Resources, Conservation & Recycling 199 (2023) 107189

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.elsevier.com/locate/resconrec

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

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ARTICLE INFO

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)

ABSTRACT

Heating buildings in Northern communities is carbon-intensive and existing low-carbon technologies are ill-suited for northern conditions. Pyrogenic carbon capture and storage (Pyro-CCS), which heats biomass anoxically to produce fuels and biochar, could provide low-carbon heat in this climate. We calculate the carbon footprint of Pyro-CCS in Northwest Territories (NWT), Canada 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 g CO_2 eq. MJ^{-1} using wood-pellets and sequesters -10.3 g CO_2 eq. MJ^{-1} using fire-killed trees, compared to emissions of 59.7 g CO_2 eq. MJ^{-1} for wood-pellet combustion, and 79.4-89.9 g CO_2 eq. MJ^{-1} for fossil fuels. Scenarios suggest that widespread Pyro-CCS could allow 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), Canada, the 2014 *Summer of Smoke* burned 34,000 square kilometres (km^2) of forest, causing evacuations and doubling emergency room visits for asthma (Dodd et al., 2018, Howard et al., 2018). Unprecedented flooding, thawing permafrost, and coastal erosion are making communities uninhabitable and jeopardizes natural and built infrastructures (Paulson, 2021). Supply chain disruptions are increasingly frequent as trucks fall through thawing ice roads (Scott, 2020). Declining animal populations threaten traditional subsistence hunting and livelihoods (Worden et al., 2020).

Northern communities in Canada and elsewhere must urgently adapt to climate change and decarbonize. 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 (Canada Energy Regulator, 2020, Statista, 2021, The World Bank, 2020). Space and water heating alone account for roughly 30% of energy use and emissions (Canada Energy Regulator, 2020).

Heat in NWT is primarily from fossil fuels – natural gas, propane, heating oil– and biomass – wood pellets and firewood (Canada Energy Regulator, 2020. Decarbonization strategies for milder climates, such as electric heating with photovoltaics or passive solar work poorly in arctic conditions (Pinto and Gates, 2022). Current drop-in biofuels cannot meet demand, and their carbon benefits remain contested (Maia and Bozelli, 2022, Barnabe et al., 2013, Saskatchewan Research Council, 2021, International Energy Agency, 2022). 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 (Schmidt et al., 2019). Long-chain organic molecules in the biomass decompose to gaseous alkanes and hydrogen, also called pyro-gas, and bio-oils (Hoang et al., 2021). 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 (Schmidt et al., 2019). For example, biochar production decreases with higher temperature (Demirbas, 2004, Zhang et al., 2020, McBeath et al.,

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https://doi.org/10.1016/j.resconrec.2023.107189
Received 21 March 2023; Received in revised form 28 June 2023; Accepted 26 August 2023
Available online 21 October 2023

2015).

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 (Smart Tampere, 2018), Sweden (Azzi et al., 2019), and Norway (Karachristianidis, 2019). 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 (Sohi et al., 2010). The carbon in biochar is exceedingly stable (Wang et al., 2016)— buried, it remained 97% stable after 100 years (Leng et al., 2019). 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 (Peters, 2021). The ability for Pyro-CCS to produce heat and stable carbon positions the technology as a low-carbon or potentially carbon-negative energy source.

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. 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. Fig. 1 details what such a system might look like.

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 (Bui et al., 2018) . Globally, the technology can contribute between 6% and 35% of the negative emissions needed to stabilize the climate under optimistic scenarios (Werner et al., 2022). Studies in China suggest that agricultural residues, forestry residues, and municipal waste can provide significant shares of local energy demands (Zhou et al., 2011), albeit unevenly across the country (Yanli et al., 2010). Spatial analysis shows that Pyro-CCS could supply 222 GW of power using 0.9 Gt biomass (50% agricultural residues) (Xing et al., 2021) and that CCS more broadly can offset sunk emissions in planned coal plants (Li et al., 2022).

Despite the promise of Pyro-CCS to aid decarbonization, none of the above studies analyzed the technology in northern regions nor did they consider fire-killed trees (FKT) as a novel bioenergy feedstock. As such, the carbon footprint of Pyro-CCS using traditional feedstocks and FKT, and its potential contributions to decarbonizing the North are presently unknown.

We address this gap through a case study of Pyro-CCS in NWT. NWT covers 1,346 million km^2 in the Canadian North with a population of 44,826 in 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 some of 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 estimated carbon emissions to supply 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. Fig. 2 summarizes the inputs to our systems and Table 5 through Table 12 detail the Ecoinvent 3.8 processes in our OpenLCA model.

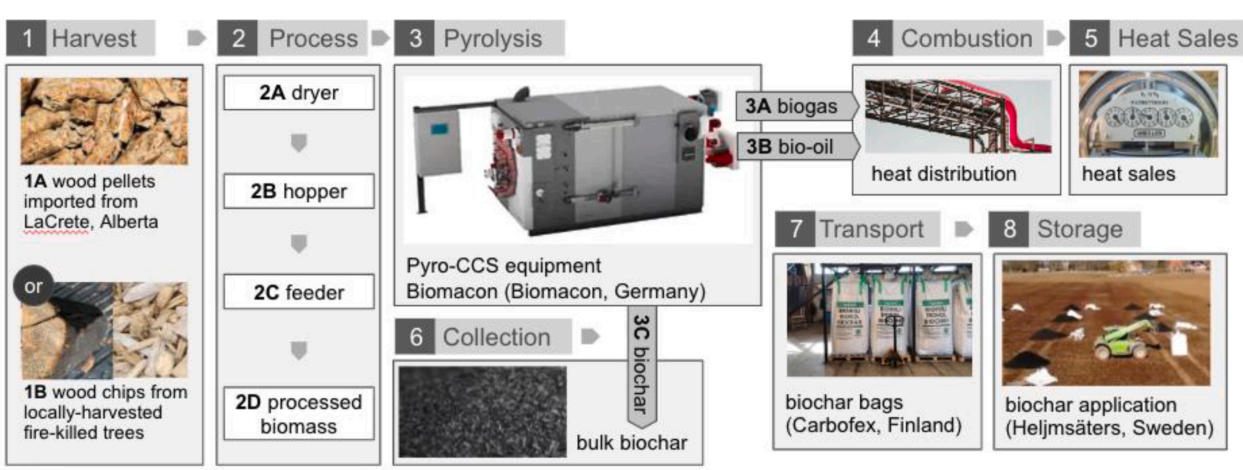

Fig. 1. Representation of the proposed Pyro-CCS system with examples from around the world. 1B, 7, author photo. 1A, 3, 4, 5, 6, 8 with permission.

