Decarbonizing the North : carbon analysis of space heating combined with carbon capture & storage

William Gagnon[1*], Benjamin Goldstein[2], Adekunbi Adetona[3], Elaine Gillespie[4]

[1]B.Eng., LEED AP BD+C, LEED AP ND, Cornell Fellow, M.Sc. Candidate, Bioresource Engineering, McGill University, Yellowknife, NT, Canada
[2]PhD, Assistant Professor, Bioresource Engineering, McGill University, Montreal, QC, Canada
[3]PhD, Department of Biological Sciences, University of Calgary, Calgary, AB, Canada
[4]P.Eng., LEED AP BD+C, Mechanical Engineering Lead, TAG Engineering Ltd., Yellowknife, NT, Canada

*corresponding author : william.gagnon@mail.mcgill.ca

SUMMARY

Heating, cooling and electrifying Canadian households emitted 65 million tons of carbon dioxide equivalent in 2018 or 12% of total greenhouse gas emissions in Canada. In the solar-dark Northern winters, space heating is the largest driver of residential energy use. Pyrogenic carbon capture and storage (PyCCS) from residual and forest biomass has the potential to make space heating carbon-negative across this region. PyCCS generates heat that can substitute fossil-based counterparts and biochar, which increases soil carbon storage and plant productivity in the forest and croplands. Evidence shows that biochar application increases biomass productivity by enhancing nutrient uptake and water use; PyCCS is a potential win-win for emissions and crop production in the Sub-Arctic. Although existing PyCCS projects in Finland, Sweden, Germany and Norway show the technology to be both profitable and effective at eliminating emissions, there is a lack of studies on the effectiveness of PyCCS in reducing emissions in the Northern Canadian context. This performed carbon and economic analyses of a hypothetical PyCCS system that utilizes imported wood pellets, and locally-harvested fire-killed trees as feedstocks and compared with fossil-based heating systems as well as the conventional combustion of wood pellets in Yellowknife, Northwest Territories in Canada. We found that emissions per unit of energy delivered to a household using PyCCS were substantially lower (-191.1 and -193.3 kg CO_2 eq. per kWh for locally harvested fire-killed trees and imported wood pellets, respectively) than those generated from residential heating oil (341.0 kg CO_2 eq. per kWh), gas (293.4 kg CO_2 eq. per kWh), and wood pellets (46.0 kg CO_2 eq. per kWh). The forecasted increase in the price of carbon at the national level as well as the various federal grants supporting a low-carbon economy and CCS will make PyCCS competitive with conventional systems. Discussed in closing is the increased scrutiny on biogenic emissions and relative cost-benefit factors of PyCCS to conventional and commonly used technologies, with an anticipated carbon pricing factor.

INTRODUCTION

Climate change & decarbonization: a driver of economic development and innovation

Residents of the Northwest Territories (NWT) are dependent on diesel for electricity production, heating oil for space heating and jet fuel for transportation[1]. Northerners (residents of NWT) have the highest per capita greenhouse gas emissions of all Canadian Territories at 28.1 tonnes of CO_2 (eq.), at the high end of average emissions for an affluent country, and 43% above national average[2]. Space heating is one of the largest components of this carbon footprint[3]. Climatic conditions, remoteness, and low population density make it a challenge to decarbonize[4].

Pyrogenic Carbon Capture and Storage (PyCCS) is a promising technology that could provide low-carbon heating fuels and biochar as a valuable byproduct. Evidence shows that biochar application to soil increases plant productivity[5,6] by enhancing nutrient uptake and water use; PyCCS is a potential win-win for emissions and crop production in the Sub-Arctic. Although existing PyCCS projects in Finland[7], Sweden[8,9], Germany[10] and Norway[11] show the technology to be both profitable and effective at eliminating emissions, more research within the Canadian context is necessary to build confidence for investors and project developers.

Conventional biomass is often used as a feedstock in PyCCS, but harvesting these feedstocks can have unintended environmental consequences such as deforestation, which has detrimental impacts on biodiversity. Biomass from fire-killed trees may provide a more ecological alternative to conventional biomass. There are immense reserves of fire-killed trees in the NWT, with 3.4M hectares burned during the *2014 Summer of Smoke* alone[12].

