DISMANTLING THE GREEN MACHINE: A CRITICAL REFLECTION ON TECHNOLOGY AND ECOMODERN ENVIRONMENTAL POLICY

by

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Table of Contents

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Addressing the scale of negative environmental changes brought on by the rapid expansion of human populations and economic growth has become one of the most pressing policy issues of the twenty-first century. Technological innovation helped power this rapid expansion while also increasing the magnitude and extent of environmental degradation. Government and corporate policy responses to this challenge are largely directed towards engineering a new industrial revolution based on the design and deployment of green technologies and products. Ecomodern policies that have dominated environmental management approaches for several decades are based on a premise that substitution of eco-efficient technologies and products can solve global environmental challenges while fostering a new era of green economic growth. Yet despite the widespread adoption of this approach, the empirical data show that environmental conditions have continued to decline and are poised to continue declining into the middle of this century and beyond.

The objective of this dissertation was to use an interdisciplinary approach to critically reflect on the failure of ecomodern approaches of green technology substitution to resolve environmental problems. A series of case studies on the environmental impacts and benefits of wood biomass energy systems was provided to illustrate the mechanics of assessing and optimizing green technologies. Insights from the philosophy of technology were used to conceptualize the Green Machine, a macro-technology system that embodies ecomodern approaches and the process of green technology development and deployment. Drawing on material from the wood biomass case studies, principles from ecological economics were used to critically reflect on the biophysical limitations of technology substitution and on the role of environmental systems analysis tools like LCA in reinforcing flawed ecomodern approaches. Findings from the critical reflection were used to reconcile the technological optimism of ecomodern policies with the reality of worsening global environmental challenges and to underscore the limitations of pursuing green technology as the sole solution.

LIST OF ABBREVIATIONS USED

ADP	acidification potential
BAU	business as usual
BTU	British thermal unit
CED	cumulative energy demand
CHP	combined heat and power
CO_2	carbon dioxide
CO_2-eq	carbon dioxide equivalent
CTU	comparative toxicity unit
EUT	eutrophication potential
GHG	greenhouse gas
GJ	gigajoule
GPP	gross primary productivity
GWP	global warming potential
ha	hectare
IEA	International Energy Agency
I=PAT	impact = population * affluence * technology
IPCC	Intergovernmental Panel on Climate Change
ISO	international Organization for Standardization
kg	kilogram
km	kilometre
LCA	life cycle assessment
LCI	life cycle inventory
LCIA	life cycle impact assessment
LFO	liquid fuel oil
LHV	lower heating value
MC	moisture content
MJ	megajoule
MMBTU	million British thermal units
NBP	net biome production

NCG	non-condensable gases
NEP	net ecosystem production
NPP	net primary productivity
NS	Nova Scotia
ODP	ozone depletion potential
ODT	oven dry tonne
POFP	photochemical oxidant formation potential
QC	Québec
RESP	respiratory effects
Ra	plant respiration
Rh	heterotrophic respiration
SMOG	photochemical oxidant formation
SRW	short rotation willow
tkm	tonne-kilometre
TRACI	Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts
TPD	tonne per day
UNEP	United Nations Environment Program
UNFCCC	United Nations Framework Convention on Climate Change

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CHAPTER 1: INTRODUCTION

The rapid acceleration of technological change since the mid-20th century has been a driving force for the increased scale and magnitude of impacts from human activities on the environment (York et al. 2003; Steffen et al. 2007; Williams et al. 2015). The global environmental changes caused by human activities since the industrial revolution have been at such a large scale that some geologists have described this period as a new epoch in geologic time called the Anthropocene (Crutzen 2002; Steffen et al. 2007; Waters et al. 2016). This represents a shift from the relative environmental stability of the Holocene into a period of human-induced environmental change, the results of which are pushing human society towards the potential crossing of critical biophysical thresholds which could cause serious disruption to ecosystems, economies, and society at large (Rockström et al. 2009a; Steffen et al. 2018; Rees 2020). Large-scale environmental changes during this period include over-exploitation of non-renewable resources (IRP 2017), declines in freshwater and marine ecosystem health and biodiversity (UNEP 2005; Worm et al. 2006; Halpern et al. 2008; WWF 2018; ISPPBES 2019; Tickner et al. 2020), and the accumulation of greenhouse gases (GHG) in the atmosphere leading to changes in global climate which pose substantial risks to human well-being and ecosystem health (IPCC 2014; Hansen et al. 2017; Peters et al. 2019).

Since the late-1980's, members of the international community have generally come together around the concept of sustainable development to address global environmental problems while also improving socioeconomic conditions in lesser-developed countries. Sustainable development, or sustainability, are terms which have come to mean different things in different contexts (Solow 2000; Davison 2001), but in general it is the concept within which governments and corporations have set out policy and planning to reduce the environmental impacts of human activities for over three decades. The most recent manifestation of this approach is the development of the United Nations (UN) Sustainable Development Goals (SDGs). The UN SDGs were introduced as part of the 2030 Agenda for Sustainable Development, with many governments and industries now working to align their economic development and environmental management policies with the SDGs goals and targets (Costanza et al. 2016; Schramade 2017; Pedersen 2018; Frederik et al. 2019; United Nations 2019).

Despite the varied and contested meanings ascribed to sustainable development, government and corporate policies for environmental management have largely been formed around the main premise for sustainable development set out in the Brundtland Commission's landmark report: 1) Economic growth must be pursued to address a range of global issues related to development and the environment and this can be achieved while reducing society's environmental impacts; and 2) Increasing the eco-efficiency of our production and consumption by way of technological innovation represents mankind's most effective strategy for fostering economic growth while reducing environmental impacts to more sustainable levels (Davison 2001, York et al. 2003; Karlsson 2018). It is a policy manifestation of the environmental Kuznets curve, which is the belief that over the long-term, growth reduces the environmental impact of economic activity (Stern & Common 1996).

The belief that sustainability can be achieved through continued economic expansion fueled by the design and deployment of more eco-efficient technologies is referred to as ecological modernization, or ecomodernism (Davison 2001; York et al. 2003). Global environmental management approaches have long been rooted in ecomodern principles and the resulting policies and environmental management systems are orientated to treat environmental problems largely as technological or engineering problems (Mol 1995; Davison 2001; Huesemann 2003; Keith 2013; Gunderson et al. 2018). This generally involves a process of identifying the environmental impacts of a technology or product, developing an eco-efficient alternative, and quantifying and monitoring the resulting changes in resource use and environmental impacts. The impact and benefits of technology deployment are assessed using environmental systems analysis tools such as material flow analysis (MFA), energy analysis (EA), ecological footprinting (EF), and life cycle assessment (LCA) (Finnveden & Moburg 2005).

The central theme of this dissertation is that technology is both a fundamental driver of worsening environmental conditions and viewed as the fundamental solution, and thus our understanding of how technologies interact with society and the biosphere is critical to developing appropriate responses to global environmental challenges (Haff 2014). On the one hand, the negative global environmental change of the Anthropocene has been facilitated by the development of large-scale technological systems (Haff 2014). The technosphere itself has been described as a new stage in geologic evolution, a human-constructed geological element on the same level of influence as the lithosphere, the atmosphere, the hydrosphere, and the biosphere (Haff 2013). On the other hand, technological innovation is at the core of global efforts to mitigate or reverse these negative environmental changes and is considered to be an essential tool in these efforts (Steffen et al. 2007). Despite the role of technological development in driving environmental threats to humanity, we have broadly chosen to respond to these threats by pursuing more technological development to create a new era of economic expansion while reducing environmental impacts. The age of green technology is aimed at improving the efficiency of human economic activities and thereby reducing our impacts to the environment while increasing economic growth and well-being (White 2002; Lau 2010; Hickel & Kallis 2019).

Humans have largely pursued this sustainable development strategy centered on eco-efficiency and technological innovation for over 30 years, and yet global environmental problems have continued to increase in scale and complexity over this time period, including: climate change impacts fueled by increasing anthropogenic GHG emissions (Hansen et al. 2017; Peters et al. 2019); the global spread of persistent organic pollutants (Fernandez & Grimalt 2003; European Commission 2017); ocean acidification (Feely et al. 2009) and marine and freshwater eutrophication (Rabalais et al. 2009); human health and disease impacts (Costello et al. 2009; Wu et al. 2016); and depletion of increasingly scarce resources such as fossil fuels, minerals, and groundwater (Ehrlich & Ehrlich 2012). In a recent study of humanity's ecological footprint, which is a measure of a population's resource consumption and waste assimilation requirements (Wackernagel & Rees 1995), it was determined that the global ecological footprint of human activities has doubled since 1966 and human society's collective activities currently require the natural resources and waste assimilation capacity of 1.75 planet earths (WWF 2018). The Millennium Ecosystem Assessment (MEA) (UNEP 2005) provided stark details to characterize the impacts of our increasing ecological footprint on the global ecosystems that support human life on Earth. This global scientific study found that to meet rapidly growing global demands for food, fresh water, timber, fiber and fuel, humans have changed Earth's ecosystems more rapidly and more extensively in the last 50 years than in any comparable period of time in human history. The broad results of these changes are a substantial and largely irreversible loss of diversity of life on Earth, and an increased risk of nonlinear changes in ecosystems, including: accelerating, abrupt, and potentially irreversible changes to ecosystems and ecosystem services such as disease emergence; dead zones in coastal waters; the collapse of fisheries; and shifts in regional climate (UNEP 2005). The negative impacts to biodiversity and ecosystems that were highlighted in the MEA have only continued to worsen in recent years (Williams et al. 2015; ISPPBES 2019). These findings add to "…a cascade of data…" which shows human society is in ecological overshoot (Rees 2020, pg. 168).

In light of the increasing extent and magnitude of environmental degradation during this era of ecomodern environmental policy, there is a clear need to reflect on and critically analyze the ecomodern approach. This includes the mechanics of its practice (i.e. how we design, deploy, and assess green technologies) and its core principles of technological optimism and the continuation of modernization and progress via economic expansion. The objective of this dissertation was to contribute to this need by undertaking both a practical and philosophical reflection on ecomodern environmental policy.

1.1 Dissertation Overview

The motivations and research questions that form the foundation of this dissertation were largely developed in the corporate office of an environmental consulting company while I tried to reconcile the nature of my work in environmental management with the increasing environmental degradation caused by human activities. A defining moment in my internal struggle was the consideration of a project to use LCA to identify opportunities to reduce the GHG emissions associated with oil extraction in the Alberta oil sands. On its surface the project was consistent with the prevailing approach to environmental management, which is to seek opportunities to improve the eco-efficiency of our industrial, commercial, and personal activities and choices. The use of LCA for this project was also consistent with its typical application to assess the environmental impacts of all the activities that make up the life cycle of a given process or product, and identify sources of high impact that could be reduced by optimizing or replacing materials, energy sources, or technologies (Rebitzer et al. 2004; Guinée & Heijungs 2017).

Beneath the surface, however, was an instinct that this project was somehow fundamentally flawed because the objective, even if indirectly, was to sustain and increase the extraction of oil from the oil sands, albeit with fewer GHG emissions released per unit of production. This objective was contradictory to the science on global warming and climate change which indicate very clearly that fossil fuel consumption must be decreased significantly to achieve environmental sustainability. The focus on GHG emissions also ignored a number of other local and regional environmental problems caused by oil sands extraction, including land use change and negative impacts to freshwater ecosystems, wildlife, and human health (Hodson 2013; Liggio et al. 2016; Rosa et al. 2016; Dabros et al. 2018; Volik et al. 2020). In short, in a time when the leading scientific advice is that we must try to leave this resource in the ground, a project was being proposed in the name of sustainability which would potentially create social license to increase the level of extraction of this resource.

In recent years there has been extensive research done to assess and reduce the GHG emissions per barrel of oil extracted in the Canadian oil sands. These have included many government-funded research programs, corporate research programs, and academic research programs. According to Natural Resources Canada (NRCan), many years of technological innovation in the oil sands have led to improvements in energy efficiency and reduced GHG emissions per barrel by upwards of 26% (NRCan 2013). An impressive number of industry and academic publications have been produced over the years to quantify the GHG emissions from oil sands operations, identify opportunities to reduce emissions per barrel, and to improve the assessment methods used to quantify these emissions (e.g. LCA methods improvement) (Charpentier et al. 2009; Brandt 2012; Bergersen et al. 2012; Nimana et al. 2015; McKellar et al. 2017; Katta et al. 2019; Janzen et al. 2020).

The work being carried out to reduce the per unit GHG emissions of oil sands operations is well-intentioned, and the extent of peer-reviewed publications on this matter indicates that it is generally robust and scientifically sound work. However, beneath the mechanics of this process of improving the efficiency of oil sands operations, more fundamental questions have remained: are these efforts leading to reductions in global GHG emissions in the aggregate, or are these efforts indirectly sustaining an industry which leading climate change scientists and policy makers argue we should be phasing out? Are the methods we use to assess GHG emissions, such as LCA, providing adequate representation of reality and accurate signals about the impacts of these activities? Are there more fundamental issues with the prevailing approach to sustainability, which values this kind of eco-efficiency project, that need to be reconsidered?

The oil sands example is one of many such instances that I have wrestled with as an environmental management professional over the years, and it provides an illustration of the general mechanics of the ecomodern approach being employed to achieve sustainability. I have been grounded in this approach during my prior post-secondary education in environmental management and my work as a professional in this field. Most of my academic and professional training has been couched within this vision of sustainable development, which is that economic growth and environmental improvement could be realized simultaneously through investment in eco-efficient technologies (Davison 2001). My education and professional career have largely been built around related concepts of industrial ecology, eco-efficiency strategies, and environmental impact assessment. I have focused particularly on the latter, working with quantitative impact assessment tools such as LCA with a belief that by using environmental systems analysis tools to quantify the environmental costs and benefits of alternative technologies, I could generate information which could lead to better environmental policy decisions.

1.1.1 Research Objectives

The general objective of this dissertation is to examine and critically reflect upon the different elements of the ecomodern approach to sustainability to understand why the expected results of applying this approach are not being realized. The dissertation is organized into three parts, using practical case studies and an interdisciplinary critical reflection to consider the research questions at-hand. The approach was to take a matter of current environmental management policy concern (wood biomass energy) and first use LCA research to examine the environmental impacts and benefits of the proposed solution. Secondly, it was to reflect on the findings and limitations of this work and use the practical case studies as subject matter for a deeper critical reflection on the mechanics and more fundamental questions about the ecomodern approach. The research questions that were examined in this dissertation include:

- How can environmental conditions continue to worsen despite the increased implementation of ecomodern policies and deployment of eco-efficient technologies and products over the last three decades?
- How can we reconcile worsening environmental conditions with the seemingly encouraging results from quantitative assessment methods like LCA which indicate that green technology substitution can yield substantial environmental benefits across many sectors of the economy?
- If the data on key environmental trends indicate that the expected improvements in environmental conditions are not being realized, are there problems with the scope or methods used to assess the impacts of green technologies?
- Given the lack of progress on key environmental sustainability objectives, is the ecomodern approach flawed in its assumption that green technology can be the fundamental driver of sustainability?

1.1.2 Part I: Ecomodernism and Eco-Efficient Technology Substitution

The declaration of the post-Industrial Revolution period as The Anthropocene was based on empirical observations of the large-scale environmental changes driven by human activities and intended to reflect a level of concern about the implications of this newfound technological power (Rockström et al. 2009a; Steffen et al. 2018). However, for others, the Anthropocene is viewed as a credit to human inventiveness and technological capabilities. As one group of scientists recently stated, the "…knowledge and technology, applied with wisdom, might allow for a good, or even great, Anthropocene." (Asafu-Adjaye et al. 2015, pg. 6). Further, a "good Anthropocene" demands that humans use their growing social, economic, and technological powers to make life better for people, stabilize the climate, and protect the natural world." (Asafu-Adjaye et al. 2015, pg. 6). These statements are from The Ecomodernist Manifesto, a document produced by an international group of scientists intended to rally researchers and policy-makers around the belief that our technological capabilities are the best tool we have for sound environmental management and sustainability into the future (Asafu-Adjaye et al. 2015). According to the manifesto, "…there is still remarkably little evidence that human populations and economic expansion will outstrip any capacity to grow food or procure critical material resources in the foreseeable future." (Asafu-Adjaye et al. 2015, pg. 9).

In Chapter 2 of this dissertation the findings of a literature review are used to explain the origins and principles of ecomodernism, and to show its establishment as the dominant paradigm for pursuit of sustainable development that has been adopted by governments, corporations, and environmental groups across the globe. The core values of eco-efficiency and technology substitution are also briefly explored. Further to this, the role of technology assessment using environmental systems analysis tools in supporting the design, deployment, and evaluation of eco-efficient technologies is introduced. Given the current focus on achieving sustainable development by way of technological innovation, the practice of assessing the environmental implications of new technologies is certainly necessary work, as there is a need to quantitatively assess the environmental costs and benefits of proposed technological options before they are deployed. However, the question being posed in this dissertation is whether or not these assessments are based on flawed or outdated assumptions, and whether or not the current practice is contributing to a more sustainable society or is simply reinforcing a faulty premise of sustainable development based on technology and eco-efficiency.

In establishing the need for the present research, Chapter 2 also includes a detailed summary of declining global environmental conditions which indicate that despite optimistic statements like those in the Ecomodern Manifesto, environmental degradation is still increasing on all fronts.

1.1.3 Part II: Wood Biomass Energy Case Studies

Part II of the dissertation includes three practical case studies in which LCA was used to quantify the potential environmental impacts and benefits of substituting wood biomass energy systems for conventional fossil fuel systems in a range of energy applications in Canada. These case studies provide a practical illustration of the ecomodern approach to sustainability using real-world examples. In particular, these case studies illustrate the design and deployment of eco-efficient technologies, the substitution of these technologies for conventional systems, and the use of environmental systems analysis methods to quantify the impacts and benefits to inform technology optimization and technology selection. The objectives of carrying out these case studies were: 1) to examine a current environmental policy issue and generate data and insights to inform policy developers and technology developers; and 2) to illustrate the mechanics of the ecomodern approach and provide material for the interdisciplinary critical reflection on ecomodern approaches in Part III of the dissertation.

In Chapter 3, LCA was applied to quantify the life cycle environmental impacts of wood biomass as a substitute for light fuel oil and natural gas in industrial heating applications. The study included the modelling of short-rotation willow (SRW) crops as a feedstock for wood pellet production and represents one of the first published LCAs to use primary data from an actual willow plantation. The study also included a model of changes in soil organic carbon that are based on local conditions at the plantation in Guelph, Ontario.

Results of the study indicated that global warming potential (GWP) could be reduced by up to 85% by substituting SRW pellets for fossil fuels in an average industrial furnace. The results also indicated that potential environmental trade-offs exist due to increases in eutrophication from fertilizer inputs to the SRW plantation and increases in emissions contributing to respiratory effects from combustion of the SRW pellets. The study included recommendations for optimizing the SRW cultivation and management process to improve environmental performance prior to deployment.

In Chapter 4, LCA was used to quantify the life cycle environmental impacts of producing bio oil and biochar from fast pyrolysis of forest harvest residues as a substitute for fossil fuels (i.e. coal, petroleum coke) used in Canadian cement production facilities. The study was based on demonstration-scale data for a mobile pyrolysis system developed in Canada and on the average energy supply mix for Canadian cement producers. The study is of particular interest because it examines the environmental benefits of a potentially renewable fuel source for heavy industrial producers that have very few options to replace fossil fuels in their energy mixes. The study also includes consideration of the carbon sequestration and carbon decay of the forest harvest residues when left in the forest rather than used for bioenergy and how this affects potential reductions in life cycle GHG emissions, an aspect which has typically not been included for harvest residues in wood biomass LCAs. The results of the study showed that GWP associated with energy provision could be reduced by up to 50% over the study period by substituting the maximum amount of bio oil and biochar, and that three 50 tonne per day (TPD) pyrolysis units could increase the share of renewable energy used by an average cement producer by up to 73%. The conclusions of the study also highlighted the need to assess the availability of forest harvest residues to avoid the need to harvest standing biomass to fuel the pyrolysis unit.

In Chapter 5, LCA was used to quantify the life cycle environmental impacts of substituting wood pellets for fossil fuels in residential space heating in Nova Scotia and for large-scale electricity generation in Europe. The study included an analysis of converting 9,600 Nova Scotian homes from oil-fired heat to wood pellet heat, and the export of 50,000 metric tonnes of wood pellets per year from Nova Scotia to Europe for co-firing in coal-fired electricity generation plants. Both of these scenarios are currently occurring in Nova Scotia and in Canada and the United States more broadly. The study included primary data from Atlantic Canadian wood pellet producers and explored the differences in environmental impact of producing pellets from sawmill residues or from incremental harvesting of unmerchantable roundwood. The study also used forest carbon modelling provided by the Canadian Forest Service (CFS) to produce an integrated LCA-forest carbon analysis of the studied energy applications over a 100-year time horizon. Results of the study showed that potentially significant reductions in cumulative GHG emissions could be achieved by using pellets produced from sawmill residues for either space heating or for export to Europe for electricity generation. However, the results also indicated that the use of pellets produced from the harvesting of standing biomass could lead to substantial long-term increases in cumulative GHG emissions relative to the existing fossil fuel systems.

Chapter 6 provides a connection between the practical case studies in Part II and the interdisciplinary critical reflection in Part III and includes a summary of the key findings and limitations of the wood biomass case studies and a set of research questions for the critical reflection.

1.1.4 Part III: Critical Reflections on Green Technology and Ecomodernism

One of the objectives of this dissertation was to develop a deeper understanding of the principles of the ecomodern approach to sustainability, and to develop insights on why this approach has not seemed to result in the expected improvements in environmental conditions. This includes an effort to better understand the role of LCA in providing data and insights the optimization and deployment of eco-efficient technologies, and whether this role is signaling appropriate policy actions.

In Chapter 7, a review of foundational literature in the philosophy of technology was used to gather insights and develop a more comprehensive understanding of technology and how it interacts with social and economic systems. These insights were then used to develop a novel conception of the mechanical nature of the ecomodern approach called the Green Machine. The Green Machine was defined as a representation of the macro-system of social, political, and environmental factors that surround eco-efficient technologies. Insights from ecological economics were then used to analyze and provide a critique of the operating principles and mechanisms of the Green Machine, including a deeper exploration of eco-efficiency as a foundational principle and of the limitations of technology substitution which may be overlooked in the ecomodern approach. Critical analysis is also provided on LCA as a decision support tool in the Green Machine for modelling the potential impacts and benefits of green technologies. Of particular interest is a critique of the flawed assumption of 1:1 substitution of conventional technologies with green technologies and the implications of this assumption on LCA study results and perceptions of green technologies.

Chapter 8 includes discussion of some further manifestations of the Green Machine in the form of “negative emissions” technologies that are of increasing policy interest, including carbon capture and storage (CCS) technologies and geoengineering technologies. The dissertation is concluded with a summary of the critical reflection, a discussion on identifying leverage points to promote change in macro-systems of technology, and recommendations on future considerations for ecomodernism, LCA, and wood biomass energy systems.

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CHAPTER 2: FOUNDATIONS OF ECOMODERN ENVIRONMENTAL POLICY AND WOOD BIOMASS ENERGY CASE STUDIES

2.1 Ecological Modernization and Environmental Policy

Since the recognition of global environmental change as a large-scale societal concern in the mid-to-late 1900's, there have been a number of approaches put forth as an appropriate response to eliminate or manage and mitigate environmental challenges (Devall 1980; Drengson 1995; Gibbs 1998; Foster 2012). These approaches range from more radical approaches involving a shift away from the industrial model by a large-scale restructuring of society (Naess 1973; Devall 1980; Drengson et al. 2011) through to less radical approaches based on a belief that market instruments and technology can restore an equilibrium between the human economy and the environment while maintaining the basic socioeconomic form of society (Torgerson 1995; Huber 2000; York & Rosa 2003). As global environmental problems have grown in scale and complexity, elements of these different approaches have remained and evolved. One particular approach to environmental management came to prominence in the late 1980's and has remained the dominant approach for governments and industry globally to the present day. This approach is generally referred to as ecological modernization, or ecomodernism.

2.1.1 Origins and Manifestations of Ecological Modernization

The first wave of environmental concern during the late 1950's and through to the late 1970's was part of a broader counter-culture movement, a rejection of business as usual industrialism through radical change of social and economic structures in society (Drengson 1995; Davison 2001; Drengson et al. 2011). During this time there was an awakening to the environmental damage caused by increasing industrialization and economic growth, brought on by landmark works such as Rachel Carson's *Silent Spring* (Carson 1962) (Drengson 1995). Images of Earth from the first space flights brought about a realization that the Earth is a finite planet, and this concept was articulated in more sobering terms in the *Limits to Growth* in 1972 (Meadows et al. 1972; Davison 2001). In many ways this first wave of environmental concern was a movement against the modernist model of human progress that is based on the pursuit of expanding economic growth and material wealth. Having the roots of the environmental movement integrated with this broader desire to restructure society towards an alternative view of human progress was also likely one of the reasons that this first wave of environmentalism failed to garner widespread support and faded away in the late 1970's and early 1980's (Cohen 1997).

The origins of ecomodernism are generally rooted in the second wave of environmental concern which came along with the sustainable development movement in the late 1980's (Andersen & Mass 2000; Huber 2000; Davison 2001; York & Rosa 2003). This was a more optimistic period where rather than seeking social reconstruction, there was a growing movement towards reconciling the existing socioeconomic structures with the environment (Andersen & Massa 2000). Ecomodernism was an attempt to dissolve the familiar conflicts between economic growth and environmental responsibility (Cohen 2006). The strategy of ecomodernism was aimed at the improvement of both ecological and economic efficiency to develop a harmonization of industry with ecology (Jänicke 1988; Mol 1995; Orsato & Clegg 2005).

The concept of ecomodernism was coined by a pair of German political scientists in the 1980's, Huber and Jänicke, who developed the concept as a more foresighted and preventative type of environmental policy (Andersen & Massa 2000). Jänicke established the concept to operationalize the precautionary principle, which was adopted as part of the new environmental management approach in the 1980's (Andersen & Massa 2000). The precautionary principle has four central components (Kriebel et al. 2001): 1) taking preventative action in the face of uncertainty; 2) shifting the burden of proof to the proponents of an activity; 3) exploring a wide range of alternatives to possibly harmful actions; and 4) increasing public participation in decision-making. In the context of ecomodernism, this meant a foresighted and long-term approach to environmental protection in which the main tools are science and technology. Science is used to detect potential environmental problems, and technological innovation is used as the tool to develop alternative paths of development (Andersen & Massa 2000; Mol & Sonnenfeld

2000). The added dimension of ecomodernism is the belief that these alternative developments can be done in a way that is also economically beneficial to society (Andersen & Massa 2000; York et al. 2003; Karlsson 2018).

Key elements of ecomodernism are certainly present in the articulation of sustainable development as a concept in the Brundtland report in 1987 (WCED 1987). This report served to codify the sustainable development movement which underpins much of global environmental management policy up to the present day. Among the rules for sustainable development in the 1987 report, several speak directly to ecomodern principles, including (Huber 2000):

- The consumption rate of exhaustible resources (ecologically sensitive resources such as land or oil, coal, and natural gas, but not commonplace materials such as sand and stones) is to be minimized by:
    - Substituting renewable resources for exhaustible resources;
    - Increasing material and energy efficiency; and
    - Recycling to the extent that is ecologically reasonable and economically justifiable.
- The development and introduction of ecologically benign, clean resources, technologies, and new products is to be intensified.

Within the sustainable development approach documented in the Brundtland report, these directives to actively develop and deploy clean technologies that are more material- and energy-efficient (or ecologically benign) were coupled with the concept that continued economic expansion is essential for addressing global social challenges such as poverty and human health. The resulting approach was therefore that sustained economic growth coupled with more efficient technologies and resource management are the keys to achieving sustainability (Davison 2001; Foster 2012).

Over the course of the 1990's and into the early 2000's, the ecomodern approach was increasingly adopted within government and corporate policy circles, in particular through increased uptake by industry. Industry had often found themselves accused of being the main polluters in the earlier days of the environmental movement, and thus adopted ecomodern approaches to take a more active role in environmental protection (Huber 2000). Over the course of the 1990's, this led to development of environmental management systems and the founding of international green business networks such as the World Business Council for Sustainable Development (WBCSD) in 1992. The establishment and proliferation of environmental management systems led to the integration of environmental concern into all aspects of industry and business, including (Huber 2000):

- The development of environmental information programs for monitoring, analysing, reporting, and communicating on resource use and emissions and other environmental statistics;
- The establishment of green education and training within businesses; and
- The development of strategic and operational environmental management systems relating to environmental compliance, green purchasing and supply-chain management, developing environmental vision statements, and associating corporate identity with environmental improvements.

Through the uptake of environmental management systems and the concept of sustainable development, the ecomodern principles that underpinned this movement were further entrenched in global corporate and government policy and set a path for the pursuit of sustainability which is still prevalent today. Key developments out of this time period include the increased adoption of approaches with explicit technological features such as clean technology, eco-efficiency, material flow and supply chain management, management of industrial metabolism, design for environment, industrial ecology, and constructive technology assessment (Huber 2000).

All of these elements and others form the foundation of current approaches to resolving environmental challenges, and as environmental problems have grown in scale and complexity, ecomodern principles have become increasingly dominant in government and corporate policy (Davison 2001; Orsato & Clegg 2005; Machin 2019). An example is a recent mission statement published by a global group of scientists, technologists, and policy developers putting forth ecomodernism as the only path to a sustainable human society (Asafu-Adjaye et al. 2015). *The Ecomodernist Manifesto* exemplifies the technological optimism of ecomodernism and takes it to new heights by arguing that a sustained commitment to clean technology development will not only resolve our current environmental challenges but will allow humans to manage the Earth in a way that creates a "good Anthropocene" (Asafu-Adjaye et al. 2015, pg. 6). The latter takes the recent concept of the Anthropocene, which was a concept developed to highlight the massive scale of negative impacts that societal expansion has had on the environment, and suggests that through eco-efficient technologies we can flip this on its head by decoupling human development from environmental impacts and allowing nature to restore itself (Asafu-Adjaye et al. 2015).

The Ecomodernist Manifesto has received considerable critique for being too technologically optimistic and being disconnected from biophysical reality (Latour 2015; Hamilton 2015; Caradonna et al. 2015; Collard et al. 2015). However, the ecomodern principles at the root of this manifesto have dominated environmental management policy through the last three decades and are a central part of current government and corporate strategies for sustainability (Davison 2001; Orsato & Clegg 2005; Machin 2019).

2.1.2 Principles and Objectives of Ecomodernism

The central principle of ecomodernism is that unlike the first wave of the environmental movement which called for radical changes in social and economic structures, sustainability can be achieved through modernization of existing structures rather than destroying or dismantling them (Gibbs 1998). It is a view that environmental problems are a structural design fault in the organization of production and consumption in modern societies and that these design faults can be corrected in order to avoid ecological crisis

(Mol 1995). Similar to the concept of sustainable development, ecomodernism indicates the possibility of overcoming environmental crises without having to leave the broader path of modernization through economic expansion (Mol & Spaargaren 1993). Ecomodernism is based on the assumption that the processes of production and consumption can be restructured on ecological terms through the institutionalization of ecological aims (Mol 1994).

Huber (1982) referred to this process as an “ecological switchover”, a transition of industrial society towards an ecologically rational organization of production. The central objectives of this switchover include (Gouldson & Murphy 1996):

- The restructuring of production and consumption towards ecological goals. This involves the development and diffusion of clean production technologies and decoupling economic development from the relevant resource inputs, resource use, and emissions;
- “Economising ecology” by placing an economic value on nature and introducing structural tax reform; and
- Integrating environmental policy goals into other policy areas.

The other key principle of ecomodernism is that this ecological switchover will be financially advantageous for businesses, as it allows for a response to environmental issues by way of profitable enterprise (Harvey, 1996; Weale, 1992). This is possible as a result of five features of ecomodernism (Dryzek 1997):

- Reduced pollution and waste production will result in greater business efficiency;
- Future financial liabilities associated with environmental clean-up will be avoided;
- A better corporate environment will be created to provide benefits for a company’s workforce and ability to attract a workforce;

- Profits will be earned through the sale of environmentally friendly products and services; and
- Profits will be earned through the sale of pollution prevention and abatement technologies.

Following on this asserted economic advantage of ecomodernism, Harvey noted that this would also leave ecomodern approaches vulnerable to be corrupted or usurped as a means to maintain power by transnational corporations, national governments, and big science in the name of sustainability (Harvey 1996). Given the potential for new economic development one may expect the business and finance community to promote technological innovation and development as the primary means to achieve sustainability. However, Davison (2001) suggests that there is mounting evidence that the business community has largely used ecomodernism to co-opt the sustainable development movement as a means to increase profits and market share by promoting and capitalizing on increased consumer demand for green products and services. This issue will be discussed further in Chapter 7.

ECO-EFFICIENCY AND TECHNOLOGY SUBSTITUTION

At a functional level, ecomodernism is centered on the design and deployment of eco-efficient technologies and products to serve as more sustainable substitutes for conventional technologies and products. The term eco-efficiency is a play off the more general term of efficiency and was first described by Schaltegger and Sturm (1989) and then widely publicized in 1992 in *Changing Course* by the WBCSD (Ehrenfeld 2005). Eco-efficiency has come to encompass dematerialization, the production of a good or service using less energy and fewer materials than previously. The ecomodern view of eco-efficiency is that it is possible through development of new and integrated technologies to reduce the consumption of raw materials as well as the emissions of various pollutants while at the same time creating innovative and competitive products to fuel economic expansion (Andersen & Massa 2000). Ultimately it is expected that eco-efficiency, the reduction of resource use and environmental impact per unit of output (unit of value or mass), can lead to decoupling of human economic activity from environmental degradation (Mol & Sonnenfeld 2000).

The realities of technology substitution in practice are not discussed in detail in much of the ecomodern or eco-efficiency literature. However, the pursuit of eco-efficient technology substitution is a hallmark of current corporate and government policy and it has translated into significant financial investment in what are often referred to as clean or green technologies. For example, Sustainable Development Technology Canada (SDTC), which is a not-for-profit organization housed within the Canadian federal government to support sustainable technology development, has invested over 1.15 billion dollars in clean technology projects and leveraged an additional 2.93 billion dollars in public and private sector investment for clean technology companies in Canada as of 2018 (SDTC 2019). This funding has supported just under four hundred clean technology projects in Canada, including projects in biofuels, the forest sector, electricity generation, transportation, agriculture, and waste management (SDTC 2019).

In 2019, the European Commission announced an investment of over 15 billion dollars for low-carbon technologies, stating that "Innovative climate action has a range of benefits for the health and prosperity of Europeans with an immediate, tangible impact on people's lives – from the creation of local green jobs and growth, to energy-efficient homes with a reduced energy bill, cleaner air, more efficient public transport systems in cities, and secure supplies of energy and other resources." (European Commission 2019). In the United States, clean energy investment alone reached 64.2 billion dollars in 2018 (S&P Global Market Intelligence 2019). These are but a few examples of the myriad international, national, and regional clean technology funding programs dedicated to investing in green technologies, along with an increased push to attract more private investment in clean technology (Polzin 2017). From a global environmental policy standpoint, the development of eco-efficient technology and product substitutes has become the primary approach to pursue sustainability.

A more detailed description and analysis of eco-efficiency and technology substitution is provided in Chapter 7.

ENVIRONMENTAL SYSTEMS ANALYSIS TOOLS

In discussing the integration of ecomodern approaches into government and corporate policy, Spaargaren (2000) noted that the greening of production will result in a process of monitoring and guarding of all the major substances and energy flows in the economy. As part of this process, environmental performance indicators and environmental quality norms are becoming increasingly important in supporting ecomodern objectives by quantifying the environmental impacts and benefits of alternative technologies and policies (Spaargaren 2000). The use of environmental systems analysis tools has become a central component of ecomodern policies, being used to inform the design of technologies and policies and to assess the potential for green technologies and products to improve eco-efficiency (Gasparatos et al. 2008; Singh et al. 2009).

A number of tools are available to quantify different aspects of the environmental performance and sustainability of products, processes, companies, regions, nations, and global economic sectors (Ness et al. 2007; Gasparatos et al. 2008). Gasparatos et al. (2008) grouped available tools into monetary tools, biophysical tools, indicators, and composite indices. Ness et al. (2007) classified available tools into similar groups, including:

- Indicators and Indices – simple measures, most often quantitative that represent a state of economic, social, and/or environmental development in a defined region (e.g. economy-wide material flow analysis, input-output energy analysis, genuine progress indicators, ecological footprint, etc.);
- Product-related assessment tools – focus on flows in connection with production and consumption of goods and services, evaluate resource use and environmental impacts along the production chain (e.g. LCA, energy analysis, product material flow analysis, etc.);

- Integrated assessment tools - used for supporting decisions related to policy or projects in a specific region, they typically integrate nature and society aspects (e.g. risk analysis, environmental impact assessment, etc.; and
- Monetary evaluation – not sustainability assessment techniques themselves, but tools that can be used to assist other tools that require monetary values, such as life cycle costing or cost-benefit analysis.

Each tool has particular strengths and limitations and the selection of an assessment tool will depend on the objectives of the analysis and the intended application of the results (Finnveden & Moberg 2005). Of particular interest for this dissertation is LCA, the most established and well-developed product-related assessment tool (Ness et al. 2007) and which has become the most prominent environmental systems analysis tool (Freidberg 2013/ 2014). An entire industry of academic, governmental, and private technology assessment experts has been established to support ecomodern policies with the data required to manage this process, including increased reliance on LCA by government policy developers, technology developers, and researchers (Freidberg 2013; 2014)..

LCA is a methodological framework used to quantify a wide range of industrial process-related environmental impacts associated with the entire life cycle of a product or process (Rebitzer et al. 2004; Guinée & Heijungs 2017; Hauschild et al. 2018). The assessment generally encompasses the resource use and emissions associated with all of the major phases of the production chain, including the extraction and processing of raw materials, manufacturing processes, transportation at all stages, use of the product, and recycling or disposal of the product after use (Consoli et al 1993). As a result, LCA is often referred to as a “cradle to grave” analysis (Guinée et al 2001). The LCA methodology has been standardized by the International Organization for Standardization in the 14040 and 14044 environmental management standards (ISO 2006a; ISO 2006b).

In Part II of this dissertation, LCA is applied to the assessment of wood biomass energy systems as a substitute for conventional fossil fuels systems. Further description of the

LCA methods are found in Chapters 3, 4, and 5, and a critical reflection on LCA as a tool for supporting environmental decision-making is provided in Chapter 7.

2.2 Key Trends in Global Environmental Impacts

Despite several decades of international agreements and commitments and the global investment of billions of dollars in more eco-efficient technologies, the data show that total throughput of materials and energy in the economy continues to increase and environmental degradation has continued at unprecedented levels. The objective to do more with less that has underpinned the ecomodern approach is only being realized on a per unit basis and not being realized in the aggregate.

2.2.1 Efficiency Relative to Total Resource Use and Emissions

A broad analysis of trends in total resource use and environmental impacts relative to eco-efficiency gains in several OECD countries provides several examples of the inability of eco-efficiency improvements to halt overall demand and impacts (as compiled in Huesemann & Huesemann 2011):

- Between 1973 and 2000 the energy efficiency of the total economy (GDP/total primary energy use) increased by almost 50%, yet total primary energy use also increased by almost 36% (OECD 2004). During this same period GDP grew by 200% (Huesemann & Huesemann 2008; Huesemann & Huesemann 2011).
- Between 1974 and 1998 automobile fuel efficiency in International Energy Agency (IEA) countries improved by 20% yet total fuel consumption increased by 40% (OECD 2004). During this same period total passenger kilometers driven increased by almost 75% (Huesemann & Huesemann 2008; Huesemann & Huesemann 2011).
- Between 1923 and 1996 the efficiency of public lighting in the United Kingdom. increased almost 19-fold yet the total amount of energy used in public lighting increased by more than 36-fold (Herring 1999). During this same period there was

a nearly 700-fold increase in public lighting (Huesemann & Huesemann 2008; Huesemann & Huesemann 2011).

- Between 1975 and 1993 the efficiency of total material use (GDP per total material requirements) in the United States increased by 60% yet the total use of materials did not decline but remained constant (Adriaanse et al. 1997).
- Between 1980 and 2002 the efficiency of carbon use (GDP/total carbon emitted) in the United States improved by more than 60% yet total carbon emissions increased by 20%. During this same period GDP in the United States increased by 200% (Huesemann & Huesemann 2008; Huesemann & Huesemann 2011).

The data compiled by Huesemann & Huesemann (2011) only reflect conditions up to the late-1990's and early-2000's, but provide quantitative examples to show that improvements in eco-efficiency have not historically translated directly to reductions in overall consumption of a resource or in total environmental impacts. In the following sections a review of more recent data on global resource use and environmental degradation is provide and indicates that these upward trends in total impacts have continued into the 2010's and are poised to continue into the 2020's and beyond.

2.2.2 Global Greenhouse Gas Emissions

Global fossil carbon dioxide (CO_2) emissions have continued to increase despite growing public and policy attention, the completion and dissemination of five cycles of IPCC Assessment Reports, and almost 30 years of international climate negotiations and agreements for reductions (Peters et al. 2019). Growth in fossil fuel use and the associated CO_2 emissions has continued despite considerable progress in deploying renewable and low-carbon energy technologies (Peters et al. 2019).

Data from the Global Carbon Project estimated that by the end of 2019 global fossil CO_2 emissions would reach an all-time high of 36.8 Gt, representing an increase of over 60% from 1990 levels (Figure 2-1). Global CO_2 emissions have continued to move in the opposite direction of targets set in international agreements, particularly relative to statements from climate scientists indicating that rapid reductions in global GHG emissions are needed. These reductions will likely require negative emissions using CCS technology to have any hope of keeping global warming at levels that will not result in catastrophic climate change impacts (Hansen et al. 2017).

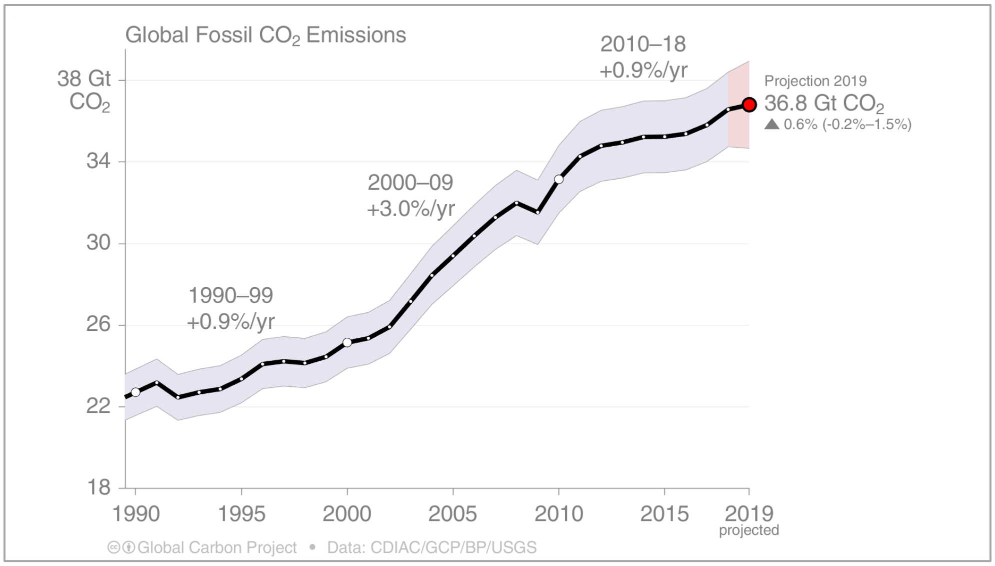

Figure 2-1. Global fossil CO_2 emissions between 1990 and 2019, including average rates of change for each decade.
Source: Friedlingstein et al. (2019) and Global Carbon Project (2019).

Along with continued increases in global CO_2 emissions, atmospheric concentrations of CO_2 and CH_4 have continued to rise, increasing from approximately 277 parts per million at the beginning of the industrial era in 1750 to well over 400 parts per million in 2019 (Friedlingstein et al. 2019). Measured data from the Mauna Loa Observatory in Hawaii show that atmospheric CO_2 concentrations have nearly reached 420 ppm in early 2020 (Figure 2-2). These continually increasing concentration levels are well above the recommended level of 350 ppm to avoid significant climate change impacts (Hansen et al. 2017) and are still rising. At a global level, measured CO_2 concentrations have exceeded 410 ppm as of early 2020 and continue to rise (Figure 2-3).

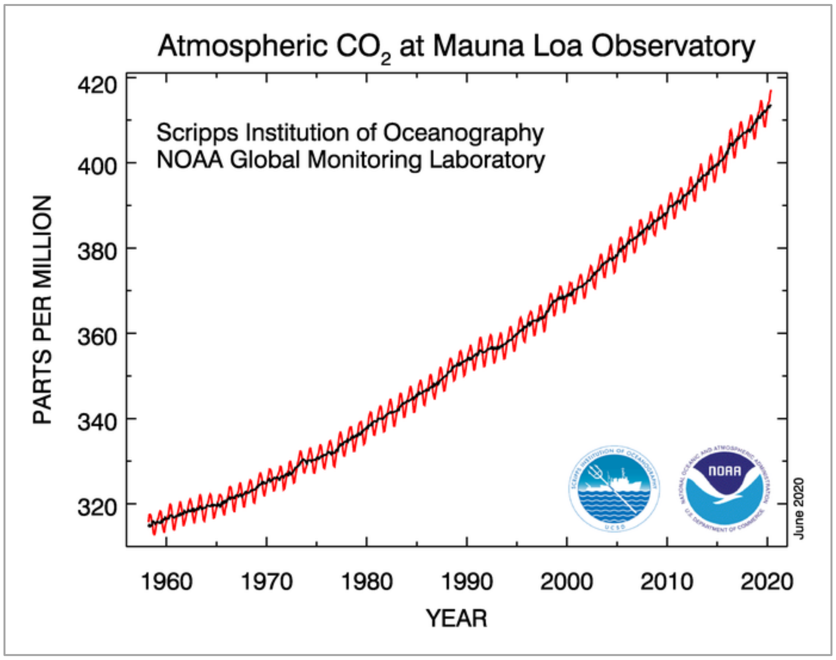

Figure 2-2. Monthly mean atmospheric concentrations of CO_2 measured at Mauna Loa Observatory, Hawaii between 1960 and 2020. Measured as mole fraction in dry air and expressed in parts per million corrected for the average seasonal cycle.
Source: NOAA/ESRL (Tans 2020) and SIO (Keeling 2020).

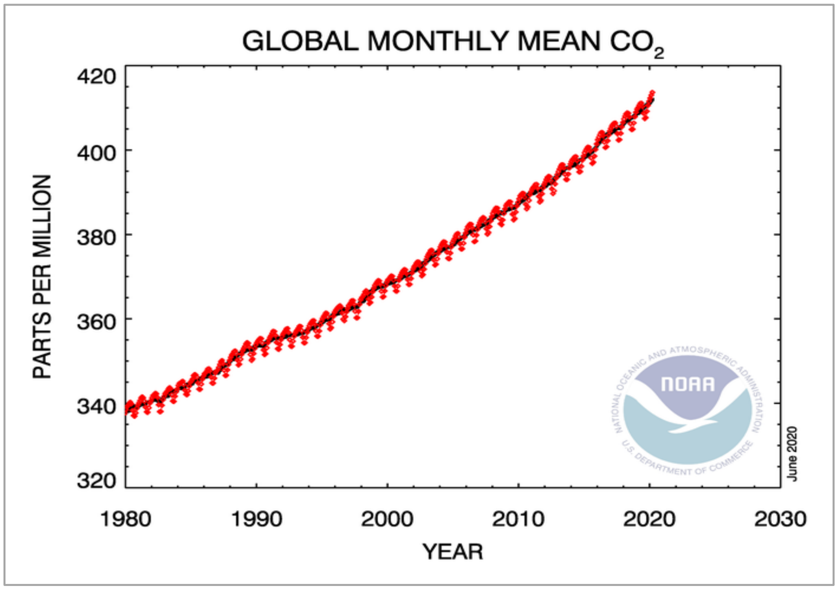

Figure 2-3. Monthly mean CO_2 concentrations globally average over marine surface sites. Measured as mole fraction in dry air and expressed in parts per million corrected for the average seasonal cycle.
Source: NOAA/ESRL (Tans 2020) and SIO (Keeling 2020).

Similar to global trends identified by Huesemann & Huesemann (2011), these increases in fossil CO_2 emissions have continued despite reductions in the overall CO_2-intensity of economic activities on average (Figure 2-4). The amount of CO_2 emitted per unit of GDP produced globally has remained steady and begun to show gradual decline between 2010 and 2019, while total fossil CO_2 emissions have continued to rise.

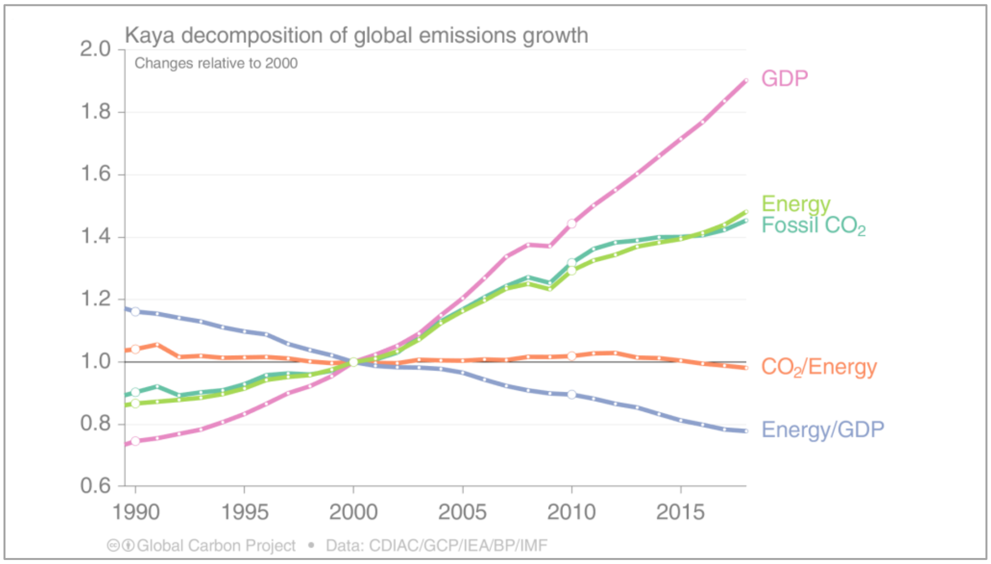

Figure 2-4. Trends in global economic output, total energy demand, fossil CO_2 emissions shown relative to energy efficiency (energy/GDP) and CO_2-intensity of global energy between 1990 and 2019. Source Jackson et al. (2019) and Global Carbon Project (2019).

2.2.3 Global Energy Demand

Closely linked to global GHG emissions, global energy demand has continued to rise year-over-year as well, with fossil fuels continuing to provide the overwhelming balance of global energy needs (Figure 2-5). Total primary energy supply increased by 55% between 1990 and 2015 (IEA 2019a). As shown in Figure 2-6, this was despite noted improvements in global energy efficiency, with the amount of amount of total energy supply per unit of GDP decreasing by nearly 22% during that same time period.

Despite heavy investment in development and deployment of low-carbon fuel sources, fossil fuels have continued to be the primary energy source used to meet global demands.