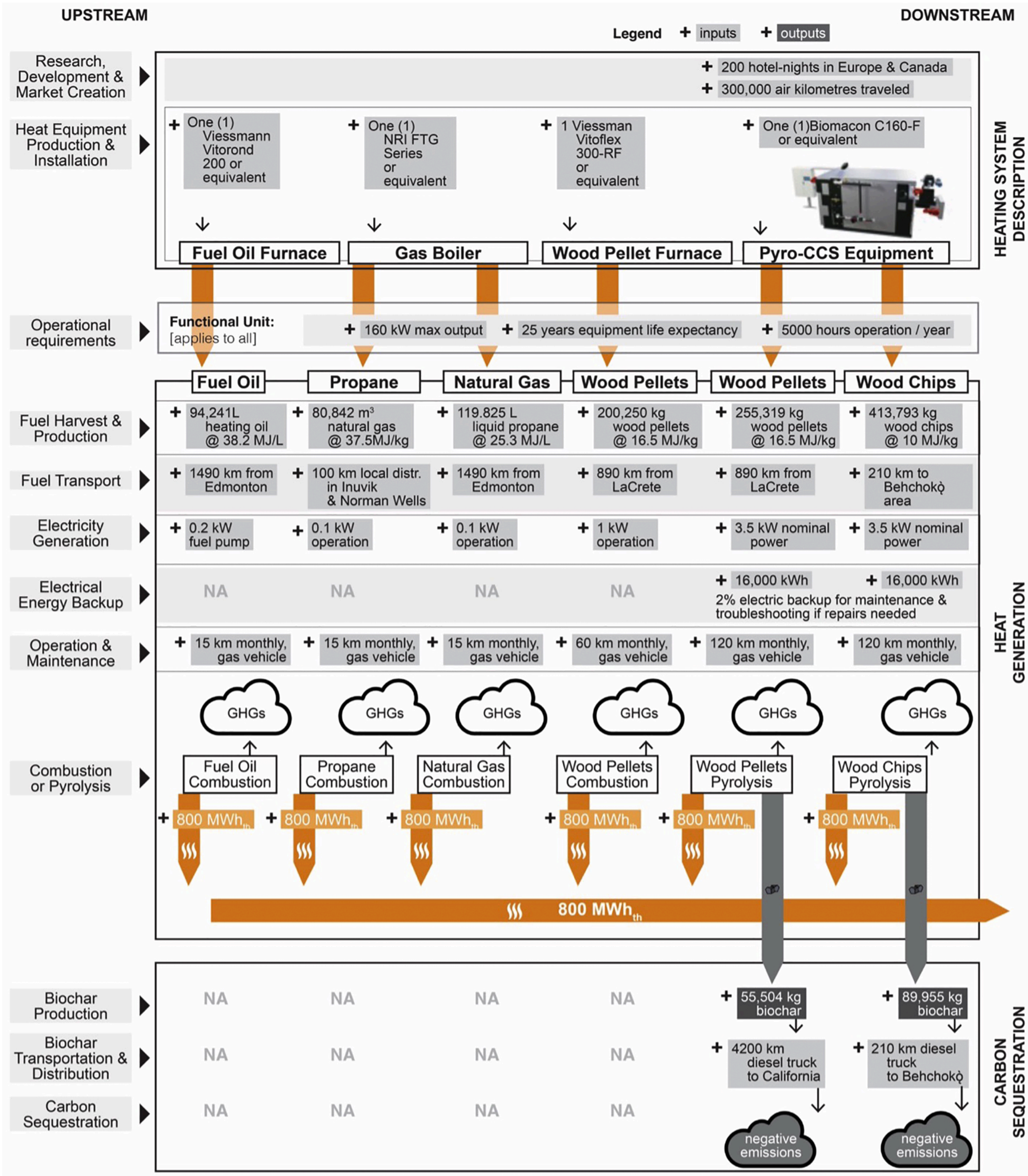

Fig. 2. Overview of inputs and outputs for the system. Images and icons from Freepik, AbtoCreative, Kosonicon and Biomacon (Flaticon, 2023).

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 (Biomacon GmbH, 2021). 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 (Biomacon GmbH, 2021), 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 (Natural Resources Canada, n.d.) 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 as California is a major market for biochar and because this provides a conservative estimate of environmental and economic performance of our system. We tested the influence of this assumption on the results using a sensitivity analysis. 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 (Biomacon GmbH, 2021).

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 (Natural Resources Canada, n.d.), 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 7). 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 (Natural Resources Canada, n.d.), 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) (Viessman, 2023). 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%) (Series, 2023), heating oil (80%) (Viessman, 2023), and propane (95%) (Series, 2023). 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 (Brassard et al., 2021). 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.

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

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 (Fan et al., 2021, Cherubini et al., 2011, Liu et al., 2017, Cherubini et al., 2016).

We use Equation 2 to determine C_{case}, where m_{in} is the mass of feedstock required for our unit of analysis 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) (Basu, 2018), and $\rho_{biochar}$ —the percentage of undegraded biochar after 100 years (Wang et al., 2016).

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

To determine m_{in}, we use Equation 3. Here, E_{in} is 1 MJ, η_f is the furnace efficiency (assumed 85% (US Dept of Energy n.d.)), and ρ_{fs} is the heating value of the feedstock (Natural Resources Canada, n.d.).

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

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 (Campbell et al., 2016).

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

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

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 (Canada Energy Regulator, 2020). 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 lack of data, we assumed that between 22% (Canada Energy Regulator, 2020) and 28% (6 PJ) (Cunningham, 2022) 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 modeled decarbonization using two scenarios. The *1.5°C Paris Agreement* scenario charted the decarbonization of the heating sector in NWT to remain below the 1.5°C target of the Paris Agreement by reducing emission to 45% below 2010 levels before 2030, and to net-zero before 2050 (Allen et al., 2018). The *Sequester* scenario 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. We used conversion rates to capture the different types of systems that might replace conventional boilers. For example, a 30% conversion rate represents a 30% conversion to Pyro-CCS, and 70% to wood pellets combustion. Our model assumes that the carbon performance of

Pyro-CCS improves by 5% every year, a conservative assumption considering that several clean tech sectors have been improving at 10% or more annually (International Energy Agency, 2023, IEA, 2022, International Energy Agency, 2022, IEA, 2023) and that a significant share of those emissions, related to transportation, are forecasted to see drastic emissions reductions in the next decade (Vaillancourt et al., 2017).