Despite the huge opportunity of using fire-killed trees as a sustainable feedstock in PyCCS towards space heating, we still lack basic knowledge of the technical and economic feasibility of this technology in the NWT.

Pyrogenic carbon capture and storage: an overview

As demonstrated by project teams on the market in Europe (mainly Sweden, Finland, Norway, Germany), PyCCS is seemingly one of the heat production technologies with the highest carbon sequestration potential. Thus, PyCCS offers the promise of a viable low-carbon energy source in the NWT. PyCCS works as follows: biomass is pyrolyzed in a low-oxygen environment, producing bio-oil, bio-gas and biochar. The bio-oil and bio-gas are burned to produce heat, which can be used for local or district heating. The bio-oil can be collected and stored, although reducing the heat output for the same given quantity of input biomass. Biochar, similar to charcoal, is also collected and stored. Biochar has a large variety of potential uses, and is lauded to be a promising solution to the climate crisis by its carbon sequestration potential, the increase of forest soil fertility, and increase to agricultural yields[13]. 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[14]. Heating rate, chamber temperature and residence time affect the quality and quantity of biochar, bio-oil and bio-gas produced.

Goal of this study: high-level assessment of life-cycle emissions of Pyrogenic Carbon Capture and Storage (PyCCS) for space heating

This paper compares carbon emissions from three commonly used heating systems in Northwest Territories communities, namely heating oil combustion, natural gas combustion, and waste biomass combustion with two scenarios for PyCCS systems, one utilizing imported waste biomass and the other, locally-harvested fire-killed trees. This paper determines the **carbon footprint of PyCCS in the Northwest Territories using two available sources: fire-killed trees and wood pellets from LaCrete, AB.**

METHODS

Systems description

We accounted for life-cycle emissions associated with the three heat production systems that are currently used in Yellowknife and the two hypothetical PyCCS systems (Figure 1). Heating oil and natural gas imported from Edmonton, AB; wood waste saw dust pellets from LaCrete, AB and fire-killed trees from Enterprise, NT— Upstream emissions from rail and diesel road transportation to Yellowknife were also accounted for. Lacking data, the emissions related to the production and transportation of the heat production equipment (furnace, burner, stove, and

PyCCS machines) were estimated, including those from steel production and its shipment from overseas by marine vessel. It was assumed that the sale of biochar on the market will require collection and transportation which will generate road diesel emissions. Thus, these emissions were also included in this analysis.