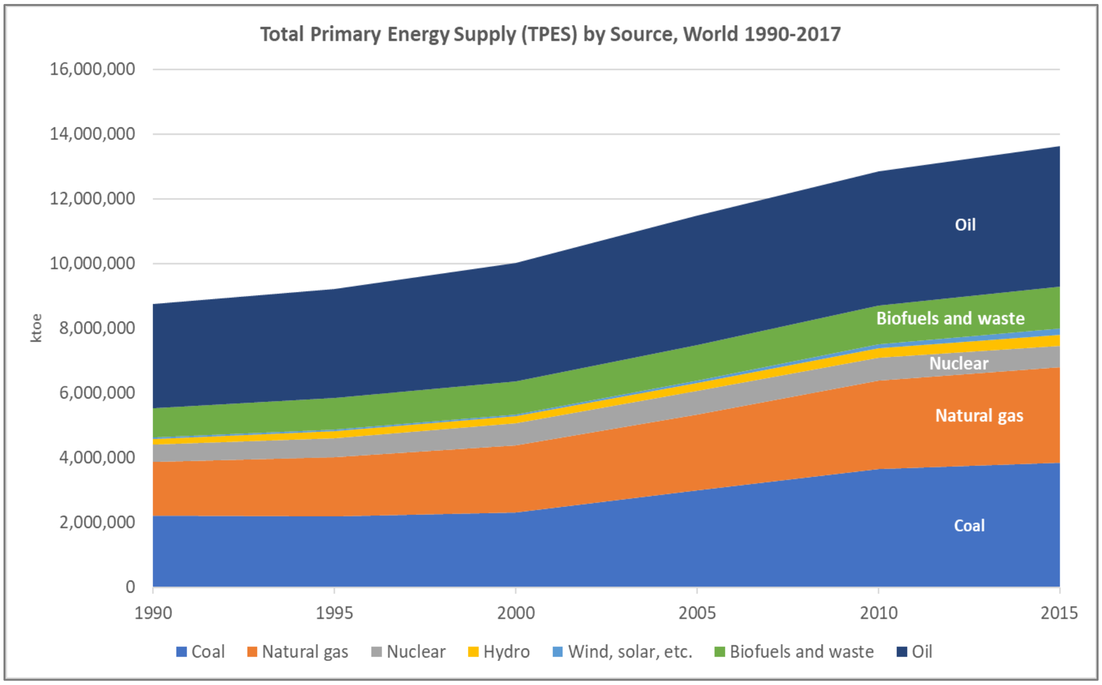

Figure 2-5. Total primary energy supply by source. Global totals expressed in kilotons of oil equivalents (ktoe) from 1990 to 2017. Source: IEA 2019a.

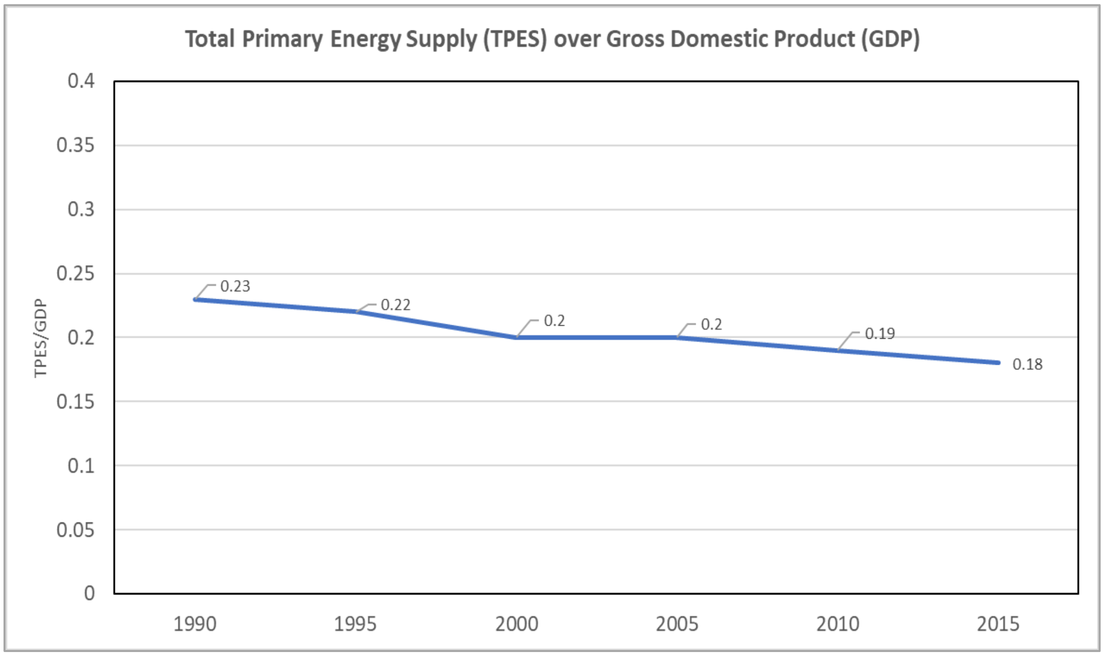

Figure 2-6. Total primary energy supply (TPES) relative to GDP between 1990 and 2015, global. Expressed in tons of oil equivalents (toe) per thousand 2010 USD. Source: IEA 2019b.

The share of total energy supply provided by wind and solar totaled 1% by 2015, and the total supply of renewables (wind, solar, hydro, biofuels) reached only 12% by 2015. Meanwhile the share of energy supplied by coal increased by 3% between 1990 and 2015, and the reduction in oil use of 5% was met by an increase in natural gas consumption of 3%.

2.2.4 Global Material Demand

One of the UN SDGs is to reduce the material footprint of human activities, which refers to the total amount of raw materials extracted from the Earth to meet final consumption demands (UNEP 2020). The extraction of natural resources is essential to human economic activity, but raw material extraction industries have a number of negative impacts on ecosystems and human health, including impacts on air quality, water quality, soil quality, biodiversity and habitat, and continued depletion of non-renewable resources which may limit access by future generations (OECD 2012).

According to indices develop by the United Nations Environment Program (UNEP) (2020), society's material footprint has been increasing steadily, from 43 billion metric tonnes in 1990 to 54 billion metric tonnes in 2000, and 92 billion tonnes as of 2017. This marked an increase of 113% since 1990 levels of extraction (Figure 2-7).

Remarkably, resource extraction from non-renewable stocks has grown over the last century while extraction from renewable stocks has declined (OECD 2012). Per capita consumption of raw materials has also increased, with the growth rate in material footprint far exceeding the rate of population growth (UNEP 2020). Between 1970 and 2010, the share of global material extraction for biomass decreased from 37% to 27% and the share of fossil fuels decreased from 26% to 19%. The share of metal ores remained at approximately 10%, while the contribution of non-metallic minerals increased from 27% to 44% of total extraction (UNEP 2016).

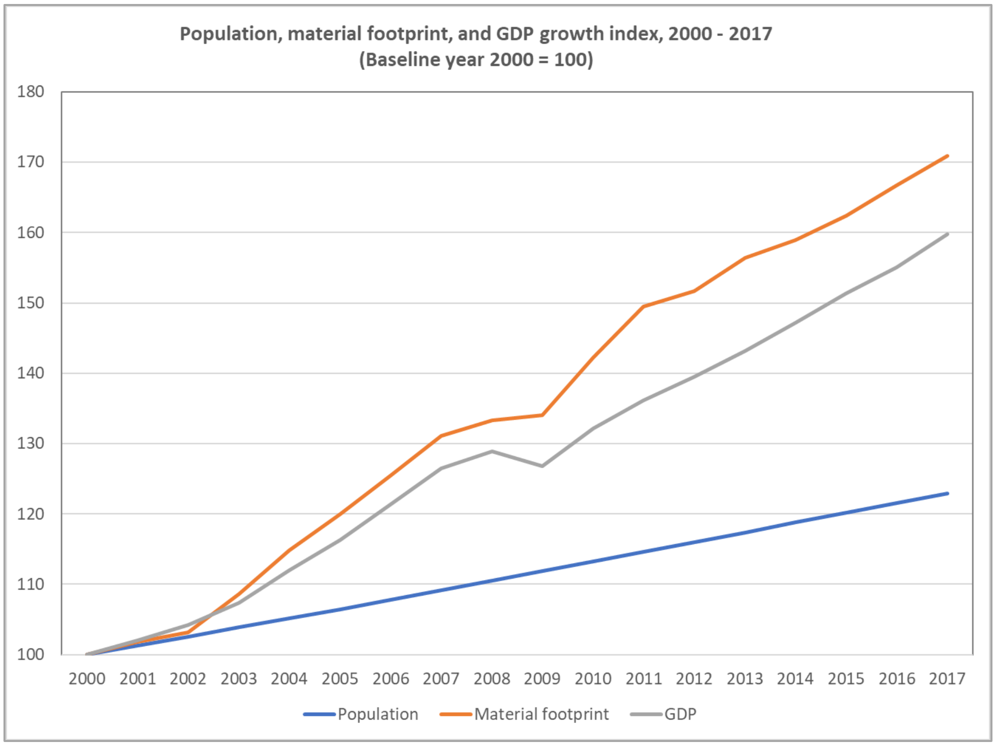

Figure 2-7. Growth indexes for global population, material footprint, and GDP between 2000 and 2017. Source: UNEP 2020.

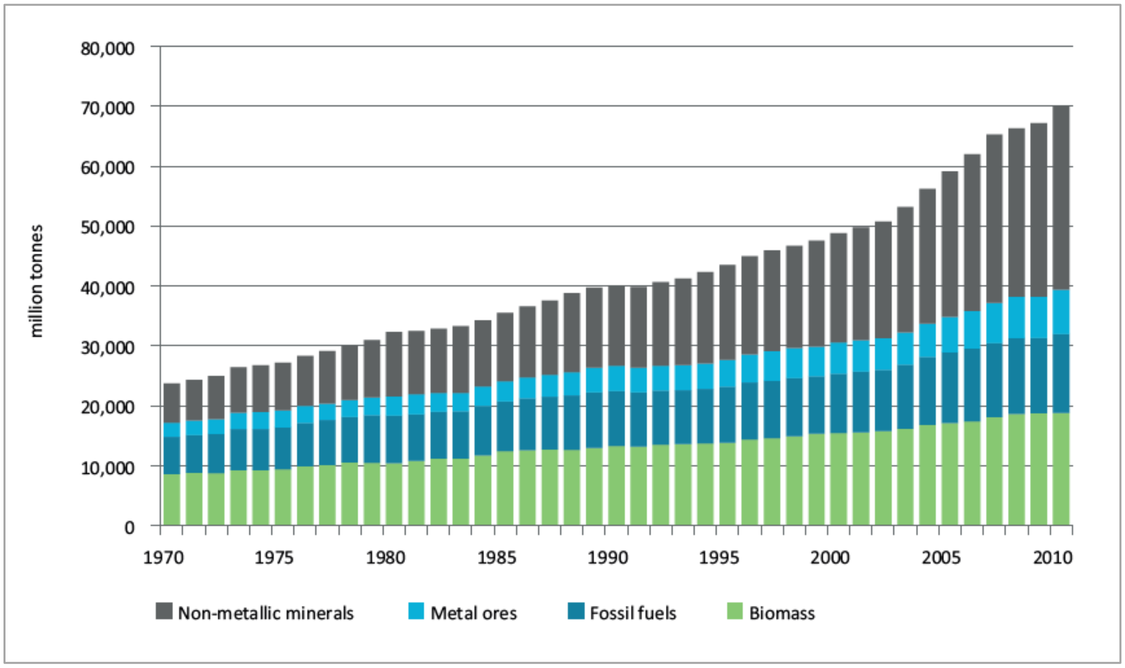

Figure 2-8. Global material extraction by four material categories, 1970 – 2010, expressed in millions of tonnes extracted. Source: UNEP 2016.

2.2.5 Global Biodiversity Impacts

Following on these trends of increasing fossil fuel use, increasing GHG emissions, and increasing raw material extraction, human activities are also resulting in dramatic declines in biodiversity. According to the 2018 Living Plant Report from the World Wildlife Fund (2018) there has been an overall decline of 60% in the population sizes of vertebrates between 1970 and 2014, an average drop of well-over 50% in 50 years. The results of the latest assessment of the Living Planet Index are shown in Figure 2-9 and show average changes in population abundance for just over 16,700 species populations.

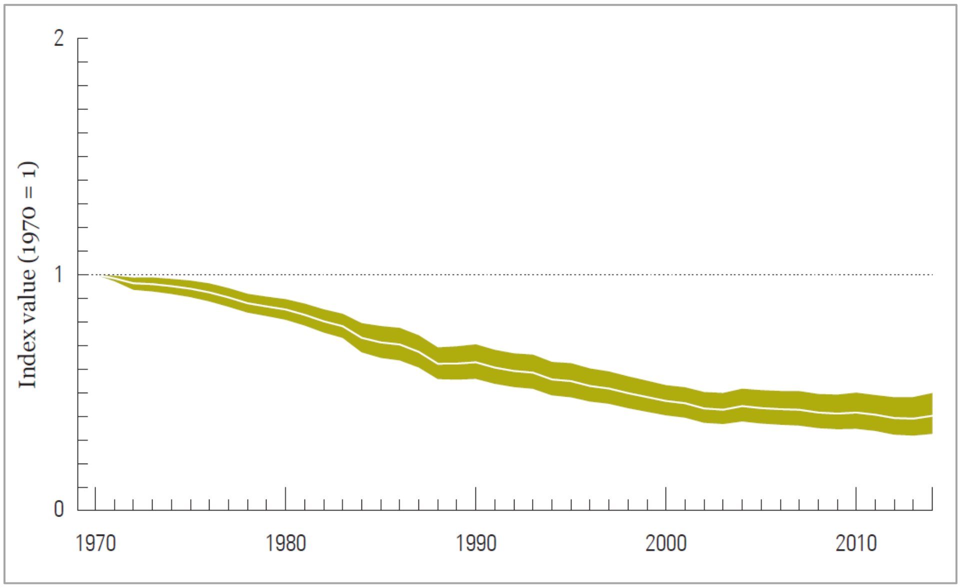

Figure 2-9. Change in the Global Living Planet Index (LPI) between 1970 and 2014. Colored areas around central white line indicate confidence limits for the calculated index value. Source: WWF 2018.

The drivers of biodiversity declines are many, but direct overexploitation of populations and agricultural activity continue to be the primary drivers (Maxwell et al. 2016; WWF 2018). These and many other drivers such as invasive species, pollution, disturbance (e.g. from mining and infrastructure), and climate change are all connected in one way or another to an ever-expanding human population and economy. The Living Planet Report connects these drivers of biodiversity loss to society's Ecological Footprint, which is a measure of the global biocapacity that is required to support human activities. Between 1961 and 2014 humanity's ecological footprint increased by 190% (Figure 2-10), far outstripping the Earth's biocapacity and any ability of technology to increase Earth's biocapacity (WWF 2018). The Ecological Footprint is driven heavily by carbon emissions from fossil fuel burning and the biocapacity required to sequester increasing carbon emissions (60%), followed by cropland and forest product impacts.

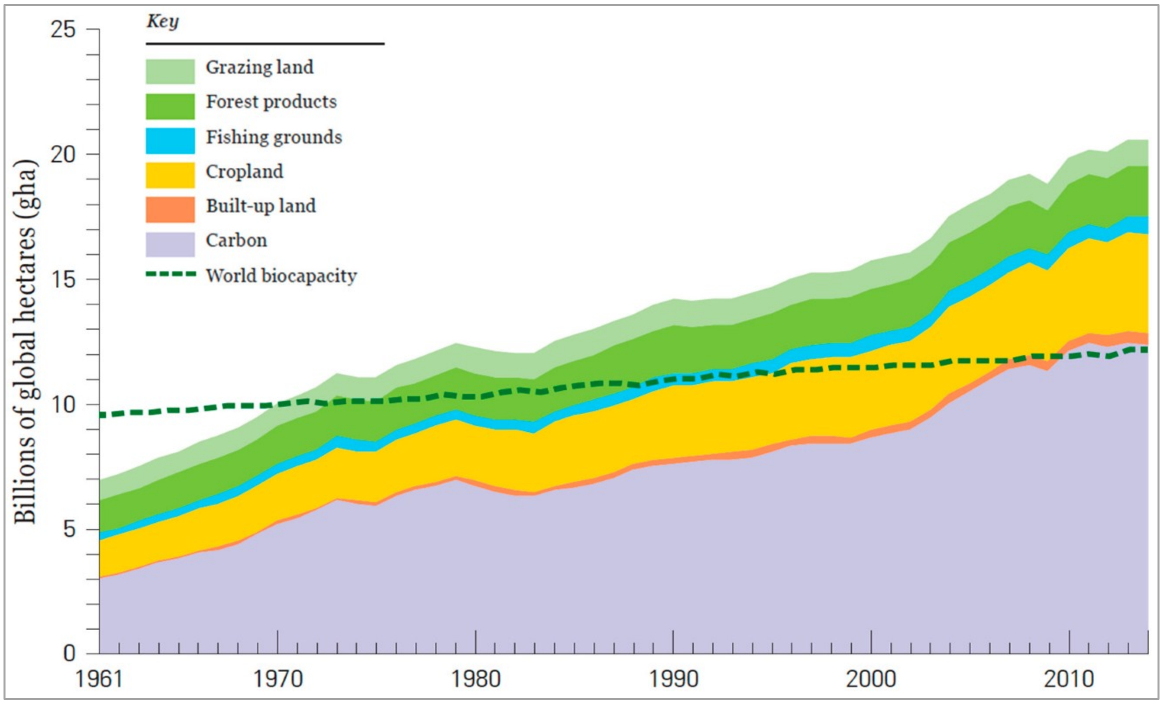

Figure 2-10. Global ecological footprint between 1961 and 2014, showing biocapacity requirements by activity type in global hectares over time. Source: WWF 2020.

2.2.6 Summary of Global Environmental Impact Trends

The data provided in Section 2.2 provide a clear indication that despite global efforts to develop and deploy more eco-efficient technologies over the last three decades, environmental degradation resulting from resource consumption and production of emissions and wastes has continued to worsen. In addition, projections indicate that the trend toward worsening environmental conditions will continue well into the middle of this century. The IEA estimates that global energy demand will continue to increase by 1.3% annually until 2040 (IEA 2019). UNEP estimates that global raw material extraction will more than double to over 190 billion metric tons by 2060 (UNEP 2020).

The IEA estimates that global GHG emissions will continue to grow at a rate of 0.6% per year out to 2050 unless significant policy changes are made (USEIA 2019).

In first half of 2020, changing behaviours resulting from the Covid-19 pandemic have created the biggest shock to the global energy system in more than seven decades (IEA 2020). Projections are that global energy demand will fall by 6% in 2020 and global CO_2 emissions may fall by almost 8% (IEA 2020). It is unclear how long this shock to the global economy will continue and the extent to which this shock will influence global energy demand and CO_2 emissions in the longer-term.

The continued worsening of environmental degradation on all fronts that are described in this section reflect the limitations of relying solely on eco-efficiency to reduce aggregate resource use and environmental impacts and provide a clear signal that critical reflection is needed. Parts II and III of this dissertation provide a contribution to this needed work.

2.3 Wood Biomass Energy Case Studies

As part of the effort to assess and understand the implications of the ecomodern approach, three case studies were completed on the substitution of renewable energy for non-renewable fossil energy in a range of energy applications in Canada. This is an issue of current policy interest in environmental management and for which new insights are needed to determine which types of renewable energy feedstocks and technologies are the best substitutes for fossil fuels in different economic sectors.

The objectives for these case studies were to use LCA to model bioenergy systems and quantify their potential environmental impacts and environmental benefits when substituted for fossil fuels in specific energy applications, and to provide practical material for the interdisciplinary critical reflection in Part III. These case studies provide a practical illustration of the mechanics of the ecomodern approach to develop, deploy, and assess clean technologies. Below, a brief overview is provided on wood biomass energy, key insights from the literature on wood biomass energy, and an introduction to the case studies in Part II.

2.3.1 Bioenergy

Energy conversion systems are a key driver of non-renewable resource use, ecosystem degradation, and the primary source of GHG emissions which contribute to global warming and subsequent climate change impacts (Hansen et al. 2017; Jackson et al. 2019). As shown in Section 2.2, the majority of global primary energy required to sustain human activities is still fulfilled using fossil fuels, including electricity generation, industrial energy conversion, space heating, and transportation. Despite eco-efficiency improvements across a number of these sectors, total global energy demand continues to increase as do GHG emissions from energy extraction and utilization (Peters et al. 2019).

Bioenergy is the most widely used renewable source of energy in the world (IEA 2017; Junginger et al. 2019), and although bioenergy is framed as a new development due to the many new innovations in conversion technologies, biomass itself is the oldest fuel used by mankind and has been the primary source of energy for cooking and heating since the dawn of civilization (IEA 2002). Bioenergy is a general term used to encompass a diverse set of energy systems that convert biomass feedstocks to usable energy for many applications. The energy in biomass feedstocks is captured solar energy from the production of carbohydrates and lignin via photosynthesis (IEA 2005). Over the last century, biomass energy has largely been replaced by fossil fuels which have higher energy density, are easier to store and handle, and are typically cheaper (IEA 2002).

Bioenergy systems are differentiated according to modern bioenergy systems, and traditional bioenergy systems. Traditional bioenergy systems refer to biomass energy used for heating and cooking in individual households in developing countries, while modern bioenergy systems refer to electricity, heat, and transport fuels derived from biomass (Smith et al. 2014).

There is a remarkable diversity in bioenergy systems, including systems currently in use and those still in various stages of development. Biomass feedstocks for bioenergy systems generally include forest and farm residues (e.g. branches, tree tops, corn stover, etc.), energy crops (e.g. annual and perennial herbaceous and woody species), processing wastes (e.g. sawmill residuals, pulp and paper residues, etc.), and municipal wastes (e.g. mixed organics, construction and demolition wastes) (IEA 2005). Bioenergy feedstocks are derived from dedicated systems for cultivation and from waste and co-product streams from existing processes. They can be converted to useful energy through several biomass upgrading processes (e.g. pelletization) and conversion pathways (e.g. direct combustion, pyrolysis, gasification, etc.). The energy applications for bioenergy are equally diverse and include transportation fuels, industrial energy and heat conversion, electricity generation, as well as institutional and residential heating applications (IEA 2005).

Bioenergy systems have been identified as important alternatives to fossil fuel energy systems that play a significant role in many projected scenarios for meeting Paris agreement objectives of limiting climate change impacts (Clarke et al. 2014; Creutzig et al. 2015; Rogelj et al. 2018). Bioenergy also figures prominently in the United Nations SDGs (United Nations 2019) and has been described as having a wide range of benefits, including (but not limited to) (IEA 2005):

- Environmental – reduced reliance on finite natural resources, enhancement and protection of various ecosystem services (e.g. carbon sinks, groundwater supplies, etc.), and reduced GHG emissions via fossil fuel substitution;
- Social – creating and retaining wealth within local economies, new employment opportunities, and increased energy security and diversification; and
- Economic – minimized costs of relying on local feedstock supplies, emerging markets for related environmental services, and enhancement of rural economies.

At present, modern bioenergy systems provide approximately 4.3% of global primary energy supply (Hanssen et al. 2019). As a result of the perceived benefits of bioenergy, particularly with respect to reducing GHG emissions, it is expected that bioenergy systems could account for 10-35% of global primary energy demand by 2050, and 10-50% by 2100 (Smith et al. 2014; Creutzig et al. 2015; Bauer et al. 2018).

In keeping with the ecomodern approach, the support for bioenergy is both for perceived environmental benefits as well as to foster economic development in the various sectors which produce feedstocks and conversion technologies. Indeed, bioenergy is a fixture of the new green economy that is expected to help fuel the transition away from fossil fuels and figures prominently in the United Nations SDGs (United Nations 2019).

This diversity of systems is one of the attractive features of bioenergy, both because they can be deployed in many sectors of the economy, and because their supply chains for feedstock production, biomass upgrading, and production of conversion technologies require participation and growth from a number of existing and emerging industries. This provides the opportunity for the increased economic development that is targeted with the ecomodern approach.

An assessment of the full spectrum of bioenergy systems is certainly beyond the scope of this dissertation. However, a focused examination of a particular form of bioenergy yielded valuable insights that could be applied to other bioenergy forms. For the purposes of this dissertation, the focus was on a specific type of lignocellulosic bioenergy called wood biomass energy.

2.3.2 Wood Biomass Energy

Wood biomass energy systems involve the conversion of woody biomass into solid, liquid, and gaseous fuels to provide energy for industrial, commercial, or domestic use (IEA 2002). Sources of wood biomass for energy include:

- Trees harvested from forests;
- Trees harvested from dedicated energy crops (e.g. short-rotation willow);
- Residuals collected from forest harvesting activities (e.g., tops, limbs, branches) and forest management activities (e.g. thinning, etc.);
- Residuals from other forest sector activities (e.g. sawdust from sawmills); and

- Waste wood from municipal solid waste (MSW) and construction and demolition (C&D) wastes.

Wood biomass feedstocks are upgraded and converted to more useful and energy dense forms through several pathways and can be used to provide energy for a number of applications, including:

- Transportation fuels;
- Industrial energy and heat production;
- Large-scale electricity generation;
- Institutional and district heating; and
- Residential heating.

There have been increasing efforts in the United States and Europe to use wood as a source of biomass energy (USEPA 2018; European Union 2009) and most global energy pathways defined for meeting the Paris climate change targets include large-scale deployment of biomass used in power plants, including with carbon capture and storage (Rogelj et al. 2018). Canada is the second leading exporter of wood pellets for bioenergy in the world with markets in the United Kingdom, Europe, and Asia (NRCan 2020). At present the most notable case may be the use of wood pellets for large-scale electricity generation in Europe, where wood pellets were among the acceptable renewable fuels under programs aimed at increasing the share of renewable energy feedstocks in electricity generation and reducing GHG emissions (European Commission 2020). The first renewable energy directive came in 2009 (European Commission 2009) and as of 2019 the European Union consumed approximately 75% of the world's wood pellets, with nearly half of the EU's renewable energy coming from combustion of solid wood biomass (Voegele 2019). This program has had global ramifications, particularly as Canada and the United States have ramped up wood pellet production and export over the last 10 years in order to supply this growing market (Krigstin et al. 2016; Dale et al. 2017; NRCan 2020).

In Canada a number of provinces rely on the wood biomass energy industry for both residential space heating and for a source of export revenue. In Ontario, two large-scale wood biomass electricity generation stations were installed to partially replace the output from the successful phase out of Ontario's coal-fired power plants which were shuttered at the end of 2014 (IISD 2015). Both Nova Scotia and British Columbia are developing wood biomass resources to produce wood pellets for domestic use and export to Europe and Asia, with British Columbia accounting for 28% of wood pellet exports from Canada (NRCan 2020).

2.3.3 Assessing the Environmental Impacts of Wood Biomass Energy

The following sections provide a summary of findings from a selection of LCA studies of wood biomass energy systems published between 2000 and 2019. This is followed by a summary of some of the key insights that are common across the studies reviewed. The focus of the literature review was specifically on studies where LCA was used or some form of life cycle GHG emissions accounting (e.g. carbon footprint), since these are the methods used in the Part II case studies and since LCA's practices and uses are a subject of the critical reflection in Part III of the dissertation.

2.3.4 Key Insights from the Literature

LITERATURE ON WOOD BIOMASS ENERGY, 2000 - 2010

Up until the late-2000s, most studies on bioenergy, and wood biomass energy systems more specifically, were based on the simplified assumption that biomass energy feedstocks are carbon neutral. A comprehensive literature review conducted by Solomon & Luzadis (2009) concluded at that time that fossil energy inputs and GHG emissions were broadly shown to be significantly lower for bioenergy systems relative to fossil fuel systems. In the late 2000s and early 2010s several new studies on wood biomass energy began to incorporate more nuanced modelling of forest carbon dynamics and to challenge the carbon neutral assumption. Papers by Searchinger et al. (2009) and Johnson (2009) directly critiqued the forest carbon neutrality assumption as being flawed and not reflective of the biophysical reality of wood biomass feedstocks.

A study by the Manomet Center in Massachusetts published in 2010 reported that forest biomass energy systems generally emit more GHG emissions per unit of energy produced than conventional fossil fuels, and that it could take up to 90 years for any GHG benefits to be realized, depending on post-harvest forest management practices (MCCS 2010). The results and the methods of the Manomet study were challenged by other experts, particularly for the use of a "carbon debt-carbon dividend" calculation approach and for modelling forest carbon changes only at a stand-level (O'Laughlin 2010; Strauss 2011). In the debt-dividend approach, forests are viewed as carbon "stocks", and the wood biomass energy system takes on a carbon "debt" when trees are harvested from the stock. Carbon "dividends" are then paid as regrowth occurs over the post-harvest period and the carbon stock is built back up via carbon sequestration in woody biomass and soil carbon. In the Manomet study the time lag between incurring the debt and the full dividend pay back (i.e. net GHG parity or reductions) was shown to be up to 90 years. Critics of the Manomet study suggested that the carbon debt-carbon dividend approach did not hold up when forest carbon flux is considered at a broader landscape level where changes in carbon storage beyond the stands being harvested for bioenergy generally result in the carbon storage of the forest being constant despite increased harvesting for biomass (O'Laughlin 2010; Strauss 2011).

The results of the Manomet study stood in stark contrast to most of the existing literature and the prevailing assumptions up to that point, and the insights from this study opened up the potential that wood biomass energy was not a lower-carbon energy option by default. Several subsequent studies began the process of merging LCA methods with forest carbon modelling to try to account for net changes in CO_2 reaching the atmosphere more accurately. An excellent example of the evolution of thought on this issue is illustrated in two Ontario LCA studies on electricity generation using wood pellets (Zhang et al. 2009; McKechnie et al. 2011). In the first publication it was assumed that emissions of CO_2 resulting from combustion of the wood pellets were entirely balanced by the carbon incorporated during regrowth of the forest (Zhang *et al*. 2009). In a subsequent publication on wood biomass electricity generation in Ontario featuring several of the same researchers, forest carbon modeling was used to show that it would take many years for the CO_2 released during wood pellet combustion to be sequestered by regrowth in the forest (McKechnie et al. 2011). It was argued that this time period could vary substantially depending on the forest management practices in place, both at the time of harvest and throughout the time needed to regenerate the stand, as well as the specific energy application and fossil fuel being displaced (McKechnie et al. 2011).

While both studies concluded that the use of wood pellets to generate electricity resulted in GHG emission reductions relative to fossil fuel feedstocks overall, the second study suggested that this reduction is not immediate, and in fact the authors concluded that GHG emissions were initially higher for the biomass system due to the immediate reduction of forest carbon stocks from tree harvest (McKechnie et al. 2011). It was concluded that GHG emission reduction benefits would only begin to be realized after a period of up to 38 years of tree regrowth. This study by McKechnie et al. (2011) served to reinforce the fact that GHG reductions cannot be assumed for wood biomass electricity generation because they are highly dependent upon forest management and silviculture practices after harvest and combustion (McKechnie et al. 2011).

The challenging of the carbon-neutral assumption in the literature has been the most significant development in terms of methods for quantifying the life cycle GHG emissions of wood biomass energy systems. However, a number of current studies and national and international GHG inventory programs are still based on the assumption that carbon emitted from combustion of wood is part of a closed, short-term carbon cycle and therefore biogenic carbon emissions from combustion are not counted. For example, technical guidance from Environment and Climate Change Canada (ECCC) indicates that to be consistent with the United Nations Framework Convention on Climate Change (UNFCCC), biogenic carbon emissions should not be included in national inventory totals (ECCC 2016). Reijnders & Huijbregts (2003) took an interesting angle in challenging the carbon-neutral assumption by questioning whether all of the credit for

CO_2 sequestration should be allocated to the wood biomass feedstock, when in fact the trees that sequester the carbon do not discriminate between CO_2 emitted by burning fossil fuels or by burning biomass. They proposed a method for allocating the sequestration credit according to the percent contribution of each feedstock to the overall electricity grid profile. This allocation step has not been applied in any of the studies reviewed, but would potentially reduce the amount of GHG emissions attributed to the combustion of fossil fuels and would potentially increase the amount of GHG emissions attributed to wood biomass relative to current estimates.

LITERATURE ON WOOD BIOMASS ENERGY, 2011 - 2019

One of the consistent findings in studies that include forest carbon modelling is that using wood residuals rather than harvesting standing biomass shows a much greater likelihood of providing GHG emissions reductions relative to fossil fuels. This is based on the assumption that feedstocks such as forest harvest residues (e.g. branches, tops, etc.) or sawmill residues (e.g. sawdust, wood chips) are a product of business-as-usual forest harvesting motivated by other human needs and these residues are often either left to decay in the forest, burned at the roadside, or stockpiled for long periods. As a result, it is often assumed that the carbon in these residuals would be emitted to the atmosphere anyway, regardless of whether the materials are used for bioenergy or not, so there would be no net emission of CO_2 if these materials were burned for bioenergy (Cleary & Caspersen 2015a; Ter-Mikaelian 2015).

Several researchers have critiqued this simplified assumption, pointing out that the carbon dynamics of wood residues must also be accounted for as rates of oxidation are slower and some residual carbon may end up in soils and not the atmosphere. It has been argued that studies that do not account for changes in carbon storage and carbon decay when using wood residuals tend to greatly overestimate the GHG reductions that can be achieved with wood biomass energy (Cleary & Caspersen 2015a; Cleary & Caspersen 2015b; Ter-Mikaelian et al. 2015).

Interestingly, the wood biomass energy literature in more recent years continues to include a mix of studies where biogenic carbon emissions are excluded, and studies where more complex forest carbon modelling is undertaken. A brief summary of recent studies is provided below, along with a brief overview of common themes, insights, and limitations. Brief literature reviews on relevant wood biomass energy systems and on various aspects of forest carbon modelling are also provided in the case studies in Chapters 3, 4, and 5.

Cambero et al. (2015) modeled the life cycle GHG emissions of substituting wood biomass energy from forest and sawmill residuals using different conversion systems (combustion and gasification) and different energy output capacities for existing energy systems in two remote British Columbia communities. Results of the study indicated that life cycle GHG emissions reductions could be achieved by this substitution in all scenarios, but it was concluded that the reductions that could be achieved would be considerably lower when using wood residues that would otherwise be landfilled when not used for bioenergy. This is because a certain portion of the carbon in these residues is sequestered when placed in a landfill thereby offsetting the benefits of displacing the existing energy source (Cambero et al. 2015).

In another study of wood biomass energy in B.C., Maier et al. (2019) also modelled the use of forest harvest and sawmill residuals for bioenergy for similar scenarios as those modelled in Cambero et al. (2015). However, Maier et al. extended the analysis to include a broader set of environmental indicators beyond just GHG emissions. The findings of the study indicated that substituting wood biomass energy for the existing energy systems would lead to reductions in impacts for nearly all of the ten indicators considered, primarily because the residues used are otherwise disposed of by uncontrolled burning in the jurisdiction modelled. The one indicator for which the impacts of the bioenergy system were higher was ecotoxicity due to the emissions from disposal of wood ash.

Both of these studies served to reinforce the general pattern in the literature which shows that using wood residuals as feedstock has the greatest potential for reductions in life cycle GHG emissions in most instances. A study by Buonocore et al. (2019) showed similar results for use of wood biomass residuals for heat and electricity production in Northern Italy. A study of Canadian wood biomass energy potential by Smyth et al. (2016) also concluded that capturing harvest residues to produce bioenergy to displace fossil energy in Canada can generally lead to reduced GHG emissions in particular regions of the country. However, in regions where bioenergy production exceeded local demand and was used to displace low-emission electricity grids there were net increases in GHG emissions.

Laganière et al. (2017) used LCA and forest carbon modelling to calculate the time to carbon parity of a wide range of wood biomass feedstocks (e.g. harvest residues, sawmill residues, harvested trees) used in a number of heating and electricity generation applications in Canada. The results generally reflected much of the existing research, indicating that life cycle GHG emission reductions were most significant and most immediate when using residues, while systems based on the harvesting of standing biomass often required over 100 years to have sufficient regrowth in the forest to reach carbon neutrality, let alone achieve any meaningful reductions in life cycle GHG emissions.

Beagle & Belmont (2019) used LCA to model the impacts of using wood pellets for electricity generation in the U.S. and exporting wood pellets from the U.S. to Europe for electricity generation. The wood pellets were assumed to be carbon-neutral in following recent guidance from the U.S. Environmental Protection Agency, and the wood pellet production was modelled as an average U.S. process with no specific geographical location. The results of the study indicated substantial reductions in life cycle GHG emissions for both biomass energy applications and concluded that the extra transport to bring wood pellets to Europe was not a major factor in the overall life cycle emissions. Röder et al. (2015) also used LCA to model the life cycle GHG emissions of using forest harvest residues and sawmill residues to produce wood pellets in the Southeast U.S. for electricity generation in Europe. By applying uncertainty analysis and quantifying methane emissions from longer-term storage of wood residues, results of the study showed the potential for an 83% reduction in life cycle GHG emissions, or up to a 73% increase in life cycle GHG emissions for the biomass energy systems depending on the conditions and assumptions.

These two studies on the wood pellet sector in the U.S. show the large range in results that can be found in the literature, even for two studies that include models of very similar supply chains and energy applications. A systematic literature review of bioenergy LCAs by Muench & Guenther (2013) concluded that there is significant variability in results for LCA's of biomass electricity and heat generation and that this variability is largely based on different assumptions and methodological choices. They recommended greater transparency and more consistent methods and assumptions for future studies. A meta-analysis of forest bioenergy GHG emission accounting studies by Buchholz et al. (2015) included classification and regression analysis to identify the assumptions and attributes from forest carbon modelling that are the strongest predictors of carbon payback period. Buchholz et al. also recommended the creation of common accounting principles such as temporal scale, system boundaries, GHG emissions metrics, baseline systems, and in particular the inclusion of natural disturbances (e.g. wildfires), which was shown to be a significant factor affecting results of studies in which it was included but that is typically excluded from other studies. The exclusion of this factor may be justified in regions where forest fire frequencies are relatively low.

OVERVIEW OF FINDINGS FROM THE LITERATURE REVIEW

Much of the focus of the literature on wood biomass energy has been an ongoing effort to refine and improve the accuracy of forest carbon modelling and integration of these data with LCA methods and calculations. A number of different approaches have been used in this respect in an attempt to reflect the nuance and complexity of carbon dynamics within forests and related to the management of forest sector residuals. Some analyses continue to work from the assumption that wood biomass is carbon neutral and that biogenic carbon emitted when wood is used for energy should be excluded from life cycle GHG emissions calculations. Within the LCA methods several different assumptions and approaches have been used, including different system boundaries, co-product allocation decisions, and inclusion of different environmental impact categories. The assessment of additional environmental impacts beyond GHG emissions has been very limited.

The variation found within the literature has led to a wide range of possible outcomes for the life cycle GHG emissions benefits of wood biomass energy systems, ranging from potentially worse than fossil fuels in some applications, to large emission reductions of upwards of 90% relative to fossil fuels. In addition, these studies typically do not include any assessment of the ecological and aesthetic impacts to forests that may result from incremental harvesting to support bioenergy, and this is a significant gap for policy-makers due to the importance of this issue to stakeholders. The variability in outcomes and impact assessment gaps in the literature have therefore made it difficult for policy-makers to determine the real potential of wood biomass energy as a renewable, low-carbon substitute (Buchholz et al. 2015).

Based on the literature, it can generally be concluded that the results of a given study for a particular jurisdiction and set of conditions are likely not broadly applicable to wood biomass energy systems more generally, such that policy-makers may need to rely on analyses that are representative of conditions in their own region and be careful when commissioning work to ensure it follows current, leading edge practices. Although results in the literature generally suggest that using residuals is preferable to harvesting of standing biomass, the use of residuals may not always lead to GHG emissions reductions relative to fossil fuels depending on the typical management of those residuals in the absence of bioenergy, and depending on the energy conversion process and the energy system that is replaced.

2.3.5 Wood Biomass Energy Case Studies

One of the objectives of this dissertation was to use LCA to quantify the life cycle environmental impacts of substituting wood biomass for fossil fuels in a range of energy applications to help determine if they can contribute to reducing GHG emissions from energy systems. Wood biomass energy is a classic example of a desirable technology substitution in the ecomodern approach, as it has the potential to reduce environmental impacts while creating new economic activity. In addition, this process of identifying an environmental problem (impacts of fossil fuel energy systems), deploying a more eco-efficient technology substitute either in theory or in practice (wood biomass energy systems), and assessing the impacts and benefits of the substitute to inform optimization (LCA of wood biomass and fossil fuel energy systems), is a practical illustration of the mechanics of the ecomodern approach.

The results of this work are summarized in the following four chapters which form Part II of the dissertation. These case studies present results for a broad range of wood biomass energy applications, including:

- Production of wood pellets from dedicated short-rotation willow crops to substitute for fossil fuels in industrial furnaces;
- Production of bio oil from pyrolysis of forest harvest residues to replace fossil fuels in cement production;
- Production of wood pellets from sawmill residuals and/or harvesting of low-value hardwoods to replace oil in residential space heating; and
- Production of wood pellets from sawmill residuals and/or harvesting of low-value hardwoods to replace coal in large-scale electricity generation in Europe.

The environmental systems analysis tool used to assess the wood biomass energy systems is LCA, which has become particularly prominent in recent years and which is currently being used to inform government policy and alternative technology design on a global scale. In addition to providing practical insights on the potential contribution of wood biomass energy systems to developing more sustainable energy systems, the completion of these case studies is an illustration of the ecomodern approach, and therefore was also used to provide sufficient material for the critical reflection on ecomodern approaches in Part III.

2.4 Works Cited

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CHAPTER 3: LIFE CYCLE ASSESSMENT OF THERMAL ENERGY PRODUCTION FROM SHORT-ROTATION WILLOW BIOMASS IN SOUTHERN ONTARIO, CANADA

3.1 Publication Information

This manuscript has been published in the journal *Applied Energy*. I worked directly with the lead author and my contributions included literature reviews, compilation of the life cycle inventory, modeling of the energy systems in LCA software, calculation of life cycle impacts, interpretation of the study results, and substantial contributions to preparation of the manuscript.

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3.2 Abstract

As part of efforts to address the root causes of climate change and non-renewable resource depletion, many regions in the world are considering sustainable biomass feedstocks for renewable energy production. Prior to making such large-scale shifts in primary energy feedstocks, location-specific research is still needed to understand the environmental impacts and benefits of biomass associated with its many potential applications. The objective of this study was to evaluate environmental and energy impacts associated with generating 1 MJ of thermal energy from direct combustion of short rotation willow (SRW) pellets for 2 purposes: to determine where improvements could be made in the life cycle of SRW bioenergy to reduce impacts, and to compare SRW bioenergy to fossil fuel (light fuel oil and natural gas) for thermal energy. Life cycle assessment (LCA) was conducted using primary data on SRW biomass production collected from field trials at the Guelph Agroforestry site in Guelph, Ontario, Canada, as well as carbon sequestration rates modeled based on local conditions. Results showed that direct combustion of SRW pellets reduced global warming potential (GWP) by

almost 85% relative to the fossil fuels. However, relative to fossil fuels, SRW energy had higher impacts in certain categories (e.g. eutrophication and respiratory effects), due to biomass combustion and N inputs (inorganic fertilizer and SRW leaf inputs) for biomass production. Soil nitrous oxide emissions, from the N inputs, dominated the GWP, but a sensitivity analysis showed that soil carbon sequestered by SRW biomass during growth could reduce the GWP by 23%. Pelletizing the SRW biomass prior to combustion affected the energy ratio and accounted for almost 85% of non-renewable energy use in the life cycle of bioenergy. Location-specific factors that affected environmental performance of the bioenergy system included agroclimatic conditions, management practices, and conversion technologies. Nevertheless, most of the impacts associated with SRW thermal energy generation can be minimized through better fertilizer management, by using alternate sources of fertilizer, by improving yields, and by the use of cleaner wood combustion technologies with emissions controls.

3.3 Introduction

Wood biomass has been identified globally as a renewable energy feedstock with potential to displace non-renewable fossil fuels, reduce global greenhouse gas (GHG) emissions, promote local and regional energy security, and create new economic opportunities for rural communities (Bright et al. 2010; Kaygusuz et al. 2009; Liu et al. 2014). Despite its potential benefits, the use of wood biomass energy can result in several environmental and human health issues, including competition with arable land for growing economically-viable wood energy crops (Sanscartier et al. 2014), increases to short and medium-term greenhouse gas (GHG) emissions relative to fossil fuels (Cleary & Caspersen 2015a; Ter-Mikaelian et al. 2015; Buchholz et al. 2016), emission of air pollutants during combustion (Puettmann 2017; Fantozzi & Buratti 2010), ecological impacts to forest ecosystems from increased harvesting (Hesselink 2010; Thiffault et al. 2010), and biodiversity impacts related to use of “marginal” land for growing energy crops (Anderson & Fergusson 2006; De Schutter & Giljum 2014). The potential environmental impacts and benefits are dependent upon the energy conversion technology, the fossil fuel energy being displaced, and the source and type of feedstock used (Ter-Mikaelian et al. 2015; McKechnie et al 2011; Muench & Guenther 2013;

DeCicco et al. 2016; Cherubini et al. 2009). Of particular importance in determining environmental performance is the source and type of feedstock, which can include wood fiber residuals and co-products from forestry and sawmill operations, construction and demolition waste, harvesting of standing trees, and perennial short-rotation woody crops. Assessing the environmental impacts of wood biomass feedstock options is therefore important for bioenergy producers and policy makers. Several studies suggest that the use of residuals is environmentally-preferable to harvesting of standing trees (Ter-Mikaelian et al. 2015;Smyth et al. 2016), particularly from a GHG emissions perspective since there is no incremental impact on forest carbon sequestration potential; however, as bioenergy systems are deployed at a larger scale, the demand for forest harvest and sawmill residuals will increase, and the availability and economic viability of accessing alternative sources of residuals will increasingly become a barrier (Hesselink 2010; Neupane et al. 2011; Bouchard et al. 2013; Paré et al. 2011; Ralevic et al. 2010). The identification of other, sustainable feedstock alternatives is therefore critical for advancing the use of wood biomass energy systems.

Short-rotation woody crops such as willow (*Salix spp*.) are becoming increasingly attractive as a source of wood biomass feedstock supply (Dubuisson & Sintzoff 1998; Hoogwijk et al. 2005; Rockwood et al. 2008), and could reduce pressure on primary forest harvesting, in addition to providing a sustainable alternative to limited stocks of wood biomass residuals. Short-rotation willow (SRW) has been cultivated as a biomass energy crop in both Europe and North America due to its desirable characteristics such as rapid growth (>15 oven-dried tonnes ha^{-1} year^{-1} on 3- to 4-year rotations over 20 – 25 years (Volk & Luzadia 2009), vigorous shoot production, ease of propagation, tolerance to high plant density and potential for genetic improvement. Short-rotation willow crops are also associated with many other environmental and socio-economic benefits, such as enhancing biodiversity (Volk et al. 2006), remediating sites contaminated by various industrial and agricultural wastes (Mirck et al. 2005; Witters et al. 2009), recycling and managing soil nutrients (Volk et al. 2004), improving rural farm economies by promoting farm crop diversification and creating an additional source of income for farmers (Volk et al. 2006), and potentially reducing GHG emissions in energy applications (Ter-Mikaelian et al. 2015; Keoleian & Volk 2005).

Despite its attractiveness as an energy feedstock, there is still a need to assess the environmental impacts of SRW across different geographies to understand potential environmental trade-offs with other energy feedstocks. Life cycle assessment (LCA) is a method for quantifying the resource use and emissions to the environment across the full supply chain of products and processes, from raw material extraction through processing, distribution, use, and end-of-life (Pennington et al. 2004; Rebitzer et al. 2004). This method allows for the identification of environmental hot spots in the supply chain, the comparison of environmental impacts for alternative products and technologies, and modeling of alternative production scenarios. The LCA method has been used extensively to quantify the life cycle impacts and benefits of a range of wood-based bioenergy systems (McKechnie et al. 2011; Zhang et al. 2010; MCCS 2010). In particular, several LCA studies have revealed environmental and energy benefits and impacts of willow biomass production (Keoleian & Volk 2005; Lettens et al. 2003) and of various willow utilization pathways, such as electricity generation, direct combustion, combined heat and power, or bioethanol (Ericsson et al. 2014; Gonzalez-Garcia et al. 2012; Gonzalez-Garcia et al. 2013; Buonocore et al. 2012; Heller et al. 2003; Heller et al. 2004; Rafaschieri et al. 1999; Gasol et al. 2009; Goglio & Owende 2009; Porsö & Hansson 2014). The earliest use of LCA to study the impacts of SRW was based on a US plantation (Keoleian & Volk 2005). Studies that followed have used parameters and chemical composition data for SRW feedstocks from previously published studies instead of using measured data that reflect actual feedstock characteristics for a given region.

In a review of 26 studies, Djomo et al. (2011) highlighted the large range of energy balances and GHG emissions of bioenergy production from poplar and willow, which depend on yield and management practices (e.g. types and amount of fertilizer used and harvesting methods), and conversion technologies. It is important to quantify these differences for a range of feedstocks and technologies, across a range of geographic and climatic conditions, so that there is a stronger understanding of how bioenergy feedstocks can become more sustainable.

Therefore, the objective of this study was to evaluate environmental and energy impacts associated with generating 1 MJ of thermal energy from direct combustion of short rotation willow (SRW) pellets produced in Canada for 2 purposes: to determine where improvements could be made in the life cycle of SRW bioenergy to reduce impacts, and to compare SRW bioenergy to fossil fuel (light fuel oil and natural gas) for thermal energy. The study uses primary data from a SRW plantation at a research site at the University of Guelph, Ontario, Canada, the largest experimental willow establishment in eastern Canada. This study includes site-specific SRW characteristics and carbon sequestration modeling and provides an assessment of additional environmental impacts and benefits beyond GHGs and energy balance, which is missing from many other studies (Djomo et al. 2011). Although this study is based on a case study in Canada, the findings and insights are relevant for other types of short-rotation crops in regions with similar climate and operating conditions, and also provide a better understanding of the geographical and management influences on biomass and bioenergy. The results can be used to support SRW cultivation activities and to understand the barriers and opportunities for sustainable expansion of SRW biomass production in other regions.

3.4 Methodology

We used the life cycle assessment methodology as described by the ISO 14040 (ISO 2006a) and 14044 (ISO 2006b) guidelines to conduct a comparative LCA for thermal energy generation from SRW biomass and conventional fossil fuels. The scope of the study is from cradle-to-grave, beginning with resource extraction and ending with heat generation and associated emissions in an industrial furnace.

3.4.1 Goal and Scope

Our objectives were to: 1) identify environmental hot spots in the SRW bioenergy life cycle to suggest improvements to the system, and 2) compare the life cycle impacts of producing thermal energy with SRW biomass and conventional fossil fuels. The main function of the system is to generate heat, therefore the functional unit for analysis of the bioenergy pathway is defined as the production of 1 MJ of thermal energy using average combustion technologies with 75% efficiency.

The system boundaries and process flow diagram for this study include the following major processes in the supply chain: production of material and energy inputs, SRW biomass production, pelletization, feedstock transportation, and combustion of pellets in an industrial furnace. Inputs to SRW cultivation included willow cutting production, herbicide and fertilizer manufacture, production and combustion of various energy sources (e.g. diesel) used in cultivation and harvesting, and electricity use (Figure 3-1).

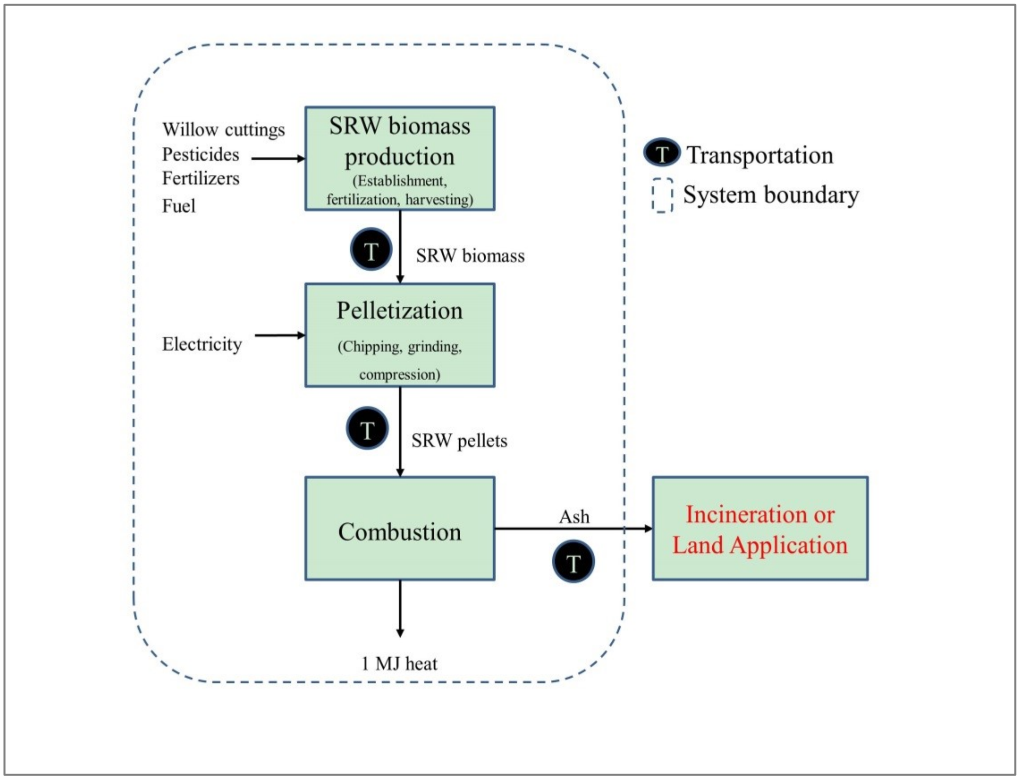

Figure 3-1. System boundaries and flow diagram for SRW bioenergy

It was assumed that biomass production, pelletization, and thermal energy generation activities occurred in Ontario, including electricity generation based on an average 2015

Ontario grid mix. Emissions and energy requirements associated with construction and decommissioning of infrastructure and equipment were not included.