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 (Brassard et al., 2021);
- Furnace efficiencies: between 50% to 95% efficiency (US Dept of Energy n.d.);
- Fuel production upstream emissions: assuming reported emissions are more optimistic and adding 20% for fugitive or unaccounted for emissions, lacking better data (Brandt, 2012);
- 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 (Fan et al., 2021);
- 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 (Canada Energy Regulator, 2020);
- 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) (Wernet et al., 2016);
- Equipment lifespan (years): allowing for boilers lasting from 5 years to 50 years (Wernet et al., 2016);
- 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 (Campbell et al., 2016).

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

Fig. 3 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 using 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 (Forest Research, 2023) and 200 g CO_2e MJ^{-1} (DEFRA, 2007) compared to 79.4 g CO_2e MJ^{-1} here. For heating oil, estimates range between 70 g (United States Energy Information Administration U.S, 2021), 72 (Forest Research, 2023) to 300 g of CO_2e MJ^{-1} (Cherubini et al., 2009), 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 (Pehnt, 2006), 30 (Cherubini et al.,

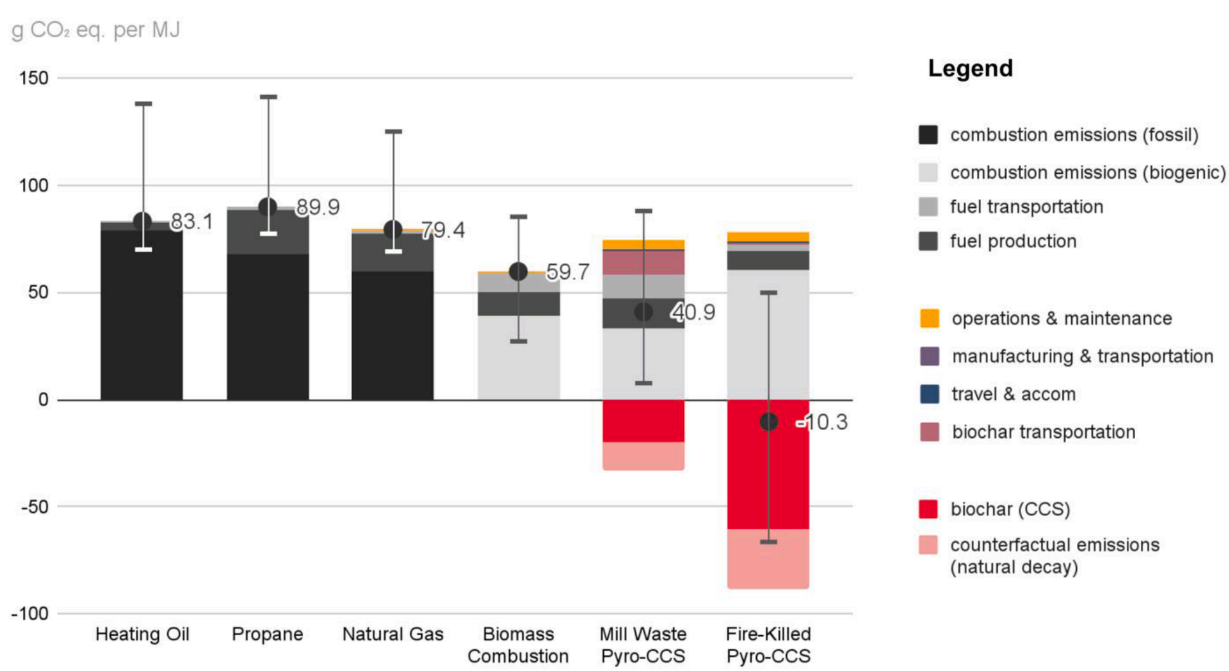

Fig. 3. Carbon intensity of heat in Yellowknife, NWT. Carbon intensity in grams CO2e per MJ for six heating systems in NWT. Error bars represent the range of values given uncertainty in modeling parameters.

2009), and 92 g CO_2e MJ^{-1} (Partnership for Policy Integrity n.d.). This suggests that combusting biomass residues in NWT is favorable to fossil fuels for heat.

A shortage 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 (Yang et al., 2016), 25 (Gaunt and Lehmann, 2008), 29 (Hsu, 2012) 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} (Yang et al., 2016). Other studies of carbon sequestration with pyrolysis