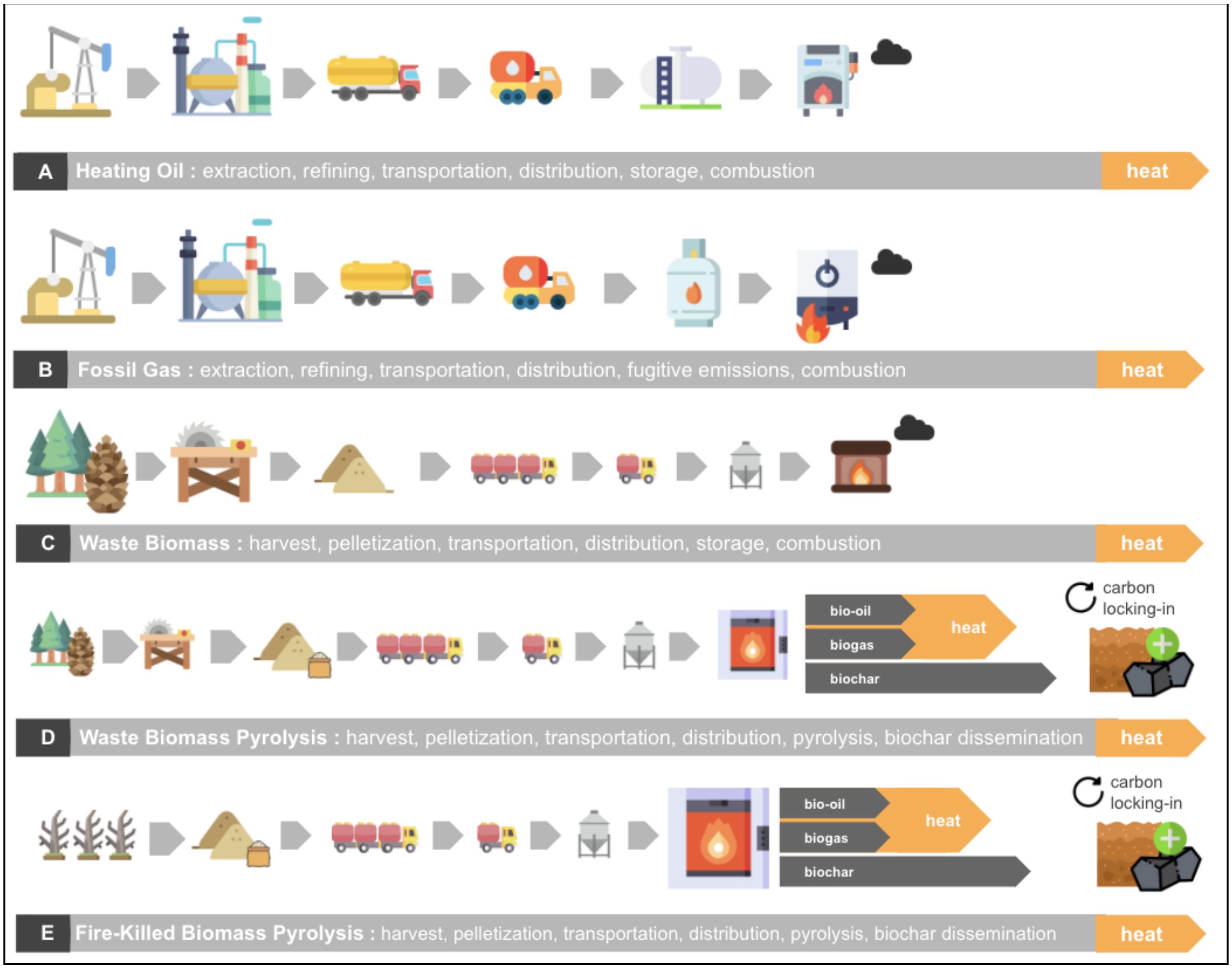

Figure 1: Processes included in the carbon footprinting analysis of the three heat producing technologies currently used, and two proposed, for use in Yellowknife, NT.

Functional unit

To compare the carbon intensity of the five systems, the functional unit is defined as 1 kWh of heat delivered in Yellowknife with a 98% reliability for a system of about 160 kW capacity, running 5000 h per year. This is used as a starting point and might be modified for future investigations. For example, the PyCCS machine could run during summer months on lower heat but higher biochar outputs— see discussion section.

Life-cycle inventory analysis and data sources

Data was obtained from from industry groups, including Biomacon and Carbofex[15,16,17,18,19,20], government databases and reports[21,22,23] (Government of the Northwest Territories, Government of Canada), census data[24], reports[25,26] (Biomacon, Carbofex), peer-reviewed academic publications[27], through personal communications[28], and others.

Accounting for carbon sequestration

It is assumed that the biochar produced will act as carbon storage for at least the next 1000 years[29]. This explains the negative emissions for both PyCCS systems, as the fossil emissions from the process are largely offset by the biochar production.

RESULTS

PyCCS systems have the lowest life-cycle greenhouse gas emissions of all the systems that were modelled (Figure 2). PyCCS systems rely on biomass that ultimately sequesters carbon, as opposed to fossil fuel systems and even conventional biomass heating, that release additional carbon in the atmosphere during combustion. The magnitude of these benefits are unclear because of uncertainties in modelling biogenic carbon emissions.