3.4.2 System Description

The product systems considered in this study are thermal energy generation from SRW biomass, natural gas, and light fuel oil.

SRW BIOMASS THERMAL ENERGY GENERATION

The primary system modeled in this analysis is the production of SRW biomass established on Class 4 and 5 land (infertile land not suitable for agriculture) at the Guelph Agroforestry Research Site in Ontario in 2006 (Cardinael et al. 2012). A previously completed internal screening LCA identified key environmental and technical data gaps and provided initial insights on the SRW biomass production system (Dias et al. 2010), informing further field research priorities and data collection. These updated field data are the foundation for this study.

It is assumed that the plantation would operate for 6 harvest cycles (harvesting occurs every 3 years) for a lifetime of 19 years, including the establishment year. Based on the first harvest in 2010 at the Guelph site, the yield is 21 ODT/ha per harvest, or 7 ODT/ha/year. At the end of operation, the willow plantation is terminated by applying herbicide. All inputs and emissions associated with the establishment and termination of the plantation are amortized based on the duration of the plantation lifetime (i.e. 18 years). Sensitivity analysis, as described in Section 3.4.4, was also conducted to determine the impact of varying yields on the study results.

The SRW plantation is established in Year 0 by first cultivating the land and applying herbicides (Table 3-1). Willow cuttings are then planted at a rate of 15,000 cuttings/ha, with an additional 1,500 cuttings to account for 10% failed plantings in Year 0. The willow cuttings are produced in Quebec, Canada and transported 700 km to the Guelph site. The willow is coppiced in the Spring of Year 1. Thereafter, the plantation is maintained by applying urea fertilizer at a rate of 161 kg/ha every 3 years, starting in the spring of Year 1. The SRW is harvested every 3 years starting in the Fall of Year 3. A bio baler (Lavoie et al. 2001) is used to simultaneously cut and roll the SRW stems into bales, which are left on the field over winter, collected in the spring, and transported by truck to a pellet manufacturing plant. When they are collected, the bales have a moisture content of 12%, therefore no additional drying is required at the pellet plant.

Table 3-1. Key performance parameters used to model SRW biomass production at the Guelph Agroforestry Research Site in Ontario

Parameter	Value	Units	Comments
SRW establishment and maintenance			
Willow cutting planting density	15,000	cuttings/ha	Initial planting density
Additional cuttings	1,500	cuttings/ha	Replacement for unestablished cuttings
Dual II Magnum (82.4% a.i. S-Metachlor)	0.92	kg a.i./ha	Establishment
Goal 2XLm (22% a.i. Oxyfluorofen)	1.12	kg a.i./ha	Establishment
Urea; 46% N	161	kg/ha	Maintenance, every 3 years
Triple Super Phosphate; 45% P2O5	94	kg/ha	Maintenance, every 3 years
Muriate of Potash; 60.5% K2O	95	kg/ha	Maintenance, every 3 years
Roundup (49 % a.i. glyphosate)	2.5	kg a.i./ha	Termination at end of plantation life
Biomass Characteristics			
Moisture content of SRW bales	12	%	In spring following harvest; measured
Yield	7	odt/ha/y	Based on first harvest
Willow leaf input	1,800	kg/ha/y	Based on average at several sites
Pelletization Parameters [a]			
Energy content (LHV)	16.3	MJ/kg	Actual, based on analysis
Pellet Moisture content	5.1	% (dry)	Actual, based on analysis
Fixed carbon	5.1	%	Actual, based on analysis
Ash content	11.4	%	Actual, based on analysis

[a] Measured using proximate analysis

FOSSIL FUEL THERMAL ENERGY GENERATION SYSTEMS

The fossil fuel reference systems are light fuel oil (LFO) and natural gas (NG) combusted in an industrial boiler (<100kW). System boundaries for the fossil fuel systems include: raw material extraction, refining, storage, and transportation/ distribution. Infrastructure was excluded from this analysis to maintain consistent boundaries for both the biomass and fossil fuel systems.

3.4.3 Life Cycle Inventory Data

The life cycle inventory (LCI) is a compilation of the resource use and emissions to air, soil, and water that occur over the life cycle of the studied system. It is typically derived from a combination of primary data from the producers under study, and secondary data from peer-reviewed LCA databases and scientific literature (Lavoie et al. 2001). These LCI typically consist of activity level data, which is the amount of material or energy inputs required, and the associated emissions to the environment related to various impacts.

MATERIAL AND ENERGY INPUTS

Primary data were used to model production of willow cuttings and SRW biomass production. Data (confidential) on cutting production was provided by a Quebec company that maintains a willow nursery for cuttings. Data for the SRW biomass production were collected from field trials at the Guelph Agroforestry Research Site and from facility records. At the time of this study, the Guelph SRW plantation had been established 9 years and only 2 cycles had been completed, but data on yields, fertilizer rates, leaf fall, etc. are continually being collected as the SRW plantation matures. Fuel data were also estimated from the amount of time that equipment is used, or through fuel purchases (Table).

Secondary data on pelletization of wood biomass in Ontario were obtained from a publication on the life cycle impacts of generating electricity from wood pellets [34] and from the Ecoinvent 2.2. database (Frischknecht et al. 2005). The data for the pelletization process included electricity inputs to run the pelletization process and inputs of SRW biomass required to produce 1 ODT of pellets at 5% moisture content. Pelletization requires 1.3 tonnes of SRW biomass for every 1 tonne of SRW pellets produced (final moisture content=5%). The SRW pellets had a lower heating value (LHV) of 16.27 MJ/kg, which is considerably lower than values found in the literature for densified woody biomass.

Thermal energy generation was modeled based on an average industrial furnace from the Ecoinvent 2.2 database with an assumed average efficiency of 75%. Inputs to the heating process included SRW pellets, electricity to power the furnace, and transportation (50 km) of the SRW pellets from the pellet plant to the end user. Based on the LHV of pellets, and the assumed efficiency rating of the furnace, 82.0 g of SRW pellets (or 106.5 g of SRW biomass) are required to generate 1 MJ of heat.

EMISSIONS DATA AND MODELING

Secondary data from the Ecoinvent 2.2 database were used to characterize background processes such as the production and combustion of fossil fuel energy feedstocks, the manufacture and disposal of infrastructure components, the manufacture of agrochemical inputs, emissions and fuel consumption for various modes of transportation, and emissions from combustion of biomass and conventional fossil fuels.

Site-specific emissions for the SWR plantation were determined. Direct and indirect nitrous oxide (N_2O) emissions from N-fertilizers applied to fields and from SRW leaf litter were calculated based on Rochette et al. (2008), who provide Canada-specific emission factors (i.e. IPCC Tier II), while emissions of ammonia, nitric oxide, and phosphorus from fertilizers were estimated based on factors obtained from various studies (Table 3-1).

The air emissions profile for combustion was based on an Ecoinvent 2.2 process for combustion of wood pellets in an average industrial furnace. Air emissions from furnaces and boilers can be quite specific to the combustion technology employed and the nature/condition of the feedstock; therefore, these average values are appropriate for the goal and scope of this study, and allowed for consistent data quality for the comparison of SRW and reference fossil fuels. Carbon emissions from the combustion of SRW pellets were not included in the environmental impact calculations based on the assumption that the carbon uptake during SRW cultivation would offset any carbon emitted to the atmosphere during combustion of SRW pellets. This assumption is consistent with previous publications on perennial biomass systems (Ter-Mikaelian et al. 2015; Ericsson et al. 2014). Ash produced from combustion was assumed to be incinerated 50% of the time and applied to farmland 50% of the time, and these end-of-life processes were modeled using data from Ecoinvent 2.2.

Electricity use was modeled based on the average Ontario mix of electricity feedstocks between January and July of 2015: 60.4% nuclear, 23.9% hydro, 9.9% natural gas, 5.3% wind, 0.3% biofuel, and 0.1% solar (IESO 2017). Electricity generation processes for these six feedstocks were modeled using average unit processes for North America from the Ecoinvent 2.2 database, including material and energy inputs, power plant emissions and transmission losses.

3.4.4 Sensitivity Analysis

Sensitivity analysis was conducted on the following parameters associated with the plantation: yields (using 10 ODT/ha, based on yields from the most recent harvest cycle at Guelph and based on the lowest yields reported in other studies (Djomo et al. 2011; Gonzalez-Garcia et al. 2012) and assuming no change in fertilizer amounts to achieve these yields); fertilizer application rates (20% lower based on recent field studies at the Guelph willow site, showing no yield response to fertilizer (i.e. unfertilized plots had similar yields to fertilized plots; unpublished data)). Sensitivity analysis was also conducted on heating value for SRW pellets (using 19.8 MJ/kg as reported by Heller et al. (2003) and as used in other SRW LCA studies).

Since there is high uncertainty in soil carbon (C) sequestration rates, a sensitivity analysis was conducted to determine life cycle results with soil carbon sequestration. Soil carbon (i.e. soil carbon losses from the conversion of land from annual crop to SRW, and soil carbon gains due to SRW biomass production) were estimated using the Introductory Carbon Balance Model (ICBM) (Andren & Katterer 1997). This model has been successfully applied to Eastern Canadian agricultural regions (Bolinder et al. 2008) and has been previously used by Sanscartier et al. (2013, 2014) in Ontario bioenergy studies, and by Ericsson et al. (2014) in Sweden.

The ICBM estimates changes in soil C content based on initial soil C, annual input of fresh biomass (crop residue and below ground biomass based on harvested material at the Guelph site), biomass mineralization, and humification rates. The values for the parameters were selected to represent Ontario soils (Table). The annual C input of 2.65 t/ha/y from leaf and root biomass was calculated as follows:

- Total C mass returned to soil = C mass returned to soil from leaf fall + C mass returned to soil as root biomass
- C mass returned to soil from leaf fall = Leaf biomass (t/ha/y) * Foliar C (%) = 0.9 t/ha/yr
- Root biomass = SRW biomass yield (t/ha/y) x Root: Shoot ratio = 3.5 t/ha/yr
- C mass returned to soil as root biomass = Root biomass (t/ha/y) * Root biomass C (%) = 1.75 t/ha/yr

where Leaf biomass = 1.8 t dry matter/ha/y (measured at GARS site), Foliar C = 50%, Root: shoot ratio = 0.5, and Root biomass C = 50%.

The ICBM model was initialized to be at equilibrium as described in previous studies (Sanscartier et al. 2013; 2014) (i.e. initial distribution between young and old soil carbon was set to steady-state values for modeling). Soil carbon accumulation in the SRW plantation was determined over the lifetime of the SRW plantation (18 years).

3.4.5 Life Cycle Impact Assessment

Life cycle impact assessment (LCIA) involves the grouping and characterization of resource use and emissions from the LCI into environmental impact assessment categories (Pennington et al. 2014). The results for each impact category are then expressed relative to a reference unit (e.g. CO_2 equivalents). We used the SimaPro 8.04 LCA software program (Pré 2017) to model the studied systems and calculated life cycle impacts using the TRACI 2.1 (version 1.00) method which was developed by the U.S. EPA and is the only LCIA methodology available that is based on North American impact characterization factors (Bare et al. 2003). Only a subset of TRACI impact categories was chosen to focus on the most relevant environmental indicators for understanding the impacts of SRW bioenergy in Ontario, namely climate change, smog and air quality concerns, and eutrophication and acidification of water bodies (e.g. the Great Lakes). Therefore, the impact assessment included contributions to global warming potential (GWP), photochemical ozone formation potential (POFP), respiratory effects (RE), eutrophication potential (EP), and acidification potential (AP). In addition, total life cycle energy use was quantified using the Cumulative Energy Demand (CED) method v. 1.08 (Frischknecht et al. 2005).

3.5 Results

Results are presented for the generation of 1 MJ of thermal energy from SRW willow pellets, and include an analysis to identify what activities contribute the most impact in the life cycle of SRW bioenergy, and an analysis comparing SRW bioenergy to thermal energy from natural gas (NG) and light fuel oil (LFO).

3.5.1 Life Cycle Contribution Analysis of SRW Bioenergy

The production of SRW biomass, from cradle-to-farm gate, was the largest contributor to most impact categories in generating 1 MJ of thermal energy from SRW pellets (Figure 3-2), contributing 69% to GWP, 65% to AP and 88% to EP, which is similar to patterns found in other studies of biomass based energy (Gonzalez-Garcia et al. 2012; Gonzalez-Garcia et al. 2013). SRW biomass production and pelletization contributed to 37% and 33% of ODP, respectively. Combustion of SRW pellets was a major contributor to POFP (59%) and RE (75%), likely because we used data for average wood combustion and a low-efficiency furnace**.** The complete life cycle impact assessment results can be found in Table 3-2 and

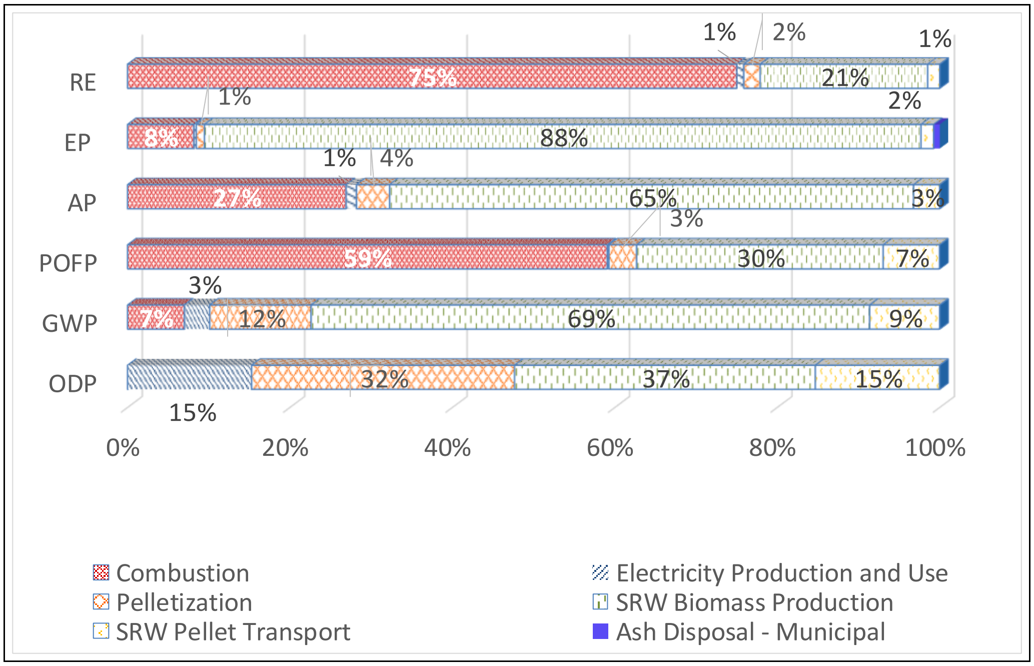

Figure 3-2. Contribution analysis for SRW heat production. GWP=global warming potential, POFP= photochemical ozone formation potential, RE=respiratory effects, EP=eutrophication potential, AP= acidification potential, and ODP=Ozone depletion potential.

The cradle-to-gate GWP for SWR biomass production is 93 kg carbon dioxide equivalents (CO_2eq)/ODT biomass (Table 3-2) or 5.7 g CO_2eq/MJ biomass. This is in the mid-range of other LCA studies (0.6 to 10.6 g CO_2eq per MJ biomass as reported by Djomo et al. (2011), but much higher than the GWP reported by Keoleian and Volk (2005) (GWP= 3.5 t CO_2eq for production of 274 t, or 13.5 kg CO_2eq/t of SRW biomass produced). The GWP is dominated by soil nitrous oxide emissions from urea fertilizer application (36%) and leaf inputs (26%). Smaller contributions to GWP were related to fertilizer production (16%) and equipment operation (14%) (Figure 3-3). Fertilizer-related emissions also dominate all other impact categories, contributing to 54% of EP (from phosphorus and nitrogen fertilizers), almost 50% to POFP, 84% to AP, and 66% to RE. Diesel combustion associated with field equipment operation is the other major contributor, being responsible for almost 50% of ODP and 44% of POPF. Other processes (i.e. transportation of inputs, cutting production, and herbicide production), accounted for less than 1% of all impacts, with the exception of ODP where herbicide production contributed to 6% of the impacts.

Table 3-2. Life cycle impact assessment results for production of 1 oven dry tonne of short-rotation willow biomass for TRACI indicators. GWP=global warming potential, POFP= photochemical ozone formation potential, RE=respiratory effects, EP=eutrophication potential, AP= acidification potential, and ODP=Ozone depletion potential.

Impact category	ODP	GWP	POFP	AP	EP	RE
Unit	kg CFC-11 eq	kg CO_2 eq	kg O_3 eq	kg SO_2 eq	kg N eq	kg $PM_{2.5}$ eq
Pesticide Production	3.4E-07	3.3E-01	1.8E-02	3.8E-03	3.2E-03	2.8E-04
Fertilizer Production	2.6E-06	1.5E+01	6.5E-01	1.1E-01	2.2E-01	1.3E-02
Equipment Operation	2.7E-06	1.3E+01	5.2E+00	1.6E-01	1.4E-02	1.1E-02
Transport	2.0E-11	4.7E-01	6.9E-02	2.1E-03	1.4E-04	4.2E-05
Cutting Production	7.3E-14	1.7E-06	7.1E-08	3.7E-09	7.5E-10	3.3E-10
Fertilizer Soil N2O	0.0E+00	3.3E+01	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Leaf Input Soil N2O	0.0E+00	2.4E+01	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Fertilizer Non-N2O	0.0E+00	5.6E+00	5.9E+00	1.5E+00	2.8E-01	4.7E-02
Total	**5.7E-06**	**9.3E+01**	**1.2E+01**	**1.7E+00**	**5.2E-01**	**7.2E-02**

The CED for SRW biomass production is 497 MJ/ODT (3.5 GJ/ha), of which 99% was non-renewable energy sources (see Appendix A – Table A5). Most of the CED was related to fertilizer production (58%) and diesel use in field equipment operation (39%), particularly for harvesting. This result is consistent with values reported by Djomo et al. (2011) in a review of several SRW studies. The net energy ratio (ER) (Energy contained in harvested biomass divided by fossil energy consumed to produce the biomass) for the SRW biomass in this study is 33. Keoleian and Volk (2005) reported an ER of 16.6 after the first rotation, but when considering increasing yields with time (from 10 to 13.6 ODT/ha), the ER increased to a value of 55. Accounting for differences in methodologies and boundaries in several studies, Djomo et al. (2011) report a range of ER from 13 to 79. The ER found for this SRW plantation is in the middle of this range and could potentially improve with higher yields as the plantation matures. This is explored further in the sensitivity analysis.

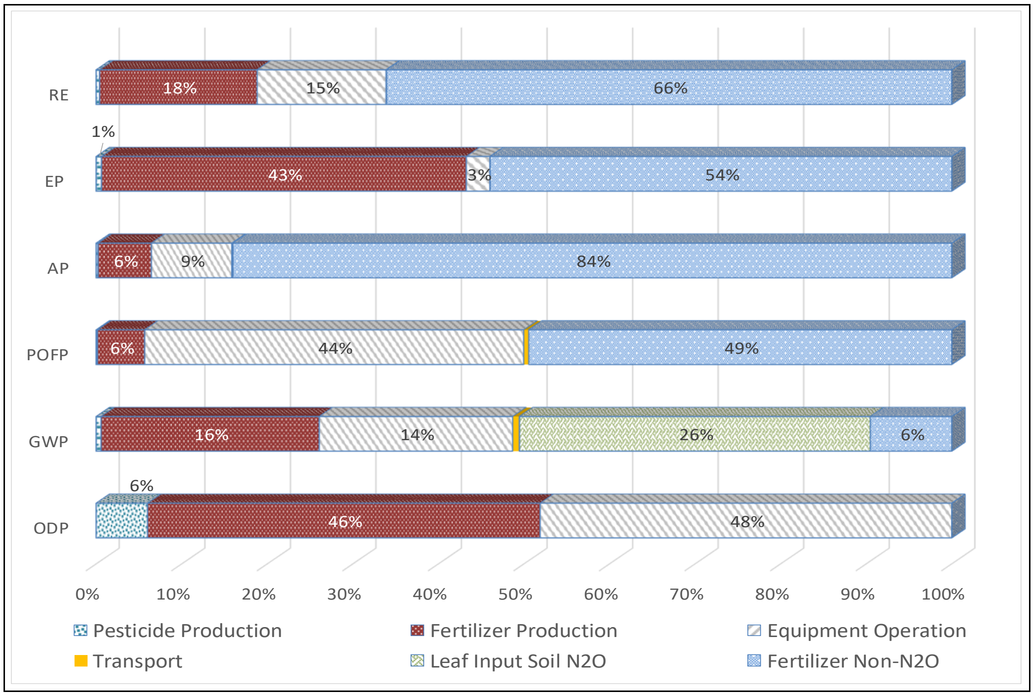

Figure 3-3. Contribution analysis for short-rotation willow biomass production. GWP=global warming potential, POFP= photochemical ozone formation potential, RE=respiratory effects, EP=eutrophication potential, AP= acidification potential, and ODP=Ozone depletion potential.

The production of 1 ODT of SRW pellets produces 102 kg CO_2eq, which is 6.3 g CO_2eq/MJ of energy (based on the pellet energy content of 16.27 MJ/kg). This value is lower than the values reported in Chapter 5 for Nova Scotia wood pellets made from sawmill residues at 368 kg CO_2eq/ODT (19.9 g/MJ at 18.5 MJ/kg) and wood pellets made from chipping of harvested primary forest at 251 kg CO_2eq/ODT (13.6 g/MJ). However, this study had similar values to those of wood biomass electricity generation in Ontario (Zhang et al. 2010) (113 kg CO_2 eq/ODT (5.79 g/MJ at 19.5 MJ/kg) for wood pellets from chipping of harvested primary forest) and a study of wood pellets made from sawmill residues in British Columbia (Magelli et al. 2009) (87.2 kg CO_2 eq/ODT (4.72 g/MJ at 18.5 MJ/kg). The importance of the source of energy supply for pelletization and drying energy was shown by Magelli et al. (2009), since using natural gas for drying energy increased GWP to 278 kg CO_2 eq/ODT (15 g/MJ) for British Columbia pellets.

3.5.2 Comparison of SRW Pellets and Fossil Fuels for Thermal Energy Generation

The GWP for SRW heat generation is 14.3 g CO_2eq/MJ of thermal energy generated (Table), which is 85% lower than for LFO and NG (86.5 and 75.1 g CO_2eq/MJ thermal energy generated, respectively). In contrast, for all other impact categories (except ODP), using SRW pellets as fuel resulted in higher EP, AP, POFP, and RE, compared to using either LFO or NG (Figure 3-4). Although few SRW bioenergy studies assess these impact categories, those that have considered impacts other than GWP, also show trade-offs in environmental performance of SRW bioenergy, particularly with respect to EP (Gonzalez-Garcia et al. 2012; Gonzalez-Garcia et al. 2013).

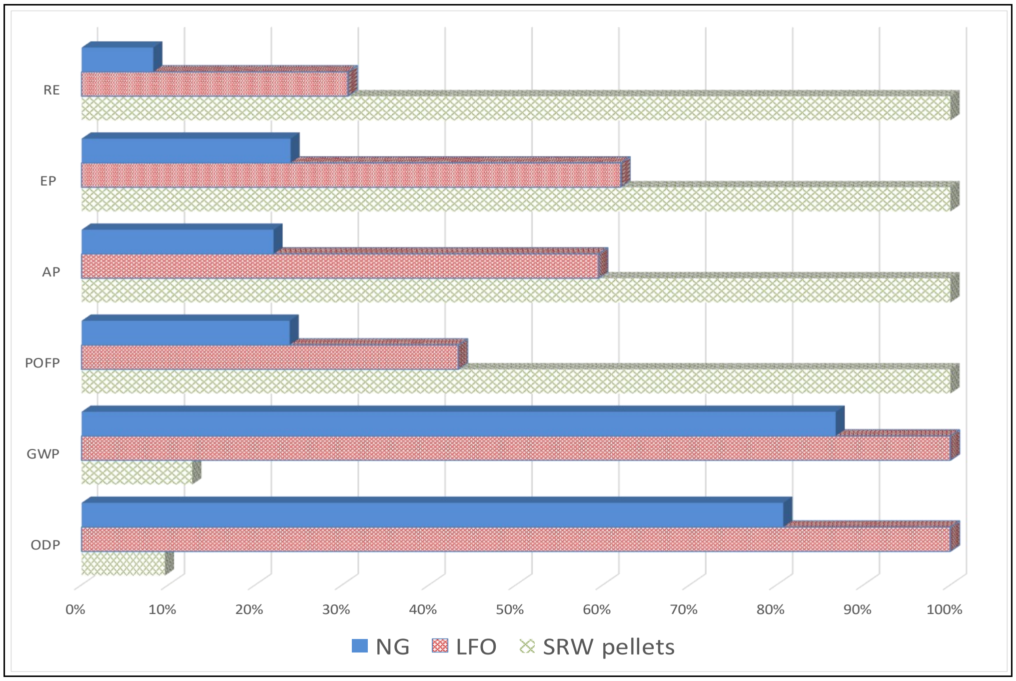

Figure 3-4. Comparison of impacts for 1 MJ of heat produced using short-rotation willow pellets and conventional fuels. GWP=global warming potential, POFP= photochemical ozone formation potential, RE=respiratory effects, EP=eutrophication potential, AP= acidification potential, and ODP=Ozone depletion potential.

The CED for the production of 1 MJ of thermal energy using willow pellets is 2.0 MJ (Table), which is higher than that for LFO (1.27 MJ) and NG (1.28 MJ); however, over 85% of the CED for SRW thermal energy is related to the input of SRW biomass and is renewable, compared to less than 1% renewable energy inputs for the LFO and NG life cycles. The energy ratio (usable energy produced/total fossil energy input) is 3.6 over the life cycle, which is on the lowest end of the range of ER (3 to 16) reported by Djomo et al. (2011) for SRW feedstocks. This low ER is partially due to the lower LHV of SRW biomass in this study, compared to other studies, which generally use a value of 19.8 MJ/kg based on Heller et al. (2004). The effect of using different values for these parameters is explored further below through a sensitivity analysis.

3.5.3 Sensitivity and Improvement Analysis

Sensitivity analysis was conducted on key study parameters and assumptions. Specifically, we considered higher yields (10 ODT/ha), lower fertilizer application rates (20% less), and higher biomass energy content (19.8 MJ/kg as reported by Heller et al. (2003)). Results are reported relative to the initial modeling conditions for the SRW case, and not relative to the fossil fuel scenarios.

Achieving higher yields could provide the greatest reductions in GWP, AP, and EP (18%, 19%, and 27%, respectively (Table 3-3). By including potential soil carbon sequestration by SRW biomass there is a 23% GWP reduction, to 62 kg CO_2eq/ODT biomass or 3.8 g CO_2eq/MJ biomass. This value is in the lower range of 0.6 to 10.6 g CO_2eq per MJ biomass reported by Djomo et al. (2011). Reducing the amount of fertilizer applied resulted in a 17% reduction in EP.

Table 3-3. Sensitivity analysis showing percent change for 1 MJ of heat generated using short-rotation willow pellets relative to short-rotation willow base case. Sensitivity analysis provided for changes in yield, fertilizer use, lower heating value (LHV), and including soil carbon sequestration (SCS).

Impact category	Yield: 10 ODT/ha	Fertilizer: 20% less	Soil Carbon Sequestration	LHV: 19.3 MJ/kg
ODP	-11%	-3%	0%	-11%
GWP	-21%	-8%	-23%	-13%
POFP	-9%	-3%	0%	-5%
AP	-19%	-12%	0%	-11%
EP	-27%	-17%	0%	-14%
RE	-6%	-4%	0%	-4%
CED	-1%	0%	N/A	-21%

If a higher heating value for SRW pellets could be achieved, CED could be reduced by 21%. The ER was also recalculated based on the results of the sensitivity analysis, and was most influenced by energy content of the biomass, increasing from 3.6 in the base case to 4.1 when SRW pellets have higher energy content, but still in the lower range of ER values reported (Djomo et al. 2011).

3.6 Discussion

Dedicated energy crops, such as SRW biomass, are increasingly being used globally for various applications, such as greenhouse heating (Dias et al. 2017), electricity production (Sanscartier et al. 2013), and household heating (Fantozzi & Buratti 2010). Therefore, it is important to have a broad understanding of the effect of site- and technology-specific factors on the environmental performance of these systems so that they can be implemented sustainably.

This study compared the use of SRW pellets and fossil fuel feedstocks for thermal energy generation through direct combustion. Studies of the environmental performance of SRW biomass are diverse in the energy scenarios assessed, ranging from using willow for electricity production, to anaerobic digestion, to thermal energy generation. This makes it challenging to directly compare the performance across studies. Nevertheless, energy production from SRW has been shown to result in a lower GWP than using fossil fuels (Lettene et al. 2003; Ericsson et al. 2014; Heller et al. 2003; Heller et al. 2004; Rafaschieri et al. 1999; Gasol et al. 2009; Goglio & Owende 2009) and our findings are consistent with the literature in this regard.

The only directly comparable study is a recent study on thermal energy generation through direct combustion of SRW chips in an industrial boiler, Gonzalez-Garcia et al. (2013) report a GWP of 35.2 g CO_2eq/MJ thermal energy generated, which is more than double what we found in this study. The difference could be a result of the higher moisture content of the chips (40%), which requires more drying energy. There is a slight advantage to using the SRW harvest system developed in Canada, which cuts, shreds and bales the willow stems (Lavoie et al. 2001). The bales can be left to dry on the field before being chipped or pelletized, reducing moisture content from about 50% to 12%.

Despite some of the benefits of using SRW biomass, the biomass production phase of the life cycle dominates most of the impacts associated with generating 1 MJ of heat in an average furnace, and this needs to be addressed in order to maximize the benefits of SRW biomass-based energy. The ability to procure environmentally and economically sustainable feedstocks for bioenergy is a major concern globally. The sensitivity analysis showed that areas to target for improving environmental performance of SRW include achieving higher yields. Recent field results (unpublished) support potential of yields of at least 10 ODT/ha. Various authors have claimed that much higher SRW yields are achievable. Volk and Luzadis (2009) suggested that new willow clones could grow >15 ODT ha^{-1} $year^{-1}$ on 3- to 4-year rotations, and fertilized and irrigated willow crops in 3-year rotation can achieve yields >27 ODT ha^{-1} yr^{-1} in North America (Adegbidi et al. 2001) and >30 ODT ha^{-1} yr^{-1} in Europe (Christersson et al. 1993). However, these yields have yet to be realized, with recent studies reporting yields that are much less than 17 ODT/ha (Ericsson et al. 2014; Gonzalez-Garcia et al. 2012; Gonzalez-Garcia et al. 2013; Djomo et al. 2011).

Research is needed on how to reduce fertilizer rates without affecting SRW yields, since the manufacture and use of fertilizers is a major contributor to impacts. Recent field results from the Guelph SRW site have shown a lack of fertilizer response, with no significant difference in yields for fertilized and unfertilized SRW plots. Furthermore, more research is needed on using different types of fertilizers (organic), or wastes (e.g. municipal or agricultural wastewater) to increase SRW yields. Buonocore et al. (2012, pg. 76) explored the integration of urban wastewater with SRW biomass production and bioenergy production and found it to create a “quasi zero-emission” situation that when properly integrated maximizes resource use and environmental management. Using municipal and agricultural wastewaters along with marginal and degraded land resources has the added benefit of improving feedstock productivity while providing environmental restoration (Gopalakrishnan et al. 2009) and could reduce costs, leading to the goal of producing sustainable low-cost feedstocks. Nevertheless, fertilizer-related emissions are also a function of agroclimatic conditions, and in this study they were more than twice those reported by Keoleian and Volk (2005), despite the higher application of N in the study by Keoleian and Volk (100 kg N/ha compared to 74 kg N/ha in this study). This underscores the influence of site-specific factors on impacts related to SRW bioenergy.

Carbon sequestration at the willow plantation represents a significant opportunity to offset GWP in the life cycle of SRW bioenergy. The SRW plantation was established on low quality land that is not suitable for food production, and this may have also affected SRW biomass yields. Nevertheless, given that the effects of carbon sequestration on GWP largely depends on the previous land use, soil type, and initial soil organic carbon (Bare et al. 2003), with lower initial carbon leading to the highest short-term sequestration rates, this is an advantage of using marginal land. In some cases marginal land could be pasture, which has higher initial soil C, leading to a carbon debt, and less GHG benefits. However, these dynamics require further research to maximize this benefit.

On a full life-cycle basis, the ER in this study was very low relative to what was reported for several other studies, all of which used chips instead of pellets (Djomo et al. 2011). The energy used to pelletize and transport the pellets, accounted for 84% of the life-cycle non-renewable energy use. Pelletization is often seen as a way to reduce the costs of transportation by increasing energy density of the feedstock, but the energy trade-offs do not seem to be beneficial from an energy return perspective. Thus, the technology used to transform biomass is an important aspect to consider in terms of the environmental performance of SRW biomass.

Despite the high energy use for pelletization, our study showed that producing wood pellets from SRW could result in lower GHG emissions relative to other pellet feedstocks, such as sawmill residues and chipping of harvested roundwood from primary forest production. There are additional benefits of using SRW biomass relative to other wood biomass feedstock sources, such as providing ecosystem services and improvements in biodiversity (Rowe et al. 2009). It also has potential to serve as living snow fences, windbreaks, riparian buffers, and alternate landfill covers (Volk et al. 2006; Volk et al. 2004). Finally, properly-managed SRW plantations could provide a steady supply of feedstock which can reduce pressures on limited stocks of sawmill and forest harvest residues, and can reduce pressures to increase primary forest harvest to supply feedstock which can have a number of negative impacts on forest ecosystems (Thiffault et al. 2010; Hesselink 2010).

Finally, combustion emissions were another important source of impacts. Data quality was an issue because it reflected older technologies with fewer air emission controls. Keoleian and Volk (2005) suggest that combustion emissions (e.g. NOx) from biomass are case-specific as they depend on the composition of the biomass as well as boiler configurations and the operating parameters. Although commercial providers of pellet stoves and furnaces claim cleaner combustion with newer models, there are no data available to support these claims. It is likely that technological improvements in air emission controls can be realized to manage these impacts associated with combustion of SRW biomass.

This study only considered direct combustion for the production of bioenergy. From an energy security and resource maximization perspective, other bioenergy technologies need to be explored. Other studies have shown that conversion of SRW biomass to liquid fuels is not as beneficial as direct combustion or combined heat and power (CHP) for reducing GWP and energy use (Ericsson et al. 2014; Gonzalez-Garcia et al. 2012). Future research should consider CHP or pyrolysis, as the latter can also provide other benefits, such as soil improvements through the application of bio-char by-products resulting from pyrolysis.

3.7 Conclusions

This study presented an LCA of bioenergy production based on primary SRW biomass production data from Canada, with the goal of identifying areas of improvement for enhancing environmental performance of SRW biomass production and use. The full life cycle results show that there are substantial reductions of GWP relative to fossil fuels in direct combustion in a furnace to generate thermal energy. Nevertheless, there are some challenges in the environmental performance of SRW biomass for bioenergy which require further research to reduce or manage. Specifically, further research is required to improve SRW biomass yields, to understand fertilizer response by SRW crops, to determine how SRW crops respond to organic or waste sources of fertilizer and water and how this affects environmental performance, and to improve conversion technologies, such as low emission wood pellet stoves.

Future research on SRW biomass should consider other end uses for willow, such as ethanol, gasification, and combined heat and power to compare and optimize environmental and technical performance of willow bioenergy. Additionally, non-energy uses should be explored, such as activated carbon, as these might be even more beneficial environmentally and financially. Finally, to meet the goal of low-cost sustainable feedstocks, life cycle costing and the assessment of the economic feasibility of SRW biomass-based bioenergy is needed.

The use of biomass for bioenergy could be an important way to mitigate climate change, and produce economic benefits, but it is crucial that this source of energy does not come with other environmental costs. This study showed that it is important to consider site-specific and technology factors in the environmental performance of bioenergy systems.

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CHAPTER 4: SUPPLYING RENEWABLE ENERGY FOR CANADIAN CEMENT PRODUCTION: LIFE CYCLE ASSESSMENT OF BIOENERGY FROM FOREST HARVEST RESIDUES USING MOBILE FAST PYROLYSIS UNITS

4.1 Publication Information

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4.2 Abstract

Cement production contributes over 5% of global greenhouse gas (GHG) emissions, and the industry has seen increasing use of fossil fuels over time. Heavy manufacturing industries like cement production continue to rely primarily on fossil fuels for primary energy production and have limited renewable energy options. This study used life cycle assessment (LCA) to quantify the potential environmental benefits of substituting bio oil and biochar from mobile fast pyrolysis of forest harvest residues for fossil fuels in an average cement plant in Québec, Canada. Bioenergy Pathways for cement production showed reductions in non-biogenic GHG emissions as high as 50% relative to the Reference Pathway for energy provision in the plant. The use of bio oil and biochar from mobile pyrolysis units increased the share of renewable energy in the cement plant energy mix from just under 15% in the Reference Pathway up to 47% and 73% in the Bioenergy Pathways, depending on the scale of fuel substitution. Bioenergy Pathways also led to decreases in potential acidification, ozone depletion, respiratory effects, and eutrophication impacts, with slightly higher contributions to smog-forming emissions. The environmental and socioeconomic sustainability of fast pyrolysis units are strongly

linked to the availability of, and proximity to, sufficient forest harvest residues, such that regional-level analysis of feedstock availability is needed prior to wide-scale deployment of these systems.

4.3 Introduction

Despite global efforts to reduce greenhouse gas (GHG) emissions from industrial activities, carbon dioxide (CO_2) emissions from fossil fuel combustion have continued to rise, and increasing atmospheric concentrations of CO_2 are pushing global average temperatures beyond thresholds associated with significant climate change impacts (Hansen et al. 2017). More aggressive emissions reduction strategies are required to mitigate or reverse these trends, including the need for fundamental changes to primary energy generation systems to reduce dependence on fossil fuels across all sectors of the economy. This change has begun in the large-scale electricity generation sector, where the increasing substitution of renewable energy from solar, wind, and biomass have led to significant reductions in fossil fuel use worldwide (World Energy Council 2016). However, other large-emitting industrial sectors which rely on both liquid and solid fossil fuels for transportation, resource extraction, and process heat production still have limited technological options to switch to renewable, lower-carbon fuels. This includes heavy resource extraction and mining industries, as well as primary material manufacturing industries such as the production of steel and cement. For example, CO_2 emissions from global cement production have more than doubled in the last decade, and now account for 5.8% of global CO_2 emissions (Borden et al. 2017). Over 40% of these emissions can be attributed to onsite fossil fuel combustion for process heat and energy (Nyboer and Bennet 2014). In Canada, cement production currently accounts for 1.4% of national GHG emissions totals, and in stark contrast to the urgent need to reduce fossil fuel consumption, the use of carbon-dense fuels such as coal and petroleum coke in Canadian cement production has risen from 55% of energy production in 1990 to well-over 80% as of 2012 (Nyboer 2014).

Cement is one of the most basic building materials used throughout the economy, and significant efforts are needed to reduce the reliance of this industry on fossil fuels (Salas et al. 2016). The recent development of pyrolysis technologies in Canada to convert wood biomass feedstocks into renewable fuels for use in industrial energy production has the potential to contribute to this objective. Pyrolysis is a process by which organic materials are converted to a complex mixture of oxygenated compounds, including a condensable liquid, a charcoal product, and a mixture of non-condensable gases (syngas) (Steele et al. 2012). To target the pyrolysis oil, a fast pyrolysis process is used in which the feedstock is rapidly heated to approximately 400 degrees Celsius in less than 2 seconds (Steele et al. 2012). This technology is currently available in the form of mobile fast pyrolysis units in Quebec, which can be used to convert forest harvest residuals into bio oil, biochar, and syngas. These systems have the potential to supply cement manufacturing facilities with renewable fuels in areas where harvest residuals are available; however, despite the potential for reducing GHG emissions relative to fossil fuels, the life cycle environmental performance of these pyrolysis fuels have not yet been quantified in the Canadian context.

We used life cycle assessment (LCA) to quantify the environmental impacts and benefits of using mobile pyrolysis units to produce bio oil and biochar from forest harvest residues as a substitute for fossil fuels in an average Canadian cement production plant. The cement plant was assumed to operate in Québec, which is Canada’s second largest cement producing province contributing 17% of national production (Natural Resources Canada 2009). The pyrolysis technology under study is currently available in Québec and is being targeted for use with heavy emitting producers, in-part because of recent carbon cap-and-trade regulations established by the provincial government (Government of Québec).

In addition to supplying heavy industrial producers with renewable fuels and potentially reducing GHG emissions from this sector, the development of these technologies could also help to support and diversify Canada’s forest industry, which is currently shifting towards supporting greater bioenergy and biomaterial production (Natural Resources Canada 2017). Reducing GHG emissions is particularly important for the competitiveness of Canada’s manufacturing sector, as federal legislation will be introduced in 2017 to implement a carbon tax that will result in significant cost increases for heavy emitters (Government of Canada 2016).

4.3.1 Assessing the Life Cycle Impacts of Wood Biomass Energy

Wood biomass energy has been of increasing interest as a renewable, potentially low-carbon substitute for fossil fuels in a range of energy applications, and the life cycle environmental impacts of many different wood biomass energy systems have been quantified in the scientific literature. Particular emphasis has been on quantifying changes in life cycle GHG emissions relative to fossil fuels (Lippke et al. 2012; Muench 2015; Suopajarvi et al. 2017; Weldemichael & Assefa 2016; Zhang et al. 2010). More specifically, LCA has been used to assess the environmental impacts of several wood pyrolysis systems (Ibarrola et al. 2012; Kung et al. 2013; Manyele 2007; Page-Dumroese et al. 2009; Peters et al. 2015; Steele at al. 2012).

The literature on wood biomass energy systems contains considerable variability in study results and conclusions, in particular with respect to GHG emissions, where there remains ongoing debate about the appropriate accounting of carbon emissions from biogenic sources (Miner et al. 2014; Ter-Mikaelian et al. 2015). Ultimately, the environmental impacts and benefits of wood biomass energy can vary substantially depending on the source and type of feedstock available, the conversion technology, the combustion technology, and the type and quantity of fossil fuels displaced (Cherubini et al. 2009; Dias et al. 2017; Roy & Dias 2017). Given these sources of variability, and the variability observed in methodological approaches and assumptions in the literature, it can be challenging to draw broad conclusions on the environmental impacts of biomass energy systems (Bentsen 2017). It is therefore important to separately evaluate emerging bioenergy technologies and consider the more specific conditions under which they will be deployed, and to consider environmental impacts beyond contributions to global warming from GHG emissions. Thus, the overall objective of this study was to use LCA to characterize the potential environmental benefits of using commercially-available mobile fast pyrolysis units to convert forest harvest residues to renewable bio oil and biochar for the displacement of fossil fuels in cement manufacturing in Québec.

4.4 Methodology

4.4.1 Life Cycle Assessment

Life cycle assessment is an internationally-recognized and standardized environmental management tool under the ISO 14040 and 14044 guidelines (ISO 2006). It can be used to quantify the environmental impacts of products and processes throughout the entire supply chain, from raw material extraction through to use and end of life. The use of LCA allows for the broad consideration of impacts to ecosystems, human health, and resource depletion to inform the identification of improvement opportunities and potential environmental trade-offs between products and production methods. The method consists of an iterative, four-stage process including goal and scope definition, compilation of the life cycle inventory, estimation of potential life cycle environmental impacts, and interpretation of results.

4.4.2 Goal and Scope Definition

STUDY OBJECTIVES

The objectives of this study were to:

- Quantify the potential environmental impacts and benefits of substituting bio oil and biochar from mobile fast pyrolysis of forest harvest residues for fossil fuels in an average Canadian cement production facility in Québec; and
- Quantify the life cycle impacts of producing bio oil and biochar from forest harvest residues in a novel mobile fast pyrolysis plant to identify opportunities to improve the environmental performance of the pyrolyzer and its supply chain.

FUNCTIONAL UNIT AND SYSTEM BOUNDARIES

The functional unit for this study is based on the annual production of 300,000 tonnes of cement clinker in an average Canadian cement plant located in Québec using either a Bioenergy Pathway or the Reference Pathway for onsite energy generation. The system boundary for the Bioenergy Pathway is outlined in Figure 4-1 and includes feedstock acquisition, transport and processing, production of bio oil and its co-products (fast pyrolysis), manufacturing of the pyrolysis plant, and transport and use of bio oil and biochar at an average Canadian cement production plant in Québec.

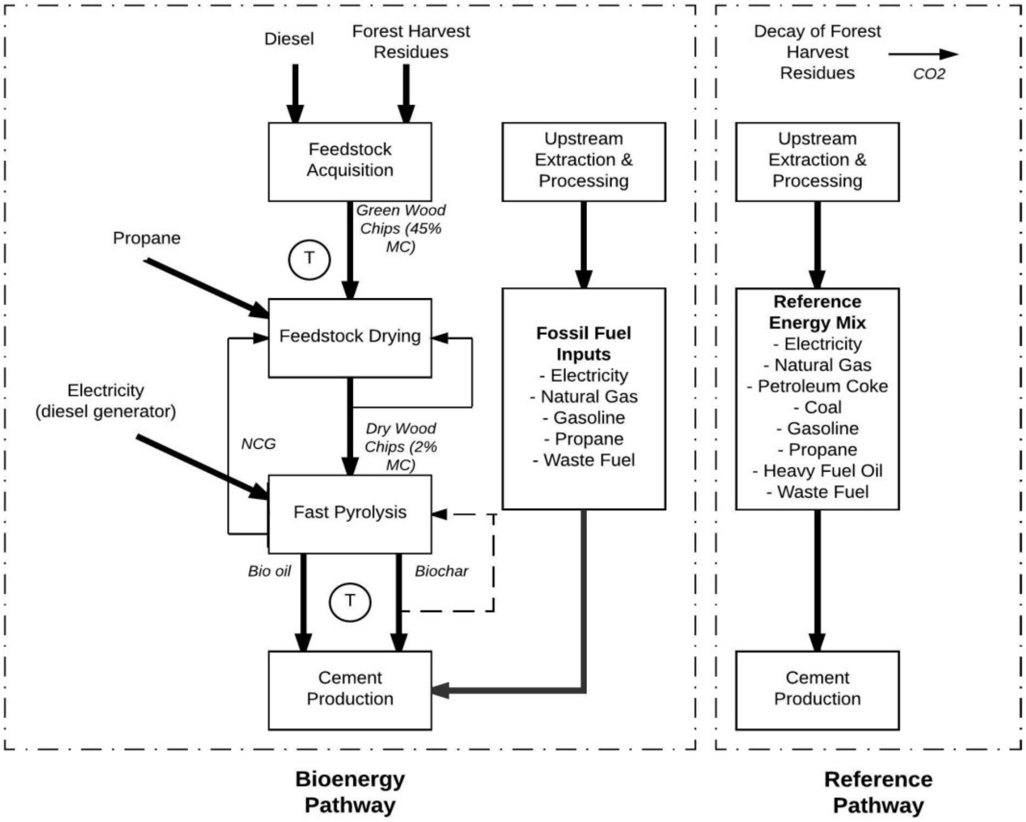

Figure 4-1. System boundaries for the LCA of bio oil production in mobile fast pyrolysis units, including use of bio oil and biochar in an average Canadian cement production plant, and a reference cement production scenario. "T" denotes transportation of products between production points.

The fast pyrolysis plant modeled in this study is a 50 tonne per day (TPD) mobile plant that uses steel-shot fluidized bed technology and feedstock drying process at the front-end. Before undergoing pyrolysis, green wood chips are fed into a modified chain flail dryer which simultaneously dries and pulverizes the wood chips to a moisture content of 2%. The dryer is heated by a 110 HP fluidized bed combustion furnace which burns dry biomass and is periodically started up with a propane burner. Wood chips are fed continuously into the dryer and then into the pyrolysis chamber, which is heated by a second 110 HP fluidized bed furnace and powered by a 25 HP electric motor.

Feedstock acquisition includes the collection and processing of forest harvest residues, including the tops and branches of harvested trees, which are typically left in piles at the side of logging roads by primary log harvesters. The residues are chipped in a mobile chipper at the roadside and loaded into trucks for delivery to the pyrolysis plant. The green wood chips are approximately 5 cm in diameter and have a moisture content of 40-50%.

The outputs of the fast pyrolysis process consist of approximately 65% bio oil (17.7 MJ/kg), 20% biochar (25.6 MJ/kg) and 15% syngas (NCG) (12.7 MJ/kg). The bio oil and biochar can be used as substitutes for liquid and solid fossil fuels in industrial furnaces, while the syngas is primarily used to generate heat for wood chip drying within the pyrolysis process itself.

Dry wood chips derived from forest harvest residues are used in three streams within the process, including the front-end drying process, heating of the pyrolysis chamber, and as feedstock that is converted to bio oil. It is assumed that the forest residues have no upstream environmental burden associated with them as they are produced as part of forestry operations and left at the forest roadside as a waste. Based on Section 4.3.4.2 of the ISO 14044 guidelines, environmental burdens are not to be allocated to wastes (ISO 2006). Syngas from the pyrolysis process is used within the pyrolysis system to provide heat to the front-end drying and pulverizing process. Biochar can be used for heat within the pyrolyzer instead of dry wood chips or can also be sold to external producers for energy production or other applications.

The pyrolysis outputs are assumed to substitute for only a portion of the fossil fuel inputs to cement production, with the level of substitution depending on the number of 50 TPD pyrolysis plants operated. As such, the Bioenergy Pathway also includes the upstream extraction and processing, and onsite combustion emissions of the remaining fossil fuel inputs to the cement production process.

The system boundary for the Reference Pathway includes the upstream extraction and processing of energy feedstocks and related infrastructure, as well as onsite energy production and emissions based on the energy mix for an average Canadian cement producer (Nyboer 2014).

For both the Bioenergy and Reference Pathways, other material inputs and processes involved in cement manufacturing have been excluded from the analysis (e.g. mineral inputs, chemical reactions in clinker production). These other inputs and processes are equivalent between the two production pathways regardless of the energy generation pathway used to support cement production.

4.4.3 Life Cycle Inventory and Scenario Descriptions

The life cycle inventory (LCI) is a compilation of all the relevant inputs and outputs associated with production of the functional unit, including material and energy extraction and emissions to air, water, and soil. The LCI for this study was compiled through a combination of primary data on the inputs and outputs of the fast pyrolysis process, and secondary data from the Ecoinvent 3.3 database (Frischknecht et al. 2005) and other literature sources for other life cycle materials and processes. The LCI was used to build process flow models of the studied systems in the openLCA 1.6 LCA software program (Winter et al. 2015). Primary and secondary data sources are summarized in the following sections.

FAST PYROLYSIS FOR BIO OIL PRODUCTION

Process data for the pyrolysis unit were based on an actual material and energy balance for a 50 TPD mobile fast pyrolysis system provided by a confidential Canadian producer. These data were used to calculate the feedstock and energy inputs required to produce 1 kg of bio oil (Table 4-1). Diesel consumption for the chipping of forest residues was provided by the confidential producer for a 150 HP chipper operating 8 hours per day and producing 10 tonnes of green wood chips per hour. Upstream inputs and emissions from diesel production and emissions from diesel combustion were modeled using an average Ecoinvent 3.3 unit process. The transport distance (40 km) for green wood chips to the pyrolysis plant is based on one potential production scenario, and data on the resource use and emissions associated with large truck transport were obtained from the Ecoinvent 3.3 database.

The feedstock drying unit requires a start-up twice per week using a propane burner, and a steady input of dry wood chips and syngas from the pyrolysis process. Since the mobile pyrolysis unit would be located close to remote forest residues there is no grid power available; therefore, it was assumed to be powered by a diesel-electric generating set. It was assumed that the pyrolysis unit would operate 24 hours a day for 330 days per year for a total operating capacity of 7,920 hours per year. At this production level, a single 50 TPD pyrolysis facility could produce approximately 10,700 tonnes of bio oil, 3,295 tonnes of biochar, and 2,480 tonnes of syngas. Material inputs for manufacturing of the pyrolysis unit were modeled based on primary data from specification sheets for a 50 TPD pyrolysis unit provided by the confidential producer.

