.220	0.000	50	CA$ -
2024	0.273	0.284	❌	3,631,311,977	10%	0.5%	0.001	2,148,923,373	0.173	788,161,994	0.071	232,892,250	0.018	461,334,360	0.022	0	0.000	0.220	0.000	80	CA$ 428,736
2026	0.255	0.288	❌	3,631,311,977	20%	1.0%	0.002	2,127,434,139	0.177	780,280,374	0.070	230,563,327	0.018	489,864,159	0.023	3,169,978	0.000	0.220	0.000	110	CA$ 161,314
2028	0.238	0.285	❌	3,631,311,977	30%	2.0%	0.006	2,084,455,672	0.173	764,517,134	0.069	225,905,482	0.018	540,583,801	0.025	15,849,888	-0.001	0.220	0.000	140	CA$ 691,064
2030	0.220	0.277	❌	3,631,311,977	40%	4.0%	0.016	1,998,498,737	0.166	732,990,654	0.066	216,589,792	0.017	629,343,174	0.029	53,889,619	-0.002	0.220	0.000	170	CA$2,201,316
2032	0.198	0.258	❌	3,631,311,977	50%	6.0%	0.030	1,826,584,867	0.152	669,937,695	0.060	197,958,412	0.016	781,502,100	0.037	155,328,903	-0.006	0.220	0.000	197	CA$6,120,504
2034	0.176	0.228	❌	3,631,311,977	80%	8.0%	0.064	1,568,714,062	0.130	575,358,255	0.052	170,011,342	0.013	971,700,757	0.045	345,527,560	-0.013	0.220	0.000	225	CA$ 13,874,624
2036	0.154	0.174	❌	3,631,311,977	80%	8.0%	0.064	1,224,886,323	0.102	449,252,336	0.040	132,748,582	0.011	1,073,140,040	0.050	751,284,695	-0.028	0.220	0.000	254	CA$ 29,218,215
2038	0.132	0.121	✅	3,631,311,977	80%	8.0%	0.064	881,058,583	0.073	323,146,417	0.029	95,485,822	0.008	1,174,579,324	0.055	1,157,041,830	-0.044	0.220	0.000	282	CA$ 47,620,027
2040	0.110	0.067	✅	3,631,311,977	80%	8.0%	0.064	537,230,843	0.045	197,040,498	0.018	58,223,062	0.005	1,276,018,608	0.060	1,562,798,965	-0.059	0.220	0.000	311	CA$ 69,080,059
2042	0.088	0.014	✅	3,631,311,977	80%	0.6%	0.005	193,403,104	0.016	70,934,579	0.006	20,960,302	0.002	1,377,457,892	0.064	1,968,556,100	-0.075	0.220	0.000	340	CA$ 93,598,312
2044	0.066	0.010	✅	3,631,311,977	80%	0.6%	0.005	167,616,023	0.014	61,476,636	0.006	18,165,595	0.001	1,385,065,838	0.065	1,998,987,885	-0.076	0.220	0.000	368	CA$ 102,952,25
2046	0.044	0.006	✅	3,631,311,977	80%	0.6%	0.005	141,828,943	0.012	52,018,692	0.005	15,370,888	0.001	1,392,673,784	0.065	2,029,419,670	-0.077	0.220	0.000	397	CA$ 112,535,55
2048	0.022	0.002	✅	3,631,311,977	80%	0.6%	0.005	116,041,862	0.010	42,560,748	0.004	12,576,181	0.001	1,400,281,730	0.065	2,059,851,455	-0.078	0.220	0.000	425	CA$ 122,348,22
2050	0.000	-0.002	✅	3,631,311,977	80%	0.6%	0.005	90,254,782	0.008	33,102,804	0.003	9,781,474	0.001	1,407,889,677	0.066	2,090,283,240	-0.079	0.220	0.000	454	CA$ 132,390,26
Total						97.00%	0.669	2.49%		0.91%		0.27%		38.77%		57.56%					

4. Fire-killed trees image

Figure 14: *Fire-killed biomass images (author photos except when indicated)*

SI3— 1: The terrain visited was composed of trees expressing a diameter of a maximum of 25 cm. A significant portion of the wood had already been harvested by previous residents. The terrain was easy to access from the highway with a rear wheel drive vehicle. Author photo.

SI3— 2: One (1) cord of firewood harvested. Author photo. The wood in this photo was collected by a local Indigenous harvester in Behchokǫ̀, Northwest Territories. The outside layer was roughly cleaned with a chainsaw blade; some of the charred components have been removed.

SI3— 3: Light charring is expressed on one side of this log. The charring seems to remain limited to the outside surface of the log. About 10% of the trees harvested demonstrated similar outer-layer charring. Author photo.

SI3— 4: Satellite photography of the approximate area where the wood was harvested. In the upper left general area, we observe an intact forest. On the right side of the picture, West of Highway 3, we observe a fire-decimated area, where the wood was harvested. Google Maps.