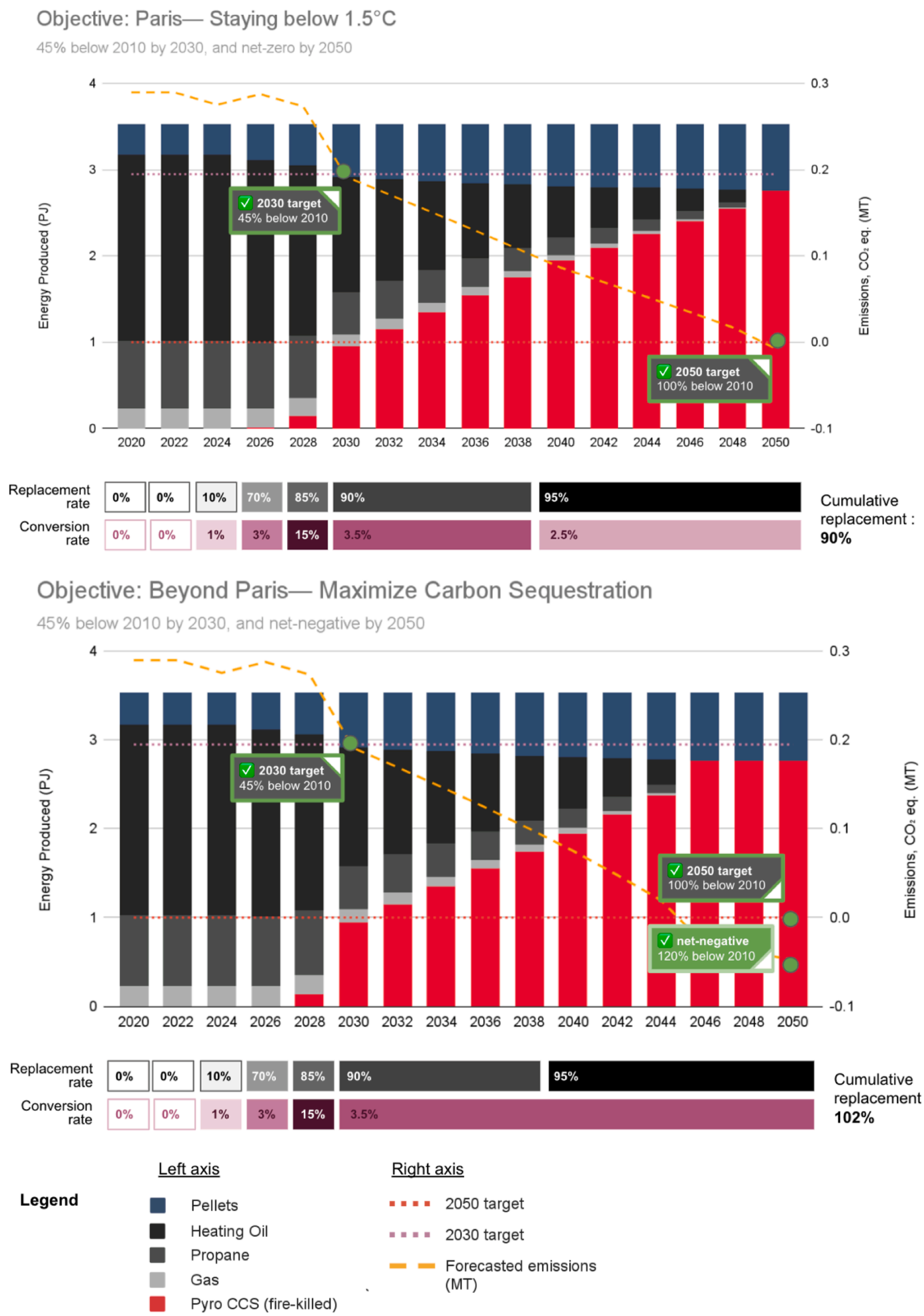

Fig. 4. Decarbonization forecasts for Northwest Territories, Canada. The 1.5°C scenario requires heavy innovation investments to spur rapid conversion rates this decade followed by very high replacement rates next decade (top). The "Sequester" scenario is similar but keeps a higher pace throughout the 2030s and 2040s, to become carbon-negative by 2044 (bottom).

reported near-zero or negative net emissions per unit of biochar produced (Rajabi Hamedani et al., 2019) or per unit of land harvested (Tisserant et al., 2022), 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 (Natural Resources Canada, n.d.). 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 though we included significant employee travel for installation.

Carbon sequestered as biochar is represented as negative bars in Fig. 3. 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

Fig. 4 shows projected decarbonization pathways and required annual heating system replacement rates and rates of conversion to biomass systems. Results from the *1.5°C Paris Agreement* scenario suggest that Pryo-CCS can plan an important role in helping the heating sector meet these targets. 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. Replacement rate exceeds 100% because units have lifespan of 25 years and so some units were replaced twice in our model. 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 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.

Fig. 4B depicts results of the *Sequester* scenario, where carbon capture and storage capacity is increased significantly in the heating sector after 2030. The years prior to 2030 were kept unchanged from the previous scenario, but the replacement rate in the 2030s and 2040s was kept steady at 4% per year. This would meant that 115% of all heating systems in NWT would be replaced— a likely scenario considering a boiler lifespan of approximately 25 years. With this scenario, the heating sector in the territory can achieve a 112% emissions reduction from 2010 levels by 2050.

Fig. 5 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 (Pisaric et al., 2018) 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 (Girardin and Mudelsee, 2008). 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.

4. Discussion

Results suggest that Pyro-CCS with wood-pellets or FKT can be a low- or negative-emissions heat source that can help NWT and similar regions decarbonize. Below we discuss policies to support implementation of Pyro-CCS in NWT and outline 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 (Seto et al., 2016), 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 earlier.

Decarbonizing heating requires 3-15% annual replacement rates, far above those of other Canadian jurisdictions (International Energy Agency, 2022). GNWT can take inspiration from Ireland which aims to retrofit 8% of its homes annually (O'Sullivan, 2021). 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. Fig. 6 shows that modest carbon taxes will provide payback for decarbonizing heat in NWT, in the order of approximately $150M by 2050 in NWT alone.

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 per ton (Jirka and Tomlinson, 2015), although higher-end, smaller quantities consumer products can go as high as CAD $60k per tonne (Jirka and Tomlinson, 2015, State, 2021, Kim et al., 2015, Nematian et al., 2021). Revenue from biochar and heat should be considered in future techno-economic analysis.

Policy 2: Improved energy and emissions data

Existing data on energy and emissions in NWT are unavailable at the

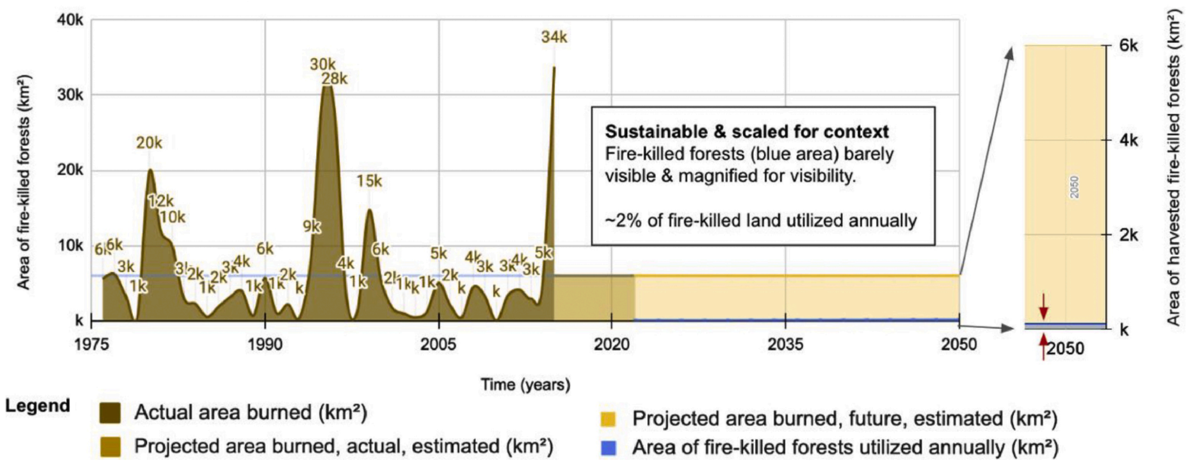

Fig. 5. Forest area killed by wildfire and fire-killed forest area utilized for energy purposes for the *Sequester* scenario, from 1975-2050, hectares (km^2).