Primary data on air emissions from the pyrolyzer and from bio oil combustion were not available for the technology under study, so secondary data from a published LCA on pyrolysis of forest harvest residues in the United States were used (Steele et al. 2012). Sensitivity analysis was conducted to determine the influence of these secondary data on the study results (Section 4.6).

CEMENT PRODUCTION SCENARIOS

We modeled the use of bio oil and biochar as substitutes for fossil fuels in an average cement production plant in Québec, Canada (system boundaries in Figure 4-1). Data on the primary energy sources used in average Canadian cement production were obtained from a 2014 industry report for the most recently-available year of data in 2012 (Table 4-2). The life cycle impacts of this Reference Pathway were modeled using Ecoinvent 3.3 processes for average electricity production and on-site heat production in an industrial furnace in Québec. These are the energy inputs to all processes in the cement manufacturing process and are based on data collected from actual Canadian facilities (Nyboer & Bennett 2014).

Table 4-1. Life cycle inventory modeling assumptions for producing 1 kg of bio oil in a 50 TPD mobile fast pyrolysis unit. Data from confidential producer.

Model Parameter	Amount	Units	System Modeling Assumptions and Sources [a]
Feedstock Acquisition			
Inputs			
Forest harvest residues	3.21	kg	Harvest residues chipped at forest roadside
Diesel (wood chipper)	0.32	L	*wood chipping, chipper, mobile, diesel, at forest road*
Outputs			
Green wood chips (45% mc)	3.21	kg	Assumed 100% material capture
Transport, to pyrolysis unit	0.13	tkm	*transport, freight, lorry 16-32 metric ton*
Feedstock Drying			
Inputs			
Green wood chips (45% mc)	3.21	kg	
Propane	0.16	g	*heat production, propane, at industrial furnace*
Dry wood chips (2% mc)	0.14	kg	
Syngas (NCG)	0.23	kg	Syngas input is from pyrolysis unit
Outputs			
Dry wood chips (2% mc)	1.77	kg	
Water	1.44	kg	Evaporation
Fast Pyrolysis			
Inputs			
Electricity (diesel generator)	0.075	kW	*diesel, burned in diesel electric generating set 10MW*
Dry wood chips – feedstock	1.54	kg	Used as feedstock for the pyrolysis process
Dry wood chips - heating	0.09	kg	Used for heating in the pyrolysis unit
Outputs			
Bio oil	1.00	kg	Energy content: 17.7 MJ/kg
Biochar	0.31	kg	Energy content: 25.6 MJ/kg
Syngas (NCG)	0.23	kg	Energy content: 12.7 MJ/kg
Air Emissions (Pyrolyzer)			
HCl	6.7E-05	g	(Steele et al., 2012)
SO_x	4.1E-03	g	(Steele et al., 2012)
CH_4	1.0E-04	g	(Steele et al., 2012)
NO_x	5.7E-03	g	(Steele et al., 2012)
CO	5.1E-04	g	(Steele et al., 2012)
PM_{10}	1.9E-04	g	(Steele et al., 2012)
VOC	2.9E-05	g	(Steele et al., 2012)
Transport to Cement Plant			
Transport, bio oil, to plant	0.25	tkm	Distance: to cement plant - 250 km
Transport, biochar, to plant	0.08	tkm	Distance: to cement plant – 250 km
Material Inputs to 50 TPD Pyrolysis Unit [b]			
Inputs			
Stainless steel	4.0E-05	kg	*steel, chromium steel 18/8 – GLO*
Carbon steel	1.8E-04	kg	*steel production, electric, low-alloyed – Québec*
Rock wool	4.0E-06	kg	*stone wool, packed – GLO*
Cement	1.4E-05	kg	*cement production, Portland cement – Québec*
Welding	4.0E-06	m	*welding, arc, steel - Québec*

[a] Unit processes listed in this table are from the Ecoinvent 3.3 database

[b] Material inputs to the pyrolysis unit include a 15% maintenance factor and a 20-year service life for the unit

Other material inputs to cement production (e.g. limestone) and air emissions from chemical conversions during clinker production were excluded from the analysis since they would be equivalent between the Reference Pathway and the Bioenergy Pathways.

We developed a set of cement production scenarios to quantify the change in life cycle impacts associated with substitution of bio oil and biochar from fast pyrolysis for conventional fossil fuels used in cement production. These scenarios are defined in Table 4-3 and include production using a single 50 TPD mobile pyrolysis unit, and production using three 50 TPD mobile pyrolysis units to supply the cement plant with renewable fuel. The single pyrolysis unit scenario was modeled as a baseline production scenario, while the three-unit scenario was modeled to determine the resource use and emissions associated with full displacement of heavy fuel oil and coal in the plant's energy mix.

Table 4-2. Primary energy inputs to 1 tonne of cement production for an average Canadian cement plant in 2012 (Reference Pathway) (Nyboer and Bennett 2014)

Input	Amount	Unit	System Modeling Assumptions and Sources [a]
Conventional Cement Production			
Electricity	605	MJ	*electricity, medium voltage – Québec*
Natural gas	724	MJ	*heat production, natural gas, at industrial furnace >100kW – Québec*
Petroleum coke	1,610	MJ	*heat production, at coal coke industrial furnace 1-10MW - Québec*
Hard coal	1,400	MJ	*heat production, at hard coal industrial furnace 1-10MW – Québec*
Heavy fuel oil	49	MJ	*heat production, heavy fuel oil, at industrial furnace 1MW – Québec*
Light fuel oil [b]	99.6	MJ	*heat production, light fuel oil, at industrial furnace 1MW - Québec*
Propane [b]	64.6	MJ	*heat production, propane, at industrial furnace >100kW - Québec*
Waste fuel	415	MJ	*heat production, wood, postconsumer at furnace 1000-5000kW - ROW*
Total per tonne	**4,970**	**MJ**	

[a] Unit processes listed in this table are from the Ecoinvent 3.3 database

[b] Light fuel oil and propane were used to represent energy use data listed as "Confidential" in the cement industry report. The amounts were based on an energy use profile of the Canadian cement production industry from 2009 (Natural Resources Canada 2009)

Table 4-3. Life cycle inventory data and scenario descriptions for cement manufacturing using the Reference Pathway and two alternative Bioenergy Pathways for the use of bio oil and biochar from mobile fast pyrolysis units.

Model Input	Amount	Units	Scenario Description
Reference Pathway			
Pyrolysis units operated (50 TPD)	0	units	A Québec cement plant produces 300,000 t of cement in one year using the Canadian average mix of primary energy inputs to cement manufacturing. Forest residues are not utilized and are assumed to be left to decay at the forest roadside.
Forest residues collected	0	t	
Cement Plant Inputs			
- Average 2012 energy mix for Canadian cement plants (see Table 2)			
Bioenergy Pathway 1			
Pyrolysis units operated (50 TPD)	1	units	Forest harvest residues are collected at roadside and used to fuel one pyrolysis unit to supply the Québec cement plant with bio oil to fully replace heavy fuel oil for energy production, as well as a portion of coal-fired heat at the plant. The biochar co-product is used to replace a portion of petroleum coke energy production. These substitutions account for 18% of total energy demand at the plant
Forest residues collected	34,400	t	
Transport to cement plant	250	km	
Cement Plant Inputs			
Bio oil input	10,700	t	
• Heavy fuel oil reduction	342 (100%)	t	
• Coal reduction	6,240 (42%)	t	
Biochar input	3,290	t	
• Petroleum coke reduction	2,560 (17%)	t	
Bioenergy Pathway 2			
Pyrolysis units operated (50 TPD)	3	units	Forest harvest residues are collected at roadside and used to fuel three pyrolysis units to supply a Québec cement plant with bio oil to fully replace heavy fuel oil and hard coal for energy production. A portion of the biochar co-product is used to replace wood chips for drying energy in the pyrolysis units, with the rest being used to replace petroleum coke at the cement plant. These substitutions account for 42% of total energy demand at the plant
Forest residues required	103,100	t	
Transport to cement plant	250	km	
Cement Plant Inputs			
Bio oil input	24,500	t	
• Heavy fuel oil reduction	342 (100%)	t	
• Coal reduction	15,000 (100%)	t	
Biochar input	7,600	t	
• Petroleum coke reduction	5,900 (40%)	t	

The Reference Pathway is based on assumed annual production of 300,000 tonnes of cement. Energy inputs per tonne from the Canadian average data were scaled according to this annual production amount. In the Reference Pathway, no bio oil is produced, and it is assumed that forest harvest residues would remain at the forest roadside to naturally decay, as this is the current management method being used. The decay of the residues

For each of the Bioenergy Pathways, it is assumed that bio oil is used to replace heavy fuel oil and coal in cement production, and biochar is used to replace petroleum coke energy.

4.4.4 Life Cycle Impact Assessment

The primary life cycle impact assessment (LCIA) methodology used in this study was the TRACI 2.1 method, which was developed by the United States Environmental Protection Agency (USEPA) and is the only LCIA methodology that is based on North American impact characterization factors (Bare et al. 2003; USEPA 2012). We chose a subset of the full suite of indicators available in TRACI to focus on indicators that have robust characterization factors and that reflect impacts of concern for bioenergy systems, including: global warming potential (GWP); acidification potential (ADP); ozone depletion potential (ODP); photochemical oxidant formation (SMOG); respiratory effects (RESP); and eutrophication potential (EUT). Ecotoxicity and human toxicity impact categories were excluded due to uncertainty about their relevance for the systems under study. All TRACI impact categories provide mid-point assessments, which indicate potential contributions to impacts and do not reflect actual damage to ecosystem and human endpoints.

For global warming impacts, biogenic carbon emissions from the combustion of wood biomass feedstocks were excluded from the calculations. We excluded these emissions to be consistent with current national reporting requirements for Canada's National Inventory Report on Greenhouse Gas Emissions. Technical guidance from Environment and Climate Change Canada (ECCC) indicates that to be consistent with the United Nations Framework Convention on Climate Change (UNFCCC), biogenic carbon emissions should not be included in national inventory totals (Environment and Climate Change Canada 2016). The exclusion of carbon emissions from biomass sources has been challenged and explored in great detail in the scientific literature (Johnson 2009; Smyth et al. 2016; Ter-Mikaelian et al. 2015), and so we provide sensitivity analysis in Section 3.3 in which biogenic carbon emissions are accounted for to show how the results may change due to these assumptions.

In addition to the TRACI indicators used, life cycle energy consumption was quantified separately using the Cumulative Energy Demand (CED) method v. 1.08 (Hischier et al. 2010). This method provides a summation of total energy use across all life cycle activities and breaks the energy use demand down into non-renewable and renewable sources.

IMPROVEMENT SCENARIOS FOR THE PYROLYSIS SUPPLY CHAIN

A key objective of this study was to identify potential environmental improvement opportunities for the mobile fast pyrolysis system. We assessed two scenarios that could potentially reduce the environmental impacts within the bio oil supply chain, including:

- Complete substitution of wood chips used for drying in the front-end unit and pre-heating in the pyrolysis unit with biochar produced by the pyrolysis process; and
- Complete substitution of the diesel used to power the mobile wood chipper and diesel used in the electric generating set with bio oil produced by the pyrolysis process.

The latter is a hypothetical scenario because at present, the ability to use bio oil in diesel engines is limited by the available combustion technologies. We include this scenario to show the potential benefits and to highlight the broader need for engines capable of burning biofuels within industrial supply chains.

4.4.5 Sensitivity Analysis

As part of the interpretation of the study results, we conducted sensitivity analysis on key study parameters. Sensitivity analysis is a systematic procedure for estimating the effects of the chosen methods and data on the outcome of a study using either arbitrarily selected ranges of variation, or variations that represent known ranges of uncertainty (Guo & Murphy 2012). In accordance with ISO 14044 guidelines for LCA, we identified a series of sensitivity tests based on issues predetermined by the goal and scope, results of the LCIA, and expert judgement on key parameters (ISO 2006).

Table 4-4. Summary and rationale for sensitivity analyses conducted on the study results for bio oil production and for both cement production scenarios.

Parameter	Sensitivity Test	Rationale
Fast Pyrolysis – 1 kg of bio oil		
Transport – green wood chips from forest to pyrolysis unit	Base case – 40 km Test 1 – 100 km Test 2 – 250 km	Increasing demand for biomass feedstocks across several sectors (i.e. biofuels, electricity generation, space heating, biomaterials) could force producers to obtain wood chips from more distant sources. These sensitivity tests show the potential change in results when base case supply chain assumptions are varied.
Air emissions – combustion emissions from the pyrolyzer	Test 1 – base case emissions +50% Test 2 – base case emissions -50%	Primary data were not available to characterize the emissions from running the pyrolyzer. These tests show the sensitivity of the study results to the secondary data used.
Cement Production – Bioenergy Pathways 1 and 2		
Transport – bio oil and biochar from pyrolysis producer to cement plant	Base case – 250 km Test 1 – 50 km Test 2 – 500 km	The base case study results are based on one potential production scenario in which we assumed a specific distance between the pyrolysis unit and the cement plant. These transport distance tests show how the sensitivity of the study results to shorter and longer distances of final product transport.
Air emission – combustion emissions from use of bio oil in an industrial furnace	Test 1 – base case emissions +50% Test 2 – base case emissions -50%	Primary data were not available to characterize the emissions from burning the bio oil and biochar in an industrial furnace. These tests show the sensitivity of the study results to the secondary data used.
Biogenic Carbon – Bioenergy Pathways 1 and 2		
Carbon emissions – decay of carbon from harvest residues and carbon emissions from bio oil and biochar combustion	Base case – biogenic carbon excluded Test 1 – biogenic carbon emissions from harvest residue decay and combustion included	The prevailing assumption is that forest harvest residues are a carbon neutral energy feedstock. We tested the sensitivity of the study results to the inclusion of biogenic carbon emissions from the forest harvest residues used as feedstock.
Rate of carbon decay from harvest residues	Base case – k-value of 0.056 Test 1 – k-value of 0.087 (for wood debris in Ontario (Cleary and Caspersen, 2015))	Carbon emissions from wood biomass decay can vary significantly depending of regional conditions. This is reflected in the k-value used to characterize the carbon decay rate. This test shows the sensitivity of the study results to the assumed k-value.

The key variables explored for sensitivity analysis were transportation distance to the pyrolyzer, variation in pyrolyzer air emissions and in bio oil combustion emissions, and the inclusion of biogenic carbon in the impact calculations, as summarized in Table 4-4. Results of the sensitivity analyses are provided in Section 4.6.

BIOGENIC CARBON

To test the sensitivity of the study results to the exclusion of biogenic carbon emissions, we conducted a sensitivity test for each cement production scenario to include biogenic carbon emissions from forest harvest residue decay and combustion of bio oil and biochar (Table 4-4). For the Reference Pathway, it was assumed that forest harvest residues left at the roadside would naturally decay and gradually release CO_2 to the atmosphere over the study period. In the Bioenergy Pathways, these residues are converted to bioenergy products and CO_2 is released to the atmosphere when they are combusted for energy production. We modeled these scenarios over a 100-year study period with the assumption that there are no technology changes or changes in the supply chain activities. The rate that residues decay when left on the forest floor is:

Eq. 1. $C_t = C_0 e^{-kt}$

where C_0 is the mass of carbon stored in the residues at the time of harvest, C_t is the remaining mass *t* years after harvest, and *k* is the rate of decomposition (Cleary and Caspersen 2015). We assumed a carbon content of 0.5 tonnes of C per dry tonne of residues, and a k-value of 0.056, which is an average estimate for the decay rate of forest residues in the clay-belt region of Ontario and Québec. The results for global warming are based on cumulative emissions to the atmosphere in each scenario across the study period. Results are provided for year 20 to match the expected service life of the pyrolysis unit, and then for every 25 years beyond that.

4.5 Results

Results of the LCIA are summarized below, including comparative results for the substitution of bioenergy for fossil fuels in cement production, contribution analysis showing the primary sources of environmental impacts in bio oil production using fast pyrolysis, and results of the improvement analysis and sensitivity analysis.

4.5.1 Impacts of Bioenergy Substitutions in Energy Provision for Cement Production

The primary objective for this study was to determine the life cycle impacts of substituting bio oil and biochar for fossil fuels in average Canadian cement production, as described in Table 4-3. Results of the LCIA for the Reference Pathway and both Bioenergy Pathways are summarized in Figure 4-2 and Table 4-5 and Table 4-6.

For Bioenergy Pathway 1, 18% of total energy use at the cement plant was converted from fossil fuels to bioenergy, resulting in substantial reductions in life cycle environmental impacts associated with energy provision across most impact categories considered (Figure 4-2, Table 4-5). This included a 20% reduction in GWP, 19% reduction in ACD, 27% reduction in EUT, 13% reduction in RESP, and a 6% reduction in ODP.

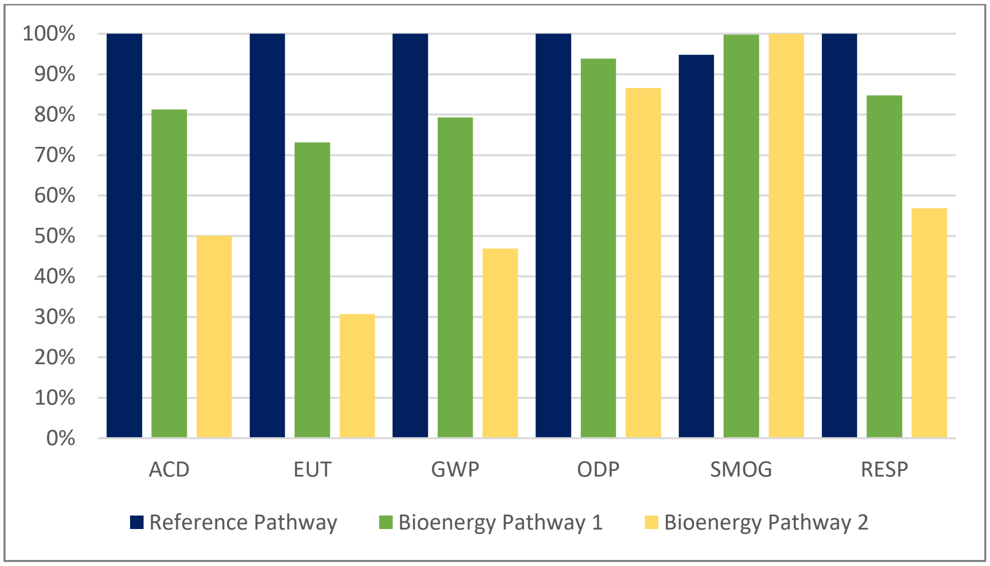

Figure 4-2. Comparison of the life cycle environmental impacts of the Reference Pathway for cement production with two alternative Bioenergy Pathways featuring the substitution of bio oil and biochar from mobile fast pyrolysis units for fossil fuels in energy production for the cement plant. ***GWP = Global Warming; ACD = Acidification; ODP = Ozone Depletion; SMOG = Photochemical Oxidant Formation; RESP = Respiratory Effects; EUT = Eutrophication***

These lower impacts were largely due to the reduced use of heavy fuel oil and coal (14,700 GJ and 175,000 GJ, respectively). Additionally, the substitution of biochar for petroleum coke energy (84,300 GJ) contributed significantly to these impact reductions. These three fossil fuels were the primary contributors to life cycle impacts in the Reference Pathway (Table 4-5). There was a slight increase in life cycle SMOG impacts (~4%), resulting primarily from combustion of wood chips in the pyrolysis unit and combustion of the bio oil and biochar at the cement plant.

Table 4-5. Life cycle environmental impacts for the energy provision required for annual production of 300,000 tonnes of cement from an average cement plant (Reference Pathway), and from two alternative Bioenergy Pathways with bio oil and biochar substituted for fossil fuels in energy production at the plant. Percent change in total impacts is shown bioenergy scenarios relative to the reference pathway.

Life Cycle Stage	GWP *kg CO_2 eq.*	ACD *kg SO_2 eq.*	ODP *kg CFC-11 eq.*	SMOG *kg O_3 eq.*	RESP *kg $PM_{2.5}$ eq.*	EUT *kg N eq.*
Reference Pathway						
Petroleum coke	7.3E+07	5.2E+05	3.1E+00	4.0E+06	8.9E+04	1.8E+05
Hard coal	5.1E+07	3.8E+05	2.7E-01	3.2E+06	3.0E+04	1.8E+05
Natural gas	1.8E+07	4.9E+04	5.9E+00	4.8E+05	6.9E+03	1.2E+04
Heavy fuel oil	1.4E+06	9.1E+03	3.4E-01	5.5E+04	7.2E+02	7.6E+02
Other fuels	2.2E+07	2.8E+04	1.2E+00	5.9E+05	9.6E+03	7.2E+03
Total	**1.7E+08**	**9.8E+05**	**1.1E+01**	**8.3E+06**	**1.4E+05**	**3.9E+05**
Bioenergy Pathway 1 – One Pyrolysis Unit						
Petroleum coke	6.1E+07	4.3E+05	2.6E+00	3.3E+06	7.3E+04	1.5E+05
Hard coal	3.0E+07	2.2E+05	1.6E-01	1.9E+06	1.7E+04	1.1E+05
Natural gas	1.8E+07	4.9E+04	5.9E+00	4.8E+05	6.9E+03	1.2E+04
Other fuels	2.2E+07	2.8E+04	1.2E+00	5.9E+05	9.6E+03	7.2E+03
Bioenergy production [a]	9.1E+05	2.2E+04	2.2E-01	7.3E+05	5.0E+03	2.0E+03
Bioenergy combustion [b]	2.7E+04	5.0E+04	0.0E+00	1.7E+06	2.7E+03	3.1E+03
Transport – to plant	5.2E+05	2.4E+03	1.3E-01	5.6E+04	2.8E+02	5.8E+02
Total	**1.3E+08**	**8.0E+05**	**1.0E+01**	**8.7E+06**	**1.2E+05**	**2.8E+05**
Percent Change	**-24%**	**-18%**	**-9%**	**+5%**	**-14.3%**	**-28%**
Bioenergy Pathway 2 – Three Pyrolysis Units						
Petroleum coke	3.5E+07	2.5E+05	1.5E+00	1.9E+06	4.2E+04	8.7E+04
Natural gas	1.8E+07	4.9E+04	5.9E+00	4.8E+05	6.9E+03	1.2E+04
Other fuels	2.2E+07	2.8E+04	1.2E+00	5.9E+05	9.6E+03	7.2E+03
Bioenergy production*	2.0E+06	5.0E+04	4.8E-01	1.7E+06	1.1E+04	4.6E+03
Bioenergy combustion**	6.2E+04	1.1E+05	5.5E-10	4.0E+06	6.3E+03	7.1E+03
Transport – to plant	1.2E+06	5.5E+03	2.9E-01	1.3E+05	6.5E+02	1.3E+03
Total	**7.8E+07**	**4.9E+05**	**9.3E+00**	**8.7E+06**	**7.7E+04**	**1.2E+05**
Percent Change	**-54%**	**-50%**	**-15%**	**+5%**	**-45%**	**-69%**

GWP = Global Warming; ACD = Acidification; ODP = Ozone Depletion; SMOG = Photochemical Oxidant Formation; RESP = Respiratory Effects; EUT = Eutrophication

[a] Bioenergy production includes feedstock acquisition, feedstock drying, and fast pyrolysis for bio oil and biochar

[b] Bioenergy combustion includes air emissions from combustion of both bio oil and biochar

For Bioenergy Pathway 2, 42% of total energy use at the plant was converted from fossil fuels to bioenergy, resulting in substantial reductions in life cycle environmental impacts from energy generation for nearly all environmental indicators, including reductions of 50% or greater for GWP, ACD, and EUT. Respiratory effects were 45% lower than the Reference Pathway, while ODP saw a more modest reduction of approximately 15%. This is due to the substitution of bio oil for heavy fuel oil and coal energy (14,700 and 419,000 GJ, respectively), and the substitution of biochar for petroleum coke energy (195,000 GJ annually). Similar to Bioenergy Pathway 1, there was a relatively small potential increase in life cycle SMOG impacts (5%).

Table 4-6. Cumulative Energy Demand (CED) for the energy provision required for annual production of 300,000 tonnes of cement from an average cement plant (Reference Pathway) and from two alternative Bioenergy Pathways in which bio oil and biochar are substituted for fossil fuels for onsite energy production.

Production Scenario	Non-Renewable (MJ)	Renewable – Biomass (MJ)	Renewable – Other (MJ)	Total (MJ)
Reference Pathway	1.5E+09	1.2E+07	2.2E+08	1.7E+09
Bioenergy Pathway 1 – 1 unit	1.2E+09	3.4E+08	2.1E+08	1.7E+09
Bioenergy Pathway 2 – 3 units	7.0E+08	7.7E+08	2.0E+08	1.7E+09

It should also be noted that there is an excess amount of 7,600 tonnes of bio oil produced annually in Bioenergy Pathway 2. This bio oil could be sold to another industrial user to replace heavy fuel oil, or potentially substituted for diesel in the pyrolysis supply chain (see Section 4.4.3) leading to the potential for additional overall impact reductions beyond what is presented here, but these have been excluded to focus on changes occurring directly at the cement plant.

4.5.2 Contribution Analysis for Cement Production Energy

For cement production using the Reference Pathway, life cycle environmental impacts associated with the production and combustion of petroleum coke and hard coal were the greatest contributors across all impact categories considered, together accounting for over 80% of impacts in each category. For Bioenergy Pathway 1, only a portion of the petroleum coke and hard coal were replaced with bioenergy, and as such, petroleum coke and hard coal continued to be the environmental hot spots across all impact categories considered for this pathway. Bio oil production and combustion made relatively minor contributions to life cycle impacts for Bioenergy Pathway 1, ranging from < 1.0% of GWP impacts up to approximately 8% of ACD impacts. The one exception was SMOG, where bio oil production and combustion accounted for more than 25% of the impacts.

For Bioenergy Pathway 2, the fraction of petroleum coke which was not displaced by bioenergy remained a key contributor to several impact categories, including GWP (45%), ACD (50%), RESP (55%) and SMOG (22%). Impacts associated with bio oil production and combustion made up a greater proportion of the impacts in several impact categories in Bioenergy Pathway 2, most notably ACD (30%), SMOG (65%), and RESP (23%).

Cumulative energy demand was shown to be essentially equivalent between the Reference Pathway cement production and both Bioenergy Pathways (Table 4-6); however, as the amount of bio oil and biochar substituted for fossil fuels is increased across the scenarios, the share of energy demand met by consumption of renewable energy sources increases. While the Reference Pathway is reliant on over 85% non-renewable fossil fuels, the substitution of bioenergy for fossil fuels in Bioenergy Pathways 1 and 2 provides an increase in renewable energy use of 32% and 58% of total CED, respectively.

4.5.3 Life Cycle Impact of Bio Oil Production

The second objective for this study was to quantify the life cycle impacts of producing bio oil from forest harvest residues in mobile fast pyrolysis units to identify environmental hot spots and improvement opportunities along the supply chain.
For the production of 1 kg of bio oil, the main contributor to most impact categories were the air emissions from the pyrolyzer, accounting for over 70% of SMOG, RESP, and ACD impacts, and nearly 50% of EUT impacts (Figure 4-3 and Table 4-7). These impacts are from air emissions resulting from the combustion of wood chips in the pyrolyzer. The roadside chipping of forest harvest residues was the second largest environmental hot spot, accounting for 46% of GWP impacts, 45% of ODP impacts, and

19% of EUT impacts. These impacts were due to the production and combustion of diesel used to power the chipper. The use of a diesel-powered electric generator to power the pyrolyzer was also a hot spot, accounting for over 25% of GWP and ODP impacts, and 10-15% of all other impact categories. The transportation of green wood chips from the forest roadside to the pyrolysis unit was also a hot spot, accounting for just over 25% of both GWP and ODP impacts.

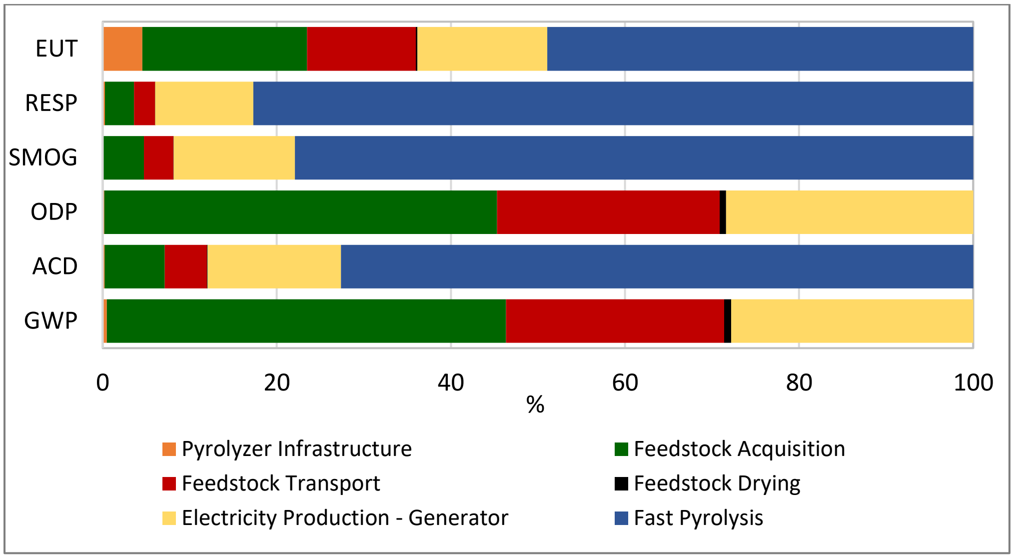

Figure 4-3. Contribution analysis for the life cycle environmental impacts of producing 1 kg of bio oil in a mobile fast pyrolysis unit.

The total energy demand (CED) for producing 1 kg of bio oil in a mobile fast pyrolysis unit is approximately 7 MJ of energy, consisting of 1.3 MJ of non-renewable energy and 5.7 MJ of renewable energy. Considering the bio oil energy content of 17.7 MJ/kg, the pyrolysis system requires approximately 0.4 MJ of energy input to produce 1 MJ of available energy. Nearly all of the renewable energy demand for pyrolysis is coming from the combustion of dry wood chips and syngas for drying incoming feedstock. Additionally, the Energy Ratio (ER), which is a measure of renewable energy produced relative to non-renewable energy inputs (Dias et al. 2017), is 13.4 for bio oil from mobile fast pyrolysis.

Table 4-7. Life cycle environmental impacts of producing 1 kg bio oil in a mobile fast pyrolysis unit using forest harvest residues.

	GWP	**ACD**	**ODP**	**SMOG**	**RESP**	**EUT**
	kg CO_2 eq.	*kg SO_2 eq.*	*kg CFC11 eq.*	*kg O_3 eq.*	*kg $PM_{2.5}$ eq.*	*kg N eq.*
Pyrolyzer Infrastructure	1.0E-15	1.5E-03	4.3E-23	5.3E-02	3.9E-04	8.7E-06
Feedstock Acquisition	3.9E-02	1.4E-04	9.2E-09	3.2E-03	1.6E-05	3.6E-05
Feedstock Transport	2.1E-02	9.8E-05	5.2E-09	2.3E-03	1.1E-05	2.4E-05
Feedstock Drying	9.0E-05	1.7E-07	1.9E-11	2.0E-06	1.6E-08	4.4E-08
Electric Generator	2.4E-02	3.1E-04	5.8E-09	9.5E-03	5.3E-05	2.9E-05
Fast Pyrolysis	6.0E-04	1.1E-06	1.3E-10	1.4E-05	1.1E-07	9.3E-05
Total	**8.5E-02**	**2.0E-03**	**2.1E-08**	**6.8E-02**	**4.7E-04**	**1.9E-14**

GWP = Global Warming; ACD = Acidification; ODP = Ozone Depletion; SMOG = Photochemical Oxidant Formation; RESP = Respiratory Effects; EUT = Eutrophication

4.5.4 Improvement Scenarios for the Pyrolysis Supply Chain

Substituting biochar to completely replace wood chips for drying energy reduced life cycle impacts by approximately 1% to 9% across all impact categories considered, with the highest reductions being for GWP (-9.3%) and ODP (-9.3%) (Table 4-8). This substitution also reduces the demand for forest harvest residues by approximately 0.42 kg per kg of bio oil, which leads to an annual reduction in forest residue demand of over 4,500 tonnes, or 13% (assuming 330 days of production) per 50 TPD pyrolysis unit. Furthermore, the substitution of biochar for dry wood chips in pyrolysis drying reduces CED by 12%, down to 6.2 MJ per kg of bio oil (Table 4-9), because of reduced consumption of diesel in the mobile chipper and the reduced transportation of green wood chips to the pyrolysis plant.

Substituting bio oil for diesel in wood chipping and in the diesel-electric generator for the pyrolysis unit reduced GWP by 35% and ODP impacts by 36%, and a moderate decrease in EUT impacts; however, it leads to slight increases in ACD, SMOG, and RESP impacts.

Using bio oil in the electricity generation unit could lead to reductions across all impact categories, with particularly large reductions to GWP (27%) and ODP (27%) and approximately 10% reductions for all other categories. The CED decreases by less than 5% when substituting bio oil for diesel in both mobile wood chipping and onsite electricity generation for the pyrolysis unit (Table 4-9); however, this substitution does increase the use of renewable energy within the supply chain.

Table 4-8. Life cycle environmental impacts for production of 1 kg of bio oil in a mobile fast pyrolysis unit for the base case (wood chip drying) and alternative feedstock drying option using biochar, and substitution of bio oil for diesel in mobile wood chipping and power generation for the pyrolysis unit. Percent change is relative to the base case.

Sensitivity Test	GWP *kg CO_2 eq.*	ACD *kg SO_2 eq.*	ODP *kg CFC-11 eq.*	SMOG *kg O_3 eq.*	RESP *kg $PM_{2.5}$ eq.*	EUT *kg N eq.*
Base case production of 1 kg of bio oil						
	8.5E-02	2.0E-03	2.1E-08	6.8E-02	4.7E-04	1.9E-04
Substitution of biochar for wood chips in drying unit						
Impact	7.8E-02	2.0E-03	1.9E-08	6.8E-02	4.6E-04	1.8E-04
% Change	-9.3%	-1.6%	-9.3%	-1.1%	-0.8%	-4.1%
Substitution of bio oil for diesel in mobile wood chipper						
Impact	5.5E-02	2.1E-03	1.3E-08	7.0E-02	4.7E-04	1.8E-04
% Change	-35.2%	+0.9%	-36.1%	+2.6%	+0.7%	-5.6%
Substitution of bio oil for diesel in generator for pyrolysis unit						
Impact	6.3E-02	1.8E-03	1.5E-08	6.2E-02	4.2E-04	1.7E-04
% Change	-26.5%	-10.4%	-27.1%	-9.1%	-10.1%	-10.9%

Table 4-9. Cumulative Energy Demand (CED) for the production and combustion of bio oil, and for the combustion of bio oil and heavy fuel oil in an average industrial furnace.

Production Scenario	Non-Renewable (MJ)	Renewable – Biomass (MJ)	Renewable – Other (MJ)	Total (MJ)
Feedstocks				
1 kg bio oil – base case	1.3E+00	5.7E+00	7.6E-03	7.0E+00
1 kg bio oil – biochar drying	1.2E+00	5.0E+00	6.8E-03	6.2E+00
1 kg bio oil – bio oil wood chipping	8.6E-01	5.8E+00	5.9E-03	6.7E+00
1 kg bio oil – bio oil power unit	9.8E-01	5.8E+00	6.2E-03	6.8E+00

4.6 Sensitivity Analysis

4.6.1 Bio Oil Production

The cradle-to-pyrolyzer gate environmental impacts of producing 1 kg of bio oil are quite sensitive to the distance required to transport green wood chips to the plant. In particular, GWP and ODP impacts could increase by over 100% when the distance is extended to 250 km. This distance may not be economically feasible, however even at a more moderate increase to 100 km, GWP and ODP impacts could increase by nearly 40%

(Table 4-10). We also tested the sensitivity of the study results to the decision to treat forest harvest residues as a waste product. In the sensitivity analysis we included the fuel consumption for harvesting of softwood logs and allocated the impacts to residues on a mass basis of 39% (as per Pierobon et al. 2018). The inclusion of allocated harvesting impacts had a negligible effect on the results, only increasing the GWP of producing 1 kg of bio oil by 0.001 kg.

Table 4-10. Results of sensitivity analyses for producing 1 kg of bio oil in a mobile fast pyrolysis unit, and for the use of bio oil and biochar in two alternative Bioenergy Pathways for cement production.

Sensitivity Test	GWP	ACD	ODP	SMOG	RESP	EUT
	kg CO_2 eq.	*kg SO_2 eq.*	*kg CFC-11 eq.*	*kg O_3 eq.*	*kg $PM_{2.5}$ eq.*	*kg N eq.*
Production of 1 kg of bio oil						
Transport of chips to pyrolysis unit (base case 40 km)						
100 km	+37.6%	+7.2%	+38.4%	+5.1%	+3.7%	+18.7%
250 km	+187%	+25.3%	+134%	+17.7%	+12.8%	+65.6%
Air emissions from pyrolysis unit						
-50%	0%	-36.3%	0%	-39%	-41.3%	-24.5%
+50%	0%	+36.3%	0%	+39%	+41.3%	+24.5%
Bioenergy Pathway 1 – Operation of one pyrolysis unit						
Transport of bio oil (base case 250 km)						
50km	-0.4%	-0.3%	-1.3%	-0.6%	-0.2%	-0.2%
500 km	+1.2%	+0.9%	+3.8%	+1.9%	+0.7%	0.6%
Air emissions from bio oil combustion						
-50%	0%	-3.1%	0%	-10%	-1.2%	-0.6%
+50%	0%	+3.1%	0%	+10%	+1.2%	+0.6%
Bioenergy Pathway 2 – Operation of three pyrolysis units						
Transport of bio oil (base case 250 km)						
50km	-1.6%	-1.1%	-3.2%	-1.5%	-0.9%	-1.1%
500 km	+4.9%	+3.5%	+10%	+4.7%	2.7%	+3.6%
Air emissions from bio oil combustion						
-50%	0%	-11.5%	0%	-22.8%	-4.1%	-3.0%
+50%	0%	+11.5%	0%	+22.8%	+4.1%	+3.0%

GWP = Global Warming; ACD = Acidification; ODP = Ozone Depletion; SMOG = Photochemical Oxidant Formation; RESP = Respiratory Effects; EUT = Eutrophication

Variations in the combustion emissions from the pyrolyzer could change SMOG and RESP impacts by +/- 40%, and EUT and ACD impacts by +/- 25% and 36% respectively (Table 4-10). Note that GWP impacts were not affected by these changes because carbon dioxide emissions from biomass combustion in the pyrolysis unit were excluded.

The total life cycle impacts for both Bioenergy Pathways for cement production are not particularly sensitive to bio oil transport distances (less than 4% change), except at 500 km, which is at the upper range of economically feasible transport distance for the bio oil and biochar. The results were not sensitive to bio oil combustion emissions with the exception of ACD and SMOG impacts (12% and 23% variation, respectively). These scenario results are not as sensitive to changes in the bio oil production process because the bio oil process accounts for a relatively small portion of life cycle impacts of cement production overall (Table 4-5).

4.6.2 Biogenic Carbon

When biogenic carbon emissions are accounted for, there are smaller GWP reductions for Bioenergy Pathways 1 and 2 relative to the Reference Pathway (-8% and -13%, respectively, over the 20-year pyrolyzer lifetime, compared to -20 and -50%, respectively, when biogenic emissions are excluded), and these reductions take longer to materialize than when biogenic carbon is excluded (Table 4-11 and Table 4-12).

For Bioenergy Pathway 1 there are virtually no GWP reductions beginning in year 1 (-1%) when biogenic carbon is included, and then increasingly larger reductions are observed, although the emissions reductions somewhat plateau beyond year 50 (-12% in year 50 and -15% in year 100). For Bioenergy Pathway 2, there is an initial increase in GWP when biogenic carbon emissions are included, and then significant reductions in GWP by year 20 (-13%) and by year 100 (-28%).

Changing the decay rate (k-value) for biogenic carbon in forest harvest residues from 0.056 to 0.087 assumes higher rates of carbon emissions from decaying harvest residues that might occur under different climatic conditions (Table 4-11 and Table 4-12). As a result, for Bioenergy Pathway 1, this change in decay rate showed minor increases to base case GWP reductions, with no overall change in reductions at year 100, which remained at 15% relative to the Reference Pathway. For Bioenergy Pathway 2, this change in decay rate resulted in slightly greater increases to base case GWP reductions, with total GWP reductions reaching 30% relative to the Reference Pathway by year 100. These modest changes in GWP reductions can be attributed to the fact that although carbon emissions from decaying harvest residues are higher with the increased decay rate, these emissions are 1-2 orders of magnitude smaller than the GHG emissions occurring elsewhere in the life cycle (e.g. from combustion of fossil fuels) and so make a relatively small contribution to total GWP across the cement production life cycle.

Table 4-11. Results of sensitivity analyses when including biogenic carbon emissions from decay of forest harvest residues in the Reference Pathway and combustion of wood chips for Bioenergy Pathway 1. Includes sensitivity analysis results for varying the k-value for carbon emissions from decaying forest harvest residues in the reference pathway.

	Year					
	1	*20*	*25*	*50*	*75*	*100*
Reference Pathway (k-value of 0.058)						
Life Cycle Emissions [a]	1.7E+05	3.3E+06	4.1E+06	8.3E+06	1.2E+07	1.7E+07
Forest Residue Decay	2.0E+03	2.9E+05	4.2E+05	1.2E+06	2.0E+06	2.9E+06
Total Emissions	**1.7E+05**	**3.6E+06**	**4.6E+06**	**9.5E+06**	**1.4E+07**	**1.9E+07**
Reference Pathway (k-value of 0.087)						
Life Cycle Emissions [a]	1.7E+05	3.3E+06	4.1E+06	8.3E+06	1.2E+07	1.7E+07
Forest Residue Decay	2.9E+03	3.8E+05	5.3E+05	1.4E+06	2.2E+06	3.1E+06
Total Emissions	**1.7E+05**	**3.7E+06**	**4.7E+06**	**9.6E+06**	**1.5E+07**	**2.0E+07**
Bioenergy Pathway 1						
Life Cycle Emissions [b]	1.3E+05	2.6E+06	3.3E+06	6.6E+06	9.8E+06	1.3E+07
Biomass Combustion	3.5E+04	6.9E+05	8.7E+05	1.7E+06	2.6E+06	3.5E+06
Total Emissions	**1.7E+05**	**3.3E+06**	**4.1E+06**	**8.3E+06**	**1.2E+07**	**1.7E+07**
% Change (k-value 0.058)	**-1%**	**-8%**	**-9%**	**-12%**	**-14%**	**-15%**
% Change (k-value 0.087)	**-1%**	**-10%**	**-11%**	**-14%**	**-15%**	**-15%**

[a] Life cycle emissions include all upstream and combustion emissions associated with fossil fuel use in cement production.

[b] Life cycle emissions include all upstream and combustion emissions for fossil fuels used in cement production, and all upstream emissions associated with bio oil production.

Table 4-12. Results of sensitivity analyses when including biogenic carbon emissions from decay of forest harvest residues in the Reference Pathway and combustion of wood chips for Bioenergy Pathway 2. Includes sensitivity analysis results for varying the k-value for carbon emissions from decaying forest harvest residues in the reference pathway.

	Year					
	1	*20*	*25*	*50*	*75*	*100*
Reference Pathway (k-value of 0.058)						
Life Cycle Emissions [a]	1.7E+05	3.3E+06	4.1E+06	8.3E+06	1.2E+07	1.7E+07
Forest Residue Decay	5.9E+03	8.8E+05	1.3E+06	3.6E+06	6.1E+06	8.7E+06
Total Emissions	**1.7E+05**	**4.2E+06**	**5.4E+06**	**1.2E+07**	**1.8E+07**	**2.5E+07**
Reference Pathway (k-value of 0.087)						
Life Cycle Emissions [a]	1.7E+05	3.3E+06	4.1E+06	8.3E+06	1.2E+07	1.7E+07
Forest Residue Decay	8.7E+03	1.1E+06	1.6E+06	4.1E+06	6.7E+06	9.3E+06
Total Emissions	**1.7E+05**	**4.4E+06**	**5.7E+06**	**1.2E+07**	**1.9E+07**	**2.6E+07**
Bioenergy Pathway 2						
Life Cycle Emissions [b]	7.8E+04	1.6E+06	1.9E+06	3.9E+06	5.8E+06	7.8E+06
Biomass Combustion	1.0E+05	2.1E+06	2.6E+06	5.2E+06	7.8E+06	1.0E+07
Total Emissions	**1.8E+05**	**3.6E+06**	**4.5E+06**	**9.1E+06**	**1.4E+07**	**1.8E+07**
% Change (k-value 0.058)	**+6%**	**-13%**	**-16%**	**-23%**	**-26%**	**-28%**
% Change (k-value 0.087)	**+6%**	**-18%**	**-21%**	**-26%**	**-29%**	**-30%**

[a] Life cycle emissions include all upstream and combustion emissions associated with fossil fuel use in cement production.

[b] Life cycle emissions include all upstream and combustion emissions for fossil fuels used in cement production, and all upstream emissions associated with bio oil production.

4.7 Discussion

Unlike previously-published LCAs of pyrolysis systems which have relied on literature, laboratory-scale, or modeled data, this study was based on primary operating data from a commercially-available mobile pyrolysis unit to quantify the environmental implications of substituting bio oil and biochar for fossil fuels in cement production in the province of Québec, Canada. Results of the LCA indicate there are potential environmental benefits to be realized by this substitution in Canadian cement plants, and that there are limited environmental trade-offs associated with this substitution under the assumed supply chain conditions.

Currently, combustion emissions from the generation of energy to supply Canadian cement plants accounts for approximately 40% of GHG emissions for cement production (this excludes upstream emissions in fuel supply chains) (Nyboer and Bennett 2014), suggesting that there is a significant opportunity to reduce these emissions by reducing reliance on fossil fuels. We found that substitution of renewable bio oil and biochar for fossil fuels in cement production created substantial reductions across almost all environmental impacts from energy provision at the plant (except for SMOG). In particular, non-biogenic GWP reductions were as high as 50% relative to the Reference Pathway when replacing just over 42% of total energy demand at the plant. Additionally, we calculated non-biogenic GWP for the production of 1 MJ of energy from bio oil to be approximately 0.07 kg CO_2 eq./L, less than the GWP found in other studies for bio oil production from woody biomass and residues, which ranged from 0.11 to 0.74 as reported in a review by Roy and Dias (2017). In total, the substitution of bio oil and biochar for fossil fuels reduced life cycle GWP by 40,000 metric tonnes of CO_2 eq. under Bioenergy Pathway 1, and by 92,000 metric tonnes of CO_2 eq. for Bioenergy Pathway 2. While these are significant reductions, it is noted that GHG emissions from the chemical conversion of limestone into cement accounts for approximately 50% of onsite GHG emissions for cement production, so there may be additional opportunities to reduce the overall GWP associated with the cement production process that are beyond the scope of this study.

This study also demonstrated that the use of bio oil from a small number of pyrolysis units can increase the share of renewable energy use at the cement plant by 32% in Bioenergy Pathway 1 and 58% in Bioenergy Pathway 2. The calculated energy ratio (renewable energy output/fossil fuel input) of 13.4 was also very favorable. The CED was 0.4 MJ of energy input for 1/MJ of energy output, similar to the value of 0.5 MJ/MJ of energy from bio oil found by Steele et al. (2012).

Despite these clear benefits, we identified several environmental improvement opportunities for bio oil and biochar production via fast pyrolysis. From cradle-to-pyrolyzer gate, the production and combustion of diesel makes substantial contributions to several life cycle impact categories, most notably GWP and ODP. This is due to its use in roadside chipping of forest harvest residues, provision of electricity to the pyrolysis unit with a diesel-electric generating set, and truck transportation of wet wood chips from the forest roadside to the pyrolysis plant. An improvement analysis showed that substituting bio oil from the pyrolysis process for diesel in wood chipping and in generating power for the pyrolysis unit reduced non-biogenic GWP and ODP impacts, with mixed results for other impact categories depending on whether it was used in chipping or for electricity. However, the use of bio oil for supply chain energy applications would increase demand for forest harvest residues for pyrolysis feedstock, a potential environmental issue which is discussed below. If biogenic emissions are considered, this could also lower the GWP reductions, as discussed below.

One potential environmental trade-off that was identified for the substitution of bio oil and biochar for fossil fuels was the potential for increased smog-forming emissions. Air emissions from the combustion of biomass for drying energy in the pyrolysis unit were the primary source of ACD, SMOG, and RESP impacts in the life cycle. We used proxy data from a published LCA source to characterize these emissions, and a sensitivity analysis showed that several impact categories were somewhat sensitive to these values. In particular, total life cycle SMOG impacts for the Bioenergy Pathways could vary by 10% when these emissions levels were increased or decreased by 50%. Bio oil combustion could also increase ODP relative to fossil fuels. Therefore, further research is required to characterize and manage these emissions, as ultimately the emissions will depend on many factors such as type and condition of the feedstock used, and the pyrolysis technology configuration (e.g. the combustion technology and pollution controls in place for the pyrolysis system).

The environmental and economic sustainability of mobile fast pyrolysis units are strongly linked to the availability and proximity of sufficient forest harvest residues for feedstock. A sensitivity analysis- where the transportation distance for delivering wood chips to the pyrolyzer was increased from 40 to 100 km - showed that the cradle-to-pyrolyzer gate life cycle impacts of producing 1 kg of bio oil production are quite sensitive to this distance (e.g. almost 40% increase in GWP). Therefore, efforts should be made to reduce the amount of forest residues required to supply the pyrolysis system, as well as to accurately quantify the amount of regularly available feedstock within an economically feasible transport distance from the pyrolysis plant. Although mobile pyrolysis units provide opportunities to reduce feedstock distances, they require about 3 days for set up and take down, and that ideally, they should be moved only once per year.

Although producing bio oil from forest harvest residues yielded significant reductions in non-biogenic GHG emissions relative to fossil fuels, a sensitivity analysis showed that including biogenic emissions resulted in more modest reductions (8 and 15% for Bioenergy Pathways 1 and 2, respectively compared to 20% and 50% when not including biogenic GHGs) during the 20-year lifetime of the pyrolyzer. Biogenic emissions are a critical feature of bioenergy systems and are heavily influenced by the feedstock used, and by the management of these feedstocks in the Reference Pathway. In this instance, the feedstock for the pyrolysis process is forest harvest residues left at the roadside, which are generally accepted to be preferable to newly-harvested trees in terms of overall carbon balance (McKechnie et al. 2011; Ter-Mikaelian et al. 2015). If the primary feedstock for the pyrolysis unit were wood chips obtained from newly harvested trees, the carbon implications would not likely be as favourable according to other studies (Bentsen 2017; Miner et al. 2014; Ter-Mikaelian et al. 2015; Zhang et al. 2010). As such, the GWP reductions reported here for bio oil and biochar from fast pyrolysis are heavily dependent upon the continued availability of forest harvest residues.

This is an important conclusion in that it highlights the need to assess the availability of forest harvest residues over the long-term in advance of pyrolysis system deployment. Once the system is operating and the cement plant has fully integrated the bio oil and biochar into energy production, there will be an impetus to keep the system running even when the environmentally-preferable feedstock is not available, and this could lead to the harvesting of standing trees to maintain adequate feedstock supply. If this were to occur, the study results presented here would no longer be applicable, and there could be other potential environmental implications associated with harvesting standing trees for bioenergy, including impacts to carbon storage, and potential impacts to forest ecosystems and wildlife habitat (Hesselink 2010; Schulze et al. 2012; Thiffault et al. 2010).

Interestingly, by using the biochar co-product instead of wood chips for drying the feedstock, there would be a reduction in both the demand for forest harvest residues (~15%), and in the impacts associated with processing and transporting residues to the pyrolysis unit; however, this creates notable trade-offs. For example, in a recent study, Peters et al. (2015) used LCA to study several applications of biochar, and concluded that co-firing biochar with coal was the environmentally-optimal choice for reducing GHG emissions and a number of other impacts (e.g. acidification, eutrophication) compared to use as charcoal and use as a fuel for heat generation. There are other studies that have considered other energy applications, and using biochar as a soil amendment in agriculture, the latter being particularly beneficial in creating GWP reductions through potential soil carbon sequestration (Case et al. 2013; Gaunt et al. 2008; Han et al. 2013; Ibarrola et al. 2012). This is a topic that requires further research and consideration of additional factors beyond the scope of the present study, particularly the economic aspect of using biochar as energy compared to using it as a soil amendment.