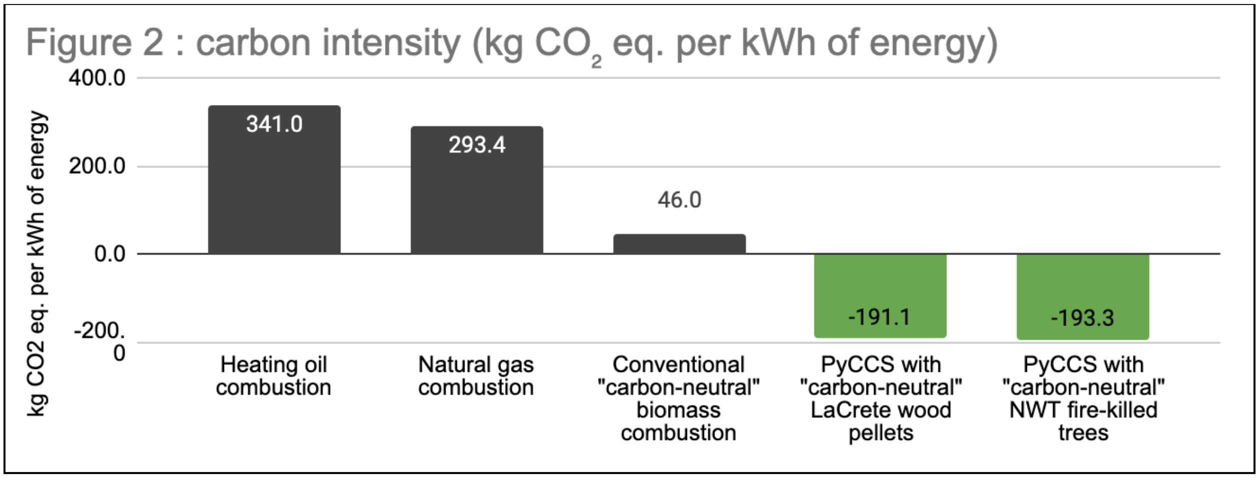

Figure 2 : carbon intensity (kg CO_2 eq. per kWh of energy)

Figure 2 depicts the carbon intensity in kg CO_2 (eq.) per type of heating system. Heating oil combustion depicts the highest carbon intensity, at 341.03 kg CO_2 (eq.) per kWh of heat– natural gas combustion presents the second highest carbon intensity at 240.22 kg CO_2 (eq.) per kWh. Conventional biomass combustion presents significant carbon emissions savings compared to the two previous systems, at only 40.48 kg CO_2 (eq.) per kWh (note that this excludes biogenic emissions). Lastly, Pyrogenic Carbon Capture and Storage Heating Systems (PyCCS) present the lowest carbon intensity– or the highest carbon sequestration– at -191.12 and -193.28 kg CO_2 (eq.) per kWh for the LaCrete imported wood pellets and the NWT fire-killed trees, respectively. Notice the difference in emissions between the two PyCCS systems– which is less than 2%— and mostly created by the increased diesel trucking transportation emissions for biomass imported from LaCrete, AB.