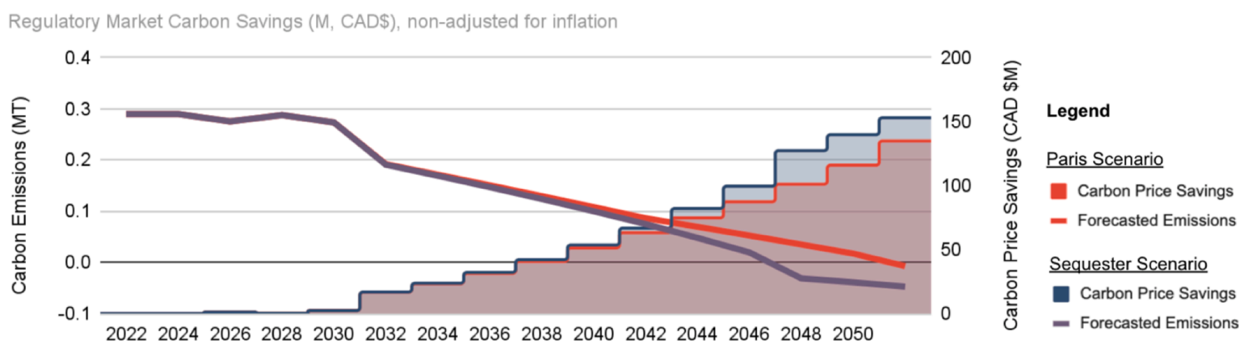

Fig. 6. Cumulative Savings for Pyro-CCS in NWT (CAD $M) from 2022 to 2050. More than $150M could be saved annually by the territory. These prices are all in 2022 dollars and represent regulatory market savings from avoided carbon taxes. Carbon tax rate increases of $15/year (Government of Canada, 2020) is assumed sustained post-2030.

community level, by fuel type, or by end use (Canada Energy Regulator, 2020). 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 (US EIA, 2021). Private energy providers can assist by publishing anonymized, aggregate consumption data.

Plugging data gaps will help 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 (Auditor General of Canada, 2017).

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 (Cools, 2022). 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 (Berardi and Jones, 2022). DES can simplify decarbonization for the customer, as it is handled privately (Yoon et al., 2015). Establishing an energy governance structure, leading public engagement, and developing legal frameworks can eliminate barriers for low-carbon energy adoption (Angelidis et al., 2023).

Policy 4: Include local stakeholders

NWT and the two other Canadian territories house a large Indigenous population (Statistiques Canada, 2019). 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 (Hoffman et al., 2022, Hoffman et al., 2021), which are likely to enhance soil carbon. Some 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 (Souza, 2023). 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 4 show that sequestered carbon depends on emission from decaying FKT and regenerative carbon uptake (accounted using the biogenic emission factor) (Fan et al., 2021). There exists only a handful of studies on post-fire carbon dynamics in boreal forests (Campbell et al., 2016, Mkhabela et al., 2009, Milakovsky et al., 2012), 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, albeit, still less so 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 (Sohi et al., 2010, Wang et al., 2016, Leng et al., 2019). All studies point towards high stability of biochar in soil (McBeath et al., 2015, Sohi et al., 2010, Wang et al., 2016, Leng et al., 2019, Mašek et al., 2013, Al-Wabel et al., 2013, Steiner, 2016, Leng and Huang, 2018). 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 (Maroušek et al., 2019, Shackley et al., 2011). Potential uses include filler for local roads (Zhang et al., 2022) or for mining remediation (Gao et al., 2022, Anawar et al., 2015). 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 (Meyer et al., 2012).

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 (Berardi and Jones, 2022). 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, such as the Yukon.

Lastly, further research is needed to develop small-scale Pyro-CCS. Systems below 40 kW are not yet commercially available. 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-lines 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 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.

Supplementary Information

SI 1: OpenLCA inputs, ouputs and results per fuel type;
SI 2: Decarbonization Scenarios; Conversion & Replacement Rates
SI 3: Fire-killed biomass in Yellowknife, Northwest Territories, Canada (images)
SI 4: Detailed results, carbon footprint by fuel type and emissions category

1. OpenLCA inputs, ouputs and results per fuel type
Table 5: OpenLCA global references
Table 6: OpenLCA heating oil results, inputs and outputs
Table 7: OpenLCA natural gas results, inputs and outputs
Table 8: OpenLCA propane results, inputs and outputs
Table 9: OpenLCA biomass combustion results, inputs and outputs
Table 10: OpenLCA biomass combustion results, inputs and outputs (continued)
Table 11: OpenLCA imported wood pellets Pyro-CCS results, inputs and outputs
Table 12: OpenLCA locally-harvested fire-killed Pyro-CCS results, inputs and outputs
2. Decarbonization scenarios, conversion & replacement rates
Table 13: Emissions forecasting, scenarios A and B
3. Fire-killed trees image
Figure 7: Fire-killed biomass images
4. Detailed results, carbon footprint
Table 14: Summary results, carbon intensity per fuel type
5. Carbon flow calculations
Table 15: Base case and proposed scenarios carbon and emissions flow for locally-harvested necromass
Table 16: Base case and proposed scenarios carbon and emissions flow for imported forestry industry waste wood pellets

CRediT authorship contribution statement

William Gagnon: Conceptualization, Formal analysis, Methodology, Investigation, Data curation, Writing – original draft, Visualization. **Benjamin Goldstein:** Conceptualization, Methodology, Validation, Writing – review & editing, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: William Gagnon reports financial support was provided by Natural Sciences and Engineering Research Council of Canada.