Ultimately, the environmental benefits and impacts of bioenergy production and use are context-dependent and vary based on feedstock used and conversion technology. Thus, the applicability of our study results is generally limited to the specific supply chain scenarios modeled. Nevertheless, our results provide important insights for other northern regions (e.g. in North America, and N. Europe, Russia), which are using forest biomass for bioenergy, and where due to climate, the density of forest and its residues are limited. Our results show that even with forest residues that would decay with time if left in the forest, there are still modest GWP reductions if biogenic emissions are included. The issue of whether forest feedstocks are climate neutral when used for bioenergy as opposed to being left in the forest is highly context-specific, as it depends on reginal decay rates and forest management practice. Furthermore, the LCA results presented in this study do not include ecological impacts in the forest associated with removal of forest residues, for example impacts to wildlife habitat or nutrient cycling. These are very important sustainability considerations that need to be assessed with other approaches for each bioenergy application. Nevertheless, when properly assessed to consider a larger systems approach, and implemented appropriately, our results indicate that pyrolysis products have potential to reduce the impacts associated with fossil fuel consumption in heavy manufacturing like cement production.

4.8 Conclusions

We used life cycle assessment to quantify the environmental impacts and benefits of substituting bio oil and biochar from mobile fast pyrolysis of forest harvest residues for fossil fuels used in energy provision for cement manufacturing in Québec, Canada. Our study was based on primary LCI data from a commercially available pyrolysis technology and included an assessment of environmental improvement opportunities for the pyrolysis supply chain. Results of this study indicate that displacing fossil fuels in Canadian cement production with bio oil and biochar produced from the conversion of forest harvest residues in mobile fast pyrolysis units could decrease reliance on non-renewable fossil fuels significantly and lead to environmental impact reductions for a number of indicators, including GWP.

In addition to bio oil, fast pyrolysis units produce two useful co-products which provide good operational flexibility that can be capitalized on to improve environmental performance. The syngas co-product can be used for drying and reduce the demand for wood chips and forest harvest residues, and the biochar co-product can be used internally in the system for drying, or sold externally to other industrial users to displace fossil fuels. There are a number of other potential end-uses for biochar and our preliminary analysis indicates that there are environmental trade-offs to be considered when determining the optimal use for biochar and further research on these trade-offs could direct sound environmental decision-making for the pyrolysis process.

More research is required on the air emissions from the pyrolyzer and from the combustion of bio oil, as results showed potential issues related to smog-forming emissions that could be more easily addressed once these emissions have been characterized. Further research should also be undertaken on the socio-economic impacts of the Bioenergy Pathways presented in this paper to determine if they are economically feasible, if adequate feedstock is available, and to quantify impacts they may have more broadly in the economy in terms of providing the forestry sector with a new source of revenue.

4.9 Acknowledgements

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CHAPTER 5: LIFE CYCLE ENVIRONMENTAL CONSIDERATIONS FOR DOMESTIC AND EXPORT BIOENERGY PATHWAYS FOR NOVA SCOTIA WOOD PELLETS

5.1 Publication Information:

This chapter includes material that is being prepared for submission to the journal Environmental Science and Technology. I am the lead author, and other contributions include forest carbon modelling by Eric Neilson of the Canadian Forest Service and provision of Nova Scotia forest inventory data by Rob O'Keefe of the Nova Scotia Department of Lands and Forestry.

5.2 Introduction

The foundation for the United Nations (UN) Sustainable Development Goals (SDGs) is the bioeconomy, an emerging economic sector where producers extract, collect, and transform bio-based materials into products and energy (Anand et al. 2016). The bioeconomy is directly linked to over half of the UN SDGs and is increasingly a part of sustainability strategies developed by governments and businesses to align with the SDGs (Anand et al. 2016; Rahman et al. 2019; Sharma et al. 2016; Meletiou et al. 2019). Bioenergy systems are a key part of the bioeconomy and have been identified as an important alternative to fossil fuel energy in most scenarios for meeting the Paris agreement climate change objectives (Clarke et al. 2014; Creutzig et al. 2015; Rogelj et al. 2018). Modern bioenergy systems involve the conversion of various biomass feedstocks to usable energy for electricity, heat, and transportation applications (Smith et al. 2014). They have been identified as having several social, economic, and environmental benefits including the potential to reduce GHG emissions by displacing fossil fuels (IEA 2005).

The global wood pellet sector is a rapidly growing part of the bioeconomy. Globally, wood pellets are on the verge of becoming a commodity, with production reaching 2.6 million tonnes in 2016 and global markets for this energy feedstock rising by 14% annually since 2010 (Schaubach et al. 2018). Wood pellets are produced from a variety of primary and secondary wood fiber sources and are used for residential space heating and large-scale electricity generation, with more moderate levels of use for institutional space heating and district heating (IEA 2017). Europe is the global leader in both wood pellet production and consumption, followed by North America, where the United States and Canada are primarily exporters of wood pellets to Europe and increasingly to Asian markets (Schaubach et al. 2018).

Wood pellets have become an attractive alternative to fossil fuels such as oil and coal because they represent a potentially renewable, low-carbon energy source whose supply chain can contribute to local economic development by supporting and diversifying forest sector activities (IEA 2005; Mabee et al. 2011). Among these attributes, the potential for displacing fossil fuels and thereby reducing GHG emissions is of particular interest and is helping to drive growth in global wood pellet production. This is exemplified in European policy instruments such as the Renewables Obligation in the United Kingdom (UK) which have prompted major investments in electricity generation with wood pellets (European Commission 2019; European Commission 2020). In North America, the United States Environmental Protection Agency (USEPA) has formally declared wood biomass energy feedstocks derived from managed forests in the U.S. as carbon neutral energy sources (USEPA 2018).

In Nova Scotia (N.S.), Canada there has been increasing interest in developing wood biomass energy systems of various forms in recent years. The provincial government included wood biomass energy as part of a suite of renewable energy systems that may be used to meet legislated renewable electricity generation targets (NSDOE 2010) and subsidized a number of wood biomass systems under the Community Feed-In Tariff (COMFIT) program (NSDEM 2020). Subsidy programs are also available in the province to incentivize homeowners to replace their fossil fuel heating systems with wood pellet stoves (Clean NS 2020), and the provincial government recently announced a program to convert several institutional buildings to wood chip heat (NSDLF 2020). A study by BioApplied and FPInnovations (2017) indicated that Nova Scotia is well-positioned to be a leader in the bioeconomy and recommended establishment of a biorefinery system in the province to produce biomaterials and biofuels from forest resources. There are currently two wood pellet manufacturing plants operating in Nova Scotia that together produce approximately 150,000 tonnes of wood pellets annually (Canadian Biomass 2020). Pellets from these plants are sold for residential space heating in domestic markets and exported in bulk to Europe for large-scale electricity generation (SBC 2016).

With the increasing development of wood biomass energy in Nova Scotia there is a need to understand the environmental implications of growth in this industry, and in particular the potential to reduce GHG emissions. Wood biomass energy systems have typically been considered as carbon neutral energy sources due to an assumption that the biogenic carbon emitted during their combustion will be offset by carbon sequestration in new tree growth following bioenergy harvests (Johnson et al. 2009; Ter-Mikaelian et al. 2015). Wood pellets that are produced from forest harvest residuals or sawmill residuals also tend to be treated as carbon neutral because they are considered as waste products that would otherwise be burned or left to decay (Ter-Mikaelian et al. 2015). These assumptions about the carbon implications of wood biomass feedstocks have informed the position of many regulatory and governing bodies that currently exclude biogenic carbon from wood biomass energy production from their GHG emission accounting frameworks (Environment and Climate Change Canada 2016; USEPA 2018).

A more nuanced picture of the life cycle GHG emissions for wood biomass energy systems has emerged in the scientific literature (Johnson 2009; Ter-Mikaelian et al. 2015; Favero et al. 2020). Life cycle GHG emissions studies have been conducted on a range of wood biomass energy feedstocks and applications, including electricity generation (McKechnie et al. 2011; Muench 2015; Laganière et al. 2017), space heating (Cespi et al. 2014; Buchholz et al. 2017), industrial energy production (Dias et al. 2017; Ayer & Dias 2018), and production of transportation fuels (Neupane et al. 2011; Steubing et al. 2012; Wong et al. 2016). Results from the literature have generally been inconclusive about whether substituting wood biomass energy systems for conventional fossil fuel systems results in reductions to GHG emissions (Bentsen 2017). Röder et al. (2015) explored the uncertainties in accounting for the life cycle GHG emissions of producing electricity from wood pellets and showed the results could range from a decrease in GHG emissions of up to 83% relative to coal-fired electricity to an increase in GHG emissions of up to 73%.

A review of other recent publications on the life cycle impacts of wood pellet energy systems indicated that the findings of studies are quite variable. Katers et al. (2012) modelled the life cycle GHG emissions of wood pellet heating in Wisconsin compared to natural gas and residual fuel oil. Biogenic carbon emissions from wood pellet combustion were excluded from the analysis, and the results of the study indicated that substitution of wood pellets could lead to reductions in GHG emissions of 59% relative to residual fuel oil and 27% relative natural gas (Katers et al. 2012). Dwivedi et al. (2014) analyzed the export of wood pellets produced in the US to Europe for electricity generation and calculated reductions in life cycle GHG emissions of 50-63% relative to coal-fired generation. McKechnie et al. (2016) modelled the life cycle GHG emissions of producing both standard and torrefied wood pellets from harvested wood in Ontario forests. The biogenic carbon emissions from combustion of the wood pellets were excluded from the analysis, and results of the study indicated that using wood pellets for electricity generation in Ontario could reduce life cycle GHG emissions by up to 90% compared to coal, and by up to 85% compared to natural gas. Studies by Morrison & Golden (2017) and Beagel & Belmont (2019) looked at the co-firing of wood pellets in large-scale electricity generation in the U.S. and the U.K. In both studies the biogenic carbon emissions of pellet combustion were excluded and the results indicated substantial reductions in GHG emissions, ranging from 76% - 92% relative to coal-fired electricity.

In contrast to these studies, Buchholz et al. (2017) modelled both the life cycle GHG emissions and changes in forest carbon resulting from the manufacturing of wood pellets for space heating in the U.S. Northeast. The study included assessment of several wood fibre sources and forest product scenarios to explore changes in forest carbon balances over a 50-year study period. Results of the study indicated that the outcomes were heavily driven by biogenic carbon fluxes in forest carbon pools, and that GHG emissions were higher than fossil fuels in cases where baseline harvest levels increased to support pellet production (Buchholz et al. 2017). Hanssen et al. (2017) modelled the life cycle GHG emissions of exporting wood pellets from the U.S. to the U.K. to displace coal-fired electricity generation. The study included a range of wood fibre feedstocks and production scenarios and looked at the carbon implications of several alternative fates for the wood fibre if not used for wood pellet production. Results of the study indicated that GHG emissions for wood pellet electricity were higher than the base case for up to 21 years into the study period, particularly for pellets produced from newly harvested roundwood (Hanssen et al. 2017). Pellets produced from sawmill residuals and commercial thinning of forest land showed the greatest potential for achieving GHG emission reductions in the short-term.

These types of varied results have made the development of broader conclusions and policy development for wood biomass energy challenging (Bentsen 2017) and have highlighted the need for more regionally-specific assessments that consider the forest carbon effects of bioenergy harvests. Despite the variance in study results, what is clear from the literature is that the environmental impacts of wood biomass energy systems are dependent on the context of their application and the impact assessment methods used, including: 1) the source and type of feedstock (including forest management); 2) the feedstock processing and transport required; 3) the energy conversion technology (e.g. efficiency, etc.); 4) the conventional energy feedstock and system that will be displaced (e.g. oil, coal); and 5) the assumptions and methodological choices that inform the assessment (Cherubini et al. 2009; Bentsen 2017; Roy & Dias 2017; Laganière et al. 2017). Within the wood pellet industry all these factors are in play, as wood pellets can be produced from both primary and secondary fibre feedstocks, converted to energy via several technology pathways, and can substitute for a number of fossil fuel feedstocks in several different energy applications.

As efforts continue in Nova Scotia to develop and deploy wood biomass energy systems, there is a need to quantify the life cycle environmental impacts that may result from this emerging sector. Given the policy expectations for wood biomass energy systems to reduce GHG emissions, there is a particular need to quantify the GHG emissions and reductions that can be attributed to these systems using regionally-specific data on the forest resource that supports them, and to understand the implications of using both primary and secondary fibre feedstocks.

In this study, life cycle assessment (LCA) and an integrated LCA-forest carbon analysis were used to quantify the potential change in atmospheric carbon that could result from two wood pellet bioenergy pathways originating in Nova Scotia, Canada. Wood pellet producers in N.S. are currently using N.S.-sourced wood fibre to make pellets for residential space heating in Atlantic Canada and exporting pellets to Europe for co-fired electricity generation in coal power plants. These activities are driven, in-part, by provincial government incentives for homeowners to convert to wood pellet heat from oil and electric space heating, and by European renewable energy policies prompting the use of wood pellets to displace coal-fired electricity generation to increase renewable energy and reduce GHG emissions. Using N.S. forest inventory data and primary data collected from Atlantic Canadian wood pellet producers, the net changes in life cycle GHG emissions were quantified for the substitution of wood pellets for fossil fuels in domestic home heating, and the export of wood pellets to Europe for large-scale electricity generation. The influence on GHG emissions of using sawmill residuals or standing forest biomass was quantified, and contributions of these wood pellet energy pathways to a range of other life cycle environmental impacts were estimated. The results provide key information for determining appropriate bioenergy applications for N.S. wood pellets, both domestically and in international markets.

5.3 Methods

LCA was used to conduct a comparative assessment of the environmental impacts of the wood pellet energy systems and the conventional fossil fuels they are used to replace, separate from any potential changes in forest carbon pools. The GHG emissions results of the LCA were then integrated with results from forest carbon modelling to determine the net change in GHG emissions for each wood pellet energy pathway. LCA is an internationally-recognized method for quantifying the environmental impacts of products and processes over the full life cycle, from raw material extraction through production, distribution, use, and end-of-life (Rebitzer et al. 2004; Guinée & Heijungs 2017; Hauschild et al. 2018). The LCA methods have been standardized by the International Organization for Standardization in the ISO 14040 (ISO 2006a) and ISO 14044 (ISO 2006b) guidelines. LCA is based on an iterative framework consisting of goal and scope definition, compilation of the life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation of the study results. This general framework was used to guide the study methods and was broadened to include forest carbon modelling for the specific analysis of GHG emissions. The LCA and forest carbon modelling methods are described in the following sections.

5.3.1 Goal and Scope

The objective of this study was to quantify life cycle GHG emissions and contributions to other regional to global-scale resource depletion and environmental concerns of substituting Nova Scotia wood pellets for fossil fuels in residential space heating and large-scale electricity production. An integrated LCA-forest carbon modelling approach was used to determine: 1) the net change in GHG emissions to the atmosphere for each wood pellet energy application, including emissions from the wood pellet manufacturing supply chain and emissions resulting from changes in the forest carbon cycle resulting from feedstock provision; 2) the change in life cycle GHG emissions when using residual biomass feedstocks vs. harvesting of standing biomass; and 3) the potential extent of other life cycle environmental impacts associated with wood pellet energy which may signal environmental problem-shifting.

The results of the study have been shared with the Nova Scotia Department of Environment for internal use in evaluating wood biomass energy systems. The study results may also be submitted to a suitable journal in the future to inform a broader audience.

5.3.2 System Descriptions

The scope of this study was an assessment of the impacts of two specific wood pellet energy applications that are currently taking place in Nova Scotia, including the manufacturing of wood pellets to replace oil in residential space heating, and the manufacturing of wood pellets for export to Europe to replace coal in large-scale electricity generation. Within each application, two pellet energy pathways were modelled to assess the change in life cycle impacts when using residual wood feedstocks versus the harvesting of standing forest biomass to provide wood fibre for pellet production. The wood pellet energy pathways are described in the following sections, with further details provided in Appendix B1.

PELLET HEAT PATHWAYS 1 AND 2 – RESIDENTIAL SPACE HEATING

The first pellet energy application modelled was residential space heating. As of 2017, oil heat accounted for approximately 39% of total energy use for space heating in Nova Scotian homes (NRCan 2020). Homeowners are currently being offered financial subsidies to convert their space heating systems from oil furnaces to wood pellet stoves as part of efforts to improve energy efficiency and reduce the use of fossil fuels (Clean Nova Scotia 2020). The life cycle environmental impacts of residential space heating using wood pellet stoves were quantified and compared with space heating using conventional oil-fired furnaces.

The residential space heating analysis was based on the annual manufacturing of 45,000 tonnes of wood pellets in Nova Scotia. It was assumed that homeowners used an average residential wood pellet stove with an output of 40,000 BTU (42.2 MJ) and a stored chemical to thermal energy conversion efficiency of 80%. At an energy content of 18.5 MJ/kg (Magelli et al. 2009), the available supply of wood pellets modelled could support the conversion of approximately 9,600 homes from oil to wood pellet heat (See Appendix B1 for more details on these assumptions). The functional unit for the assessment of residential space heating was the provision of 789,100 MMBTU of heat (approximately 832,000 GJ) for all 9,600 homes using either wood pellet stoves or conventional oil furnaces.

The wood pellets were assumed to be manufactured in a Nova Scotia wood pellet plant. For Pellet Heat Pathway 1 (PH1) it was assumed that wood pellets were produced solely by using wood fibre obtained from sawmill residuals. Sawmill residuals were assumed to consist of sawdust and planer shavings produced as co-products of lumber production at local sawmills and delivered to the pellet plant by truck.

For Pellet Heat Pathway 2 (PH2) it was assumed that wood pellets were produced using wood fibre obtained entirely from the harvesting and processing of unmerchantable roundwood from Nova Scotia forests. Unmerchantable roundwood consists of small-diameter logs not suitable for lumber production that would otherwise be left standing in the forest. These logs were assumed to be harvested from Nova Scotia forests and delivered to the wood pellet plant by truck where they were debarked and chipped prior to entering the pelletization process.

Pellet Co-Fire Pathways 1 and 2 – Pellet Export for Electricity

The life cycle GHG emissions of co-firing Nova Scotia wood pellets in coal-fired electricity generating plants in Europe were quantified and compared with the conventional production of electricity from coal. This analysis was based on the manufacturing and export of 50,000 tonnes of wood pellets from Nova Scotia to Rotterdam in the Netherlands (NL) to be co-fired in an 800 MW coal-fired electricity generating station with a stored chemical to electrical conversion efficiency of 46% (Ehrig & Behrendt 2013). The functional unit for analysis of the pellet co-fire pathways was the provision of 1,840,000 MWh of electricity per year from co-firing of wood pellets with coal or from coal-fired generation only. See Appendix B1 for additional details on the assumptions used to define these pellet energy pathways.

The wood pellets were assumed to be manufactured in Nova Scotia from a mixture of sawmill residues and harvesting of unmerchantable roundwood. For Pellet Co-Fire Pathway 1 (CF1), it was assumed that 80% of the wood pellets were produced from unmerchantable roundwood, and 20% of the pellets were produced from sawmill residuals. For Pellet Co-Fire Pathway 2 (CF2) it was assumed that 80% of the wood pellets were produced from sawmill residuals and 20% were produced from unmerchantable roundwood. These splits between residuals and roundwood were chosen to explore the change in study results when different sources of wood fibre are used.

Business as Usual Forest Harvesting and Energy Provision

The reference case for comparison with the pellet energy pathways was defined to be the business as usual (BAU) forestry operations in Nova Scotia, and the provision of energy for space heating and electricity generation with conventional fossil fuels. In the BAU case it was assumed that no new bioenergy activity would occur in Nova Scotia such that forestry activities would include a typical annual harvest regime with no incremental harvesting to support wood pellet production (see Section 5.3.7 and Appendix B2 for further details on the BAU forestry modelling). For residential space heating, it was assumed that the 9,600 homes from the PH1 and PH2 pathways were using oil furnaces. For electricity generation in the Netherlands it was assumed that the energy supply provided by wood pellets in the CF1 and CF2 pathways would be met by burning hard coal imported from overseas into the Netherlands.

5.3.3 System Boundaries

The system boundaries for the LCA of pellet energy pathways were from raw material extraction through to final use of wood pellets for energy provision, including relevant activities required for:

- Harvesting and processing (chipping and grinding) of unmerchantable roundwood from Nova Scotia forests to produce chips for pelletization;
- Harvesting and processing of saw logs at Nova Scotia sawmills to generate sawdust and planer shavings for pelletization;
- Transport of wood fibre feedstocks to Nova Scotia pellet plants;
- Pelletization of wood fibre feedstocks into wood pellets for energy, including energy and material inputs and emissions;
- Delivery of wood pellets from a Nova Scotia pellet plant to either a local retail outlet (for homeowner purchase) or to Europe via truck, ocean freighter, and rail;
- Combustion of wood pellets in pellet stoves, including transport of pellets to the home, electricity required to operate the stove, and air emissions from combustion; and
- Co-firing of wood pellets with coal in a large-scale electricity generation plant, including air emissions from combustion.

Systems boundaries for the reference case oil heat and coal-fired electricity systems included:

- Extraction, refining, and processing of petroleum and coal feedstocks;
- Transport of oil and coal fuels from the processor to the end user;
- Combustion of oil in an average residential oil furnace, including delivery of oil to the home, electricity required to operate the furnace, and air emissions from combustion; and
- Combustion of coal in a large-scale electricity generation plant, including air emissions from coal combustion.

System boundaries for the forest carbon modelling are described more fully in Section 5.3.7 and Appendix B2. All forest harvesting and changes in forest carbon were assumed to take place in Nova Scotia.

Some life cycle activities were excluded from the analysis because they were determined to be immaterial to the study objectives and results. These included:

- Activities associated with BAU forest harvesting for wood products, which would be equivalent between the BAU and all pellet energy pathways;
- Manufacturing and disposal of packaging and/or bulk shipping containers used for transport and storage of wood pellets;
- Emissions and product loss during storage of wood biomass feedstocks (e.g. sawdust piles) and storage of finished wood pellets;
- Material and energy inputs and waste management associated with replacement or modification of residential space heating infrastructure to accommodate wood pellet stoves;

- Material and energy inputs and waste management associated with replacement or modification of electricity generation infrastructure to enable co-firing of wood pellets with coal; and
- Waste management for wood ash produced during residential space heating and during combustion of wood pellets for electricity.

5.3.4 Life Cycle Inventory

The LCI is a compilation of the resource use and emissions to the environment associated with the various activities required to deliver the functional unit of the studied system. Confidential primary data were collected for wood pellet production from four wood pellet producers in Atlantic Canada and used to calculate a production weighted average data set for 2012 operations. Data on forest harvest and other feedstock processing activities (collection, chipping, etc.) were derived from published secondary sources. LCI data for sawmilling to produce co-product sawdust and planer shavings were obtained from a Canadian report based on primary data from Eastern Canadian sawmills. The life cycle resource use and emissions associated with sawmilling were allocated to lumber and to each of the co-products based on their mass (ASMI 2012).

LCI data for the reference fossil fuel systems were obtained from published average data from the Ecoinvent 3.4 database (Wernet et al. 2016) and relevant literature sources. Data for secondary processes such as the combustion of fuels in transportation and waste management processes were derived primarily from the Ecoinvent 3.4 database and literature sources. Key assumptions and parameters for co-firing wood pellets with coal in the Netherlands were based partially on a previously published study (Ehrig & Behrendt 2013). Detailed summaries of the LCI for each of the bioenergy pathways are provided in Section 5.4.

5.3.5 Life Cycle Impact Assessment

The LCIA involves modelling of the LCI and calculation of potential environmental impacts for each studied system using a published LCA impact assessment method. The results of the LCIA are then expressed relative to the functional unit of the analysis. The LCIA for the wood pellet energy pathways was conducted using the USEPA TRACI 2.1 impact assessment method (Bare 2012). The TRACI method is based on US background conditions and provides characterization factors for a set of mid-point indicators covering impacts to resources, ecosystems, and human health. The global warming potential (GWP) indicator from TRACI was used to characterize the life cycle GHG emissions of the pellet pathway life cycles in carbon dioxide equivalents (CO_2 eq.). These results were then integrated with the GHG emissions reported from the forest carbon analysis (see Section 5.3.7 for a summary of these calculations). In addition to GHG emissions, nine other impact categories were assessed in parallel to address research question 3. They are: carcinogenics, non-carcinogenics, ecotoxicity, respiratory effects, smog, acidification, eutrophication, fossil fuel depletion, and ozone depletion.

The LCA modeling and LCIA were conducted in the openLCA 1.7 software program (Winter et al. 2015). This dedicated LCA software program was used to build the pathway models, calculate environmental impacts, and conduct sensitivity analysis.

5.3.6 Sensitivity Analysis

Sensitivity analysis was conducted to determine how the results of the study may change when key assumptions or modelling decisions are varied. Results of the sensitivity analysis are provided in Section 5.4.4 and provide insight on the influence of electricity source on the impacts of wood pellet production, the effect of changing the assumed energy source that is displaced by wood pellets, and the effect of changing the assumptions about the rate of displacement of fossil fuel energy sources by substitution of wood pellets.

5.3.7 Integrated LCA-Forest Carbon Analysis

The primary objective of this study was to quantify the net change in GHG emissions resulting from the substitution of wood pellets for fossil fuels in residential space heating and co-fired electricity generation. Recent publications on the life cycle impacts of wood biomass energy have indicated that changes in forest carbon stocks and emissions can play a significant role in determining the overall GHG emissions balance between bioenergy and fossil fuel systems (Buchholz et al. 2017; Hanssen et al. 2017; Laganière et al. 2017). As such, the effects of incremental harvesting of roundwood from Nova Scotia forests on the forest carbon cycle were quantified and integrated with the life cycle GHG emissions associated with the wood pellet energy pathways. The objective was to determine the net change in atmospheric carbon for each wood pellet pathway relative to the BAU reference case, expressed as ΔC_{atm}. The methods used to generate estimates of the flux of carbon from or to Nova Scotia forests under different harvesting assumptions are summarized in the following sections. Supplemental information on forest carbon modelling and assumptions is provided in Appendix B2.

FOREST CARBON ANALYSIS

Forests play an important role in the global carbon cycle by mediating the amount of carbon that reaches the atmosphere, both through carbon sequestration and release of carbon from terrestrial pools (Morton et al. 2010). The forest carbon cycle is the exchange of carbon between the forest and the atmosphere and within forest carbon pools by way of several mechanisms, including (Kirschbaum et al. 2001):

- Carbon sequestration from the atmosphere by primary productivity in the forest;
- Incorporation of photosynthesized carbon into plant tissues and forest carbon pools;
- Release of carbon to the atmosphere via plant respiration and heterotrophic respiration;
- Removal of carbon from the forest by harvesting for wood products resulting in storage of carbon in wood products and release of carbon to the atmosphere via wood product decay and/or combustion.

The rate, magnitude, and fate of carbon flows can be influenced by a number of natural and human factors, including dominant tree species, growth rates, climate, soil characteristics, natural disturbances (i.e. forest fires or insect infestations), harvesting methods, harvesting frequency, and post-harvest forest management practices (e.g. silviculture) (Tyrell et al. 2009; Stinson et al. 2011; Goetz et al. 2012).

The harvest of trees from the Nova Scotia forest to support bioenergy has a number of effects on the forest carbon cycle because: 1) the harvesting of standing wood biomass makes previously stored carbon available for release to the atmosphere; 2) the removal of standing biomass changes the carbon sequestration potential of the forest by either increasing or decreasing carbon sequestration potential depending on existing conditions; 3) the removal of standing biomass changes age class structure which influences carbon sequestration rates; and 4) harvesting practices can potentially affect productivity and cause shifts of carbon between various forest carbon pools, and between carbon pools and the atmosphere (Morrison et al. 1993; Jiang et al. 2002; Jandl et al. 2007).

As part of the integrated LCA-forest carbon calculations for this study, an expert from the Canadian Forest Service (CFS) used 2011 Nova Scotia forest inventory data provided by the Nova Scotia Department of Lands and Forestry to model changes in the forest carbon cycle resulting from harvesting for bioenergy in Nova Scotia forests. The forest carbon modeling was carried out by inputting the Nova Scotia forest inventory data into the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3). The CBM-CFS3 is an aspatial, landscape-level, carbon stock model developed for use with forest inventories (Kull et al. 2011). It is a forest growth yield driven model that simulates the carbon dynamics of above- and belowground biomass and dead organic matter (DOM), including soils. It can represent both stand- and landscape-level forest dynamics and accounts for carbon stocks, transfers between pools, and emissions of CO_2 to the atmosphere resulting from these carbon dynamics (Kurz et al. 2009). A figure showing the general model architecture of the CBM-CFS3 program is provided in Appendix B2.

Nova Scotia forest inventory data for 2011 were used to run the forest carbon simulations. Simulations were run for a 100-year study period for the following scenarios:

- Business as usual – forest carbon simulations for the BAU harvest for wood products were based on 5-year average of harvesting levels and wood product flows in Nova Scotia. The fate of carbon stored in wood products was modelled using carbon decay and residency curves from the CFS (see Appendix B2).
- Pellet Heat Pathway 1 – it was assumed that wood pellets in PH1 were produced from sawmill residuals and that no additional harvesting occurred. The forest carbon balance was therefore assumed to be equivalent to that of the BAU;
- Pellet Heat Pathway 2 – the harvesting of unmerchantable roundwood to support the PH2 pathway was modeled as additional forest harvest beyond the BAU harvest levels. Resulting forest carbon changes were modelled based on an assumed level of harvesting within each of the three defined harvesting regions (see Appendix B1 and B2);
- Pellet Co-Fire Pathways 1 & 2 – the harvesting of unmerchantable roundwood was modeled as additional forest harvest beyond the BAU harvest levels for the share of pellets produced from newly harvested wood. For pellets made from sawmill residues the forest carbon model was the same as the BAU since there was no additional harvest.

All incremental harvesting was targeted at unmerchantable roundwood and not saw log quality stands. It was assumed that no silviculture was used to regenerate forest stands after harvest and that all regrowth was through natural succession. This was a simplifying assumption and it is noted that active silviculture after bioenergy harvests would potentially increase the rate of carbon sequestration and would change the study results. Model outputs from the CBM-CFS3 simulations were summarized in Excel spreadsheets and provided by the CFS modeler for use in the integrated LCA-forest carbon analysis. The key outputs of the forest carbon modelling were annual changes to net ecosystem production (NEP) and emissions to the atmosphere from the decay and combustion of wood products (including wood pellets). Annual changes to the forest carbon cycle were modeled at a landscape level so that while harvesting was directed at particular stands in various parts of the province, the forest carbon modelling reflects net changes in the forest carbon cycle across the entire Nova Scotia forest for each year of the study period. Raw data tables showing outputs from the CBM-CFS3 simulations are provided in Appendix B3.

INTEGRATED LIFE CYCLE GHG EMISSIONS ANALYSIS

Calculations used to integrate the life cycle GHG emissions results from the LCA and the GHG emissions data from the forest carbon modelling are summarized below.

BAU and Pellet Heat Pathway 1

The net GHG emissions released to the atmosphere (C_{atm}) for the BAU reference case, expressed in CO_2 equivalents, were calculated by using the following equation:

Eq. 2: C_{atm} (BAU) = $FP_{dec} + LCE_{fos} + NEP_{bau}$

FP_{dec} is the amount of carbon dioxide released directly to the atmosphere during the current year via carbon decay from wood products and residues and combustion of wood fibre. The value LCE_{fos} is the amount of GHG emissions released over the life cycle of the conventional fossil fuel that is used for space heating or electricity generation, including extraction, processing, distribution, and combustion of the fossil fuel feedstock. NEP_{bau} is the net ecosystem production of the forest and represents the net sequestration (or emission) of carbon dioxide associated with tree growth and respiration during the BAU scenario (see Appendix B2).

The GHG emissions for PH 1, expressed in CO_2 equivalents, were calculated by using the following equation:

Eq. 3. C_{atm} (Pellets) = $FP_{dec} + LCE_{pel} + NEP_{pel}$

FP_{dec} and NEP_{pel} for PH1 are equivalent to the values for the BAU because there is no new harvest for bioenergy and therefore there is no change in the forest carbon cycle. LCE_{pel} is the amount of GHG emissions released over the life cycle of the pellet heating scenario, including biomass harvest, processing, and distribution. The carbon contained in the sawmill residues is assumed to be emitted directly to the atmosphere in both the BAU and in the pellet heating scenario, and these emissions are accounted for in the FP_{dec} value. The net change in GHG emissions in CO_2 equivalents between PH1 and the BAU was calculated using the following equation:

Eq. 4. $\Delta C_{atm} = C_{atm}\text{ (Pellets)} - C_{atm}\text{ (BAU)}$

This value was calculated for each year of the 100-year study period giving an annual change in C_{atm} from this conversion to wood pellet heat. The cumulative change in C_{atm} was calculated by summing each year's change, so that by year 100 it was determined whether the amount of carbon dioxide reaching the atmosphere had increased or decreased for the bioenergy scenario relative to the BAU.

Pellet Heat Pathway 2

For space heating with wood pellets made from harvesting unmerchantable roundwood the forest carbon model accounted for the additional amount of carbon released to the atmosphere from removal and combustion of the wood fibre as well as changes in NEP that resulted from this additional harvest. The GHG emissions for PHP 2, expressed in CO_2 equivalents, were calculated by using the following equation:

Eq. 5. $C_{atm}\text{ (Pellets)} = FP_{dec} + LCE_{pel} + PEL_{comb} + NEP_{pel}$

PEL_{comb} represents the amount of additional carbon that is removed from the forest and transferred to the atmosphere as a result of the harvest for wood pellet production and combustion of wood pellets. A visual summary of the system boundaries and the integrated LCA-forest carbon dimensions is shown in Figure 5-1.

It is important to note that the value for NEP each year is orders of magnitude higher than the other variables in these equations. This is the case across the BAU and all wood pellet energy pathways, as the Nova Scotia forest is currently a net carbon sink (NSDNR 2017) with NEP sequestering upwards of 4,000,000 to 5,000,000 tonnes of CO_2 annually (See Appendix B3). As such, the focus of the analysis was on the difference in annual C_{atm} between the bioenergy scenarios and the BAU. By calculating this marginal change it was possible to determine if the wood pellet energy pathways had benefits from a GHG emissions perspective relative to the BAU.

The forest carbon modelling and integrated LCA-forest carbon calculations for the CF1 and CF2 pathways were based on the same procedures as the PH1 and PH2 pathways but reflected the different incremental harvest levels required to meet the specified wood pellet production (See Appendix B1).

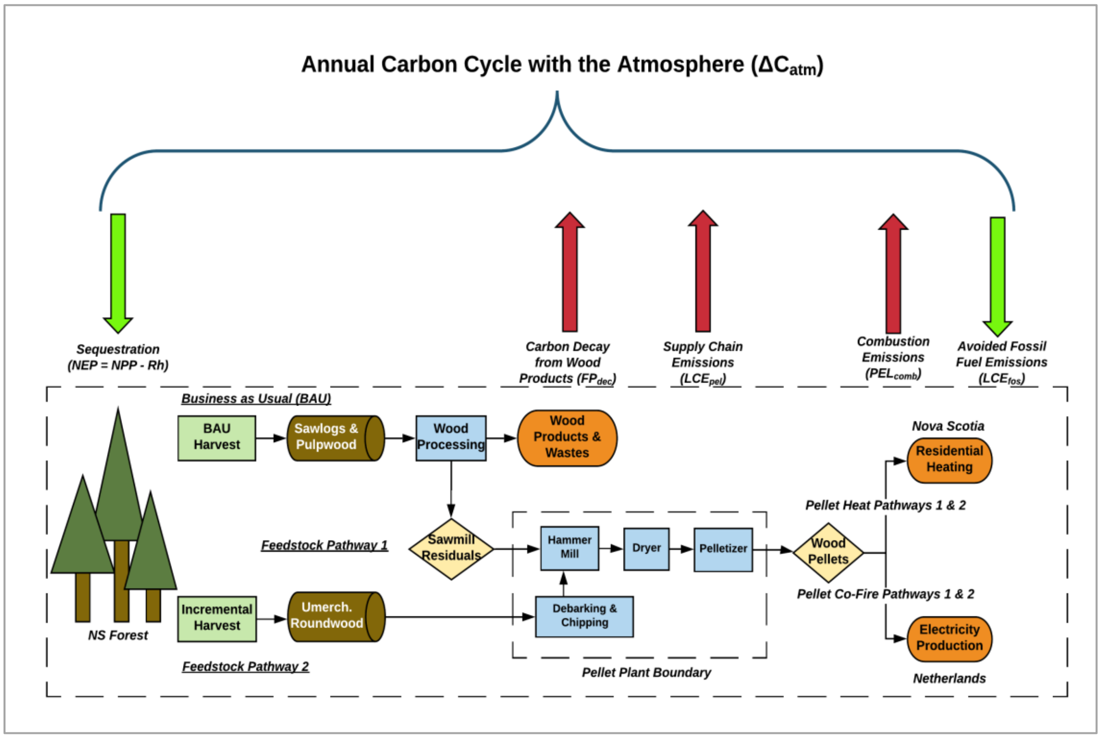

Figure 5-1. System boundaries for wood pellet energy pathways and the reference BAU scenario, including summary of carbon exchanges between the Nova Scotia forest and the atmosphere, and between BAU and bioenergy life cycles and the atmosphere. NEP = net ecosystem productivity; NPP = net primary productivity; Rh = heterotrophic respiration.

5.4 Results

5.4.1 Life Cycle Inventory

RESIDENTIAL SPACE HEATING

The primary production pathway for Nova Scotia wood pellets used in residential space heating was the collection and processing of residuals (i.e. sawdust and shavings) from local sawmills (PH1). Sawmills produce softwood lumber as a primary product along with several co-products which are either used at the sawmill, sold to other users, or stockpiled (ASMI 2012). The material and energy inputs and the co-product outputs and emissions from average Eastern Canadian softwood harvesting and lumber production are summarized in Table 5-1.

Table 5-1. Operating inputs and outputs of average Eastern Canadian softwood harvesting and lumber production.

Operating Inputs and Outputs	Amount
Harvesting of softwood logs	
Inputs	
Softwood, standing (m^3)	2.54
Diesel (l)	8.36
Electricity (kWh)	0.08
Transport – to sawmill (km)	102
Outputs	
Softwood logs (oven dry kg)	1,000
Softwood lumber production	
Inputs	
Softwood logs, green (oven dry kg)	968
Motor oil (kg)	0.11
Hydraulic fluid (kg)	0.14
Grease (kg)	0.01
Electricity (kWh)	70.9
LPG (l)	0.16
Gasoline (l)	0.04
Diesel (l)	2.11
Natural gas (m^3)	8.79
Hog fuel (kg)	40.7
Outputs	
Lumber (m^3)	1.00
Wood chips (kg)	334
Sawdust (kg)	54
Shavings (kg)	61
Bark (kg)	86
Wood ends/fines (kg)	15
Solid Waste (ash, etc.) (kg)	5.7

The sawmill operational inventory data are based on primary data collected by the Athena Institute of a sample of operating sawmills in Eastern Canada (ASMI 2012). Data for the harvesting of softwood logs for lumber production were also obtained from the Athena Institute and include energy consumption for felling and skidding saw logs to the forest roadside and an average transportation distance for hauling logs to a local sawmill. In the Athena Institute study, the material and energy inputs and emissions of the sawmill were allocated on a mass basis between lumber, wood chips, sawdust, shavings, bark, and wood ends/fines (ASMI 2012). Mass allocation was also used in calculating the life cycle impacts of the wood pellet energy pathways in the present study.

The other source of wood fibre assumed to be used by wood pellet producers was small-diameter logs chipped for pelletization. It was assumed that otherwise unmerchantable roundwood was specifically harvested for this purpose, and that these logs were obtained through commercial thinning operations related to other forest management objectives. The LCI for harvesting one oven dry tonne of hardwood from thinning operations was obtained from a study by Johnson et al. (2012) and the data are summarized in Table 5-2.

Table 5-2. Life cycle inputs and outputs for harvesting of 1,000 kg (oven dry mass) of unmerchantable roundwood logs from commercial thinning operations.

Inputs	**Amount**
Hardwood, standing (m^3)	1.93
Diesel (l)	4.11
Lubricating oil (kg)	0.16
Outputs	
Hardwood logs, oven dry mass (kg)	1,000

Source: Johnson et al. 2012

The average material and energy inputs for production of 1 tonne (oven dry mass) of wood pellets in a Nova Scotia wood pellet plant are summarized in Table 5-3. Results of the LCI for wood pellet production show that approximately 1,120 kg of dry wood fibre (or approximately 1,600 kg wet at an average moisture content (MC) of 43%) from sawmill residuals or chipped roundwood was required to produce 1 tonne of pellets. The primary input to pelletization was grid electricity, and for FP1 there was a requirement of 182 kWh of electricity per tonne of pellets. For FP2, which includes debarking and chipping of roundwood logs, approximately 201 kWh of grid electricity were required per tonne of pellets produced. The yield of pellets per input of wood fibre were assumed to be the same for both sawmill residues and chipped roundwood, and in fact pellet producers may use a combination of the two depending on the quality of pellets required.

Table 5-3. Average life cycle inputs and outputs for conversion of sawmill residuals and unmerchantable hardwood logs to wood pellets at a Nova Scotia wood pellet plant. All data are confidential primary data averaged from Atlantic Canadian pellet producers unless specified otherwise. Biogenic carbon dioxide emissions were excluded from this table because they were accounted for in the integrated LCA-forest carbon analysis.

Inputs	Amount	Detail
Pellet Pathway 1 – Sawmill Residuals		
Inputs		
Transport – sawmill to pellet plant (km)	80	Tractor trailer, wet fibre
Sawdust (kg)	838	Oven dry mass
Planer shavings (kg)	279	Oven dry mass
Electricity (kWh)	182	Nova Scotia grid, 2015
Diesel (l)	5.7	Used in mobile equipment
Wood residues (kg)	159	Collected and burned for heat
Transport – pellet plant to retail (km)	100	Tractor trailer, dry pellets
Outputs		
Wood pellets (t)	1.00	Oven dry mass, 18.5 GJ/tonne
Pellet Pathway 2 – Chipped Hardwood		
Inputs		
Transport – forest to pellet plant (km)	115	Tractor trailer, wet logs
Hardwood logs (kg)	1,117	Oven dry mass
Electricity - debarking (kWh)[a]	15.1	Debarking of wet logs onsite
Electricity - chipping (kWh)[b]	4.19	Chipping of debarked logs
Electricity – pelletization (kWh)	182	Nova Scotia grid, 2015
Diesel (l)	5.7	Used in mobile equipment
Wood residues (kg)	159	Collected and burned for heat
Transport – pellet plant to retail (km)	100	Tractor trailer, dry pellets
Outputs		
Wood pellets (t)	1.00	Oven dry mass, 18.5 GJ/tonne

[a] Electricity consumption for the debarking of logs obtained from the Ecoinvent 3.4 database.
[b] Electricity consumption for chipping of logs obtained from McKechnie et al. 2011.

Transportation requirements for pellet production included delivery of wet sawmill residuals or roundwood logs from the source to the pellet plant via transport truck, and delivery of finished, dry wood pellets from the pellet plant to retail outlets in Nova Scotia. Average distances for feedstock transportation provided by pellet producers were approximately 80-115 km. The distance for wood pellet distribution was estimated to be 100 km. These transportation distances may vary by feedstock source and retail location. For residential space heating it was assumed that wood pellets were purchased at retail outlets throughout Nova Scotia and burned in residential wood pellet stoves. The inputs and outputs of using wood pellets or a conventional oil furnace for residential space heating are summarized in Table 5-4 and are expressed relative to 1 MMBTU of heat.

Table 5-4. Inputs and emissions for generation of 1 MMBTU in an average residential wood pellet stove in Nova Scotia at 80% efficiency, and an average oil-fired furnace at 80% efficiency.

Inputs	Amount	Detail
Wood Pellet Heating – 1 MMBTU		
Inputs		
Transport – from retail (km)[a]	2	Average passenger vehicle
Wood pellets (kg)	57.0	Energy content of 17,535 BTU/kg
Electricity - stove (kWh)[b]	7.3	Power to operate the pellet stove
Outputs		
Heat (MMBTU)	1.00	
Carbon monoxide (kg)[c]	1.02	
Nitrogen oxides (kg)[c]	0.36	
Particulates, <10 µm (kg)[c]	0.11	
Sulfur oxides (kg)[c]	0.01	
Oil Furnace Heat – 1 MMBTU		
Inputs		
Transport – oil delivery (km)[d]	2	Average tractor trailer
Light fuel oil (kg)[e]	26.4	Energy content of 37,910 BTU/kg
Electricity – furnace (kWh)[f]	5.3	Power to operate the furnace
Outputs		
Heat (MMBTU)	1.00	
Carbon dioxide (kg)[g]	1.02	
Carbon monoxide (kg) [g]	0.02	
Dinitrogen monoxide (kg)	0.0002	
Methane (kg) [g]	0.0075	
Nitrogen oxides (kg) [g]	0.075	
Particulates, <10 µm (kg) [g]	0.0016	
Sulfur dioxide (kg) [g]	0.58	
TOC – total organic carbon (kg) [g]	0.01	

[a] Assumed an average trip of 20 km and 10 trips per heating season and annual heating requirement of 82,125 MMBTU to scale total consumer transport to an average per 1 MMBTU.

[b] US Department of Energy (2018) estimates electricity use of 100 kWh per month. Assumed a 6-month heating season and scaled according annual heating requirement of 82,125 MMBTU.

[c] Air emissions estimates for average residential pellet stove from USEPA AP-42 (USEPA 2003a).

[d] Assumed an average delivery distance of 20 km, an average delivery of 300 litres, and annual heating requirement of 82,125,000 MMBTU to scale the transport for oil delivery per 1 MMBTU.

[e] Light fuel modeled using the Ecoinvent 3.4 process *market for, light fuel oil, ROW*

[f] Electricity required to power the oil furnace from the Ecoinvent 3.4 database for an average residential furnace

[g] Air emissions for home heating oil obtained from USEPA AP-42 for #2 fuel oil (USEAPA 2003c).

The air emissions profile for wood pellet heating was based on average data from the USEPA and may not be representative of all pellet stove types. Actual air emissions may vary depending on the efficiency and the technology used. Biogenic carbon dioxide emissions were excluded from this table because they were accounted for in the integrated LCA-forest carbon analysis.

Wood Pellet Export for Electricity Generation

Wood pellets produced for export to Europe for co-firing were assumed to be produced in the same manner as for residential space heating, except that when unmerchantable logs are used as input it was assumed that debarking was not necessary as the industrial chips used in electricity generation do not require this. As such, the LCI data for pellet manufacturing provided in Table 5-1,

Table 5-2, and Table 5-3 form the basis of the LCI for co-firing of wood pellets with the exception of debarking of unmerchantable logs.

The LCI for two scenarios of co-firing Nova Scotia wood pellets with coal in a coal-fired power plant in the Netherlands is summarized in Table 5-5. Nova Scotia wood pellets were assumed to travel a total of approximately 6,200 km via truck, ocean transport, and rail to arrive at the power plant in the Netherlands. This is considerably longer than the distances that pellets are trucked for domestic use in residential space heating. For both co-fire pathways, the co-firing of 50,000 tonnes of wood pellets with hard coal at 46% efficiency was assumed to generate approximately 1,840,000 MWh of electricity per year. The co-firing of 50,000 tonnes of NS wood pellets at 46% efficiency was assumed to displace approximately 120,000 MWh of coal-fired electricity (see Appendix B1). It was assumed that the efficiency of the power plant was not affected by the introduction of wood pellets for co-firing feedstock (Ehrig & Behrendt 2013). Electricity generation from hard coal was modeled using an Ecoinvent 3.4 process for the Netherlands (see Table 5-5)

Proxy data were used from the USEPA for combustion of dry wood in industrial boilers (USEPA 2003b) to develop an emissions profile for wood pellet electricity generation. Biogenic carbon dioxide emissions were excluded from Table 5-5 because they were accounted for in the integrated LCA-forest carbon analysis.

Table 5-5. Life cycle inputs and outputs for export and co-firing of Nova Scotia wood pellets in a coal-fired power plant in the Netherlands. Includes two scenarios of pellet sources for the generation of 1,840,000 MWh of electricity annually.

Inputs	Amount	Detail
Pellet Co-Fire Pathway 1 – 80% Chipped Roundwood/20% Sawmill Residuals		
Inputs		
Transport – tractor trailer (km)[a]	100	Central NS to Halifax Harbour
Transport – ocean freight ship (km)[a]	6,026	Halifax to Rotterdam
Transport – rail (km)[b]	75	Rotterdam port to power plant
Wood pellets (residues) (t)	10,000	Produced from 100% sawmill residuals
Wood pellets (hardwood) (t)	40,000	Produced from 100% chipped roundwood
Hard coal, burned in power plant (GJ)[c]	1,720,000	800 MW power plant, 46% efficiency
Outputs		
Electricity, high voltage (MWh)	1,840,000	46% efficiency for pellets/coal
Carbon monoxide (kg)[d]	2.39E+05	From combustion of wood pellets only
Nitrogen oxides (kg) [d]	1.95E+05	From combustion of wood pellets only
Particulates, <2.5 µm (kg) [d]	6.37E+04	From combustion of wood pellets only
Particulates, >10 µm (kg) [d]	1.07E+05	From combustion of wood pellets only
Sulfur dioxide (kg) [d]	9.95E+03	From combustion of wood pellets only
VOC (kg) [d]	6.75E+03	From combustion of wood pellets only
Co-Fire Pathway 1 – 80% Sawmill Residuals/20%Chipped Roundwood		
Inputs		
Transport – tractor trailer (km)[a]	100	Central NS to Halifax Harbour
Transport – ocean freight ship (km)[a]	6,026	Halifax to Rotterdam
Transport – rail (km)[b]	75	Rotterdam port to power plant
Wood pellets (residues) (t)	40,000	Produced from 100% sawmill residuals
Wood pellets (hardwood) (t)	10,000	Produced from 100% chipped roundwood
Hard coal, burned in power plant (GJ)[c]	1,720,000	800 MW power plant, 46% efficiency
Outputs		
Electricity, high voltage (MWh)	1,840,000	46% efficiency for pellets/coal
Carbon monoxide (kg)[d]	2.39E+05	From combustion of wood pellets only
Nitrogen oxides (kg) [d]	1.95E+05	From combustion of wood pellets only
Particulates, <2.5 µm (kg) [d]	6.37E+04	From combustion of wood pellets only
Particulates, >10 µm (kg) [d]	1.07E+05	From combustion of wood pellets only
Sulfur dioxide (kg) [d]	9.95E+03	From combustion of wood pellets only
VOC (kg) [d]	6.75E+03	From combustion of wood pellets only

[a] Distances estimated using www.searates.com

[b] Rail transport distance from Ehrig & Behrendt (2013)

[c] Based on the Ecoinvent 3.4 process *electricity production, hard coal, electricity, high voltage Nl*

[d] Proxy air emissions based on industrial combustion of wood from USEPA AP-42 (USEPA 2003b).

5.4.2 Integrated LCA-Forest Carbon Analysis Results

The primary objective of this study was to quantify the net change in GHG emissions entering the atmosphere from the substitution of Nova Scotia wood pellets for fossil fuels in residential space heating and large-scale electricity generation. Results of the integrated LCA-forest carbon analysis are presented in the following sections, followed by a summary of other potential life cycle environmental impacts and data on the contribution of different life cycle activities to life cycle GHG emissions of the wood pellet energy supply chain.

RESIDENTIAL SPACE HEATING

Results of the LCIA for global warming potential were integrated with the forest carbon analysis to determine the net change to atmospheric carbon when substituting wood pellets for heating oil in residential space heating. Results of the integrated analysis for heating 9,600 homes in Nova Scotia over the 100-year study period are shown in Figure 5-2. The integrated results include life cycle GHG emissions for wood pellet heating and conventional oil heating, as well as changes in GHG emissions which occur due to changes in forest carbon from bioenergy harvests.