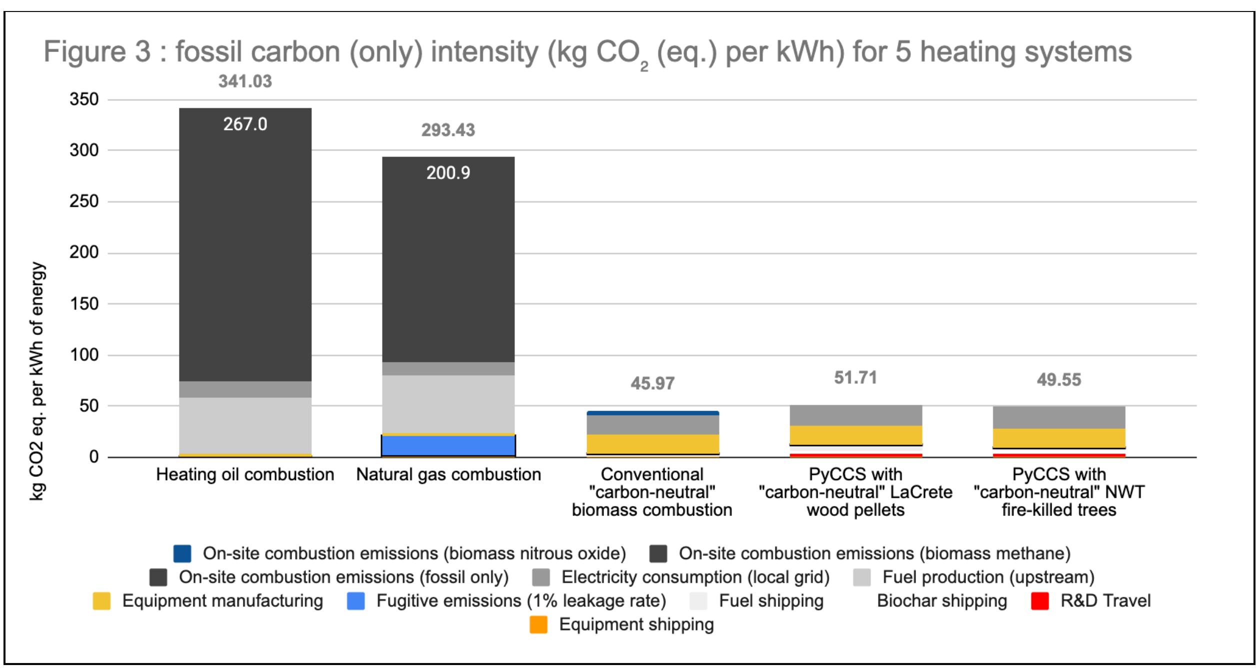

Figure 3 : fossil carbon (only) intensity (kg CO_2 (eq.) per kWh) for 5 heating systems

Figure 3 presents a breakdown of fossil carbon emissions from the 5 heating systems– note that carbon storage and biogenic emissions are omitted from this chart in order to focus exclusively on the breakdown of fossil emissions. On-site combustion emissions stand out as the highest contributor for heating oil and natural gas combustion, followed by fuel production upstream emissions, significantly higher for heating oil than natural gas. The use of the local electricity grid as a heat source backup in the event of mechanical or other failure presents a quantity of emissions that is consistent across the 5 heating system types (7.8 g per kWh). Equipment manufacturing emissions are largest for the PyCCS system (large and bulk), although conservatively overestimated– and similar to the biomass combustion system. As for both fossil fuels systems, equipment manufacturing emissions are reduced because of the reduced weight (and steel quantity) present in their manufacturing. Emissions from R&D travel, equipment shipping, and other sources are present but small. Biochar shipping emissions to get the biochar to a resale market make up 3.6 g per kWh, or less than 10% of fossil emissions, and are largely offset by the carbon storage created.

DISCUSSION

This presents a preliminary analysis of the carbon calculus of PyCCS in sub-Arctic Canadian context. Despite potentially clear carbon benefits, there remain market uncertainties about the sale of biochar and its related by-products, and the storage of bio-oil for carbon storage. Additional challenges remain, both with regards obtaining proper data to support, calculating the impacts of biogenic carbon and determining the market (and carbon accounting) forces behind this operation.

Biochar, bio-oil market demand : a sector in development

The use of biochar in Canada has yet to become mainstream; its market is not as developed as it is in the United States or in Europe. The potential uses of biochar are wide and varied, and yet to be fully understood and utilized in Canada, and around the world. A non-exhaustive list of the potential uses for biochar in Canada includes but is not limited to : agricultural soil amendment; forestry (afforestation, reforestation) amendment for carbon storage; municipal compost amendment; livestock feed amendment (with some evidence for a reduction in methane emissions from pigs); medical industry; cosmetics industry; as a growing media and carbon storage for greenhouses, gardens, sports fields, golf courses, cemeteries; filtration of air, soil and water; construction industry additive for insulation and concrete (with demonstrated results for carbon-neutral concrete); remediation of mining sites and tailings ponds; as an amendment to municipal landscaping as a way to reduce urban water and contaminants runoff; blue-green algae lake remediation; and various other streams.

An important assumption as part of the life-cycle costing of this technology is for a market price on biochar per weight. The financial success of PyCCS relies heavily on the multiple potential income streams - Biochar sales, carbon offset pricing, and heating production or sales. Biochar pricing information will be critical to develop a demand for its sale prior to the development of a prototype in Yellowknife, NT. However, early results demonstrate that even if biochar had to be transported by diesel truck to California– a "worst-case scenario", the carbon accounting balance would still play in favor of the project. Interview[30] evidence points to a price per tonne of approximately $500 USD in the United States; similar prices are observed in Sweden and Finland.