Data Availability

No primary data used. License data Ecoinvent 3.8 used for life cycle inventories of background system. Other data & sources listed the article & SI. Readers can contact author for clarification.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2023.107189.

References

Allen M, Babiker M, Chen Y, de Coninck HC. IPCC SR15: Summary for policymakers. IPCC Special Report Global Warming of 15 °C: Intergovernmental Panel on Climate Change; 2018.

Al-Wabel, MI, Al-Omran, A, El-Naggar, AH, Nadeem, M, Usman, ARA., 2013. Pyrolysis temperature induced changes in characteristics and chemical composition of biochar produced from conocarpus wastes. Bioresource Technology 131, 374–379.
Anawar, HM, Akter, F, Solaiman, ZM, Strezov, V., 2015. Biochar: An Emerging Panacea for Remediation of Soil Contaminants from Mining, Industry and Sewage Wastes. Pedosphere 25 (5), 654–665.
Angelidis, O, Ioannou, A, Friedrich, D, Thomson, A, Falcone, G., 2023. District heating and cooling networks with decentralised energy substations: Opportunities and barriers for holistic energy system decarbonisation. Energy 269, 126740.
Auditor General of Canada, 2017. October 2017 Report of the Auditor General of Canada to the Northwest Territories Legislative Assembly. Office of the Auditor General of Canada, Ottawa, Canada.
Azzi, ES, Karltun, E, Sundberg, C., 2019. Prospective Life Cycle Assessment of Large-Scale Biochar Production and Use for Negative Emissions in Stockholm. Environmental Science & Technology 53 (14), 8466–8476.
Barnabe D, Bucchi R, Rispoli A, Chiavetta C, Porta PL, Bianchi CL, et al. Land Use Change Impacts of Biofuels: A Methodology to Evaluate Biofuel Sustainability. Biofuels - Economy, Environment and Sustainability: InTech; 2013.
Basu, P., 2018. Chapter 5 - Pyrolysis. editor. In: Basu, P (Ed.), Biomass Gasification, Pyrolysis and Torrefaction, Third Edition. Academic Press, pp. 155–187.
Berardi, U, Jones, S., 2022. The efficiency and GHG emissions of air source heat pumps under future climate scenarios across Canada. Energy and Buildings 262, 112000.
Biomacon C160-F Pyrolysis Boiler. Biomacon GmbH, 2021.
Brandt, AR., 2012. Variability and Uncertainty in Life Cycle Assessment Models for Greenhouse Gas Emissions from Canadian Oil Sands Production. Environmental Science & Technology 46 (2), 1253–1261.
Brassard, P, Godbout, S, Hamelin, L., 2021. Framework for consequential life cycle assessment of pyrolysis biorefineries: A case study for the conversion of primary forestry residues. Renewable and Sustainable Energy Reviews 138, 110549.
Bui, M, Adjiman, CS, Bardow, A, Anthony, EJ, Boston, A, Brown, S, et al., 2018. Carbon capture and storage (CCS): the way forward. Energy & Environmental Science 11 (5), 1062–1176.
Campbell, JL, Fontaine, JB, Donato, DC., 2016. Carbon emissions from decomposition of fire-killed trees following a large wildfire in Oregon, United States. Journal of Geophysical Research: Biogeosciences 121 (3), 718–730.
Canada Energy Regulator. Provincial and Territorial Energy Profiles: Government of Canada; 2020 [updated 2023-03-03. Available from: https://www.cer-rec.gc.ca/en/data-analysis/energy-markets/provincial-territorial-energy-profiles/provincial-territorial-energy-profiles-yukon.html#:~:text=GHG%20Emissions,-Yukon's%20GHG%20emissions&text=Yukon's%20emissions%20per%20capita%20are,of%2017.7%20tonnes%20per%20capita.
Cherubini, F, Bird, NM, Cowie, AL, Jungmeier, G, Schlamadinger, B, 2009. Woess-Gallasch S. Energy- and greenhouse gas-based LCA of biofuel and bioenergy systems: Key issues, ranges and recommendations. Resources Conservation and Recycling 53, 434–447.
Cherubini, F, Peters, GP, Berntsen, T, Strømman, AH, Hertwich, E., 2011. CO2 emissions from biomass combustion for bioenergy: atmospheric decay and contribution to global warming. GCB Bioenergy 3 (5), 413–426.
Cherubini, F, Huijbregts, M, Kindermann, G, Van Zelm, R, Van Der Velde, M, Stadler, K, et al., 2016. Global spatially explicit CO2 emission metrics for forest bioenergy. Scientific Reports 6 (1), 20186.
Cools, E., 2022. Heating Yellowknife: District energy system helps NWT reduce carbon footprint. Canada Biomass.
Cunningham ZW. Hydrogen and Ammonia Pathways Towards Net-Zero in the Northwest Territories. 2022.
Demirbas, A., 2004. Effects of temperature and particle size on bio-char yield from pyrolysis of agricultural residues. Journal of Analytical and Applied Pyrolysis 72 (2), 243–248.
Department for Environment, Food & Rural Affairs, Government of United Kingdom, 2007. Guidelines to Defra's GHG conversion factors for company reporting.
Dodd, W, Howard, C, Rose, C, Scott, C, Scott, P, Cunsolo, A, et al., 2018. The summer of smoke: ecosocial and health impacts of a record wildfire season in the Northwest Territories. Canada. The Lancet Global Health. 6, S30.
Michigan State University. Economics of biochar. 2021. Available from: https://www.canr.msu.edu/news/economics-of-biochar.
Fan, YV, Klemeš, JJ, Ko, CH., 2021. Bioenergy carbon emissions footprint considering the biogenic carbon and secondary effects. International Journal of Energy Research 45 (1), 283–296.
Flaticon. Flaticon.com 2023. Available from: flaticon.com.
Forest Research, 2023. Carbon emissions of different fuels.
Gaunt, JL, Lehmann, J., 2008. Energy Balance and Emissions Associated with Biochar Sequestration and Pyrolysis Bioenergy Production. Environmental Science & Technology 42 (11), 4152–4158.
Girardin, MP, Mudelsee, M., 2008. PAST AND FUTURE CHANGES IN CANADIAN BOREAL WILDFIRE ACTIVITY. Ecological Applications 18 (2), 391–406.
Government of Canada, 2020. A Healthy Environment & A Healthy Economy. Canada EaCC, Gatineau, QC, p. 79.
Hoang, AT, Ong, HC, Fattah, IMR, Chong, CT, Cheng, CK, Sakthivel, R, et al., 2021. Progress on the lignocellulosic biomass pyrolysis for biofuel production toward environmental sustainability. Fuel Processing Technology 223, 106997.