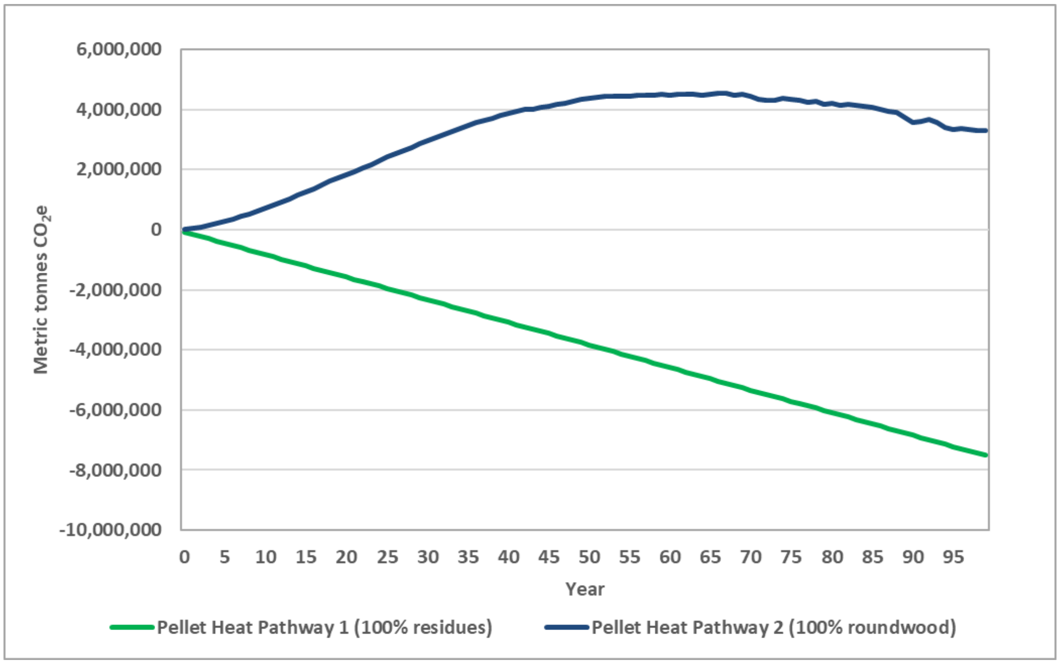

Figure 5-2. 100-year cumulative change in GHG emissions entering the atmosphere relative to the business as usual scenario for the substitution of wood pellets made from sawmill residues (PH1) and newly harvested roundwood (PH2) for oil in residential space heating.

The integrated results show that the use of wood pellets made from sawmill residuals for residential space heating results in substantial cumulative reductions in atmospheric carbon over the 100-year study period relative to oil heat. The displacement of oil with wood pellets made from sawmill residues results in an annual reduction in GHG emissions of over 75,000 tonnes of CO_2 eq. (Table 5-7), resulting in cumulative reductions of approximately 7.5 million tonnes of CO_2 eq. over 100 years (see Appendix B3). These reductions are primarily because there is no additional harvesting required to produce pellets for PH1. The carbon contained in sawmill residuals is assumed to be released to the atmosphere directly for each year of the BAU case, so the value for FP_{dec} is equivalent between the BAU and the PH1 pathway.

The use of wood pellets made from chipped unmerchantable roundwood (PH2) to displace oil heat for residential space heating results in substantial cumulative increases to atmospheric carbon of over 3 million tonnes of CO_2 eq. over the 100-year study period. The increase plateaus around the 50-year point in the study period and begins a slight decline to the end of the study period. This indicates that in the latter half of the study period, the PH2 pathway begins to yield some annual net decreases in GHG emissions. However, they are not sufficient in magnitude to overcome the cumulative increases that occurred in the earlier years of the study period. Although the life cycle GHG emissions of producing the wood pellets are considerably lower than for heating oil (Table 5-7), the harvesting of standing trees to produce the pellets transfers the carbon contained in the standing biomass from sequestration in the forest to the atmosphere after pellet combustion. Net ecosystem production, which is a measure of annual carbon uptake by the forest, declines considerably for PH2 relative to NEP in the BAU (see Appendix B3). It is only in the latter part of the study period where NEP begins to return to BAU levels and then even exceed BAU levels.

Wood Pellet Export for Electricity Generation

Results of the LCIA for GWP were integrated with the forest carbon analysis to determine the net change to atmospheric carbon when displacing a portion of coal-fired electricity generation at a European power plant by co-firing Nova Scotia wood pellets with coal. Results of the integrated analysis for generating 1,840,000 MWh by co-firing pellets and coal in the Netherlands over the 100-year study period are shown in Figure 5-3.

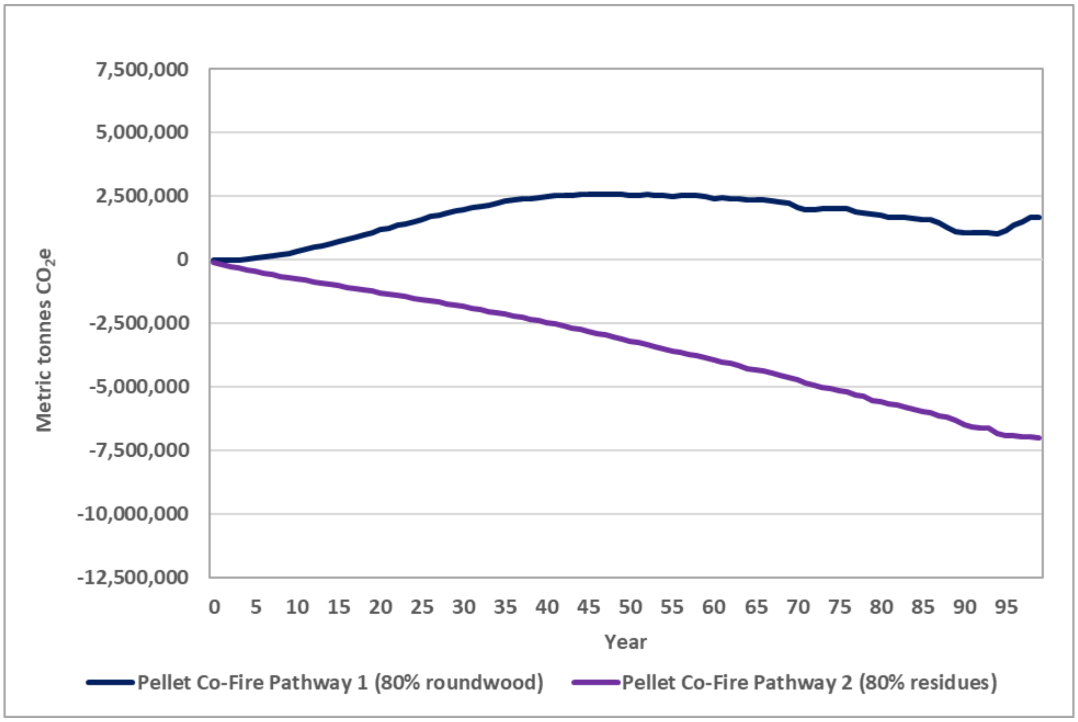

Figure 5-3. Cumulative GHG emissions relative to the BAU with coal-fired electricity generation for the export and co-firing of Nova Scotia wood pellets made from 80% sawmill residues/20% newly-harvested hardwood (Co-Fire Pathway 1) and from 20% sawmill residues/80% newly-harvested hardwood (Co-Fire Pathway 2) in a coal-fired power plant in the Netherlands.

Results of the integrated analysis indicate that displacing a portion of coal-fired electricity in a European power plant by co-firing Nova Scotia wood pellets from the CF1 pathway would result in a cumulative increase in GHG emissions of over 1.5 million tonnes of CO_2 eq. by the end of the 100-year study period. These increases are driven primarily by additional harvesting which results in a decline in NEP for the CF1 pathway relative to the BAU and which transfers additional carbon from the forest to the atmosphere via pellet combustion. Over the course of the 100-year study period, NEP for the Nova Scotia forest begins to recover and approach BAU levels again, although in the latter years of the study period we see further decline in NEP (see Appendix B3). As such, cumulative changes in atmospheric carbon remain above carbon parity with the BAU for the entire study period.

Results of the integrated analysis show that the CF2 pathway results in annual reductions in GHG emissions relative to the BAU, yielding cumulative reductions of just under 7 million tonnes of CO_2 eq. over the 100-year study period. Since 80% of the pellets used in this pathway were made from sawmill residues there is a relatively small incremental bioenergy harvest relative to the BAU. Although the incremental harvest results in a decline in NEP relative to the BAU, it is not as significant as in the CF2 pathway. Annual reductions in the net amount of atmospheric carbon result from the lower life cycle GHG emissions from wood pellet production and distribution relative to the life cycle GHG emissions of coal-fired electricity.

5.4.3 Life Cycle Impact Assessment Results

A secondary objective of this study was to quantify the potential contributions to other environmental impacts when substituting wood pellets for fossil fuels in the pellet energy pathways. These results are summarized in the following sections, beginning with a contribution analysis for the life cycle GHG emissions of the wood pellet pathways to identify hot spots.

CONTRIBUTION ANALYSIS

Residential Space Heating

Results of the contribution analysis for life cycle GHG emissions of the pellet energy pathways are summarized in Table 5-6. Contribution analysis results for the PH1 and PH2 pathways are expressed in kg of CO_2 eq. per 1 MMBTU of heat converted at 80% efficiency and exclude biogenic carbon emissions from combustion which were addressed in the integrated LCA-forest carbon analysis.

The contribution analysis results for the PH1 pathway indicate that GHG emissions from wood pellet production amount to 21 kg CO_2 eq. per 1 MMBTU, accounting for 72% of total life cycle GHG emissions of 28.6 kg CO_2 eq. Electricity from the NS grid used to power the pelletization process accounts for 34% of life cycle GHG emissions at approximately 9.8 kg CO_2 eq. per 1 MMBTU. Production of sawdust and planer shavings at NS sawmills resulted in emissions of approximately 9 kg CO_2 eq per 1 MMBTU, accounting for 32% of total life cycle GHG emissions. Similar hot spots were identified for the PH2 pathway, although the emissions from feedstock production are lower when using roundwood and therefore pelletizing electricity accounts for a greater share of life cycle GHG emissions (45%).

Table 5-6. Life cycle GHG emissions for the production of 1 MMBTU for Pellet Heat Pathways 1 and 2, and for production of 1 MWh of electricity (46% efficiency) for Pellet Co-Fire Pathways 1 and 2. Values are expressed in kg CO_2 eq. and percent contributions to the total are shown in parentheses for each life cycle stage. Method: TRACI 2.1.

Life Cycle Stage	Pellet Heat Pathway 1 (kg CO_2 eq.)	Pellet Heat Pathway 2 (kg CO_2 eq.)
Residential space heating – 1 MMBTU		
Pellet Production	***21.0 (72.0%)***	**14.4 *(63.4%)***
Feedstock production[a]	9.0 *(32%)*	2.0 *(9.1%)*
Feedstock transport	0.63 *(2.2%)*	0.95 *(4.3%)*
Pelletizing electricity	9.77 *(34%)*	9.77 *(45%)*
Other pelletizing energy	1.15 *(4.0%)*	1.15 *(5.3%)*
Pellet Distribution	**0.49 *(1.7%)***	**0.49 *(2.3%)***
Pellet Heating	**7.5 *(26.3%)***	**7.5 *(34.3%)***
Pellet transport – Consumer	0.67 *(2.3%)*	0.67 *(3.0%)*
Pellet stove electricity	6.85 *(24%)*	6.85 *(31.3%)*
Total[b]	**28.6**	**21.9**
Life Cycle Stage	**Pellet Co-Fire Pathway 1 (kg CO_2 eq.)**	**Pellet Co-Fire Pathway 2 (kg CO_2 eq.)**
Co-fired electricity generation – 1 MWh		
Pellet Production	**36.9 *(74.4%)***	**65.2 *(79.2%)***
Wood pellets - roundwood	35.5 *(53%)*	9.21 *(11.2%)*
Wood pellets - residuals	14.3 *(21.4%)*	56.0 *(68%)*
Pellet Transport	**17.2 *(25.6%)***	**17.2 *(20.9%)***
Ocean – to NL	13.4 *(20%)*	13.4 *(16.3%)*
Rail – to power plant	0.74 *(1.1%)*	0.74 *(0.9%)*
Truck – to Halifax harbour	3.0 *(4.5%)*	3.0 *(3.7%)*
Total[b]	**67.0**	**82.3**

[a] GHG emissions for feedstock production in the PH2 pathway include the debarking and chipping of roundwood prior to pelletization

[b] Biogenic carbon emissions from wood pellet combustion are excluded from these results

Results of the contribution analysis show that GHG emissions from consumption of electricity to power the wood pellet stove are not negligible, and in fact account for over 24% and 31% of life cycle GHG emissions for both the PH1 and PH2 pathways. These impacts are largely a result of relying on the Nova Scotia electricity grid which still uses nearly 60% coal-fired electricity generation. Emissions from transportation of wood biomass feedstocks and transportation of pellets to the home made relatively small contributions to total life cycle GHG emissions, ranging from 2-4%. Overall, life cycle GHG emissions were about 30% higher per 1 MMBTU for the PH1 pathway (28.6 kg CO_2 eq.) relative to the PH2 pathway (21.9 kg CO_2 eq.).

Wood Pellet Export for Electricity Generation

Contribution analysis for the life cycle GHG emissions of the CF1 and CF2 pellet pathways are shown in Table 5-6. Results are expressed in kg of CO_2 eq. per 1 MWh of electricity converted at 46% efficiency. GHG emissions from wood pellet production accounted for 79% (CF1) and 74% (CF2) of life cycle GHG emissions. Ocean transport of Nova Scotia wood pellets to the Netherlands resulted in 13.4 kg of CO_2 eq. per MWh produced, accounting for 16% (CF1) and 20% (CF2) of life cycle GHG emissions. The CF2 pathway resulted in 82.3 kg CO_2 eq. per MWh, approximately 23% higher than CF1 (67 kg CO_2 eq.).

COMPARATIVE LCIA RESULTS

Residential Space Heating

The comparative life cycle environmental impacts for residential space heating and pellet export for electricity generation are summarized in Table 5-7. Results are expressed relative to the functional unit for each wood pellet energy application. Biogenic carbon emissions from pellet combustion are excluded from these tables as they were addressed in the integrated LCA-forest carbon analysis.

Residential space heating with conventional heating oil results in higher life cycle impacts than both the PH1 and PH2 pathways for five of the ten indicators considered, including acidification, fossil fuel depletion, global warming potential, ozone depletion, and respiratory effects. Both the PH1 and PH2 pathways have higher impacts than oil heat for the remaining five impact categories, including carcinogenics, ecotoxicity, eutrophication, non-carcinogenics, and smog. The greatest contributor to all impact categories for both the PH1 and PH2 pathways is Nova Scotia electricity generation used in pelletization and in sawmilling. The one exception is smog, where both the PH1 and

PH2 pathways have significantly higher potential impacts than heating oil due to the emissions from pellet combustion. Results of the LCIA also indicate that the life cycle impacts of the PH1 pathway are higher than PH2 for all ten impact categories.

Table 5-7. Life cycle impact results for residential space heating and wood pellet export for electricity generation. Percent change in impacts relative to the reference case are shown in parentheses. Method: TRACI 2.1

Impact Category	Units	Pellet Heat 1	Pellet Heat 2	Light Fuel Oil
Space heating - 781,800 MMBtu				
Acidification	t SO_2 eq	379 *(-42%)*	330 *(-49%)*	649
Carcinogenics	CTUh	1.00 *(+56%)*	0.81 *(+27%)*	0.64
Ecotoxicity	CTUe	88,700,000 *(+46%)*	87,000,000 *(+43%)*	60,700,000
Eutrophication	t N eq	77.3 *(+33%)*	64 *(+10%)*	58
Fossil Fuel Depletion	MJ surplus	24,400,000 *(-87%)*	16,500,000 *(-91%)*	188,000,000
Global Warming [a]	t CO_2 eq	21,900 *(-78%)*	16,700 *(-83%)*	97,100
Non-Carcinogenics	CTUh	3.07 *(+30%)*	2.87 *(+22%)*	2.36
Ozone Depletion	t CFC-11 eq	0.0028 *(-87%)*	0.0017 *(-92%)*	0.021
Respiratory Effects	t $PM_{2.5}$ eq	21.6 *(-52%)*	15.4 *(-65%)*	44.5
Smog	t O_3 eq	9,750 *(+260%)*	8,680 *(+220%)*	2,730
Impact Category	**Units**	**Pellet Co-Fire 1**	**Pellet Co-Fire 2**	**Hard Coal**
Electricity generation - 1,840,000 MWh				
Acidification	t SO_2 eq	2,450 *(+8%)*	2,480 *(+9%)*	2,270
Carcinogenics	CTUh	39.0 *(-5%)*	39.1 *(-4%)*	40.9
Ecotoxicity	CTUe	3,220,000 *(-5%)*	3,230,000 *(-4%)*	3,370,000
Eutrophication	t N eq	2,010 *(-4%)*	2,020 *(-3%)*	2,091
Fossil Fuel Depletion	MJ surplus	220,000 *(-4%)*	225,000 *(-7%)*	211,000
Global Warming [a]	t CO_2 eq	1,740,000 *(-6%)*	1,750,000 *(-5%)*	1,850,000
Non-Carcinogenics	CTUh	142 *(-5%)*	142 *(-5%)*	149
Ozone Depletion	t CFC-11 eq	0.0069 *(+47%)*	0.0076 *(+62%)*	0.0047
Respiratory Effects	t $PM_{2.5}$ eq	206 *(+56%)*	210 *(+59%)*	132
Smog	t O_3 eq	40,400 *(+16%)*	41,100 *(+18%)*	34,900

[a] Biogenic carbon emissions from combustion of wood pellets are excluded from these results

Wood Pellet Export for Electricity Generation

The comparative life cycle environmental impacts of generating electricity in the Netherlands by co-firing wood pellets with coal or by using only coal are summarized in Table 5-7. Electricity generation with only hard coal in the reference case results in higher life cycle impacts than both the CF1 and CF2 pathways in six of the ten impact categories considered, including carcinogenics, ecotoxicity, eutrophication, fossil fuel depletion, global warming potential, and non-carcinogenics. Both the CF1 and CF2 pathways have higher impacts than coal-fired electricity for the remaining four impact categories, including acidification, ozone depletion, respiratory effects, and smog. For ozone depletion, heavy fuel combustion for the ocean transport of pellets to the Netherlands accounts for 10% of the life cycle impacts and is one of the reasons for higher ozone depletion impacts relative to the reference case. The higher impacts for respiratory impacts and smog are driven by Nova Scotia electricity consumption in wood pellet manufacturing and direct emissions to air from combustion of wood pellets in the electricity generation station in the Netherlands.

5.4.4 Sensitivity Analysis

The ISO guidelines for LCA specify that sensitivity analysis should be conducted to quantify the influence of key assumptions and parameters on the study results. Sensitivity analysis is a systematic procedure for estimating the effects of the chosen methods and data on the outcome of a study using either arbitrarily selected ranges of variation, or variations that represent known ranges of uncertainty (Guo & Murphy 2012).

ELECTRICITY SOURCE

The contribution analysis for all the wood pellet energy pathways showed that electricity consumption during wood pellet production and sawmilling was one of the primary contributors to life cycle GHG emissions, and to the other environmental and human health impact categories considered. This is due to the heavy reliance on coal-fired electricity generation in the Nova Scotia grid. To test the sensitivity of the study results to electricity source, the integrated LCA-forest carbon analysis was recalculated for the PH2 and CF1 pathways using the Québec electricity grid (94% hydropower) to support wood pellet manufacturing. These two pathways were chosen for the sensitivity analysis because they had the highest life cycle GHG emissions in the baseline analysis of the integrated LCA-forest carbon results. Results of this sensitivity test are summarized in Figure 5-4 and Figure 5-5

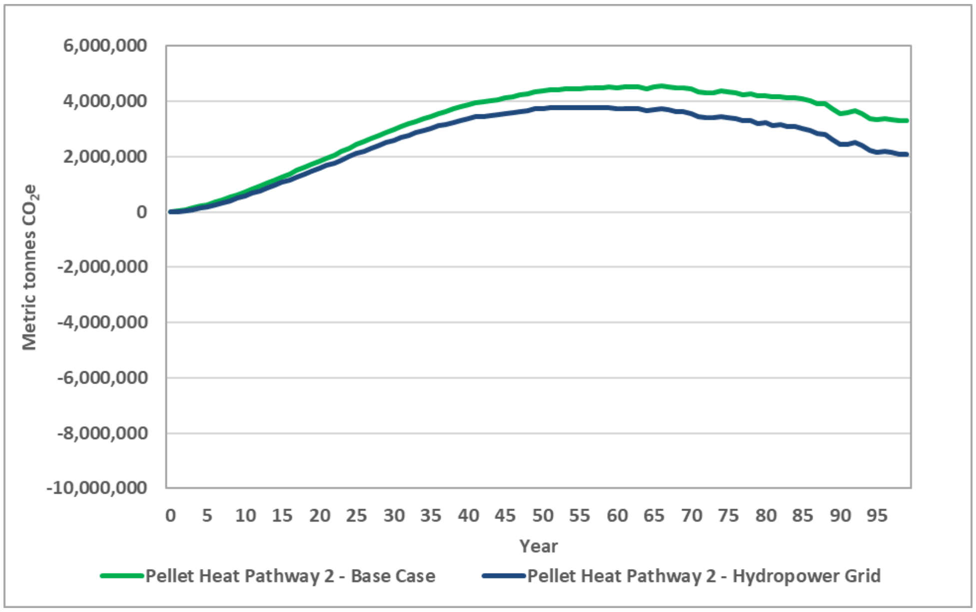

Figure 5-4. Results of sensitivity analysis for the integrated LCA-forest carbon analysis for residential space heating when an alternative electricity source (94% hydropower) is used during wood pellet production and wood pellet stove operation.

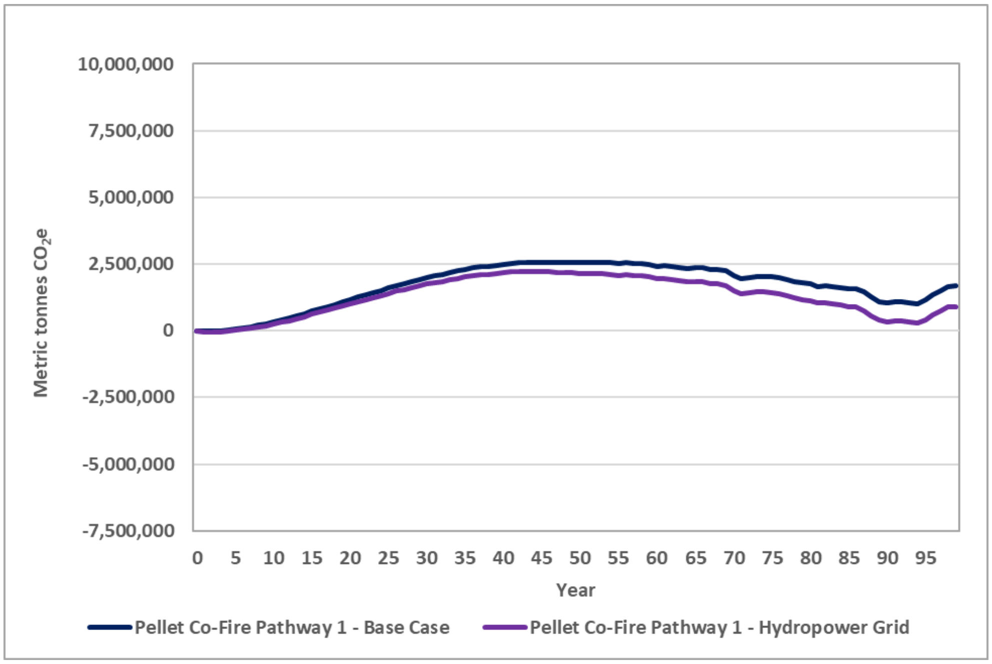

Figure 5-5. Results of sensitivity analysis for the integrated LCA-forest carbon analysis for export and co-firing of wood pellets when an alternative electricity source (94% hydropower) is used during wood pellet production.

For the PH2 pathway the manufacturing of wood pellets using a lower-carbon emitting source of grid electricity resulted in a notable reduction in life cycle GHG emissions but did very little to change to the overall trend of increased GHG emissions relative to the baseline fossil fuel scenario over the 100-year study period.

For the CF1 pathway the manufacturing of wood pellets using a lower-carbon emitting source of grid electricity resulted in a notable reduction in life cycle GHG emissions and brought this pathway closer to carbon parity with baseline coal-fired scenario near the end of the 100-year study period. However, within the first 40-50 years of the study period there is little change to the overall trend of increased GHG emissions relative to the baseline fossil fuel scenario.

CONVENTIONAL ENERGY SYSTEM DISPLACED

A key factor which influences the results of the study is the conventional energy system that is displaced by wood pellet energy. The carbon intensity and contribution to other environmental impacts can vary between different conventional fossil fuel systems, and in some energy applications there may be more than one conventional energy source that could be displaced. For example, Nova Scotians heat their homes in a number of ways, and another common source of home heating beyond oil is baseboard electric heat, which accounted for 21% of residential space heating energy in N.S. in 2017 (NRCan 2020).

To test the sensitivity of the study results to displacing another form of residential space heating, the integrated LCA-forest carbon analysis was recalculated for the PH1 and PH2 pathways with displacement of electric heat. It was assumed that the reduced demand for electricity for home heating would allow the power utility to reduce the amount of coal-fired electricity used to supply the grid, so that the conventional fuel displaced is coal-fired electricity, not the average grid mix.

The results of this sensitivity test are shown in Figure 5-6 and indicate that when wood pellets made from sawmill residues are used to displace electric heat in NS the cumulative reductions in GHG emissions increase substantially, from just over 7.5

million tonnes of CO_2 eq. to almost 28 million tonnes of CO_2 eq. by the end of the 100-year study period. Most notably, the displacement of electric heat essentially reverses the baseline result for the PH2 pathway. The results shift from a large cumulative increase in atmospheric GHG emissions over the 100-year study period to a cumulative reduction in atmospheric GHG emissions of just over 16 million tonnes of CO_2 eq.

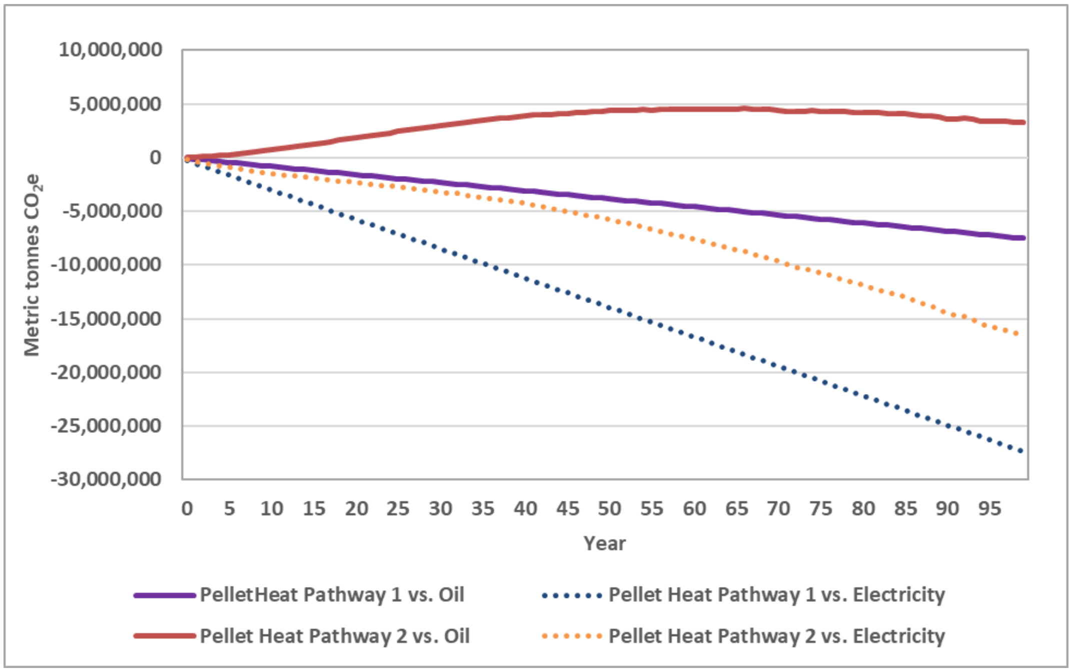

Figure 5-6. Sensitivity analysis for the cumulative change in atmospheric carbon over 100 years when substituting wood pellets for electric heating in 9,600 Nova Scotia homes.

DISPLACEMENT RATE FOR CONVENTIONAL FUELS

One of the key assumptions in LCAs of bioenergy systems is that their deployment will replace fossil fuels on a 1:1 energy equivalency basis. In the present study, it is assumed that if 9,600 homeowners in Nova Scotia switch to wood pellets then the oil that these homeowners would normally have consumed will now be left in the ground. This displacement is a key driver of reductions in life cycle GHG emissions. However, research on actual displacement rates for fossil fuels reveal that an assumption of 1:1 displacement is not supported by empirical data. In a study of global energy use trends at a national level from the last 50 years, York (2012) indicated that a unit of non-fossil energy displaced less than one quarter of a unit of fossil energy use, and for electricity use it was less than one-tenth of a unit. For non-fossil electricity sources other than nuclear and hydro, such as bioenergy, there was no displacement of fossil electricity use at all (York 2012). Hu & Cheng (2017) modeled displacement in the electricity grid in China between 1995 and 2014 and found that non-fossil electricity sources displaced approximately one quarter to one third of fossil electricity use, and that displacement rates were more significant only when the share of alternative energy became a more prominent part of the electricity mix. The reasons for the lack of displacement are explored further in Chapter 7 of this dissertation and are related to an economy-wide increase in energy demand which makes alternative energy systems more of a complement to fossil fuel systems rather than a 1:1 replacement.

Sensitivity analysis was conducted to determine the change in study results for lower displacement assumptions. The integrated LCA-forest carbon analysis was recalculated for the pellet energy pathways based on pellets made from sawmill residues (PH1 and CF2) with displacement rates of 0%, 10%, and 25%. Results for cumulative GHG emissions over the 100-year study period are shown in Figure 5-7 and Figure 5-8.

Results of the sensitivity analysis indicate that at displacement rates similar to those shown in the literature (0% up to 25%), the PH1 pathway no longer provides reductions in life cycle GHG emissions over the 100-year study period. At a 25% displacement rate the PH1 pathway is essentially at carbon parity with the baseline oil heat scenario meaning that GHG emissions have not been reduced in the aggregate over the long run, but increased available thermal space heating energy by 25% by combusting wood pellets.

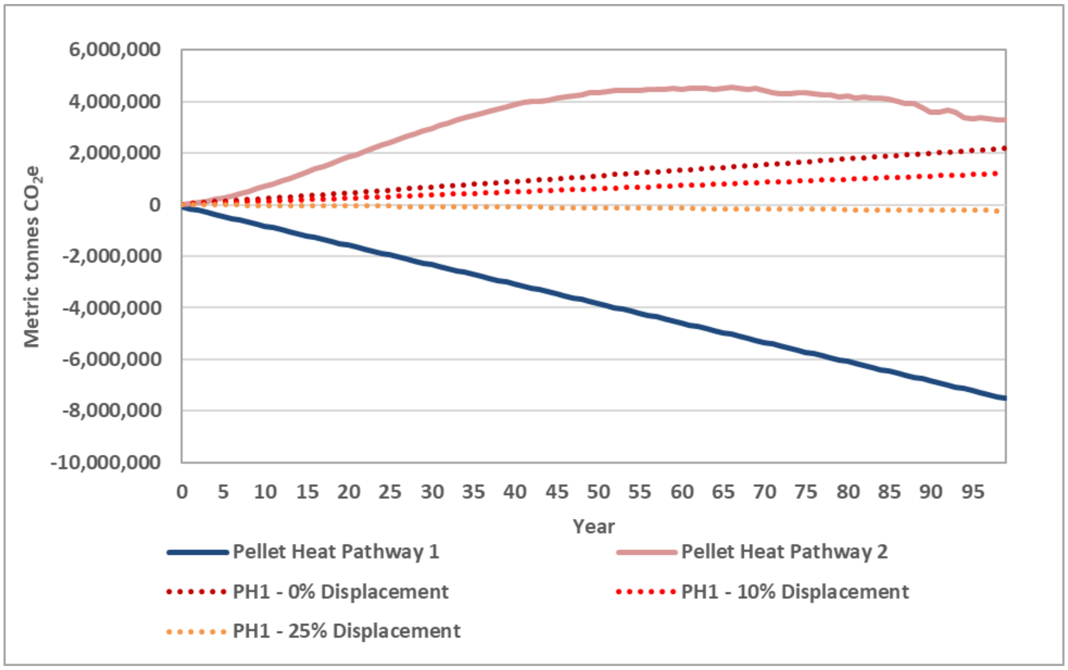

Figure 5-7. Change in 100 year life cycle GHG emissions, including changes in forest carbon emissions, for the substitution of wood pellets for oil in residential space heating in Nova Scotia, showing the change in results with different assumptions for the share of oil displaced relative to the BAU reference case.

For the CF2 pathway the results of the sensitivity analysis on fossil fuel displacement rate are similar to those for space heating, showing that the cumulative GHG emission benefits of substituting wood pellets for coal in large-scale electricity generation are reduced or completely offset at lower levels of coal displacement. At a displacement rate of 25% the CF2 is essentially at carbon parity with the baseline coal scenario. This displacement rate would be considered high or somewhat in line with empirical data based on recent studies (York 2012; Hu & Cheng 2017).

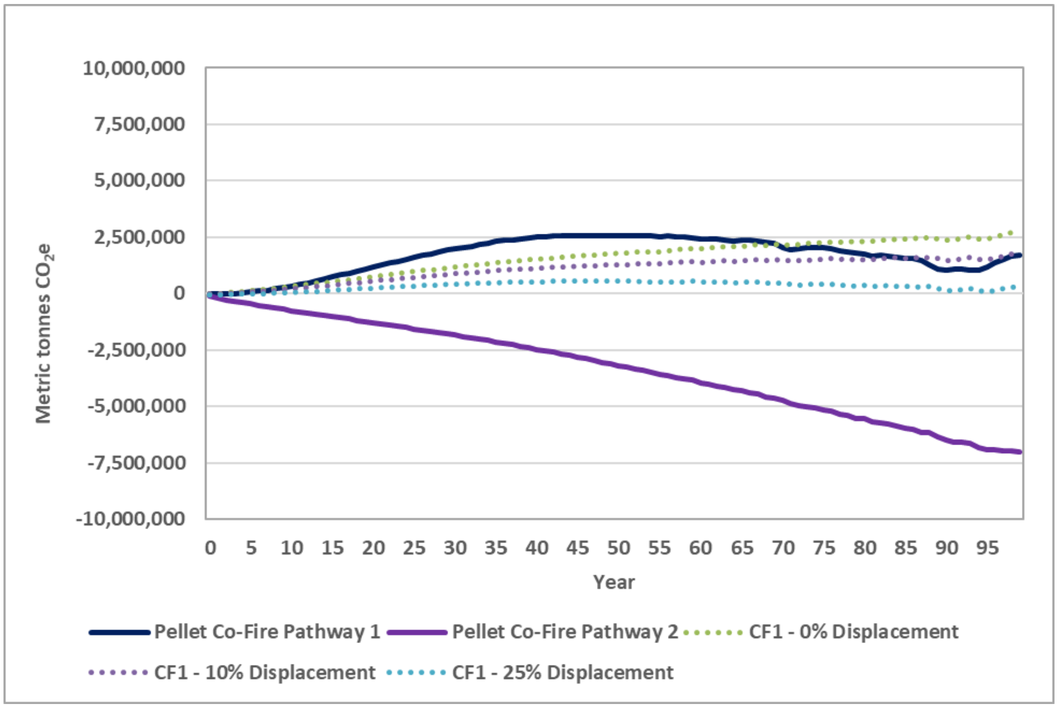

Figure 5-8. Change in 100 year life cycle GHG emissions, including changes in forest carbon emissions, for the export and substitution of wood pellets from Nova Scotia for electricity generation in Europe, showing the change in results with different assumptions for the displacement of coal-fired electricity.

5.5 Discussion

5.5.1 Key Findings

The primary objective of this study was to quantify the net change in life cycle GHG emissions of substituting wood pellets for fossil fuels in residential space heating in NS and large-scale electricity generation in Europe while also accounting for changes in forest carbon flux under different pellet source assumptions. Results of the study indicated that significant cumulative reductions could be achieved relative to oil-fired heating and coal-fired electricity generation when using wood pellets produced from sawmill residuals. The use of residuals from BAU forest sector operations does not affect carbon sequestration or emissions from the forest carbon cycle and can be used to displace the emissions associated with the conventional fossil fuel systems, leading to consistent annual reductions over the 100-year study period.

Conversely, the study results indicated that using wood pellets produced from harvesting and chipping of roundwood could lead to large increases in cumulative GHG emissions over the 100-year study period, particularly for residential space heating applications. Forest carbon modelling of the incremental harvesting required to support wood pellet production showed that in addition to transferring sequestered carbon to the atmosphere via pellet combustion, the additional harvesting led to reductions in NEP relative to BAU levels for the short to medium term after harvest. These factors together accounted for cumulative increases in GHG emissions.

These results showing greater potential for GHG emissions reductions when using wood residuals are generally consistent with other published studies on wood biomass energy where forest carbon modelling was included. Laganière et al. (2017) showed relatively immediate and reliable life cycle GHG emissions reductions associated with the use of wood residues for bioenergy compared to more uncertain and longer time periods to reach carbon parity when using harvested roundwood. In a study of wood pellet production for residential space heating in the Northeast US, Buchholz et al. also concluded that if pellet production required additional harvesting beyond current levels that life cycle GHG emissions would be higher than the conventional fossil fuel system.

An interesting difference can be noted in comparing the cumulative life cycle GHG emissions for space heating with wood pellets made from harvested roundwood in the present study to other studies that included forest carbon modelling. In many other studies where forest carbon changes were modelled there is a “carbon payback” or “return to carbon parity time” during which the initial increases in GHG emissions resulting from the bioenergy harvest are eventually offset. Carbon payback periods in the literature are often shorter than 100 years (e.g. Hanssen et al. 2016; McKechnie et al. 2011), although Laganière et al. (2017) showed some scenarios where it exceeded 100 years. For Nova Scotia space heating with pellets made from harvested roundwood there was no return to carbon parity within the 100-year study period, but only a flattening of the curve in the middle to latter parts of the study period. This is primarily due to the slow rebuilding of NEP, but it is not clear from the study results whether this reflects low overall productivity in Nova Scotia forests, of if this is driven more by forest carbon modelling choices such as the assumption that no silviculture treatments were applied post-harvest.

LIFE CYCLE ENVIRONMENTAL IMPACTS OF NOVA SCOTIA WOOD PELLET ENERGY PATHWAYS

The second objective of this study was to assess the life cycle impacts of the NS wood pellet energy pathways to identify which activities contribute the most to environmental performance and to explore the potential for environmental trade-offs from substitution for fossil fuels. Putting aside the biogenic carbon emissions addressed in the integrated LCA-forest carbon analysis, the primary drivers of the supply chain impacts for the wood pellet pathways were pelletization and production of sawmill residuals. These impacts were mostly a result of Nova Scotia's continued reliance on coal-fired electricity generation, and sensitivity analysis indicated that life cycle GHG emissions could be reduced by using more renewable, lower-carbon electricity sources. The influence of NS electricity was also the reason that electricity used to power the wood pellet stoves was shown to be an environmental hot spot, accounting for upwards of 20% of the life cycle GHG emissions for both wood pellet heating pathways. This was an interesting finding and brought forth an element of the wood pellet heating life cycle that is typically not accounted for in LCA studies.

Results of the LCIA indicated some potential for environmental problem shifting when substituting NS wood pellets for oil-fired heating and coal-fired electricity generation. Life cycle impact contributions to ecotoxicity, human cancer and non-cancer effects, respiratory effects, and smog were generally higher for wood pellet pathways than the conventional fuels. For ecotoxicity and human health effects the increases were due to life cycle impacts of the coal-fired electricity in the NS grid which powered the pelletization and sawmilling processes. For respiratory effects and smog the increased impacts were a result of criteria air contaminants emitted from the combustion of wood pellets. The latter were based on average emissions factors from the USEPA for wood combustion and may not be reflective of each combustion technology. However, these results indicate that air emissions from wood pellet combustion should be assessed further, particularly if there is continued increases in the number and geographical concentrations of homes and facilities using wood pellet energy.

5.5.2 Environmental Management Considerations

Although wood pellet energy is considered part of the bioeconomy because of the use of renewable wood fibre, at its core wood pellet energy is still very dependent upon fossil fuels throughout its supply chain. This is particularly the case in a region like Nova Scotia where the electricity grid is still highly-dependent upon fossil fuels for electricity generation. In addition, wood pellets produced from harvesting of standing forest biomass have at least temporary negative effects on the forest carbon cycle which influences net changes to atmospheric carbon when substituting wood pellets for fossil fuels in energy applications. These issues are reflected in the LCA results and the integrated LCA-forest carbon analysis and highlight the need for policy-makers and regulators to avoid drawing broad conclusions about the GHG emissions benefits of wood biomass energy.

Within the domestic energy application for space heating, the results of the study suggest a hierarchy of choices for policy-makers to consider. From a climate change perspective, the displacement of home heating oil with wood pellets made from sawmill residues shows the greatest benefit. Sensitivity analysis showed that these benefits would be significantly higher when displacing electric heat. For pellets made from harvesting standing biomass, atmospheric carbon is increased when displacing oil in home heating but decreased substantially when displacing electric heat. The decision of whether it is better to displace oil or electricity may ultimately depend on the rate at which the NS electricity grid is decarbonized.

With respect to other environmental and human health indicators, space heating with pellets made from sawmill residues had slightly higher impacts across all categories considered, suggesting some limited potential for environmental trade-offs with the climate change benefits. In addition, although there are clear atmospheric carbon benefits to substituting wood pellets made from sawmill residues for conventional heating oil, there are some potential trade-offs for other life cycle impacts where pellets have higher impacts, such as contributions of smog forming air emissions from wood pellet combustion as well as ecotoxicity and human health impacts associated with the life cycle impacts of coal-fired electricity generation for the Nova Scotia grid.

From a life cycle GHG emissions perspective, the results showed a clear preference for wood pellets made from sawmill residuals vs. the use of newly harvested roundwood. Although producing pellets from residual wood sources can avoid increased forest harvesting, in any region there is a limited supply of residual wood that is physically available and economically viable to obtain. Once wood pellet production operations are established and have customer demand to meet, they may be forced to find alternatives to residual wood fibre when they run short, and this could prompt increased harvesting of standing biomass to meet pellet production requirements. As reflected in the literature and illustrated in the present study, the shift from residual feedstocks to harvesting standing biomass has significant implications for life cycle impacts, in particular the potential to increase atmospheric carbon levels. As the bioenergy sector grows, there is increasing impetus on forest managers to account for wood biomass energy needs in establishment of sustainable regional forest harvest levels and practices. The change in life cycle GHG emissions when using these different feedstock sources should also be accounted for in planning for the scale of the wood pellet sector in Nova Scotia.

Beyond the NS context, a broader environmental management consideration is that assumptions of 1:1 displacement of fossil fuels by bioenergy systems may be overestimating the actual environmental benefits of deploying these systems in the short-to-medium term. This is more of a global-scale environmental challenge, but it is important that it be considered by policy-developers and LCA practitioners alike. The lack of 1:1 displacement is not highlighted as a reason to halt efforts to deploy renewable energy systems, but it is to highlight that in the short-to-medium term, the perceived reductions in GHG emissions from deploying bioenergy systems may be overstated as a result of continued expansion of fossil fuel consumption elsewhere in the economy. In light of urgent timelines being suggested by climate experts to rapidly decrease global GHG emissions (Hansen et al. 2017), efforts may be better served to have LCA results that reflect the reality of the current socioeconomic context. This may help to place greater impetus on other policy measures to phase out fossil fuel energy systems more quickly, or to incentivize more rapid reductions in fossil fuel consumption throughout the economy.

5.5.3 Study Limitations

Some limitations of the study and of the LCA method more generally can affect the conclusions and the broader applicability of the study results. With respect to life cycle impacts, the study is limited by the assumption that supply chain and energy conversion systems will remain unchanged for 100 years. This was a simplifying assumption because it was beyond the scope of this study to predict future improvements in energy efficiency or increased adoption of cleaner energy sources in the future. For instance, it is not likely that wood pellet production systems will remain static over the next 100 years, nor is it likely that electricity grids will remain as presently configured. Changes in technology and energy efficiency over time could shift the results of this study.

A further limitation is that the LCA and forest carbon analysis results do not include assessment of impacts to forest ecosystems or wildlife and wildlife habitat due to incremental harvesting to supply wood pellet production. This is an important consideration as demand increases globally for wood pellets.

Another limitation of the study results is that the forest carbon analysis does not reflect the full complexity and nuance of forest carbon dynamics and the implications of broader forest management strategies. From a direct carbon removal and carbon sequestration standpoint, harvesting unmerchantable roundwood in the CBM-CFSC3 forest carbon model is shown to have negative implications in that it results in the transfer of carbon to that atmosphere and at least temporarily reduces forest carbon sequestration. However, there are possible scenarios in which there may be longer-term, less direct climate benefits of removing low-quality, unmerchantable hardwoods as part of an overall forest management plan. There are cases where selective removal of these low-value stands may increase growth rates for other forest stands, thereby increasing carbon sequestration in larger, faster-growing trees. In addition, the removal of this biomass may limit future carbon emissions from the forest by limiting forest fire and disease outbreak which can lead to rapid transfer of carbon from the forest to the atmosphere (Vance et al., 2018). For example, the effects of large-scale forest fires in Western Canada in 2015 rapidly converted those forests from carbon sinks to carbon sources and influenced carbon balance in the area for several years (Natural Resource Canada, 2017). Even if there are no quantifiable carbon benefits to removing low-quality biomass for bioenergy, there may be other forest ecosystem improvements that are valued to the point that short-to-medium term increases in atmospheric carbon could be a worthwhile trade-off for some stakeholders. A more detailed forest carbon analysis and consideration of bioenergy within broader forest management regimes is required to understand and control these dynamics.

5.6 Conclusions

Life cycle assessment and an integrated LCA-forest carbon analysis were used to quantify the environmental impacts and benefits of substituting Nova Scotia wood pellets for conventional fossil fuels in both domestic and export energy applications. The analysis was based on primary LCI data from Atlantic Canadian wood pellet producers and included modeling of wood pellet production from sawmill residues and from harvesting standing biomass. Results of the integrated LCA-forest carbon analysis indicated that using Nova Scotia wood pellets derived from sawmill residues to displace fossil fuels in residential space heating or coal in large-scale electricity generation in Europe could lead to significant cumulative reductions in atmospheric carbon over the 100-year study period. Conversely, results of the study showed that using Nova Scotia wood pellets derived from the harvest of standing biomass to displace fossil fuels in these same energy applications resulted in significant cumulative increases to atmospheric carbon.

Results of the life cycle impact assessment indicated that there are some potential environmental trade-offs when substituting wood pellets of either type for fossil fuels in space heating and electricity generation. These included increased contributions to smog, eutrophication, respiratory effects, ecotoxicity human cancer and non-cancer toxicity impacts. These potential trade-offs should be explored through further research and consideration of energy conversion technology. For example, increased smog impacts should be initially addressed by compiling more specific data on air emissions from wood pellet combustion and if persistent could potentially be reduced with combustion control technology. Many of the environmental trade-offs were linked to the life cycle impacts of coal-fired electricity generation to support the Nova Scotia grid, including ecotoxicity and human toxicity impacts. These impacts could be reduced by seeking alternative energy sources, or over time if the Nova Scotia grid becomes less reliant on coal-fired electricity.

Further research should also be undertaken on the broader role of these wood pellet bioenergy pathways within the Nova Scotia forest sector. These and other bioenergy scenarios should be incorporated into broader forest management policies in Nova Scotia in order to ensure that adequate feedstock is available, and to ensure that bioenergy harvest requirements are included as part of determining sustainable harvest levels in the province. Based on the results of this study, it is concluded that the focus for biomass energy policy development in Nova Scotia should be on developing an industry that complements and enhances the current forest industry at a smaller-scale, providing potentially beneficial use of wastes and co-products and working within the biophysical and economic boundaries that exist.

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CHAPTER 6: INSIGHTS AND CONCLUSIONS FROM PART II - WOOD BIOMASS ENERGY CASE STUDIES

6.1 Overview

Part II of this dissertation included three case studies on wood biomass energy systems under development or currently deployed in Canada. In each case study, LCA was used to quantify the life cycle resource depletion or environmental impacts and benefits of adopting various wood biomass energy systems as substitutes for fossil fuels in a range of energy applications. The objective of completing these case studies was two-fold: 1) to use LCA to develop quantified, practical insights to inform policy developers and stakeholders about the life cycle environmental implications of increased adoption of wood biomass energy systems; and 2) to provide sufficient candidate material to be analyzed in a critical reflection on the broader role of technology substitution and the methods used to assess alternative technologies within the existing ecomodern approach to environmental management and sustainability (see Chapter 2). The following sections include a brief summary of the three case studies to identify key findings and insights, and to highlight key questions and limitations that arise from the case studies for consideration in the critical reflection that was undertaken in Part III.

6.2 Key Findings from Wood Biomass Case Studies

One of the challenges in developing policy and approaches for the adoption of wood biomass energy is that the environmental impacts of these systems can vary across different biomass feedstocks, conversion technologies, and energy applications. In addition, varying methods have been used to assess the environmental performance of these systems, in particular with respect to addressing changes to biogenic carbon cycles. Within the three case studies presented in Part II, several wood biomass energy pathways and biogenic carbon scenarios were assessed, including:

- Multiple sources of wood fibre, including dedicated short-rotation willow crops, forest harvest residues, sawmill residues, and primary forest biomass;

- Multiple biomass conversion processes and feedstocks, including primary harvesting, residue collection, chipping, debarking, pelletization, and conversion to biochar and bio oil using fast pyrolysis;
- Multiple energy applications, including use in industrial furnaces, residential space heating, and large-scale electricity generation; and
- Multiple biogenic carbon scenarios, including biogenic carbon sourced from short-rotation forests, the use of forest harvest residues vs. allowing natural decay of forest residues, the dynamics of biogenic carbon within the wood products cycle, use of sawmill residuals, and the influence of bioenergy systems on the natural carbon cycle in large managed forests.

The broader research questions addressed across the assessment of these diverse wood biomass energy systems were: 1) Do any or all forms of these specific wood biomass energy pathways have potential to reduce the net GHG emissions to the atmosphere relative to the use of conventional fossil fuel systems? 2) Are there potential environmental trade-offs involved beyond carbon implications when substituting wood biomass energy for conventional fossil fuel systems; 3) What are the environmental hot spots within each of the bioenergy system supply chains and are there opportunities to improve environmental performance?; and 4) What are the limitations of using LCA in this context and are there other research questions which arise from this work that could be addressed to further improve our understanding of the sustainability of wood biomass energy systems?

Answers to these questions for each of the wood biomass energy systems studied can be found in the results and discussion sections of the case study chapters. In most instances, the findings for these research questions are specific to the case study in question and within the boundaries of the life cycle of those systems. However, some broader trends are highlighted across the findings of all three case studies and are summarized here.

- **Emissions of Carbon to the Atmosphere:** All three case studies indicated that:
    - Wood biomass energy systems based on the use of dedicated short-rotation crops or residues from other forest sector activities resulted in potential reductions of GHG emissions to the atmosphere relative to conventional fossil fuel systems in both the short and long-term time horizons (See Chapters 3 and 5);
    - Wood biomass energy systems based on the additional harvesting of standing forest biomass resulted in cumulative increases to atmospheric GHG emissions relative to conventional fossil fuel systems in both the short and long-term time horizons (see Chapter 5); and
    - There are some GHG emission trade-offs involved in using forest harvest residues that would have otherwise been left to decay naturally in the forest. These residues provide some short-term carbon storage in their biomass prior to decay and may also transfer some carbon to long-term storage in forest soils if allowed to naturally decay (see Chapter 4). At a minimum, this reduces the short and medium-term reductions in emissions for wood biomass systems.

- **Environmental Trade-Offs**: In each of the three case studies, potential contributions to several other environmental impact categories beyond GHG emissions/atmospheric carbon effects were quantified. Results for these other environmental and human health indicators show that there are potential environmental trade-offs when using wood biomass energy as a tool for reducing GHG emissions. Depending on the combustion technology and nature of the feedstock, some wood biomass energy applications can lead to increases in air quality-related impacts such as smog and respiratory effects. In particular these issues would need to be managed if there were a large transition to wood biomass energy in a smaller, more densely-populated area. For wood biomass energy systems where there is increased harvesting of primary forest biomass or large-scale removal of forest harvest residues there is potential for ecological impacts to forest ecosystems and wildlife habitat. However, quantification of these impacts is beyond the scope of this study, and these impacts have not been addressed in the LCA literature. The impact assessment methods used in LCA do not have adequate characterization factors to quantify these more local and regional ecological impacts to wildlife habitat, watersheds, etc.