Future research: Carbon accounting and methodological considerations

This paper is aiming to answer the question : **What is the carbon footprint of PyCCS in the Northwest Territories using fire-killed trees and wood pellets from LaCrete, AB?** There remains two unknowns: how to handle biogenic carbon emission assumptions (and the increased scrutiny on them[31]), and life-cycle assessment data gaps. The two are discussed below.

Whereas it was initially discounted to zero as per IPCC literature, more recent carbon accounting literature points to the need to account (and not discount) for biogenic carbon emissions[32]. The *Draft Technical Guide Related to the Strategic Assessment of Climate Change*[33] in Canada points to the sector's current pursuit of better accounting and methodological practices. In the next stage of this research, biogenic emissions from biomass combustion and biomass pyrolysis will be accounted for. This initial carbon footprinting analysis is based on various sources of data, used as a starting point to add evidence to the carbon-negative operation of the PyCCS system– the Ecoinvent database and OpenLCA will be used in the next iteration of this work.

The largest unknown at time of publication is the soil carbon sequestration behaviour upon biomass harvest. Will regrowth, photosynthesis and carbon capture by biomass activity be larger under the "no-intervention" scenario, or will there be a net benefit to biomass productivity upon addition of biochar on harvest forest land? Figure 4 depicts the current systems boundaries as observed in this life-cycle emissions analysis (thin dotted line, smaller rectangle) in comparison to the desired systems boundaries which will require further investigation. To gather this information, the GWP_{bio} (biogenic global warming potential) must be determined based on forest characteristics[34]. Further research is needed and will be pursued in 2022. Here are the challenges related to biogenic carbon:
This carbon footprinting study is only completed at a high-level – additional details will be provided in a full life-cycle analysis (LCA) and life-cycle costing (LCC) as they are pursued further during this research.

Additional considerations for a complete LCA and LCC
There are additional factors that are not considered in this emissions footprinting analysis. They will need to be included in the next iteration of this work, for a complete life-cycle analysis and life-cycle costing. The next paragraph includes the main areas of focus for the next stage of research:

A determination of the GWP_{bio} (biogenic global warming potential) for the locally-harvested fire-killed trees and for the wood pellets from LaCrete, AB will help in painting a more accurate picture of the atmospheric load. Upstream emissions from waste saw dust are considered carbon-neutral; but should they be?

A fugitive emissions sensitivity analysis for fossil gas consumption should be considered, since a small amount of those emissions could change the carbon balance – and create incentives for the transition of those systems currently using fossil gas to PyCCS. The use of propane is more common than natural in most NWT communities, and as such that fuel should also be included in this research.

The carbon impact of building forest roads for the harvesting of fire-killed trees was not accounted for – it is assumed to be insignificant especially for low-quality roads, but should still be calculated to create a complete picture. Existing data[35] for urban construction might make a suitable proxy for future life-cycle analysis.