Hoffman, KM, Davis, EL, Wickham, SB, Schang, K, Johnson, A, Larking, T, et al., 2021. Conservation of Earth's biodiversity is embedded in Indigenous fire stewardship. Proceedings of the National Academy of Sciences 118 (32), e2105073118.
Hoffman, KM, Christianson, AC, Dickson-Hoyle, S, Copes-Gerbitz, K, Nikolakis, W, Diabo, DA, et al., 2022. The right to burn: barriers and opportunities for Indigenous-led fire stewardship in Canada. FACETS 7, 464–481.
Howard C, Rose C, Dodd W, Kohle K, Scott C, Scott P, et al. SOS! Summer of Smoke: An Examination of the Health Effects of a Record Wildfire Season in Canada's High-Subarctic. Summer of Smoke: An Examination of the Health Effects of a Record Wildfire Season in Canada's High-Subarctic (March 10, 2018). 2018.
Hsu, DD., 2012. Life cycle assessment of gasoline and diesel produced via fast pyrolysis and hydroprocessing. Biomass and Bioenergy 45, 41–47.
Gao, Y, Wu, P, Jeyakumar, P, Bolan, N, Wang, H, Gao, B, et al., 2022. Biochar as a potential strategy for remediation of contaminated mining soils: Mechanisms, applications, and future perspectives. Journal of Environmental Management 313, 114973.
International Energy Agency, 2022. Wind Electricity.
International Energy Agency, 2022. Solar PV.
International Energy Agency, 2022. Canada 2022: Energy Policy Review.
International Energy Agency, 2023. Demand for electric cars is booming, with sales expected to leap 35% this year after a record-breaking 2022.
International Energy Agency. Global heat pump sales continue double-digit growth. 2023.
International Energy Agency. Global biofuel production in 2019 and forecast to 2025 2022. Available from: https://www.iea.org/data-and-statistics/charts/global-biofuel-production-in-2019-and-forecast-to-2025.
Jirka S, Tomlinson T. State of the biochar industry 2014. International biochar initiative rep. 2015.
Karachristianidis, EK., 2019. Biochar for carbon neutral farming: a case study of greenhouse horticulture in Norway. Norwegian University of Life Sciences, Ås.
Kim, D, Anderson, NM, Chung, W, 2015. Financial performance of a mobile pyrolysis system used to produce biochar from sawmill residues. Forest Products Journal 65 (5-6), 189–197.
Leng, L, Huang, H, Li, H, Li, J, Zhou, W., 2019. Biochar stability assessment methods: A review. Science of The Total Environment 647, 210–222.
Li, K, Shen, S, Fan, J-L, Xu, M, Zhang, X., 2022. The role of carbon capture, utilization and storage in realizing China's carbon neutrality: A source-sink matching analysis for existing coal-fired power plants. Resources, Conservation and Recycling 178, 106070.
Liu, W, Zhang, Z, Xie, X, Yu, Z, Von Gadow, K, Xu, J, et al., 2017. Analysis of the Global Warming Potential of Biogenic CO2 Emission in Life Cycle Assessments. Scientific Reports 7 (1), 39857.
Mašek, O, Brownsort, P, Cross, A, Sohi, S., 2013. Influence of production conditions on the yield and environmental stability of biochar. Fuel 103, 151–155.
Maia, RGT, Bozelli, H., 2022. The importance of GHG emissions from land use change for biofuels in Brazil: An assessment for current and 2030 scenarios. Resources, Conservation and Recycling 179, 106131.
Maroušek, J, Strunecký, O, Stehel, V., 2019. Biochar farming: defining economically perspective applications. Clean Technologies and Environmental Policy 21 (7), 1389–1395.
McBeath, AV, Wurster, CM, Bird, MI., 2015. Influence of feedstock properties and pyrolysis conditions on biochar carbon stability as determined by hydrogen pyrolysis. Biomass and Bioenergy 73, 155–173.
Mkhabela, MS, Amiro, BD, Barr, AG, Black, TA, Hawthorne, I, Kidston, J, et al., 2009. Comparison of carbon dynamics and water use efficiency following fire and harvesting in Canadian boreal forests. Agricultural and Forest Meteorology 149 (5), 783–794.
Milakovsky, B, Frey, B, James, T., 2012. Carbon Dynamics in the Boreal Forest. Managing Forest Carbon in a Changing Climate. Springer, Netherlands, pp. 109–135.
Meyer, S, Bright, RM, Fischer, D, Schulz, H, Glaser, B., 2012. Albedo Impact on the Suitability of Biochar Systems To Mitigate Global Warming. Environmental Science & Technology 46 (22), 12726–12734.
Natural Resources Canada. Primer for solid biofuels definitions, classes/grades and fuel properties.
Nematian, M, Keske, C, Ng'ombe, JN., 2021. A techno-economic analysis of biochar production and the bioeconomy for orchard biomass. Waste Management 135, 467–477.
O'Sullivan K. 'Mass mobilisation of Irish society' needed to embrace retrofitting over coming decade. The Irish Times. 2021.
Partnership for Policy Integrity. Carbon emissions from burning biomass for energy.
Paulson H. N.W.T. communities prepare for spring floods, as high water levels persist. CBC. 2021.
Pinto, H, Gates, ID., 2022. Why is it so difficult to replace diesel in Nunavut, Canada? Renewable and Sustainable Energy Reviews 157, 112030.
Pehnt, M., 2006. Dynamic life cycle assessment (LCA) of renewable energy technologies. Renewable energy 31 (1), 55–71.
Peters, A., 2021. This startup keeps CO2 out of the air by injecting 'bio oil' underground. Fast Company.
Pisaric, M, Moser, K, Prince, T, Ceci, M, Sia, M, Warren, E, 2018. Fire and vegetation history during the Holocene epoch in the North Slave Region. In: Northwest Territories, Canada. EGU General Assembly Conference Abstracts.
Rajabi Hamedani, S, Kuppens, T, Malina, R, Bocci, E, Colantoni, A, Villarini, M, 2019. Life Cycle Assessment and Environmental Valuation of Biochar Production: Two Case Studies in Belgium. Energies 12 (11), 2166.
Saskatchewan Research Council, 2021. Assessing the Use of Liquid Biofuels in the Northwest Territories. Regina, SK, Canada.
Schmidt, H-P, Anca-Couce, A, Hagemann, N, Werner, C, Gerten, D, Lucht, W, et al., 2019. Pyrogenic carbon capture and storage. GCB Bioenergy 11 (4), 573–591.
Scott M. At least 4 vehicles fall through ice in N.W.T.'s Beaufort Delta region in November. CBC. 2020.
NTI. FTG Series 2023. Available from: https://ntiboilers.com/product/ftg-series.