- **Environmental Hot Spots**: The primary environmental hot spot across the wood biomass systems analyzed was energy use during the harvesting, collection, processing, and conversion of wood fibre into energy feedstocks. Despite their "biological" nature, wood biomass energy systems are still heavily dependent upon fossil fuels, either directly or indirectly, for the acquisition, transport, and processing of wood fibre in the bioenergy supply chain. Results of the case studies indicated that there are some improvement opportunities in this respect, such as using co-products to generate energy or to fuel vehicles, and using electricity from more renewable and non-fossil sources (see Chapter 5). The other consistent environmental hot spots identified were the various emissions to air resulting from wood biomass combustion. This is an area that is challenging to model in LCA since there are still limited data available to characterize the emissions from emerging wood combustion devices, and because the emissions can vary depending on the nature of the feedstock and the combustion technology and its efficiency. In addition, the receiving environment (i.e. existing air quality parameters) for the emissions from wood combustion would also need to be accounted for to measure the impact in a meaningful way.

- **Limitations and Research Questions:** The key limitations of applying LCA to quantify the environmental implications of substituting wood biomass energy technologies for conventional fossil fuel systems are linked to methodological challenges and to the challenges of trying to model interactions between complex natural systems. Some key limitations include:

    - Scope of impact assessment: For wood biomass energy systems that rely on harvesting standing biomass, there are potential ecological risks to forest ecosystems and wildlife habitat that are not accounted for in LCA methods and impact assessment calculations. Further, while many environmental concerns related to wood biomass energy are local in nature, impact assessment methods used in LCA typically aggregate potential contributions to life cycle impacts at a global level and generally do not refer to localized impacts;

- Scalability and Cumulative Effects: Related to forest ecosystems health is the issue of scale. These LCAs (and most others in the literature) are focused on single bioenergy system configurations and supply chains and do not account for the environmental implications of larger-scale adoption of these systems. In short, the LCAs do not account for environmental risks that are introduced by scaling these systems up to larger production levels;
- Complex Carbon Dynamics: The three case studies on wood biomass energy included several different assessments of forest carbon dynamics to account for changes in carbon balance between existing conditions and bioenergy scenarios where relevant. However, even the inclusion of basic forest carbon modeling in the Nova Scotia wood pellet study did not fully account for the complex ways that carbon is transferred within the forest and between the forest and wood products and the atmosphere. As a result, some seemingly clear insights, such as the use of standing biomass for bioenergy tending to lead to increases in atmospheric carbon, could be shown to be misleading if analyzed through a more detailed forest ecosystem management approach.
- Trade-Offs with Socioeconomic Impacts: The life cycle assessments in Part II are limited to a set of indicators referring to environmental and human health impacts. These studies ignore the potential socioeconomic benefits that may be derived from commercial-scale bioenergy operations, including improvements to local energy security, support of economic development in rural economies, and acting as a complementary and supporting industry to support broader forest sector activities. Some jurisdictions may be willing to trade off the potential of short-to-medium term increases in GHG emissions from wood biomass energy for the longer-term socioeconomic benefits.

Although socioeconomic factors are a key aspect of sustainability, their assessment was beyond the scope of the wood biomass energy case studies.

Many of these limitations can be overcome in time with further research, improved scoping, and improved methods, while some of these limitations can only be overcome through a combination of improved LCA methods and the application of other environmental management tools and the engagement of stakeholders. For example, there is ongoing research by LCA practitioners and forest carbon experts to improve the data quality and modelling capabilities for integrated analyses of the life cycle carbon emissions and sequestration associated with biomass energy systems.

The findings of these case studies also prompted more fundamental questions about wood biomass energy systems, and about the role of technology substitution in achieving sustainable development more broadly. Some of these questions about the ecomodern approach to environmental management and whether environmental impact assessment tools like LCA are serving to promote or confound efforts to achieve a more sustainable society are summarized in the following section, and explored in greater detail in Part III of the thesis.

6.3 Limitations and Need for Critical Reflection

A primary motivation for this dissertation was an observation of the disconnect between global efforts to improve the eco-efficiency of energy systems and the continued rise in total energy consumption and GHG emissions (see Chapter 2). Data generated with tools like LCA show the potential for green technologies to displace fossil fuels and reduce GHG emissions, and the wood biomass energy case studies in Part II of this dissertation provide good illustrations of this. Yet the continued worsening of global environmental conditions runs contrary to these signals from the LCA literature, and contrary to popular belief in the green economy, raising questions about the prospects for green technology to clear the path to sustainability.

In the landmark 1972 book *The Limits to Growth* (Meadows et al. 1972), computer simulations were designed to understand the future of society based on its then current trajectory, and based on potential policy changes that could be made to address issues related to population, human health, and environmental issues. This included the simulation of a number of technological improvements intended to address issues related to pollution and disease and economic productivity (efficiency of resource use). The results of the simulation indicated that rather than preventing societal collapse from the myriad challenges it faced, which is the general assumption that dominates the ecomodernist approach, the technological solutions simply extended the timeline to collapse by a few decades. In the simulations, technology could not resolve the underlying fundamental issues needed to avoid societal collapse, but rather technology shifted the limits and the timeline.

There were no certainties about societal collapse or the trajectory of human society in the simulations that underpinned the findings of *The Limits to Growth*, and one may wish to revisit the underlying assumptions and data relative to the current landscape. However, the interpretation of these simulations did provide some important insights about technology and the implications of deploying technology to resolve environmental problems associated with non-renewable resource use and emissions. In the conclusion of the chapter on technology in *The Limits to Growth*, the authors reflected on our understanding of technology and how we should assess technological development towards improving the human situation (i.e. sustainability). They provided a set of three questions that should be considered about emerging technologies before they are widely adopted. These included (Meadows et al. 1972):

1. What will be the side-effects be, both physical and social, if this development is introduced on a larger scale?
2. What societal changes will be necessary before this development can be implemented properly, and how long will it take to achieve them?

3. If the development is fully successful and removes some natural limit to growth, what limit will the growing system meet next? Will society prefer its pressures to the ones this development is designed to remove?

Reflecting on wood biomass energy within the context of a broader set of questions like this is a useful exercise for better understanding its potential and its challenges. In light of the results of the LCA case studies in Part II and in the broader literature, one might argue with respect to question 3 that in some configurations, wood biomass energy systems are not even meeting the first requirement of removing an initial limit to growth (i.e. global warming and climate change).

The observations from the wood biomass case studies and contemplating these additional questions about the use of technology to resolve environmental challenges prompt important questions about broader trends related to the reliance on technological substitution to achieve sustainability, and present an excellent opportunity for a more critical reflection. In Part III of the dissertation, core principles from ecological economics and the philosophy of technology were reviewed in an interdisciplinary critical reflection on these wood biomass energy case studies and on the broader questions about technology substitution and ecomodernism to which they are connected.

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CHAPTER 7: CRITICAL REFLECTION ON ECOMODERNISM AND TECHNOLOGY SUBSTITUTION

7.1 Introduction

The results of the LCA studies in Part II indicate great potential for environmental impact reductions from substituting wood biomass for fossil fuels in various energy applications in Canada, particularly for reducing life cycle GHG emissions. These results are consistent with general findings in the scientific literature on wood biomass energy, and for bioenergy systems more broadly (see Chapter 2). They also reinforce some of the presumed environmental and sustainability benefits associated with shifting to a bioeconomy, which is the premise for many global sustainability efforts such as the United Nations SDGs (see Chapter 5).

LCA research has been used widely to assess the impacts and benefits of adopting alternative technologies, products, and processes that have been designed and produced under the ecomodern approach to sustainability. Over the last two decades, academic and industry journals have seen an increasing number of publications on LCA studies of energy systems, food systems, infrastructure (e.g. buildings and building materials), and consumer products (Hou et al. 2015; Bjorn et al. 2017; Geng et al. 2017; Zimek et al. 2019). This is in addition to LCAs conducted by, or on behalf of, technology and product manufacturers themselves, which have been used to quantify the environmental benefits of their technologies and products and to support marketing efforts to increase adoption by consumers, and investor funding.

LCA has become one of the most widely used methods for validating environmental improvement claims associated with green technologies and consumer products. The use of environmental systems assessment tools, most notably LCA, has become the basis for both corporate and government initiatives aimed at promoting sustainability (Freidberg 2014). The research on wood biomass energy systems summarized in Part II is an example of this, and indeed was funded in part by both corporate and government stakeholders to support their respective activities related to technology and sustainability.

The work summarized in Part II is also an example of a fundamental part of the ecomodern approach to sustainability, which is assessment of the environmental benefits of alternative technologies to validate their wider deployment. Whereas the ecomodern approach is to treat sustainability like an engineering problem, the mechanics of this approach are to identify an environmental problem (e.g. climate change, fossil fuel depletion), design an alternative technology which is thought to be more eco-efficient than the conventional system in some way, and then to use methods like LCA to assess the environmental improvements. The results of the LCA are then used to inform further technology design and optimization, to promote the technology, garner additional funding to refine and deploy the technology, and convince policy developers that the technology should have a role in sustainability strategies.

Despite the widespread adoption of this approach to eco-efficient technology substitution over the last 30-40 years (as summarized in Chapter 2), and despite the significant environmental benefits of technology substitution that are signaled in the LCA literature, the empirical data suggest that environmental conditions are continuing to worsen, that human society is, in fact, less sustainable relative to most key indicators. As highlighted in Chapter 2, atmospheric concentrations of CO_2 have continued to increase and reach historical highs since the start of the industrial revolution, extraction and use of fossil fuels has continued to increase and is expected to continue to increase into the middle of this century and likely far beyond, the extraction and use of primary materials (e.g. metals) has continued to increase, and negative impacts to global ecosystems and biodiversity resulting from human activities have also continued to increase, to the point that species are being pushed to the brink of extinction at an unprecedented rate. The continued worsening in these areas is well-documented and yet the ecomodern approach remains entrenched with governments, corporations, and technology developers.

The disconnect between what is suggested as possible in our LCA models and national emissions inventories and the empirical data on environmental conditions was highlighted in a 2017 article in the New York Times about the apparent discrepancy between global GHG emissions inventories and atmospheric CO_2 concentrations (Gillis 2017). The article noted that data from measurements of atmospheric carbon dioxide levels show a continued increase, with one prominent measurement site in Tasmania recording its highest-ever concentrations in 2015 and 2016 (Gillis 2017). In contrast, data on CO_2 emissions from national inventories were indicating that emissions had stabilized in recent years, and even declined slightly. In the article, several scientific explanations for this discrepancy were posited, ranging from higher emissions due to increased forest fires in the tropics caused by El Nino effects, to other previously undocumented releases of CO_2 from unexpected carbon sinks. However, what is striking is that there were no questions posed about the accuracy of the national GHG emissions inventories, which are clearly out of step with the trends shown in measured data of atmospheric carbon. This suggests a remarkable confidence in modeled versions of reality over empirically observed phenomena.

Attempting to reconcile the increasing environmental degradation with the unfailing technological optimism of the ecomodern approach and the favourable data being supplied from quantitative assessment tools like LCA which help to fuel and validate this optimism, prompts several questions: 1) How can environmental impacts continue to increase despite the increased implementation of ecomodern policies and deployment of eco-efficient technologies and products over the last few decades?; 2) How can these impacts continue to increase when results from quantitative assessment methods like LCA indicate that technology substitution can yield substantial environmental impact reductions across many sectors of the economy?; 3) If the data on key environmental trends indicate that these expected improvements are not occurring, are there problems with the scope or methods used to assess the impacts of alternative technologies?; and 4) Given the lack of progress on key sustainability objectives, are the assumptions on the role of technology in the ecomodern approach flawed and misguided?

The objective of Part III of this dissertation was to undertake a critical reflection on the ecomodern approach of eco-efficient technology substitution to develop some initial answers to the above questions. The disconnect between empirical data and the LCA models described above indicates an incomplete understanding of the implications of technology substitution, and that methods for quantifying the environmental impacts of technology substitution are lacking and not capturing impacts fully. It suggests that LCA methods do not fully reflect the realities of technology development and deployment, and potentially represents the use of an inadequate frame from which to understand the full implications of technological innovation and technology-society-environment interactions and dynamics. It is apparent that the ability to understand, model, and predict how alternative technologies will be taken up into society and contribute to sustainable development is insufficient, and as such, the central role of technology in ecomodernism is of concern due to this lack of understanding of the full ramifications of deploying new technologies.

In this chapter, a broader understanding of the central pillar of ecomodernism, technology, and technology substitution is developed by reflecting critically on the wood biomass case studies and ecomodernist approaches more generally, through two disciplinary lenses, including the philosophy of technology and ecological economics. Insights from the philosophy of technology were used to determine if current approaches are adequate for understanding how technology is both embedded in, and acts as a formative force of change for, social, economic, and environmental issues. From the philosophy of technology, a framework was developed from which to critically examine the role of technology in sustainable development. Within this examination, insights from ecological economics were used to reflect on the biophysical realities of how technology both mediates and exacerbates the negative impacts of human society on the planet. This critical reflection also includes an examination of the strengths and weaknesses of relying on methods such as LCA to model and quantify the impacts and benefits of alternative technologies, as a means to determine which technologies should be pursued, and of predicting the contribution of technologies to achieving sustainable development goals.

7.2 Insights from the Philosophy of Technology

As part of the interdisciplinary approach to this research, literature from the philosophy of technology was reviewed to develop a framework from which to reflect critically on the practical case studies on wood biomass energy from Part II, and more broadly on the use of technology substitution as the central pillar of the ecomodern approach to sustainability.

The philosophy of technology is a relatively young subfield of philosophy which involves the interaction of several different fields of knowledge, including philosophy of science, political and social philosophy, ethics, and some aesthetics and philosophy of religion (Dusek 2006). The main branches of philosophy originated over 2,200 years ago, and while many philosophers up to and beyond the mid-nineteenth century were interested in the philosophy of science, only few produced works in which issues of technology were central. It may be that an assumption that technology is simply the practical application and extension of science led many philosophers to believe that there was little of interest in exploring this topic (Dusek 2006). The Society for the Philosophy of Technology was founded in 1976, thousands of years after the birth of philosophy, and over three centuries after philosophers began intensively examining nature and scientific knowledge (Dusek 2006). This formalization of the discipline came on the heels of a global awakening to the existential risks of technology in the form of the atomic bomb, and increasing awareness of the negative side-effects of technology, including concerns about the implications of genetic engineering and the degradation of the natural environment (Dusek 2006). Interestingly, the latter development led to the early environmental movements of the 1960s and 1970s and is also the context for an application of insights from the philosophy of technology in this dissertation.

The topics and literature in the philosophy of technology are wide-ranging. For the purposes of this dissertation, the literature consulted consisted of foundational articles and books examining the many ways that technology, in its many forms, manifests in society, and in particular the interactions between technological artifacts and social and political systems. Insights from the literature reviewed were then applied to the present inquiry on wood biomass energy, and more broadly on the ecomodern approach to sustainability. The result of this work is a framework within which to study technology substitution and ecomodern policies as they relate to sustainability.

Within the philosophy of technology literature, three key themes were explored:

- The ecomodern movement has reduced sustainability to an engineering problem with an emphasis on technology development, assessment, and deployment. Is it an adequate approach to limit the critical reflection solely to examination of the technologies (or artifacts) and their applications to understand the implications of new technologies and assess their risks and benefits in the context of sustainability? Or should the scope be broadened, and if so, how?
- Technology advances at an increasingly rapid rate and the design and deployment of new technologies often feels out of reach for those not directly involved. Does the momentum of technological progress originate from the technologies themselves, therefore making technology generally free from human control and intervention? Or can a critical reflection be used to identify points of leverage for assessment and decision-making on its trajectory?
- Those concerned about the environmental damage caused by technologies often have an antagonistic relationship with technology, while ecomodernists have a very optimistic perspective on technology. If the objective is to find ways to change or improve the potential for technology to contribute to sustainable development, what is the proper perspective or relationship that is needed for an effective critical reflection on technology?

7.2.1 Technological Artifacts vs. Technological Systems

Throughout Part I and Part II, the word “technology” or “technologies” was used primarily in reference to machines or physical technological systems used to convert energy or perform some specific function to support human activity. Within the ecomodern approach to sustainability this is also the case, where the discussions of technology are referring to physical artifacts that perform work to facilitate human economic activities. Indeed, when discussing and assessing technological development, there is a tendency to focus exclusively on the artifacts themselves. Do they serve their intended purpose? Can they be manufactured and marketed in a manner that is economically viable? And increasingly, can they be produced and used in a manner that meets government requirements and consumer expectations for reducing impacts to human health and the environment? The latter has emerged as a concern primarily in the last 30-40 years, and this, along with the rapid rate of innovation and technology development since WWII, has increased the need to assess emerging technologies to determine the environmental costs and benefits of their deployment.

Historically, environmental technology assessment has been carried out by government agencies and technology developers, as well as consultants who work on their behalf. Their focus is generally on assessing the technological artifacts themselves: Is this technology more energy efficient than the conventional form? Will adoption of this new technology result in lower greenhouse gas emissions from this activity? Is it preferable to make this technology with plastic or with steel? Once the environmental performance of the technological artifact itself has been assessed, it may then be taken up as an eco-efficient alternative, or may need further changes in design, manufacturing, or application before widespread deployment.

Stepping back from this rapidly expanding green technology revolution, there are some basic questions related to how we define and relate to technology that have typically not been explored in this context: Are there limitations to the overwhelming focus on the technological artifacts themselves (i.e., are we too focused on the "techno-fix")? Is investment in more technology a reasonable response to the environmental damage that has in many ways been enabled by technology (i.e. will adding more technology to the mix simply make things more complex and worsen environmental conditions further)? Are those invested in green technology development and deployment (i.e. government agencies, private technology developers and their consultants) best suited to assess the environmental implications of alternative technologies, or does their proximity and objectives limit their ability to think critically about a given technology?

Stephen Kline (1985) explored the different ways we tend to define technology, noting that "…the current vague use of the word technology hides from view central concepts, and a central pattern of human behaviour that we must have to make sense of our views of many critical questions in the current world…" (Kline 1985, pg. 215). Kline breaks the word technology down according to four typical usages, including (Kline 1985, pg. 215-216):

1. Hardware or artifacts: non-natural objects of all kinds manufactured by humans;
2. Sociotechnical systems of manufacture: all the elements needed to manufacture a particular kind of hardware, including people, machinery, resources, processes, and legal, economic, political, and physical environment;
3. The information, skills, processes, and procedures for accomplishing tasks (i.e., knowledge, technique, methodology);
4. Sociotechnical systems of use: a system using combinations of hardware and people (and usually other elements) to accomplish tasks that humans cannot perform unaided by such systems – to extend human capacities.

Kline suggests that our most common usage of the word technology tends to be a reference specifically to technological hardware or artifacts, and that this definition has very limited application for critical thinking about technology because "Without sociotechnical systems of use, the manufacture of hardware would have no purpose" (Kline 1985, pg. 216). Langdon Winner (1986) wrote eloquently about the risks of focusing only on technological artifacts in our analysis of technology:

> If our moral and political language for evaluating technology includes only categories having to do with tools and uses, if it does not include attention to the meaning of the designs and arrangements of our artifacts, then we will be blinded to much that is intellectually and practically crucial. (Winner 1986, pg. 25)

Val Dusek (2006) notes the limitations of simply defining technology as artifacts, in particular that defining technology only as "tools" tends to make technology appear neutral, that it is neither good nor bad, and that the user is outside of the tool and controls it. This is in contrast to the systems approach to technology, where the technology encompasses the humans; the individual is inside the technological system (Dusek 2006, pg. 36). One of the implications of this tendency to focus on technological artifacts is that we tend to see ourselves as being separate from technology, when in fact we are part of the sociotechnical system in a number of ways, and this system exerts influence over our understanding and perspective on technology.

Thomas Hughes (1987) refers to these types of large technological systems as macro-systems and argues that they take on their own momentum (Hughes 1987), or as Feenberg puts it, "…a quasi-deterministic power to perpetuate themselves and to force other institutions to conform to their requirements" (Feenberg 1999, pg. 186). In many ways, one can liken this larger technological system to a machine itself. The technological artifacts and the social and political systems which are associated with them are working in tandem to achieve a particular objective (e.g. produce and distribute energy), and they exert power and force, both physical and sociopolitical, on their surrounding environment. The technological artifacts and the social and political systems associated with them tend to develop a certain momentum as they progress and become more prevalent in society. Langdon Winner suggests that:

> What we see here instead is an ongoing social process in which scientific knowledge, technological invention and corporate profit reinforce each other in deeply entrenched patterns, patterns that bear the unmistakable stamp of political and economic power. (Winner 1986, pg. 27).

Here Winner broadens the notion of social systems that surround technological artifacts to include dimensions of politics, power, and inequality. He also highlights the concept of technological momentum where sociopolitical systems are established around technologies and create a self-perpetuating force. This momentum can potentially limit the opportunity for critical evaluation by making the macro-system resistant to change.

In reflecting on the assessments of wood biomass energy systems in Part II, and the role of eco-efficient technology in ecomodern approaches to sustainability, technology in these contexts was largely in reference to the physical artifacts, although the ecomodern approach includes discussion of amelioration of economic and social problems as a result of deploying new technologies. What is clear from the literature in the philosophy of technology is that to undertake a critical assessment of technologies and technological substitution as a means to achieve sustainability, one must also examine the social and political structures that influence the manufacturing and use of technological artifacts. This includes the sociopolitical context into which these alternative technologies are deployed, and how the deployment of eco-efficient technologies will further shape their sociopolitical context, and the resulting biophysical implications of these changes. This represents a significant shift in scope when considering the role of technology in achieving sustainability, and this is explored in more detail in Section 7.3.

7.2.2 Human Relationship with Technology

A topic explored at length in the philosophy of technology literature is the nature of the relationship between humans and technology, and in particular questions about who is in control, human or machine? In developing his Critical Theory of Technology, Andrew Feenberg (2003) explored various elements involved in determining this relationship, indicating that these relationships are defined by whether one believes that technology is autonomous or human controlled, and whether technologies are neutral or have inherent values. According to Feenberg (2003), the interactions of these elements result in four basic theories that may define the human-technology relationship:

1. Instrumentalism – This is the standard modern view where technology is a tool or instrument of the human species, an extension of human faculties which is under human control and can be used to drive human progress.
2. Determinism – Based on an assumption that technologies are neutral but have an inner logic, and that while humans are involved in technology design and deployment, they ultimately must adapt to technology as an expression of humanity.

[It is notable that for both instrumentalism and determinism, technology is viewed as neutral, and that rather than containing any value in and of itself, it is a tool to achieve a pre-existing value or objective held by humans in a more efficient way (Feenberg 2003).]

3. Substantivism – Technology is viewed as having embodied values and is not merely instrumental. The values embodied in technology are the pursuit of power and domination, and that if we use technology, we are committed to a technological way of life. As such, technology becomes more and more imperialistic, taking over one domain of social life after another, and humans become part of the technological system.
4. Critical Theory – The potential catastrophic consequences for society due to technology are recognized, but there is promise for the future if humans can develop appropriate institutions to control and direct technological development. It is a continuation of the Enlightenment values which drive the idea of progress, while recognizing the resulting problems that may emerge.

The technological optimism at the core of ecomodern approaches is certainly based on an instrumentalist view of technology, while elements of determinism and substantivism are absent. Elements of critical theory are present in ecomodern approaches, although the identification and understanding of the consequences (or environmental impacts) of deploying new technologies at a large scale are broadly overlooked.

Interpretations of the theory of autonomous technology, which was first articulated in detail by Jacques Ellul (1980), tend to describe the technological artifacts themselves as being autonomous, as being outside the control of human intervention. Ellul stated that technology is "…an organism tending toward closure and self-determination; it is an end in itself" (Ellul 1980, pg. 125). He goes on to refute the notion that humans can control technology by way of values and morality, arguing that (Ellul 1980, pg. 145-147):

- Technology does not progress in terms of a moral ideal, it does not seek to realize values, it does not aim at a virtue or a Good;
- Technology does not endure any moral judgment;
- Technology does not tolerate being halted for a moral reason, it exists beyond good and evil, it is liberated from what was once the main check on human action: beliefs (sacred, spiritual, religious);
- Technology and anything recognized as technological is accepted immediately as legitimate and any challenge to this legitimacy is suspect, viewed as pessimistic and anti-technological; and
- Technology is becoming the creative force of new values, a new ethics.

Much of what Ellul has observed in this regard would appear to hold true over the history of modern technological development. Indeed, technologies are generally viewed as being value-neutral and universally beneficial, particularly when linked to language about efficiency, and the onus is on those with concerns about negative impacts to prove otherwise. This automatic legitimacy acts as a form of protective barrier which allows technological change to be automatically constructed as progress which attracts minimal criticism and impediment. If technological development, including the development of eco-efficient technologies within the ecomodern approach, is autonomous, then how can one actually hope to influence its form and trajectory? If one subscribes to this view of autonomous technology, then any notion of technology assessment seems like an exercise in futility if technology will advance on a particular trajectory regardless of the outcome of these assessments.

With respect to eco-efficient technologies in particular, this uncritical acceptance of technology is magnified due to the perception of reduced environmental impacts that is created by the discourse, or language, of sustainability. There is a rather uncritical acceptance of green technologies as being inherently good which limits any questioning of their true environmental costs and benefits and which has allowed the development and deployment of eco-efficient technologies to progress to the level of large-scale deployment before key limitations are identified. As Winner notes, any new technology that can be shown to have even a narrow utility tends to be adopted with no consideration of its broader implications (Winner 1977, pg. 326). Does this mean that the emergence of eco-efficient technologies has been, and is, inevitable? Are they autonomous, an end in themselves that cannot be controlled? Is the development of eco-efficient technologies simply the next step in some logical progression of technological development that would happen regardless of any objections? (Heilbroner 1967, pg. 336).

While it is certainly true that technological development often feels autonomous and beyond control by broader society, Ellul makes a critical distinction that the autonomy of technology is not so much a result of technological artifacts being completely free of human intervention (although he states this is largely the case), but that the overall technological system that propagates innovation and new technologies (i.e. the technicians and the political, economic, and social systems that support them) is itself autonomous. According to Ellul, "…the technological world will itself organize technological research, the direction of application, the distribution of funds, etc. The autonomy of the technological system must be matched by the autonomy of the institutions that are part of it, that embody it." (Ellul 1980, pg. 143). As such, the technological artifacts themselves are not autonomous in the sense that they don't have their own inner logic, but rather the social, political, and economic systems that surround the technologies themselves operate in an autonomous fashion. In short, as long as the technological system itself is autonomous, then technology can be viewed as autonomous in that it operates virtually free from political, social, or moral judgment and guidance by those outside the sociotechnical system of manufacture.

This phenomenon has perpetuated itself over time and the momentum around technology has increased as the technological system has become more and more autonomous. In the case of the green technology movement, a tremendous amount of momentum has been built up as a result of actions and decisions made by the surrounding sociotechnical system that drives these innovations (e.g. government funding agencies, government regulations, corporate technology developers, etc.) and entire careers and livelihoods have been built up around this movement, including my own career in environmental management consulting. Whether these technologies are autonomous or not, the momentum of the overall system of eco-efficient technology development makes it difficult to stop long enough for critical reflection.

Ultimately, though, technology is a human construct. As Aristotle points out, a craft (or technology) is something "…whose origin is in the producer and not in the product" (Aristotle, Nichomachean Ethics 6.32, 1140a10-15). This fact has been obscured by the isolation of technology under the control of a small group of technicians, corporations, and politicians. The critical point to be made here is that technological artifacts are not developing in some autonomous, unstoppable fashion. It is the sociotechnical macro-systems that drive technological development which have been operating in virtual autonomy. The key to being able to influence the trajectory of technological development is to be able to identify and describe the broader sociopolitical context of the technologies and to find places of leverage to exert outside influence inside that over-arching sociopolitical system. This is explored in more detail in Section 7.3.

7.2.3 Optimistic and Pessimistic Perspectives on Technology

One of the risks of undertaking a critical analysis of the role of technology in sustainable development is that any insights or arguments put forward may be dismissed as coming from an anti-technology or anti-progress viewpoint. The roots of modern anti-technology movements extend to the Romantic period after the Industrial Revolution where the nature and scale of the new science and technology was perceived as destroying nature and destroying the human spirit (Dusek 2006). Variations on this Romantic-era viewpoint have evolved over the years since, ranging from the overt physical destruction of actual machines by the Luddites through to the more modern philosophical anti-technology movement exhibited in the field of deep ecology. Deep ecology is based on philosophical principles first articulated by Arne Naess which assign intrinsic value to nature and reject the anthropocentric approach to controlling nature with technology (Dusek 2006). A deeper exploration of the anti-technology movement was beyond the scope of this dissertation. However, it is important to recognize that arguments perceived as coming from an anti-technology viewpoint are often dismissed by scientists and political leaders as dogma, utopian, and of little practical value (Florman 1994), particularly in an age of extreme technological optimism. As Winner points out, "discussions of the political implications of advanced technology have a tendency to slide into a polarity of good versus evil" (Winner 1977, pg. 10). When this happens, it becomes difficult to have discussion of technology in thoughtful, critical terms (Winner 1977, pg. 10). Indeed, discussions of the implications of modern technology on the well-being of society are often clouded by strongly-held views on whether technological progress is the key to human survival or the primary cause of our environmental and social problems. As such, approaching this research from an anti-technology standpoint, or even to be perceived as such, could result in dismissal of the arguments by strong proponents of technological innovation.

These challenges of being perceived as anti-technology are exacerbated by language and talking points that emerge from the sociopolitical systems that surround technology. The words or slogans become broadly used and accepted and are used to promote a particular way of thinking as being virtuous and unquestionable. In the ecomodernist approach words like "efficient", "eco-efficient", "innovation", "green", "bio" are used and are generally viewed as being universally and unambiguously good or positive. Some of these terms have become "god terms", terms which become so commonly accepted as good that the technologies and concepts they are applied to become unassailable (Winner, 2018). Those who may question technologies that have been labeled with these positive terms may be dismissed as being cynical or anti-technology and therefore their critiques, which may be valid, may be dismissed without consideration. These words or phrases become part of the structure and thus unquestionable, which further serves to contribute to the momentum of the sociotechnical system of technology and further protecting it from questioning.

Being anti-technology is to have a very particular relationship with technology, but one that falls within the general spectrum of ways that people have tended to relate to technology historically. Carl Mitcham examined three primary ways that society has generally related to technology over time (Mitcham 1990, pg. 34-39), and they include:

- Ancient skepticism – a general distrust or wariness towards technology, a concern that technology leads one to turn away from nature and providence;
- Enlightenment optimism – a view of technology as inherently good, and the burden of proof lies on opponents of technology to prove that new inventions will not be beneficial;
- Romantic uneasiness – the first self-conscious questioning of technology, society may benefit from technological development, but there are limits beyond which reliance on technology can lead to negative outcomes.

Although Mitcham rooted these descriptions in particular historical time periods, elements of all three of these ways of relating to technology can be readily observed today. A high-level analysis of these three ways of relating to technology suggests that ancient skepticism would be very much in line with the anti-technology movement, or many factions of the more grassroots environmental movement, while it could be argued that enlightenment optimism is the dominant technological paradigm that has driven the industrial expansion of human society to where it is at present, and is the view at the core of ecomodernism. Romantic uneasiness represents a somewhat more balanced view in that it does not reflect a blind optimism in technology but also does not preclude a role for well-designed technology to bring benefit to society. It is consistent with Feenberg's description of a critical theory of technology (Feenberg 2003).

7.2.4 Summary of Insights from the Philosophy of Technology

This chapter began with a series of questions to be explored through the philosophy of technology literature. A summary of the relevant findings is provided below.

1. **Broader Scope of Assessment** - A critical reflection on technology must be broader in scope than just assessing the inputs and outputs and efficiency of the artifacts or the machines themselves. The broader context of social, economic, political, and environmental conditions within which technologies are developed and into which they are deployed must be considered, as well as the new context that is created by large scale deployment of the technology. Technologies are designed and developed within a particular context, but then when they are deployed at a large-scale, they exert influence on the social, political, economic, and environmental conditions around them. Failure to account for the broader context is a failure to account for many key factors that will influence the contribution, either positive or negative, of a given technology towards environmental sustainability. Ignoring the broader context can also reduce the accuracy of key assumptions that need to be made to undertake an assessment of a technology.
2. **Points of Leverage for Assessment and Direction** – Although the rapid pace and scale of technological development can give the appearance of autonomy, it is not the technological artifacts or machines themselves that are autonomous. It is the sociopolitical system of technology which surrounds the machine which tend to gain momentum and be difficult to slow or steer in a particular direction. These sociopolitical systems of technology also tend towards power and domination in society, and to escape outside forces. A critical reflection or assessment is therefore not futile because technology is not a runaway phenomenon with its own inherent objective or direction, it ultimately falls under human control such that there is potential for the identification of leverage points to steer technological systems in appropriate directions.

3. **Perspective on Technology** – Technological advances have brought great benefit to humanity through improvements in life expectancy, economic prosperity, growth in our sheer numbers, and extending the reach of humans to every point on the globe. However, there are also well-documented negative impacts of technologies on society and, of particular relevance to this dissertation, on the environment that supports human society. In light of these negative impacts, operating under an entirely optimistic perspective on technological development and its potential to resolve human problems is problematic. The Enlightenment optimism for technology that is the foundation of ecomodernism is therefore flawed due to its ignorance to the limitations and the negative outcomes that can occur as a result of deploying seemingly beneficial technologies at scale. It is also this blind optimism which informs the choices and use of language when it comes to technologies developed in the context of environmental sustainability. The use of language such as "eco" and "bio" and "efficient" become attached to these technologies and give the air of being unquestionably good and beneficial. We then tend to accept these things as given. On the other hand, holding an extremely pessimistic view on the role of technology in sustainable development is itself not practical. Broadly speaking, technologies are the ways that humans use to extend their capabilities and reach, it is the way we shape our environment and our society, and many positive outcomes have been achieved in this manner. Given the current and growing global population and the biophysical limits imposed by the lone planet that our society inhabits, technological development is an essential tool for achieving a sustainable society. The question becomes more about the extent of that role and how important is that role alongside other potential means of reducing the scale of human-induced environmental change.

Based on this review of the philosophy of technology literature, the approach adopted for this critical reflection is that the arc of technological development and advancement in any particular field may behave as autonomous and progress unchecked in the absence of critical assessment and input from those outside the sociopolitical system of technology. This critical assessment requires a scope that is greater than just evaluation of the technologies themselves, and requires an approach or posture that is rooted in practical pessimism, or an openness to the fact that the technologies being developed in a given field are not inherently good or appropriate just because of certain attributes that they possess or language that it is used to describe them.

One of the challenges of critically evaluating technological systems is that clearly technologies are already occupying space and being utilized in our society (Winner 1977, pg. 326), which can limit the ability to take a thoughtful, cautious approach to the development and deployment of new technologies. Within the specific context of sustainable development, it is recognized that technological innovation and substitution for conventional technologies will play a role in achieving sustainable development, and that entire industries have already been developed towards this objective, but that this role should not be defined and accepted without critical thought and reflection and without adequate assessment of the benefits and costs to society of deploying particular technologies.

Winner described a particular approach to critical analysis of technology which is generally rooted in the "uneasiness" described above when he suggested a "dismantling" of existing and proposed technologies, which is not describing a physical destruction of technologies as the Luddites did, but a method of inquiry/critical reflection on technologies before they are deployed to try to identify appropriate technologies (Winner 1977, pg. 327). As interpreted by Garcia et al. (2018), Winner proposes an approach for reassessing human relationships with current technology and innovation by detaching from them and intellectually dismantling technological systems to understand how they are affecting society, and to gain perspective on what other means are possible in terms of more appropriate technology. While Winner seemed to be referring to a physical detachment, as in not deploying technologies prior to this assessment, or not using certain existing technologies for a period of time while they are assessed, a second way would be to intellectually detach from technology to critically reflect on its implications. To intellectually remove oneself from the sociopolitical system which drives the technology in order to critically reflect on the technology.

This intellectual detachment is important because in the same way that sociotechnical systems exert influence on their surroundings, they also exert influence on those working within the sociotechnical system, such that technology developers, engineers, and consultants working on aspects of designing, deploying, and assessing technologies are influenced in how they do this work by the broader objectives and principles of the macro-system. From a personal standpoint, I am an environmental consultant and much of my work involves assessing the eco-efficiency of green technologies and products, and the way in which this work is done is heavily influenced by the broader sociotechnical system that surrounds these technologies, and that is informed by the ecomodern approach to sustainability. Undertaking this PhD research was therefore my way of detaching or removing myself temporarily from the sociotechnical system to permit a critical reflection and dismantling exercise.

7.3 Ecomodernism and the Green Machine

In Chapter 2 of this dissertation, the concept of ecomodernism was described in some detail, and it was shown how this particular approach to sustainable development has been entrenched as the dominant approach by governments and industry globally for several decades and continues to be at present. In ecomodernism, the environmental issues that are faced by society are viewed as a technological problem, and the resolution of these problems through the development of eco-efficient technologies will not only eliminate the environmental issues, but this second industrial revolution, or green industrial revolution, will fuel the next great leap in human prosperity. In essence, the pursuit of constant economic growth to support human development can be continued as a result of the new economic activity needed to design, manufacture, deploy, and manage these new clean technologies.

The substitution of wood biomass energy systems for conventional fossil fuel energy systems provides an example of this approach. These “bio-based” (i.e. biomass) technologies are presumed to reduce GHG emissions, replace a non-renewable resource (e.g. coal) with a renewable resource (wood), and provide more locally-based and sustainable feedstocks as opposed to fossil fuels which are often imported and which are subject to global geopolitical pressures. By increasing the demand for wood, these technologies can also boost rural economies and create new jobs and spin-off economic benefits. This is the classic tale of ecomodernism.

As a researcher and consultant in the field of environmental management, my motivation for many years has been to assess alternative technologies to determine if the perceived environmental benefits are supported by the available data, and to use these assessments to further optimize the technologies to maximize their potential benefit. This is demonstrated in the scope and objectives that were defined for each the LCA case studies presented in Part II of the dissertation.

For the LCA of SRW bioenergy, the objectives were to "evaluate environmental and energy impacts associated with generating 1 MJ of thermal energy from direct combustion of short rotation willow (SRW) pellets" in order to "determine where improvements could be made in the life cycle of SRW bioenergy" and "to compare SRW bioenergy to fossil fuel (light fuel oil and natural gas) for thermal energy." (Sections 3.3 and 3.4.1). For the LCA of bio oil from fast pyrolysis, the objectives were to "quantify the environmental impacts and benefits of using mobile pyrolysis units to produce bio oil and biochar from forest harvest residues as a substitute for fossil fuels" and to "identify opportunities to improve the environmental performance of the pyrolizer and its supply chain." (Sections 4.3 and 4.3.1). Lastly, for the LCA of NS wood pellet energy, the objectives were to "calculate the life cycle environmental impacts of alternative wood pellet production bioenergy pathways in Nova Scotia and Europe", to use a "more nuanced and regionalized approach" to quantifying changes in carbon emissions to the atmosphere from wood biomass energy, and to "quantify the life cycle impacts of substituting wood pellets for fossil fuels in residential space heating and large-scale electricity production" (Sections 5.2 and 5.3.1).

The objectives for the three LCA case studies are very typical of LCAs and other environmental systems analyses for assessing new technologies, which are to analyze the technology to calculate its environmental impacts and benefits, to compare the technology to the competing or conventional technology in that industry, and to identify environmental improvement opportunities for the studied technology. These are valid objectives, and along with much of the LCA literature available on energy systems and other technologies, the quantitative results generated in the LCA case studies in Part II provide some valuable insights about wood biomass energy systems (see Chapter 6). Indeed, this type of analysis has fueled ecomodernism at a large scale and has prompted the rapid development of a dedicated field of research and consulting work to assess and optimize technological innovations that can reduce the environmental impacts of human activities. This type of research is being conducted globally at a large scale by governments, academics, corporations, and consultants working for government and corporations.

There is a place and a value for this type of research on the environmental impacts and benefits of individual technologies and processes. However, insights from the philosophy of technology suggest that by using these narrow scopes of assessment (e.g. assessing the "per unit" impacts of an energy system) and pursuing an understanding of these systems at a relatively isolated level (e.g. how efficient is one technology relative to another in a single application), we are missing out on a lot of what matters when trying to assess the contribution of these technologies to the broader objective of sustainable development. It suggests that we should broaden the analysis to look beyond just the technologies themselves and to include consideration of the surrounding sociopolitical systems and how they change as the technologies are deployed.

In Section 7.2.1 the concept of macro-systems of technology was discussed, with Hughes noting that the surrounding sociopolitical systems of technologies tend to take on their own momentum, essentially self-perpetuating and imposing their requirements on other institutions (Hughes 1987). The broader macro-system of technology becomes like a machine itself, with a pre-determined objective, systems and processes, the transmitting of data, and the completion of repeated tasks toward the desired end. This phenomenon can be readily observed in the current movement toward green technologies and products. This movement has arisen in response to the global call for sustainable development, where technological innovation has been accepted as the solution to global ecological problems, more specifically the substitution of eco-efficient technologies for conventional technologies. Government agencies have directed billions of dollars toward the design and deployment of green technology, and manufacturers and technology developers have capitalized on this funding and are producing new or redesigned technologies that meet the government's sustainability criteria. Consumers in turn have increasingly begun to demand greener products and services, and increasingly are demanding evidence from suppliers that products are environmentally preferable to alternatives. This has created an entire industry built up around assessing the environmental impacts of new technologies and products and optimizing and selecting the most eco-efficient technologies. All in all, the sociotechnical system of manufacturing for green products (government agencies, private manufacturers and designers of technology), the sociotechnical system of use (consumers, governments themselves, designers themselves) and the intermediary technology assessors (which often includes government agencies and technology developers themselves) has evolved into a distinct macro-technological system which behaves like a machine itself in its propensity to carry out repeated tasks towards a particular objective, and which has a momentum resulting from the sociopolitical systems involved and is informed by ecomodernism.

In following Winner's dismantling approach for technological systems, this macro-system must be examined in greater detail to develop a deeper understanding of the role of technology in achieving sustainability. This macro-system's mechanistic approach toward a particular end of designing, deploying, and assessing eco-efficient, or green, technologies, to achieve sustainability is the physical and human manifestation of ecomodernism, the Green Machine. In seeking to understand why ecomodernism has not led to the reductions in environmental impact that were predicted, it is the Green Machine which must be dismantled, not just the individual technological artifacts (i.e. green technologies).

For a technological artifact, or physical machine, a dismantling exercise would involve a disassembly of the machine into its component parts with the objective of improving its functioning, discovering physical or technological issues that were causing the machine to malfunction, correcting them, and reassembling the machine, or to dismantle and decommission a machine that is no longer working or delivering the expected output. The basic physical elements of a mechanical system include (Norton 2010; Matthews 2005; Bhandari 2007):

- Structural components – the frame and basic parts (springs, seals, fasteners, etc.);
- Mechanisms – parts of the machine (actuators) that control movement such as gears, belts, chain drives, etc.; and
- Controllers - components with sensors that measure performance and compare the output to a performance goal and direct the input.

Missing from this list of physical components are the objectives or operating principles of the machine, and the specific work that the machine is expected to perform via the working relationship between the various physical components. Following on these operating principles for the machine is the mechanistic function of the machine, the repeated work that is completed to fulfill the function of the machine. In mapping the components of a physical machine onto the metaphorical Green Machine, one can identify similar features that make up the macro-machine of ecomodernism (Figure 7-1).

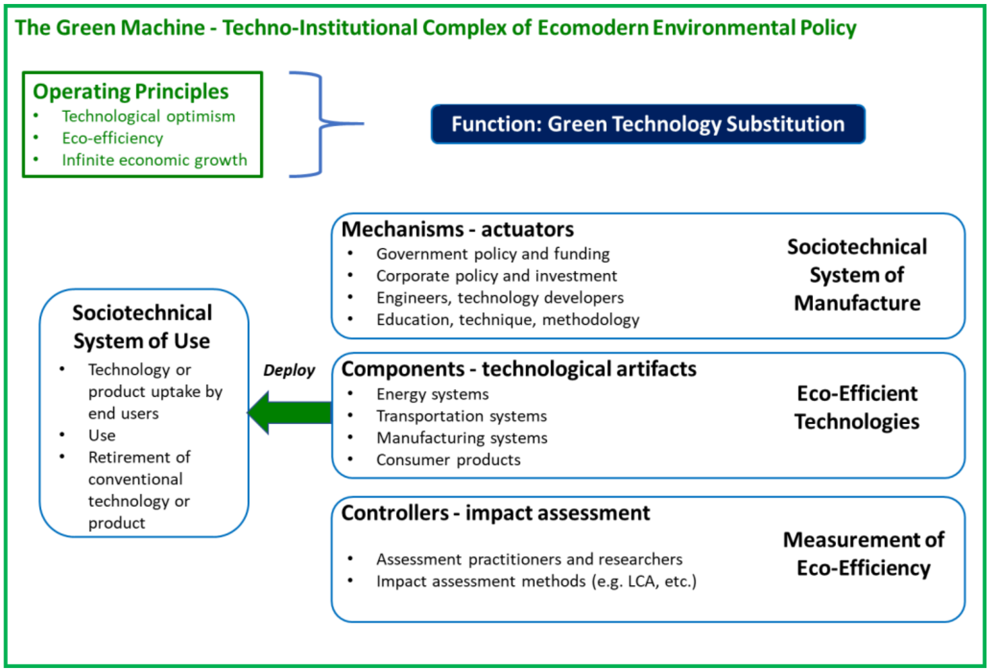

Figure 7-1. Diagram showing the components of the Green Machine, a techno-institutional complex directed towards sustainable development.

The components of the Green Machine include:

- **Operating Principles**: The operating principles of the Green Machine are rooted in ecomodernism and the neo-classical economic paradigm, and include:
  - ***Technological optimism***: technological development has supported continued expansion and thriving of the human enterprise and allowed humanity to repeatedly push back the seeming biophysical limits to growth on a finite planet (Meadows et al. 1972). As such, technological innovation is the key means by which our current environmental limits will be overcome and will allow the human enterprise to continue its expansion and progress.
  - ***Eco-efficiency***: technological systems and consumer products must be developed to be more eco-efficient, i.e. we must reduce the environmental impacts per unit of economic output. Continual improvements in efficiency will reduce resource use and emissions to the environment.

  - ***Infinite economic growth***: economic development must continue to grow in order to provide opportunities for a growing global population to rise out of poverty, whether absolute or relative, and increase their living standards and resolve social, economic, and environmental challenges (WCED 1987). The development and deployment of eco-efficient technologies will usher in a new, green industrial revolution that will allow economic growth to continue endlessly while reducing environmental impacts.

- **Function**: The function of the Green Machine is technology substitution, in particular the selection and deployment of eco-efficient technologies and products to replace conventional systems and products.

- **Mechanisms or actuators**: The actuators in the Green Machine are the social, political, and economic actors that make up the sociotechnical system of manufacture. These include governments and corporate leadership that develop ecomodern policies and fund green technology development, engineers and technology developers who design and optimize green technologies, and consultants and others involved in the sociotechnical system of manufacturing, such as international governance programs (e.g. United Nations) and agreements (e.g. Paris Accord, UN Sustainable Development Goals).

- **Components or technological artifacts**: The eco-efficient or green technologies and consumer products that are developed and deployed to create economic growth and reduce environmental impacts.

- **Controllers or impact assessment tools**: The controllers in the Green Machine are performance assessment procedures used to assess and optimize the eco-efficiency of the technological components, and to provide feedback to the mechanisms on which components to deploy and which components need substitutes. This includes the researchers and practitioners who develop, use, and optimize the assessment methods. The impact assessment methods include a range of environmental systems analysis tools, including risk assessment, ecological footprint analysis, and of particular interest for the present study, life cycle assessment.

- **Sociotechnical System of Use**: The uptake and use of technology by the end users. Includes substitution of the new eco-efficient technology or product to replace and retire the conventional technology or product.

All of the human components of the Green Machine are responsible for particular tasks, with those conducting technology assessment acting more or less as assembly line inspectors who approve green technologies before they are deployed in order to optimize their eco-efficiency and ensure their acceptance by end users. It is a self-reinforcing system, and the momentum of this system and the broad acceptance that this is what will lead to sustainable development can prevent those within the system from thinking critically about the broader implications and limitations of pursuing this technological vision of sustainable development.

The concept of a macro-system of technology has been explored in other literature beyond the philosophy of technology, in particular the behaviour of macro-systems and the influence of the macro-system on the actors within. The nature and direction of technological advance is strongly shaped by the cognitive framework of actors (Perkins 2003). There exists a set of rules, heuristics, or principles that define the boundaries of thought and action by members of the technological community (engineers, firms, technology institutes, etc.), including ideas about the nature of the technological problem and the worthwhile set of possible solutions (Perkins 2003). These sets of operating principles are often referred to as “technological regimes” (Nelson & Winter 1977) or “technological paradigms” (Dosi 1982).

The systems approach emphasizes that individual technologies are not only supported by the wider technological system of which they are part, but also the institutional framework of social rules and conventions that reinforces that technological system (Foxon 2007). Institutions include legislation, economic rules and contracts, as well as social conventions and codes of behaviour. Modern technological systems are deeply embedded in institutional structures, and this can lead to a phenomenon of technological and institutional co-evolution. This has been referred to as a "techno-institutional complex", composed of technological systems and the public and private institutions that govern their diffusion and use, and which become inter-linked, feeding off one another in a self-referential system (Unruh 2000). The Green Machine is an example of a techno-institutional complex for sustainable development (Figure 7-1).

Thinking of technology assessment in this manner, shown as the controller device in the Green Machine, puts the practice into a different light. It suggests that the methods and the desired ends of the assessment are influenced by the objectives of the broader sociotechnical system. In this context, the use of a quantitative tool such as LCA to assess technologies is influenced by the priorities and objectives of the Green Machine. This explains, in part, why LCA has been primarily used as an eco-efficiency tool, to measure the eco-efficiency of conventional and alternative technologies and to inform the design of more eco-efficient technologies. This is critical, as we tend to view models or modeling tools such as LCA as being neutral and value-free, when in fact they are subject to influence from the broader sociotechnical system under which they are conceived and used.

The use of wood biomass energy is an example of the ecomodern approach to sustainability, which is the use of alternative, more eco-efficient technologies to resolve environmental issues. The use of LCA to assess the environmental implications of these technologies has some utility, as the case studies in Part II revealed. However, there are substantial limitations to the reliance on LCA, and a look at the latest trends in global environmental problems suggests that despite the perceived eco-efficiency gains that a method like LCA shows for these alternative technologies, something is missing and perhaps a broader inquiry about relying on technological substitution is required.

In the context of sustainable development and alternative technologies, the Green Machine has a particular momentum and orientation toward particular objectives based on core principles and because technologies and the practice of technology assessment are embedded in this system, the Green Machine exerts particular influence on alternative technology design, deployment, and assessment. As a professional environmental consultant who uses LCA to assess alternative technologies in my day-to-day work, I view myself as being embedded in the Green Machine, much like all governments, corporations, and technical experts who have adopted the dominant technocratic vision of sustainable development. This critical reflection involves a process of intellectually removing myself from the Green Machine to gain a different perspective.

The conceptual framing of the Green Machine provides a new context for this dissertation. The case studies on wood biomass energy presented in Part II of the dissertation are examples of the work that is carried out in the "controller" box of the Green Machine (Figure 7-1). For example, as an LCA practitioner assessing alternative technologies, one often works only within the intellectual boundary of the LCA (Figure 7-1) and the technological artifacts themselves, with some limited interaction with the broader policy issues and discourse on methodological issues. The norms for LCA practice are of course heavily influenced by what happens beyond the LCA boundary; however, many practitioners simply work with the accepted norms and do not critically assess them. There is a need to intellectually step outside of the Green Machine and critically examine its core operating principles prior to attempting any further analysis and refinement of technology assessment tools such as LCA that are embedded in the Green Machine. This distancing of oneself from the technologies and from the mechanistic work of continuously refining the data and biophysical modeling in the LCA work allows for an appropriate perspective for critically analyzing the broader issues at hand that are rarely questioned (i.e. eco-efficiency, technological optimism).

The rest of this chapter is dedicated to a dismantling of the Green Machine. As noted in the previous section, the intellectual dismantling of technologies is more of a constructive undertaking, with an objective to better understand technologies and their implications and to inform decisions about their appropriateness for, in the context of this study, contributing to sustainable development. This dismantling must include consideration of not just the technological artifacts, but of the broader sociopolitical system of technology that surrounds them (Figure 7-1) and which informs and guides their trajectory. So in the case of the wood biomass energy research in this dissertation, the dismantling exercise is not to only evaluate the technical components of a wood-fired boiler, or simply to calculate the GHG emissions produced when a kg of wood pellets is burned as was done in Chapter 5, but rather it is to also consider the macro-system of technology in which the biomass technologies are embedded and to understand the implications for sustainability of a wider adoption of wood biomass energy systems and the social and political structures that they bring. This includes reflection on the influence of the operating principles of the Green Machine (rooted in ecomodernism) on the development, deployment, and assessment of wood biomass energy systems.