5. Detailed results, carbon footprint

Table 14: Summary resuls, carbon intensity per fuel type

Carbon intensity per fuel type (g CO2 per MJ)						
				Global Warming Potential Used (GWP)		
				0.2	0.2	0.5
	Heating Oil	**Propan e**	**Natural Gas**	**Biomass Combustion**	**Mill Waste Pyro-CCS**	**Fire-Killed Pyro-CCS**
biochar (CCS)	0.00	0.00	0.00	0.00	**-67.45**	**-109.32**
combustion emissions (fossil)	78.95	67.94	59.59	0.00	0.00	0.00
combustion emissions (bioger	0.00	0.00	0.00	25.97	21.93	54.82
fuel production	3.39	20.25	18.15	11.25	14.34	9.35
fuel transportation	0.61	1.44	1.44	8.62	10.99	2.57
biochar transportation	0.00	0.00	0.00	0.00	11.15	0.90
electricity use	0.11	0.06	0.15	0.57	2.00	2.00
electricity backup	0.00	0.00	0.00	0.00	1.83	1.83
travel & accom	0.00	0.00	0.00	0.00	0.49	0.49
manufacturing & transportatio	0.05	0.18	0.01	0.21	0.32	0.32
employee commute	0.02	0.02	0.02	0.08	0.17	0.17
ashes landfilling	0.00	0.00	0.00	0.03	0.00	0.00
Overall carbon intensity (g (	**83.1**	**89.9**	**79.4**	**46.7**	**-21.8**	**-37.9**
Low emissions	69.9	77.8	68.6	26.6	-35.3	**-48.6**
High emissions	138.2	141.5	125.1	**72.4**	61.2	82.1

6. Carbon flow calculations

Carbon flow for Locally-Harvested Necromass Feedstock								
A : COUNTERFACTUAL	**Biomass required** (g/MJ)		**C left in forest**	**Natural Decay**	**Natural Sequestration**		**Total Emissions**	
Untouched, natural decay scenario	153.6	**CARBON FLOW** (g C/MJ)	76.8	69.1	7.7	-	69.1	
		EMISSIONS (g CO2 eq./MJ)	-	126.8	-	-	**126.8**	
B: PROPOSED	**Biomass required** (g/MJ)		**C to Pyro-CCS**	**C to Fuels**	**C to Biochar**	**Biochar Degradation**	**Total Emissions**	
Pyro-CCS proposed scenario, harvested necromass	153.6	**CARBON FLOW** (g C/MJ)	76.8	48.1	28.7	2.9	50.9	
		EMISSIONS (g CO2 eq./MJ)	-	88.2	-	**5.3**	**93.5**	
					Avoided Emissions (g CO2 eq./MJ)			33.3
					reduction compared to base case			26%
FACTORS								
energy balance	0.766	GWP_bio	0.5		biochar C content	85%		
necromass)	10.0	C to CO2 conversion factor	3.67		necromass C content	50%		
furnace efficiency	85%	biochar yield	22%		functional unit	1		
natural decay	90%	biochar stability	90%		reference flow	1.176		

Table 15: *Base case and proposed scenarios carbon and emissions flow for locally-harvested necromass*

Carbon flow for Imported Wood Pellets Feedstock								
A : COUNTERFACTUAL	**Biomass required** (g/MJ)		**C in Wood Pellets**		**Combustion Emissions**		**Total Emissions**	
Status quo: wood waste burned or left to decay	92.0	**CARBON FLOW** (g C/MJ)	46.0		46.0	-	46.0	
		EMISSIONS (g CO2 eq./MJ)	-		33.8	-	**33.8**	
B: PROPOSED	**Biomass required** (g/MJ)		**C to Pyro-CCS**	**C to Fuels**	**C to Biochar**	**Biochar Degradation**	**Total Emissions**	
Pyro-CCS proposed scenario, pelletized wood waste	92.0	**CARBON FLOW** (g C/MJ)	46.0	28.8	17.2	1.7	30.5	
		EMISSIONS (g CO2 eq./MJ)	-	21.1	-	**1.3**	**22.4**	
					Avoided Emissions (g CO2 eq./MJ)			11.4
					reduction compared to base case			34%
FACTORS								
energy balance	0.766	GWP_bio	0.2		biochar C content	85%		
heating value (MJ/kg	16.7	C to CO2 conversion factor	3.67		biomass C content	50%		
furnace efficiency	85%	biochar yield	22%		functional unit	1		
combustion efficiency	100%	biochar stability	90%		reference flow	1.176		

Table 16: *Base case and proposed scenarios carbon and emissions flow for imported forestry industry waste wood pellets*

7. High-level Business Viability Assessment

High-level assessment for Pyro-CCS financial viability in NWT

The following business viability assessment is based on the harvest of 1,800 tons of FKTs per year, with six 60 kW Pyro-CCS machines operating at full capacity— meaning that they consume 300 tons of FKTs each per year, and produce 57 tons of biochar each per year. Expenses include 1 full-time manager and 2 part-time experts (mechanical engineer, and sales and marketing manager), 9,600 hours of harvesters' time, corresponding to 1.5 tons of FKT per harvester for a full 8-hour day. It is assumed that it would be possible to obtain 60% grants for the initial business investments, so only 40% of the initial costs (electric truck, Pyro-CCS equipment and other related equipment) are financed on a monthy basis. This assessment has a very high uncertainty and is meant only as a way to spark discussion on financial viability of the technology in Northwest Territories.

Expenses	**Description**	**Annual**
Harvesters salaries	6,900 hours at $25 per hour	CA$241,200
Office expenses	Internet, cell phones, etc.	CA$9,040
Equipment financing	$485,000 financed over 5 years at 5%	CA$104,664.03
Electricity for electric truck	Assuming $0.37/kWh, based on average vehicle electricity consumption	CA$19,980
Electricity for Pyro-CCS equipment	Assuming $0.37/kWh, from manufacturer's data	CA$11,840
Insurance	Estimate	CA$24,000.00
Management salaries	1 full-time manager at $80/hour, and $50k of contractors per year	CA$204,500
Revenues		
Carbon offsets	Assuming $150/ton CO_2 eq. (conservative)	CA$13,500
Heat sales	Assuming a price of $0.12/kWh (conservative)	CA$216,000
Bulk biochar sales	Assuming a price of $1500/ton	CA$461,700

Total	
Expenses	CA$615,224
Revenues	CA$691,200
Profits	CA$75,976
Margin	12.35%

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Fire with Fire
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