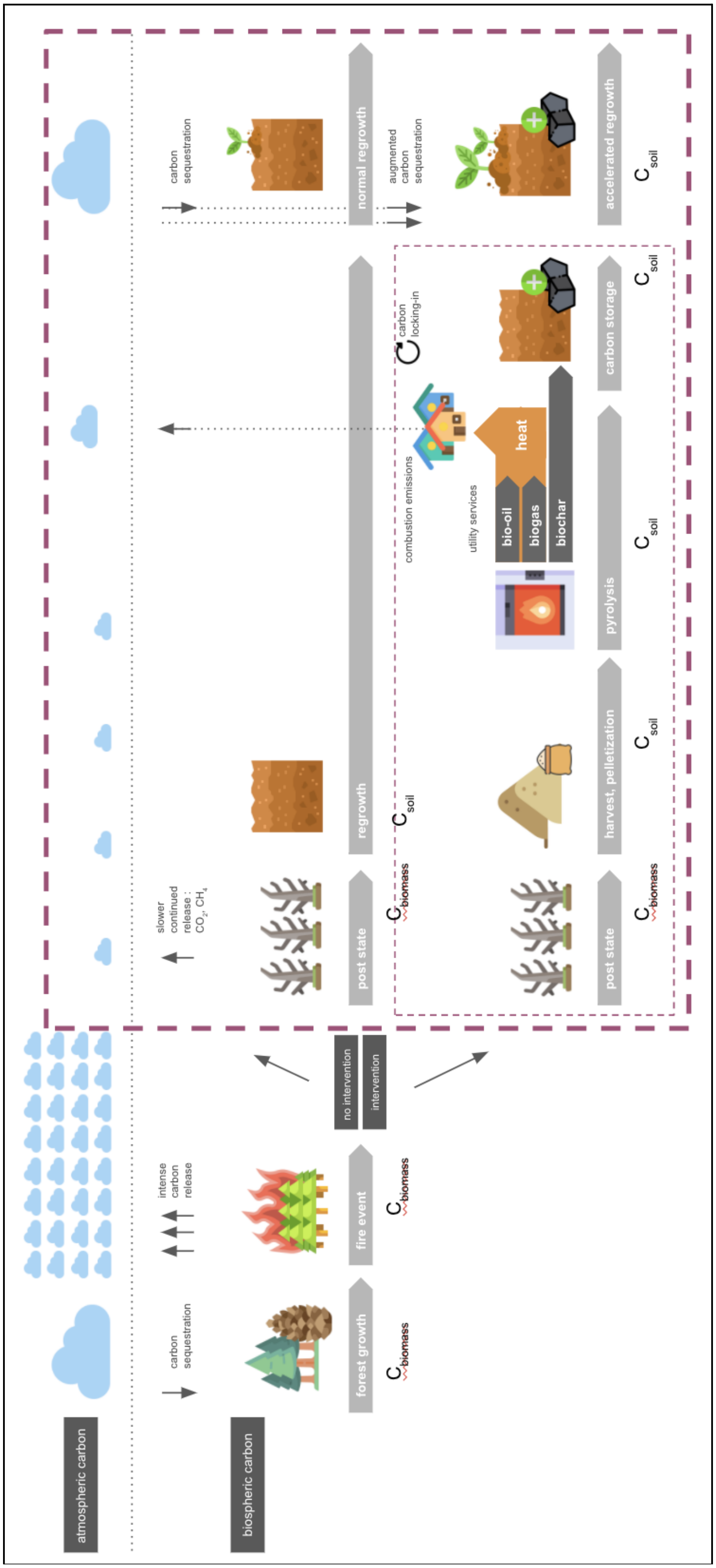

Figure 4 : Depiction of the boundaries of the current carbon footprinting versus desired life-cycle analysis boundaries

The soil carbon sequestration behaviour of adding biochar to fire-killed forest floors is unknown and needs to be better explored. Research and simulations on seasonal operating efficiencies of PyCCS systems needs to developed; with higher bio-oil and biochar sequestration in the summer, and higher heat production in the winter– can we increase the return on investment of the system if it can be used to produce biochar in the summer, when no heat loads are required? A financial and market analysis of the potential demand and its associated price per tonne is necessary in order to inform the life-cycle costing, as there is currently no biochar market price available in Northwest Territories and surrounding jurisdictions. This could help further increase carbon sequestration potential if shipping biochar to a foreign market can be eliminated.

Off-gassing emissions from the stored biomass is likely to be insignificant but needs to be calculated and taken into account. A failure rate (1%) of the systems and their replacement with new systems also need to be integrated, but are also not likely to be very significant.

CONCLUSION

This high-level carbon footprinting (CF) analysis is only the first step towards a full life-cycle analysis (LCA) and life-cycle costing (LCC) for Pyrogenic Carbon Capture and Storage in Yellowknife, Northwest Territories. This CF analysis confirms the CCS potential of pyrolysis and will be used as the basis for future research. Upon completion, the LCA and LCC will be used for the development of a startup business case. Although more work is required before producing an LCA with sufficient detail, this work confirms the initial hypothesis that PyCCS is likely to prove a viable CCS solution for the Northwest Territories and development is continuing in 2022.

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