Seto, KC, Davis, SJ, Mitchell, RB, Stokes, EC, Unruh, G, Ürge-Vorsatz, D., 2016. Carbon Lock-In: Types, Causes, and Policy Implications. Annual Review of Environment and Resources 41 (1), 425–452.
Shackley, S, Hammond, J, Gaunt, J, Ibarrola, R., 2011. The feasibility and costs of biochar deployment in the UK. Carbon Management 2 (3), 335–356.
Smart Tampere. Tampere, Finland, to produce carbon-negative district heating. October 25, 2018.
Sohi, SP, Krull, E, Lopez-Capel, E, Bol, R., 2010. Chapter 2 - A Review of Biochar and Its Use and Function in Soil. In: Advances in Agronomy, 105. Academic Press, pp. 47–82.
Souza Dd. Discussion on wildfire, Indigenous ways of managing wildfire, carbon capture and storage, climate mitigation and Indigenization of practices. In: Gagnon W, editor. 2023.
Steiner C. Considerations in Biochar Characterization. Agricultural and Environmental Applications of Biochar: Advances and Barriers 2016. p. 87-100.
Leng, L, Huang, H., 2018. An overview of the effect of pyrolysis process parameters on biochar stability. Bioresource Technology 270, 627–642.
Statistiques Canada, 2019. Population Estimates.
United States Dept of Energy. Understanding the Efficiency Rating of Furnaces and Boilers.
Wang, J, Xiong, Z, Kuzyakov, Y., 2016. Biochar stability in soil: meta-analysis of decomposition and priming effects. GCB Bioenergy 8 (3), 512–523.
Statista. Average per capita carbon dioxide emissions worldwide from 1960 to 2021: Statista; 2021. Available from: https://www.statista.com/statistics/268753/co2-emissions-per-capita-worldwide-since-1990/#:~:text=Global%20per%20capita%20carbon%20dioxide,per%20capita%20emissions%20to%20drop.
The World Bank. CO2 emissions (metric tons per capita)2020. Available from: https://data.worldbank.org/indicator/EN.ATM.CO2E.PC.
Tisserant, A, Morales, M, Cavalett, O, O'Toole, A, Weldon, S, Rasse, DP, et al., 2022. Life-cycle assessment to unravel co-benefits and trade-offs of large-scale biochar deployment in Norwegian agriculture. Resources, Conservation and Recycling 179, 106030.
United States Energy Information Administration. U.S, 2021. Energy Atlas.
Vaillancourt, K, Bahn, O, Frenette, E, Sigvaldason, O., 2017. Exploring deep decarbonization pathways to 2050 for Canada using an optimization energy model framework. Applied Energy 195, 774–785.
Viessman CA. Technical Data Manual Vitoflex 300-RF 2023. Available from: http://www.viessmann.ca/content/dam/internet-ca/pdfs/doc/bio/pyrot_tdm.pdf.
Viessman CA. VITOROND 200: Efficient, durable and reliable 2023. Available from: https://www.viessmann.ca/en/products/oil-boilers/vitorond-200.html.
Werner, C, Lucht, W, Gerten, D, Kammann, C., 2022. Potential of Land-Neutral Negative Emissions Through Biochar Sequestration. Earth's Future 10 (7), e2021EF002583.
Wernet, G, Bauer, C, Steubing, B, Reinhard, J, Moreno-Ruiz, E, Weidema, B, 2016. The ecoinvent database version 3 (part I): overview and methodology. The International Journal of Life Cycle Assessment 21 (9), 1218–1230.
Worden, E, Pearce, T, Gruben, M, Ross, D, Kowana, C, Loseto, L., 2020. Social-ecological changes and implications for understanding the declining beluga whale (*Delphinapterus leucas*) harvest in Aklavik, Northwest Territories. Arctic Science 6 (3), 229–246.
Xing, X, Wang, R, Bauer, N, Ciais, P, Cao, J, Chen, J, et al., 2021. Spatially explicit analysis identifies significant potential for bioenergy with carbon capture and storage in China. Nature communications 12 (1), 3159.
Yang, Q, Han, F, Chen, Y, Yang, H, Chen, H, 2016. Greenhouse gas emissions of a biomass-based pyrolysis plant in China. Renewable and Sustainable Energy Reviews 53, 1580–1590.
Yanli, Y, Peidong, Z, Wenlong, Z, Yongsheng, T, Yonghong, Z, Lisheng, W, 2010. Quantitative appraisal and potential analysis for primary biomass resources for energy utilization in China. Renewable and Sustainable Energy Reviews 14 (9), 3050–3058.
Yoon, T, Ma, Y, Rhodes, C., 2015. Individual Heating systems vs. District Heating systems: What will consumers pay for convenience? Energy Policy 86, 73–81.
Zhang, X, Zhang, P, Yuan, X, Li, Y, Han, L., 2020. Effect of pyrolysis temperature and correlation analysis on the yield and physicochemical properties of crop residue biochar. Bioresource Technology 296, 122318.
Zhang, Y, He, M, Wang, L, Yan, J, Ma, B, Zhu, X, et al., 2022. Biochar as construction materials for achieving carbon neutrality. Biochar 4 (1).
Zhou, X, Wang, F, Hu, H, Yang, L, Guo, P, Xiao, B, 2011. Assessment of sustainable biomass resource for energy use in China. Biomass and Bioenergy 35 (1), 1–11.