7.4 Dismantling the Green Machine

In Chapter 2 data were provided to indicate that despite global efforts over the last 30-40 years to design and deploy more eco-efficient technologies, processes, and products to reduce the environmental impacts of human activities, total material and energy consumption have continued to increase, and global GHG emissions and impacts to natural ecosystems and biodiversity have continued to increase. These trends are clear indicators that the use of technological innovation as the primary means to achieve sustainability bears revisiting. In short, the data being returned are showing that although the Green Machine is producing output at higher and higher levels, the function being provided is not meeting the objective of sustainable economic growth. At a minimum there may be different technological approaches that could be taken if we critically analyze what has been done to date, or alternatively there may be flaws in the fundamental premise with respect to the potential for technology to resolve environmental problems. In either case, the data indicate that there are potentially fundamental issues with our understanding of the biophysical interactions between technology and the environment, and further to that, fundamental issues with the methods used to quantify the environmental performance of technologies.

One field of study in particular that has examined the limitations of technology in great depth is the field of ecological economics. Even a quick glance at the literature in this discipline reveals that issues related to technology play a central role in ecological economic theory. In the following section, key insights on the biophysical implications of technology from the ecological economics literature are summarized and interpreted as further work in dismantling the Green Machine. In particular, insights from ecological economics are used to critically reflect on the operating principles of the Green Machine, including technological optimism, eco-efficiency and technology substitution, and infinite economic growth. Following this examination of the operating principles, a critical reflection is undertaken on the use of LCA as a decision-support tool within the Green Machine.

7.4.1 Insights from Ecological Economics on the Green Machine

The field of ecological economics addresses the relationships between ecosystems and economic systems, relationships which are at the core of society's most pressing sustainability problems (Costanza 1989). The aim in establishing the field of ecological economics was to: 1) provide a new approach to both ecology and neoclassical economics which recognizes the need to make economics more cognizant of ecological impacts and dependencies; 2) provide a new approach to make the field of ecology more sensitive to economic forces, incentives, and constraints; and 3) treat integrated economic-ecologic systems with a common (but diverse) set of conceptual and analytical tools (Costanza 1989). According to Costanza, the issues of concern to ecological economists (and those interested in sustainability) revolve around the central question of limits, including the biophysical limits to growth of human society presented by a finite planet, issues of equity and distribution of wealth within a finite economic system, and uncertainties about the bounds of biophysical limits and how close human activities come to exceeding them (Costanza 1989). At the core of these central issues, technology plays a pivotal role in all of them.

We need to look only as far as the first issue of the journal *Ecological Economics* to understand the importance of technology to the intellectual and analytical work in this field. In his description of the need for this emerging field of study in the late 1980's, Costanza discussed the divergence between technological optimism and technological pessimism, a debate that Costanza described as "…a fundamental question that underlies the need for an *Ecological Economics* and on which these other issues depend" (Costanza 1989, pg. 2). Costanza was referring to the conflicting assumptions held about technology by neoclassical economists and ecological economists. Technological optimism, which is the first operating principle of the Green Machine, was defined by Costanza as a belief that the Earth's biophysical limits to growth can continually be overcome by the development and deployment of new technology. Technological pessimism was defined as the belief that technology will not be able to circumvent fundamental energy and resource constraints and that eventually economic growth will be constrained by the biophysical limits of the Earth (Costanza 1989). At the root of these technology paradigms are conflicting assumptions by neoclassical and ecological economists about the substitutability of manufactured capital (technology) for natural capital (natural resources and ecosystem services).

NEOCLASSICAL VS. ECOLOGICAL ECONOMIC ASSUMPTIONS ON TECHNOLOGY

The core assumption of neoclassical economists with respect to technology and sustainability is that manufactured capital and natural capital are perfectly substitutable, so that even if there are limited amounts of natural capital available, technological progress will allow us to produce substitutes to take their place (Victor 1991, Costanza & Daly 1992). Based on this premise, it is assumed that economic growth can continue without bounds, as substitution and technological progress will allow the output of the economy to be expanded without limit, even when the stock of natural resources is being depleted (Victor 1991).

Goeller and Weinberg (1978) examined issues of resource scarcity and spoke of "The Age of Substitutability", a period in which they predicted human society would settle into a steady-state of infinite resource recycling and substitution afforded by technology, which would avert any sort of catastrophic decline of society due to resource depletion and environmental degradation. These extremely optimistic views of technology are not necessarily representative of neoclassical economists as a whole, and in fact they have likely been adopted for their computational simplicity as much as for their scientific accuracy (Costanza & Daly 1992, Ayres 2007). However, regardless of the motivations, the notion that the substitutability of technology for natural capital can lead to constant economic growth is a key component of neoclassical economic models that is manifest in current global economic and environmental policy. Technology substitution is indeed the centerpiece of ecomodern approaches to sustainability and is the primary function of the Green Machine.

As opposed to the neoclassical economic paradigm, where the factors of production are assumed to be highly substitutable, ecological economists view natural capital and manufactured capital as being complementary (Costanza *et al*. 1997). The complementary nature of this relationship is easily demonstrated by the fundamental fact that manufactured capital cannot be produced without the use of the very natural capital that it is designed to replace (i.e. fossil fuels, minerals, and other non-renewable resources) (Cleveland et al. 1984); the substitute itself requires the very input being substituted for (Costanza 1997). Natural capital is the stock that yields the flow of natural resources which are used to create manufactured capital. Because of the complementary relationship between manufactured and natural capital, the very accumulation of manufactured capital puts pressure on natural capital stocks to supply an increasing flow of natural resources (Costanza *et al*. 1997). In addition, the manufacturing, operation, and disposal of this technology can damage ecosystems and the very natural capital that is needed for further production. As such, the ecological economic paradigm with respect to technology is that due to the complementary nature of manufactured and natural capital, infinite economic growth based on technology substitution is not sustainable within the laws of thermodynamics, as human development is ultimately constrained by a biophysically finite world.

Neoclassical assumptions about technology lead to what is referred to as a weak sustainability approach. Under this approach, it is assumed that the human economy can be considered sustainable even when the stock of natural capital is reduced or degraded, as long as enough manufactured capital is created to replace the output from the lost natural capital (Gowdy & O'Hara 1997). Conversely, working from ecological economic assumptions about technology leads to strong sustainability, where efforts must be made to identify and preserve stocks of critical natural capital (Chiesura & de Groot 2003).

This need to preserve critical components of natural capital suggests that the human economy is bounded by biophysical limits to growth, as opposed to the endless economic growth that seems possible under the neoclassical paradigm (or weak sustainability). Broadly speaking, our current economic and ecomodern environmental policies as defined in the Green Machine are based on a weak sustainability approach. Even the Brundtland Report recommendations for achieving sustainability, which have formed the basis for much of the sustainability discourse, take a weak sustainability approach in which it is assumed that continued economic growth driven by technological innovation and improved efficiency will move our society towards social, economic, and environmental sustainability (Davison 2001).

THE FUNCTIONAL ROLE OF TECHNOLOGY IN REDUCING ENVIRONMENTAL IMPACTS

The primary function provided by the Green Machine is to develop eco-efficient technologies to take the place of conventional technologies and thus reducing environmental impacts. The I=PAT was developed by Ehrlich & Holdren (1971; 1972) to illustrate that environmental impacts (I) are a product of population size (P), affluence (A), and technology (T). The equation is often used as a starting point by many scholars for investigating interactions of population, economic growth, and technological development relative to global environmental impacts (Chernow 2001, Meadows *et al*. 2004), and here provides a good foundation for considering the role of eco-efficiency in reducing overall environmental impacts. This simple equation is perhaps more effective as a conceptual tool rather than a precise calculation tool, and its conception is generally credited to Ehrlich & Holdren (1971), although others such as Commoner helped move the expression from its original form to the final I=PAT equation most commonly used (Chernow 2001).

The I=PAT equation is generally defined as follows:

$I = PAT = PA/e_{eco} = GDP/e_{eco}$

where I is total environmental impact, P is the population size, A is affluence (per capita GDP) and T is the impact of technology (resource use or pollution per GDP), and e_{eco} is the GDP per resource use or pollution. The technology factor (T) is the inverse of eco-efficiency, indicating that increases in eco-efficiency will result in a reduction of technology's contribution to total environmental impacts (Huesemann & Huesemann 2011).

What is most interesting about working with this equation is that depending on the technological paradigm one ascribes to, "T" can be viewed as a key minimizing force on environmental impact or as a key driver increasing total environmental impact. Commoner was notable for assuming that the "T" in I=PAT was the most important factor in determining environmental impacts, referring to "ecologically faulty technology" that results in increased total environmental impacts (Chernow 2001). This view would be consistent with the data provided in Chapter 2 of this report showing how increased eco-efficiency has contributed to greater overall resource use and emissions.

Industrial ecologists and eco-efficiency proponents argue that the "T" in I=PAT offers the greatest hope for a transition to a sustainable society, and modifying this term to lower total environmental impact by way of greater eco-efficiency has become the central tenet of industrial ecology (Huesemann & Huesemann 2011) and ecomodernism. Chernow (2001) noted that although the I=PAT formula was first used to quantify contributions to increased environmental impacts, a new generation of technological optimists have reinterpreted the equation and determined that technology (T) provides the only viable means by which we can address environmental problems, since changing human behavior to vary the levels of population (P) and affluence (A) is too difficult, potentially immoral, and uncertain. Thus, the substitution of eco-efficient technology for conventional technologies to increase eco-efficiency and thereby reduce the technology multiplier in I=PAT is the central function of the Green Machine.

Determining the influence of technology on total environmental impact is not only dependent upon the directional influence of each parameter but is also dependent upon the rate of change for each component of I=PAT. For example, due to thermodynamic and practical material and energy constraints related to technology, overall energy conversion efficiencies can realistically only be improved by about 5-fold and material efficiencies only by about 2-fold (Huesemann & Huesemann 2011). Conversely, gross world product (GWP) is expected to increase 12 to 26-fold by 2100 relative to 1990 levels (Huesemann & Huesemann 2011). Using these rates of change in the I=PAT equation suggests total environmental impact (I) is likely to increase regardless of ambitious improvements in technological efficiency. For example, if the global economy were to expand 20-fold by 2100, and technological eco-efficiency increased by only 5-fold, then the total environmental impact of the global economy will still increase by at least 4-fold (Huesemann & Huesemann 2011). This suggests that policies focusing solely on technological efficiency as a solution to environmental problems are futile without corresponding policies to reduce the scale of the economy.

CRITIQUING NEOCLASSICAL ASSUMPTIONS ABOUT TECHNOLOGY SUBSTITUTION

Despite the current dominance of technological optimism in the policy realm, there are several critical flaws in this paradigm that are increasingly being revealed in the ecological economics literature. These flaws suggest that this approach may be misguided and devoid of biophysical reality.

Perhaps the most glaring flaw of neoclassical assumptions about the substitutability of manufactured and natural capital is that they ignore the physical interdependence of capital, labour, and natural resources (Kaufmann 1992, Cleveland *et al*. 1984). Natural capital is required to produce, operate, maintain, and dispose of technological systems, and this puts pressure on natural capital stocks to supply an increasing flow of natural resources (Costanza *et al*. 1997). This biophysical relationship begs the question: how can manufactured capital be considered a long-term substitute for natural capital when its very production and maintenance are dependent upon the continued availability of natural capital?

A related concern is the unintended environmental costs of technology substitution in which the indirect or unintended consequences of technology substitution place additional pressures on natural resources and ecosystem services. These costs have not historically been quantified and technology substitution has therefore been widely viewed as “free” from an ecological standpoint; however, when these indirect environmental costs are quantified and included in policy-making decisions, they provide an entirely different perspective on the viability of substituting technology for natural capital (Ehrlich 1989).

The environmental costs of technology substitution are often referred to as environmental problem shifting (Ayer & Tyedmers 2009; Kim & van Asselt 2016). Although improvements in technology can potentially reduce some environmental stressors, ecological economists argue that most technological development aimed at rectifying detrimental environmental effects will unavoidably cause further detrimental effects elsewhere in the economy (Small & Hollands 2006), and that many of these technical advances have been realized by increasing the quantity of fuel used directly and indirectly to perform the task (Cleveland et al. 1984). Ellul (as cited in Peet 1992) argued that history shows that every technical application presents certain unforeseeable secondary effects which are more disastrous than the lack of the technology in the first place.

While it is certainly not the case that every technology has disastrous secondary effects, it is the case that technologies often have unintended consequences. This issue was explored by Meadows *et al*. in *The Limits to Growth* (1972), where it was observed that whenever technology is used to overcome a limit to growth, it invariably pushes society towards some other limit to growth. Questions then arise about what that next limit will be, and which limit society would prefer to overcome (i.e. environmental trade-offs exist). The presence of “other limits” does not mean that the outcome is disastrous. However, failure to account for the potential of environmental problem shifting can confound efforts to reduce overall environmental impacts using technological innovation.

7.4.2 Eco-Efficiency as an Operating Principle of the Green Machine

> Demonstrating the efficiency of a course of action conveys an aura of scientific truth, social consensus, and compelling moral urgency. And Americans don't ever worry much about the specific content of numerators and denominators used in efficiency measurements. As long as they are getting more for less, all is well (Winner 1986, pg. 47)

Eco-efficiency is an operating principle of the Green Machine and is so integral to the ecomodern approach to sustainability that it bears closer examination. If one criterion were chosen that most dominated contemporary policy development and evaluation it would be efficiency (Jollands 2006), and as Langdon Winner points out in the above quote, efficiency, devoid of specific content, has become accepted as a universally positive objective and is rarely questioned. A number of authors in a range of disciplines have reflected on this seemingly untouchable concept of efficiency. Despite its varied use as a quantitative measurement and as a qualitative assessment (that job was done efficiently, for example), efficiency generally denotes approval (Alexander, in Meijers 2009). Efficiency is often accompanied by a seemingly moral imperative, that efficiency is a good thing, on its face (Alexander, in Meijers 2009). Some have described our unquestioning belief in efficiency in more extreme terms, suggesting that invoking efficiency has approached cult status in the post-industrial age (Stein 2001).

Stein's analysis rings true when one examines the grand aspirations that we ascribe to the word. For example, the publication *Factor Four* epitomizes what efficiency has come to mean in the modern world, using language such as "Moral and Material Reasons", "Efficiency Cure for the Wasting Disease", and "The Efficiency Cure" to describe how the pursuit of eco-efficiency could allow us to: live better, pollute and deplete less, make money, harness markets and enlist business, multiply use of scarce capital, increase security, and be equitable and have more employment (Weizsacker *et al.* 1997). Is efficiency up to this monumental task? These are critical observations, as efficiency (or eco-efficiency) is one of the cornerstones of the dominant ecomodern paradigm which drives the Green Machine. The suggestion that efficiency has been adopted as a core principle with little critical thought raises the question of whether efficiency can deliver on all that we ascribe to it.

The definition of efficiency tends to vary depending on the context, but in very general terms it has come to be defined as either the derivation of more good/benefit from the same amount of input, or deriving the same amount of good/benefit from less input. This applies at just about any scale of analysis, including at a societal level, an economy-wide level, at the corporate level, and even at a personal level in terms of managing one's time or household. Stein (2001, as cited in Jollands 2006) reminds us that the modern efficiency concept is context-dependent. It embodies two aspects: "fitness or success" and "the purpose intended" and both of these aspects depend on the context (Jollands 2006). Indeed, since the 1800's, the wider application of efficiency has included technical efficiency, production efficiency, profit efficiency, allocative efficiency, managerial efficiency, etc. only to name a few. For the particular context of this Ph.D. dissertation, eco-efficiency is the particular form of efficiency that is of primary interest; however, a broader analysis of efficiency as a concept is warranted here as well in order to fully understand the origins of this pervasive concept.

A number of authors have undertaken analyses of efficiency broadly or in particular contexts (e.g. Haber 1964, Hays 1959, Stein 2001, Princen 2005, Polimeni *et al*. 2009) and many refer to the origins of the word in order to get a sense of how it has become so universally accepted. The term efficiency has roots in religion, where it represented God's action in the universe and his organization of the universe (Stein 2001, Princen 2005, Alexander, in Meijers 2009). However, industrialization changed the meanings and uses of efficiency when it shifted from an idea of mere effectiveness or sufficiency to one of adequate or sufficient powers. Soon the term efficiency began to be used as a quantitative way to analyze machines and their work and outputs, and as a result of Taylorism in the early 1900's, efficiency became a national concern in the Progressive Era (pre-Depression USA), it became ubiquitous. It was not only technical, but extended to careful spending habits, fastidious bodily hygiene, and good childhood education. Efficiency expressed both sober qualities of hard and patient work, and enormous hopes for remaking society and the world (Alexander, in Meijers 2009). The Progressive Era became known as the "Age of Efficiency" as the concept of efficiency as put forth by Taylor as part of his scientific management approach for factories became accepted and embraced more broadly as a social objective as well. This process is described in detail in Samuel Haber's "Efficiency and Uplift" (1964).

Efficiency became linked with conservation due to recognition of the 2nd law of thermodynamics and represented ways to capture lost energy in mechanical processes. Classical thermodynamics was initially preoccupied with increasing the efficiency of industrial-revolution machines, leading to a definition of "useful energy output/energy input" (Jollands 2006). This alignment with conservation was eventually extended to the origins of the term eco-efficiency, which was first described by Schaltegger and Sturm and then widely publicized in 1992 in *Changing Course* by the WBCSD (Ehrenfeld 2005).

Eco-efficiency has come to represent dematerialization, the production of a good or service using less energy and fewer materials than previously. Translating dematerialization into quantitative indicators of eco-efficiency has become an attractive way of formulating environmental management goals for national policies and global environmental agreements (Hukkinen 2001), as is clearly demonstrated in the Brundtland Report (WCED 1987), Agenda 21 (UNSD 1992), guidance from the WBCSD (WBCSD 2016), and many other sustainable development strategies and policies (Davison 2001). While a focus on efficiency has been the key part of the prevailing sustainable development paradigm, there is increasing evidence that this focus may be misplaced, and some have argued that eco-efficiency is a fundamentally disruptive environmental policy objective (Hukkinen 2001, Polimeni *et al* 2009). According to Ehrenfeld (2005), there is nothing in the analytic representation of eco-efficiency that provides any indication of biophysical limits to growth on Earth, rendering eco-efficiency only a partially useful concept (Ehrenfeld 2005).

Despite these concerns, technology developers and government policy-makers cater to our unfailing belief in this concept of efficiency, always promising that the latest technology will allow us to do things more efficiently and that this will afford us extra time and resources which can be turned into more productivity. Therein lies one of the critical problems with relying on efficiency as a tool for sustainable development within a neoclassical economic paradigm of constant growth; any time or energy or resources that are saved as a result of an efficiency improvement tend to be put toward increasing productivity elsewhere at some point in time. From an environmental standpoint, this is part of the reason why we have seen total material and energy use increase over time despite significant improvements in efficiencies (i.e. energy use per unit of economic output). The other reason is that technological efficiency improvements cannot keep pace with growing population and levels of affluence (the I=PAT equation demonstrates this). So if, by way of the rebound effect or simply by way of growing population and affluence, society continues to outstrip efficiency improvements, then we are not achieving our goal of sustainability by focusing so heavily on eco-efficiency objectives.

Despite these drawbacks, eco-efficiency has been accepted as the key strategic theme for global business in relation to commitments and activities directed at sustainable development (Ehrenfeld 2005). The latest definition provided by the WBCSD is "…the delivery of competitively priced goods and services that satisfy human needs and bring quality of life, while progressively reducing environmental impacts and resource intensity throughout the life cycle to a level at least in line with the Earth's estimated carrying capacity." (WBCSD 2000) Variations on this definition of eco-efficiency abound, but the general concept has carried forward generally as meaning "do more with less", suggesting that we can increase economic output while reducing resource use and emissions.

Another landmark concept related to eco-efficiency is the "Factor X" movement, which set out targets for eco-efficiency expressed as a factor of resource productivity ranging from Factor 4 to Factor 50 (Reijnders 1998). The foundation of this movement was the publication of the book Factor 4 which suggested that technological innovation could increase resource productivity fourfold (Weizsacker 1997). This meant that the amount of wealth extracted from one unit of natural resources could quadruple by implementing more efficient technologies. In North America, these “Factor X” strategies have not prompted quantitative efficiency targets. However, the pursuit of eco-efficiency has remained a key political interest and is reflected in such documents as Agenda 21 and publications of the WBCSD.

As a result of developing eco-efficient technologies, we have seen large improvements in material and resource efficiency in our industrial processes in recent years, as well as more energy-efficient vehicles and appliances, etc. Improvements to technological efficiency have been at the forefront of the sustainability movement for many years, being promoted by governments, environmentalists, and economists alike (Davison 2001, Huesemann & Huesemann 2011). What is most interesting about eco-efficiency is that it is an approach that receives support both from neoclassical economists and from many ecological economists and subsets of the environmental movement. It is an area where a great deal of common ground exists for these otherwise divergent groups. On the surface, this is rational, as the pursuit of eco-efficiency seems to be an effective approach in which economic development interests and environmental interests can both be served.

A key concern that has been overlooked by proponents of eco-efficiency, though, is Jevons’ Paradox, or the rebound effect (Jevons 1905). The rebound effect, simply stated, suggests that increased resource efficiency creates social and economic conditions under which greater overall resource demand and consumption may occur, which serves to increase total environmental impacts rather than lowering them (Polimeni & Polimeni 2006). Eco-efficiency gains can only result in lower total environmental impacts if demand is held constant. Ecological economists suggest that the rebound effect exists because demand will not remain constant, and in fact will increase due to the lower prices that result from increased material and energy efficiency (Alcott 2005).

Rebound effects can take multiple forms, as described by Sorrell (2009):

- Direct rebound effect – a direct rebound effect occurs when we use more of something in the aggregate because of its improved efficiency. If vehicles become more fuel-efficient and driving becomes cheaper, people may choose to drive more total kilometres and consume more fuel in the aggregate despite the reduction in fuel consumed per kilometre.
- Indirect rebound effect – an indirect rebound effect occurs when people take savings from improved efficiency in one area and spend those savings to increase productivity or material and energy consumption elsewhere in the economy. Indirect rebound effects are more difficult to track, but can take a number of forms, including:
    - Embodied energy effects – the equipment used to improve energy efficiency requires energy itself to manufacture and install and this will offset some of the energy savings;
    - Re-spending effects – consumers may use the cost savings from energy-efficiency improvements to purchase other goods and services which require energy consumption and have other environmental impacts. If the money saved from using a more fuel-efficient vehicle is spent on overseas vacations that would not normally have been taken, then the efficiency benefit can be reduced or even overtaken;
    - Output effects – producers and manufacturers who achieve efficiency improvements in their operations may in turn increase overall output. This may lead to increases in capital, labour, and materials, and may also lower prices for consumers and lead to increased consumption. All of these effects can lead to increases in overall economic productivity and encourage growth and increased use of products and services elsewhere in the economy.

  - Energy market effects – large-scale reductions in energy demand may translate into lower energy prices which may cause total energy consumption to increase;
  - Composition effects – energy efficiency leading to reduced energy costs may shift consumer demand towards more energy-intensive good and services.

Many of these forms of indirect rebound effect can be difficult to track, but the overall trend is that in an economy that is based on constant growth, there are many opportunities for cost-savings from efficiency to be spent on other products and services which have environmental impacts and which can offset the impact reductions from the efficiency improvement. This paradox is apparent when examining the I=PAT equation. The eco-efficiency strategy is to lower the technological impact (T) in order to reduce the total environmental impact (I). Jevons' Paradox suggests that as the contribution of T becomes lower due to eco-efficiency improvements, overall demand for the output tends to increase as more consumption becomes possible due to lower prices (Alcott 2005).

Furthermore, not only is there a direct micro-rebound effect resulting from efficiency gains, there is also an indirect macro-rebound effect because lower prices result in higher disposable incomes, which allows consumers to purchase more goods and services in the wider economy (Polimeni & Polimeni 2006). In short, by enabling population (P) and affluence (A) to rise, eco-efficiency gains are partial causes of increasing environmental impacts (Alcott 2005). This concept is one way of potentially explaining the data on improved eco-efficiency vs. increasing total resource use and emissions provided in Chapter 2.

7.4.3 Summary of the Operating Principles of the Green Machine

A reflection on the operating principles of the Green Machine through literature from ecological economics provided insights as to why the substitution of eco-efficient technologies has not led to the expected reductions in absolute environmental impact. Despite technological optimism and the potential impact reductions that can be achieved through increased eco-efficiency, there are environmental costs associated with technology substitution that have not been fully accounted for. These environmental costs arise because even eco-efficient technology is still reliant on natural capital across its life cycle, such that even if impacts appear lower at the point of substitution (e.g. at the consumer use stage), there may be resource use and emissions to the environment which occur elsewhere in the life cycle that have environmental impacts that can reduce or even offset the environmental benefit of the substitution. Further, the rebound effect can offset environmental benefits via increasing resource use and emissions and lead to increasing total impacts despite decreasing "per unit" impacts from eco-efficiency. The ecological economics literature also establishes that the human enterprise is bounded by the biophysical limits of the Earth and its finite capacity to provide resources and assimilate our wastes and emissions, and that despite improvements in eco-efficiency, our society is continuing to push closer to biophysical limits, and so the operating principle of infinite economic growth in a finite system is not achievable (Rees 2020).

As discussed in defining the macro-system of the Green Machine, the operating principles of the machine exert influence on how the various components of the machine work. The operation of the sociotechnical system of manufacture (i.e. governments, corporations, technology developers) is influenced and directed by these operating principles, and the technological artifacts are designed in the context of these principles and in line with the eco-efficiency objective. Of particular interest in this thesis is the influence of the Green Machine operating principles on the LCA methods and practitioners that are evaluating the environmental costs and benefits of green technologies to inform the sociotechnical system of manufacture and inform green technology design and deployment. The following section includes a reflection on LCA as a decision-support tool in the Green Machine and the potential that the operating principles of the Green Machine may influence LCA practice and the insights generated in LCA research.

7.4.4 Use of LCA as an Eco-Efficiency Assessment Tool

> Although many that have become involved in risk assessment are not conservative in a political sense, it seems to me that the ultimate consequence of this new approach will be to delay, complicate, and befuddle issues in a way that will sustain an industrial status quo relatively free of socially enforced limits (Winner 1986, pg.139)

The use of environmental systems analysis tools to calculate the impacts and benefits of technologies and consumer products has become a key decision-support mechanism for government and corporate programs directed at sustainable development (Freidberg 2014). Within the definition of the Green Machine, these impact assessment tools serve as "controllers", essentially evaluating and optimizing eco-efficient technologies and products to guide their deployment. In this capacity, LCA has become the dominant tool because of its seemingly comprehensive nature, and is increasingly used by corporations for both internal decision-support and to generate customer-facing claims about products, and by governments to guide and legitimate procurement, eco-labelling, and other sustainable production and consumption policies (Freidberg 2013). In the case studies summarized in Part II of this thesis, LCA was used to assess the life cycle environmental impacts of various wood biomass energy systems that have been proposed as eco-efficient alternatives to conventional fossil fuel energy systems. These LCAs were funded in-part by both private and government stakeholders and were used to provide insights and data to support decision-making around wood biomass energy. The extent to which the results were used for decision-making is not clear, but these case studies provide an example of how LCA is used in the Green Machine, an assessment process that is repeated again and again as part of the process of green technology and product substitution.

In Chapter 6, a summary was provided of the key findings and limitations of the LCA case studies. One of the initial objectives for this Ph.D. dissertation was to use these case studies to make methodological contributions to further refine LCA as a technology assessment tool; however, the insights from the philosophy of technology and ecological economics have raised more fundamental questions about the limitations of technology and eco-efficiency as means to a more sustainable society, which has prompted more fundamental questions about the role of LCA in this process. In particular, insights from the philosophy of technology have been used to re-frame the analysis from simply focusing on how technological artifacts themselves are assessed to instead visualizing technology assessment as part of a broader sociotechnical system that is informed by the ecomodern principles of technological optimism and the pursuit of eco-efficiency. Technology assessment with tools like LCA is ultimately a component of the Green Machine that is moving toward a particular technocratic vision of sustainable development. As Winner describes so eloquently in the following quote, there is little value in continuing to refine quantitative methodologies like LCA and generating more data and analysis on the environmental impacts and trade-offs of different technologies if the tool is only being used to reinforce a flawed paradigm.

> More and more the whole language used to talk about technology and social policy – the language of "risks", "impacts", and "trade-offs" – smacks of betrayal. The excruciating subtleties of measurement and modeling mark embarrassing shortcomings in human judgment. We have become careful with numbers, callous with everything else. Our methodological rigor is becoming spiritual rigormortis (Winner 1986 pg. 176).

In this section a critical reflection is provided on the use of LCA in the Green Machine based on the new insights from the philosophy of technology and ecological economics. The objective here was to understand whether the information generated in LCAs is providing the necessary information to other elements of the Green Machine to continue working towards sustainability in an effective way, and to understand how the broader macro-system of the Green Machine might influence LCA practice. In short, is the use of LCA as an eco-efficiency assessment tool in the Green Machine contributing to environmental sustainability, or is it serving to reinforce the potentially flawed operating principles of the Green Machine?

UNQUANTIFIED IMPACTS

One of the critiques of technology substitution from the ecological economics literature is that the introduction of a new technology may reduce particular environmental impacts at the point of substitution, but it may also introduce new environmental impacts elsewhere in the life cycle of that technology or process, or elsewhere in the broader economy. The ability to identify and quantify the potential for environmental problem shifting is a critical aspect of evaluating the overall contribution of an eco-efficient technology to environmental sustainability.

Meadows et al. (1972) note that whenever a new technology is introduced to overcome a particular limit to growth, this technology will invariably push society towards a new limit to growth since our society is operating in a finite system. For example, electric cars have been promoted as an eco-efficient alternative to gas and diesel-powered vehicles due to the reduced air emissions during use; however, concerns have been raised about the impacts of producing electric car batteries due to their reliance on non-renewable precious metals that are largely found in lesser-developed countries and whose extraction may cause significant environmental and socioeconomic damage (Gemechu et al. 2015).

A key challenge in capturing environmental problem-shifting using LCA methods is that current methods cannot quantify all impacts of concern, and as a result, environmental-problem shifting may go undetected, or be under-emphasized due to the lack of quantitative impact data. These gaps in impact assessment can be important, particularly if these unintended impacts are to critical natural capital stocks.

As discussed in Chapter 6, LCAs of wood biomass energy systems fail to capture the potential ecological impacts of increased forest harvesting. Although LCAs of wood biomass energy systems have increasingly incorporated data on GHG emissions resulting from changes in forest carbon dynamics due to incremental harvesting, LCA methods are not equipped to quantify impacts to forest ecosystems. Impacts such as increased wildlife mortality and habitat loss, damage to freshwater ecosystems, and damage to other ecological functions provided by forests cannot be quantified in the way that is needed to be incorporated in an LCA. The loss of non-ecological values of forests, such as recreational and spiritual benefits, are also not captured in LCAs of wood biomass energy systems or other environmental systems analysis tools. In the LCA case studies in Part II, the need to consider the impacts of increased forest harvesting to provide wood biomass supply is identified as a concern, but the impacts are not quantified and thus this issue may be omitted or undervalued. The impact category that has garnered the most interest in published LCAs of wood biomass energy systems has been the quantification of GHG emissions, and the potential reductions in GHG emissions that may be achieved by substituting wood biomass for fossil fuels in energy applications.

Due in part to the results of LCAs showing the potential GHG emissions reductions that could be achieved with wood biomass relative to fossil fuels, wood biomass has become an attractive renewable energy feedstock in a number of applications and is being scaled up in a number of jurisdictions. The significant increase in electricity generation from wood biomass in the United Kingdom provides a current example of the tensions and uncertainty about the broader sustainability of using wood biomass energy at a large scale. One of the primary sources of wood pellets for electricity generation in the UK is from the forest industry in the Southeastern United States. Environmental groups have argued that the harvesting being done to support the export of wood pellets to the UK for electricity generation is doing significant damage to forest ecosystems in the area, and the expected increase in demand for wood pellets may exacerbate these impacts (Dogwood Alliance N.D.). Some initial research on the ground seems to refute these claims (Dale et al. 2017), while other research indicates that a significant transition from natural stands to pine plantations is occurring, and that due to the projected increase in demand for wood pellets and the potential risks to forests, close monitoring and specific policy interventions are needed (Duden et al. 2017; Hudson 2017). The LCA research is silent on this issue since these are not impacts that can be quantified in LCA methods.

As noted, this omission of forest ecosystem impacts from LCA is largely due to the limitations of the methods; however, the omission is also rooted in the eco-efficiency focus of LCA which is dictated by the operating principles of the Green Machine. The focus on eco-efficiency by stakeholders, at present the very direct focus on GHG emissions, also influences the selection of indicators in LCA research and increases the likelihood of important impacts going unquantified or under-emphasized. Following on the insights from ecological economics, the lack of accounting for these other environmental costs of technology substitutions therefore leads to overestimation of the overall impact reductions that can be achieved through this technology substitution. By focusing on eco-efficiency, and omitting or under-emphasizing other environmental aspects, the LCA research is indirectly reinforcing the flawed ecomodern principles of the Green Machine.

Implications of Technology scale and Lock-In

The issue of forest ecosystem impacts for wood biomass energy highlights some additional areas where the current LCA approach potentially falls short in assessing the environmental impacts of technology substitutions. More specifically, the assessment of environmental impacts using LCA generally fails to account for the changes in environmental impacts that can be introduced when technologies are scaled up for wider deployment, and fails to account for the unintended impacts that may occur as a result of technology lock-in.

When green technologies are developed to substitute for conventional technologies, the implicit intention is to eventually deploy them at a scale at which they can replace all or a large share of the existing stock of conventional systems and thereby reducing environmental impacts. However, LCAs are typically done on a “per unit” basis, as in assessing impacts per unit of production (e.g. per kg of product) or per unit of service provided (e.g. per provision of 1 kWh or 1 MJ of electricity), and LCA models of green technologies are frequently based on pilot-scale or early-stage deployment of the technologies, or even just on engineering projections for more novel technologies and products. This modelling approach is rooted in the operating principle of the Green Machine to pursue eco-efficiency, which is a measure of environmental impact that is done at the margins, per unit of output; however, this approach fails to account for the changes in environmental impacts that may occur at larger scales of deployment.

This issue of scale is pertinent to development and deployment of wood biomass energy systems. The findings of the wood biomass case studies presented in Part II echo the findings more generally across the LCA literature in that on a per-unit-energy basis, the use of wood residuals (e.g. sawdust from sawmills, wood chips harvesting residuals, etc.) as an energy feedstock generally results in lower life cycle GHG emissions than the comparable fossil fuels (e.g. coal, oil). These findings have contributed to the momentum behind wood biomass as a renewable energy source, and proponents of wood biomass energy systems in most jurisdictions will design and promote the benefits of their proposed systems on this assumption that using residuals is a sustainable option. However, as a greater number of wood biomass energy projects are pursued and as larger-scale systems are pursued in a given region, the demand for wood residuals grows, but there is only a finite amount of these residuals in any given region that are physically available and economically viable to collect and use. So, as the scale of the biomass energy sector grows, the pressure on available stocks of residuals grows, and subsequently the need to harvest more trees to supply enough wood fibre becomes the only option to keep these energy systems operating.

The incremental harvesting that is required to support the scaled-up biomass energy sector increases the risks of impacts to forest ecosystems due to more intensive and wide-spread harvesting (as discussed in the previous section), and it also potentially changes the carbon dynamics. As was shown in the wood pellet energy case study in Chapter 5, additional harvesting of standing biomass for wood biomass energy systems, over the otherwise BAU case, can potentially lead to increased cumulative GHG emissions relative to fossil fuels, either in the short-to-medium term, or even in the long term. So, as a result of scaling up the technology, the environmental impacts change, and the LCA results which encouraged the use of wood biomass are no longer relevant at this new scale.

A related issue is the issue of technology lock-in. As discussed previously, technological artifacts are embedded in larger sociotechnical systems which influence their design and deployment. These macro-systems are in-turn influenced by deployment of the technology and the ways in which they are taken up in society. Thinking beyond the technological artifact that is a wood biomass energy system, there is a sociotechnical system of manufacture associated with the artifact as well as a sociotechnical system of use. As the technology is deployed in society, these surrounding sociotechnical systems become established and begin to gain a momentum that makes it difficult to pull back on their deployment. Social and economic systems are built up around the design, deployment, maintenance, and distribution of the technology, and entire careers are established by individuals to carry out the various tasks involved in bringing a technology from idea to deployment, and then to large-scale deployment. As a result of these social and economic structures, technologies that reach a certain scale tend to become locked-in and difficult to change or displace.

Technology lock-in can lead to environmental implications, because although the sociotechnical system of technology may be locked in, the surrounding economic context is not locked in and is constantly changing. This may be the case with energy feedstocks, whose cost and availability may change as market conditions change. For wood biomass energy feedstocks this is particularly relevant because the availability of wood biomass is highly dependent upon the market conditions in the forest sector and the broader economy, and also dependent upon changes in natural conditions that affect forest productivity and management.

Consider the case of wood pellet energy, where currently producers in Nova Scotia are primarily using sawdust from local sawmills as feedstock to produce wood pellets for residential space heating and export to Europe for electricity generation. These wood pellet plants are now part of an established sector of the economy, with end users that are dependent upon supply of this product for their energy requirements. The results of the LCA research in Chapter 5 indicate that this use of sawmill residuals for wood pellet energy can lead to reductions in life cycle GHG emissions relative to fossil fuels, but that harvesting standing biomass to produce pellets could result in higher life cycle GHG emissions than conventional fuels. What happens if there is a shock to the supply system of residual wood fibers? It may be the case that the pellet plants would shut down; but it is more likely that as a result of technology lock-in, the pellet plants would at least temporarily shift to more incremental harvesting of forest biomass to supply their plants, thus changing the environmental profile of their supply chain significantly.

Fortunately, in the latter example, the LCA research presented in Chapter 5 includes this analysis showing the implications of using harvested forest biomass on the GHG emissions, so at least the information is available to support decision-making. However, the increased use of wood biomass energy has generally advanced on the prospect of using residuals and the resulting environmental benefits. What is not captured in the LCA research in Chapter 5 are the potential ecological impacts to Nova Scotia forests if wood pellet producers are forced to increase their use of harvested biomass to feed a growing and locked-in biomass energy sector.

The failure by LCA researchers to account for the change in environmental impacts associated with technology scale-up and technology lock-in is another way that LCAs can overestimate the potential environmental benefits of green technologies. The focus on eco-efficiency, or a "per unit" assessment of impacts, again allows for an underestimation of the environmental costs of technology substitution.

THE FALLACY OF DISPLACEMENT

One of the core assumptions about eco-efficient technologies is that once their virtue is confirmed, they will be deployed and deployed in a way that will displace conventional technologies and put them out of service. Implied in this displacement is that for every unit of renewable or clean energy introduced, an equivalent amount of non-renewable resources that are used by the conventional technology (e.g. coal) will no longer be extracted. For example, if 10,000 homeowners in Nova Scotia replace their oil-fired furnaces with wood pellet stoves for space heating, then it is assumed that the oil that these homeowners would normally have consumed will now be left in the ground. This is the premise that underpins nearly all LCA research on energy systems, and this 1:1 displacement is also a common assumption in LCAs where recycled material is assumed to replace virgin material (e.g. plastic).

The assumption of 1:1 displacement of conventional technologies by green technologies is rooted in technological optimism, and overlooks the way that technological systems behave in reality, in particular the concept of technological lock-in. As part of defining the Green Machine, the concept of macro-systems of technology was discussed. In this way of viewing technology, it is recognized that only considering the technological artifacts themselves is very limiting, and in fact the social, economic, political, and institutional context in which technologies are embedded is both influenced by technology, and play a central role in guiding the development and deployment of technologies. The existence of these techno-institutional complexes can lead to technology lock-in, in which efforts to advance the performance of technology are often focused in specific directions that build on past achievements, ideas, and knowledge, and which reinforce the mutual benefits that are derived from the system for both the institutional and technological systems involved (Perkins 2003).

This phenomenon is why technological change tends to proceed incrementally along certain trajectories and is a component of the concept of autonomous technology that was defined in the review of the philosophy of technology literature (See Section 7.2) (Perkins 2003). Although the concept of technology lock-in was described in the context of green technologies, it is even more so the case for long-standing, well-established conventional technologies. As a result, when a new technology is introduced, it is not a given that the conventional technology will cease to operate, it may just be deployed elsewhere. So assuming that there is a 1:1 displacement is flawed in this instance.

Beyond technology lock-in, the other issue which confounds the assumption of 1:1 displacement of technologies and resources is that these technologies are operating in an economic system predicated on infinite growth. So even though a new eco-efficient technology may be introduced that does not require the extraction and production of fossil fuels, those fossil fuels may be demanded elsewhere in the economy, particularly if their substitution results in lower overall prices for that fuel.

As a result, the assumption of 1:1 displacement does not reflect reality, and LCAs based on this assumption provide misleading results in terms of the actual environmental benefits of eco-efficient technologies. Some initial research on actual displacement rates reveal that 1:1 displacement is simply not supported in the empirical data. In a study of global energy use trends at a national level from the last 50 years, York (2012) indicated that a unit of non-fossil energy displaced less than one quarter of a unit of fossil energy use. The trend for displacement in electricity use was even worse, with every unit of non-fossil energy only displacing less than one-tenth of a unit of fossil energy, and furthermore that non-fossil electricity sources other than nuclear and hydro did not actually displace any fossil electricity use at all (York 2012). Hu & Cheng (2017) modeled displacement in the electricity grid in China between 1995 and 2014 and found that non-fossil electricity sources displaced approximately one quarter to one third of fossil electricity use, and that displacement rates were more significant only when the share of alternative energy became a more prominent part of the electricity mix.

In terms of material displacement, Zinc et al. (2017) examined the commonly held assumption that recycling metals will displace primary metal extraction and manufacturing on a 1:1 basis and attempted to determine a true displacement rate grounded in the market data for aluminum. Results of the study determined that increased collection and use of scrap aluminum does not displace virgin aluminum on a 1:1 basis, and in some instances leads to increased extraction and production of virgin aluminum (Zinc et al. 2017). The fact that 1:1 displacement does not occur in reality is a product of a number of factors in the economy and it is possible that displacement rates may increase over time. However, at present and for the foreseeable future, the assumption of 1:1 displacement is flawed.

In the wood pellet energy case study in Chapter 5, it was assumed that wood biomass energy would displace heating oil at a 1:1 displacement rate (i.e. for each MJ of heat produced from wood pellets, 1 MJ of heat did not have to be produced using oil, and the oil is assumed to not be extracted in the bioenergy case). In reflecting back on the potential limitations and misleading nature of this assumption, sensitivity analysis was conducted for the life cycle GHG emissions of wood pellets using different displacement assumptions. The results of this sensitivity analysis for wood pellets used to substitute for oil in residential space heating are shown in Figure 7-2, and indicate that the actual displacement rate for oil has a significant effect on the study results.

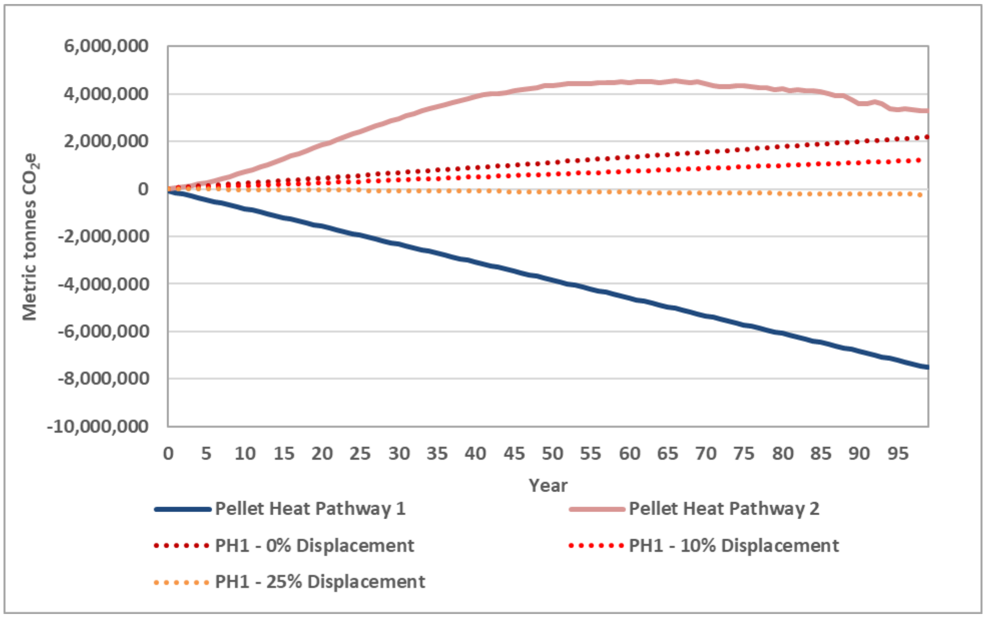

Figure 7-2. Change in 100-year life-cycle GHG emissions, including changes in forest carbon emissions, for the substitution of wood pellets for oil in residential space heating in Nova Scotia, showing the change in results with different assumptions for the displacement of oil energy use.

The results of the LCA using a 1:1 displacement of oil heat showed the potential for significant cumulative GHG emissions reductions when using wood pellets produced from sawmill residues; however, when the assumed displacement rate was changed the results changed dramatically. For displacement rates of 0% and 10%, the results showed that cumulative GHG emissions would increase over the 100 year time horizon, because not only are the new GHG emissions from the wood pellet supply chain accounted for, the equivalent amount of oil is still assumed to be extracted and combusted for energy use for net new activity elsewhere in the economy instead of this oil being left in the ground. At a displacement rate of 25%, the results indicate a reduction in cumulative GHG emissions for wood pellets from sawmill residues, but they are significantly smaller reductions and hover around the zero on the y-axis where there would be very little overall reduction relative to the current state.

A similar sensitivity analysis was conducted for the export of wood pellets to Europe for electricity generation, and the findings are shown in Figure 7-3. The results are similar to those for space heating, indicating that when the 1:1 displacement assumption is changed, the cumulative GHG emissions benefits of substituting wood pellets for coal in large-scale electricity generation are reduced or completely offset. In this instance, even a displacement rate of 25% does not lead to overall reductions in cumulative GHG emissions, which would be considered high or somewhat in line with empirical data based on recent studies (York 2012; Hu & Cheng 2017).

It is unclear why a 1:1 displacement rate is the default assumption in LCA practice, but it is reflective of the operating principles of the Green Machine. It reflects technological optimism and not technological reality and reflects an emphasis on eco-efficiency over an emphasis on system-wide impact assessment. It also ignores the implications of an ever-expanding economy. In these examples, the overly optimistic principles of the Green Machine lead to overly optimistic LCA methods and results, and these results serve to reinforce the flawed paradigm of the Green Machine. In some ways the term "displacement" is accurate, because rather than the resources being left in the ground, they are "displaced" from their current to other uses elsewhere in the economy. This is reflected in the continuing increase in fossil fuel demand shown in Chapter 2.

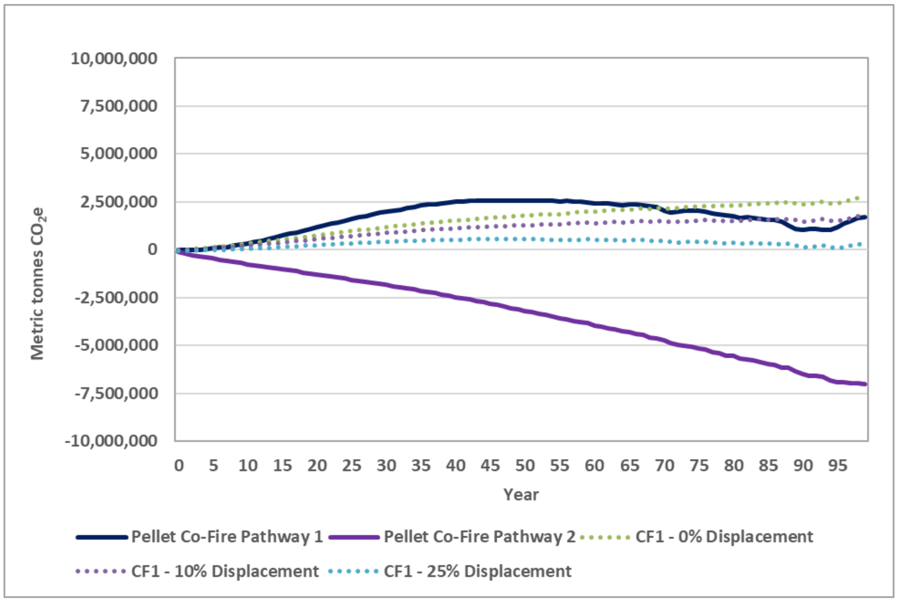

Figure 7-3. Change in 100-year life-cycle GHG emissions, including changes in forest carbon emissions, for the export and substitution of wood pellets from Nova Scotia for electricity generation in Europe, showing the change in results with different assumptions for the displacement of coal-fired electricity.

7.4.5 Summary of Dismantling of the Green Machine

The dismantling of the Green Machine in Sections 7.3 and 7.4 included a critical reflection on its operating principles, its function of green technology substitution, and the use of LCA as an assessment tool to optimize and select green technologies for deployment. Insights from ecological economics were used to show that the ecomodern operating principles of the Green Machine are flawed and are not representative of the biophysical realities of technologies and how they are taken up in the economy and how they interact with the natural environment via resource use and production of emissions and wastes. The technological optimism that drives the ecomodern approach was shown to be based on an over-estimation of the environmental benefits of green technologies, and an under-estimation of the environmental costs of green technologies across the economy. The operating principle of eco-efficiency was shown to have significant limitations stemming from the rebound effect and from the omission of other environmental impacts that occur when technologies are assessed at greater scales than the "per unit" scale used in eco-efficiency. The operating principle of infinite growth has been shown to be biophysically impossible given the finite resource use and waste assimilation capacity of the planet, and the pursuit of infinite growth was shown to be a confounding factor for eco-efficiency.

A critical reflection on LCA and its role in assessing eco-efficient technologies and products within the Green Machine indicated that as a result of several deficiencies related to the scope of the analysis and key assumptions used, there is a risk that LCA is under-estimating the environmental impacts and over-estimating the environmental benefits of eco-efficient technologies. These deficiencies are due at least, in-part, to influence by the flawed operating principles of the Green Machine, and the results of LCA research are therefore at risk of reinforcing these flawed principles rather than challenging them and modifying them.

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CHAPTER 8: CONCLUSIONS AND RECOMMENDATIONS

8.1 Further Manifestations of the Green Machine

Despite the deficiencies identified in the literature and that have been reframed and presented anew in the critical reflection in Part III of this thesis, the ecomodern approach of developing technological fixes for resolving environmental challenges and sustaining economic growth is still being pursued with greater effort and at larger scales. Although scientific data indicate that environmental conditions across all major indicators have continued to worsen over time, the issue of sustainability is still largely viewed as an engineering problem. Despite 30-40 years of developing and deploying more eco-efficient technologies and consumer products, overall global environmental conditions continue to get worse and to increasingly threaten the well-being and survival of humans, wildlife, and global ecosystems. However, despite the quantitative evidence, these negative outcomes have not prompted sufficient large-scale re-examination of the prevailing approach. Conversely, it has prompted a doubling-down on ecomodernism by government and corporate institutions, which has resulted in increasingly large-scale technological efforts to reduce impacts, particularly in combatting climate change.

Haszeldine et al. (2018) outlined three potential responses that humanity may have to the threat of climate change effects, including: 1) do nothing, and await practical consequences beyond any doubt; 2) develop and deploy engineering technologies to increase reflectance of solar radiation (i.e. geoengineering); or 3) reduce the rate of CO_2 emissions and recapture large quantities of CO_2 already emitted (Haszeldine et al. 2018). Generally speaking, the prevailing response to-date has been the first half of the third option, efforts to reduce the rate of CO_2 emissions by developing eco-efficient technologies and products. These efforts have failed to reduce emissions in the aggregate, as atmospheric carbon concentrations have continued to reach all-time highs, and global fossil fuel emissions, the principal cause of global warming, continue rising at a high and even increasing rate (Hansen & Kharecha 2018). In recognition of this failure to curb GHG emissions, efforts to reduce emissions through technology substitution have intensified, with an increasing importance being placed on pursuing “negative emissions” technologies. The need for negative emissions technologies has been incorporated into more recent IPCC climate change scenarios, and it has been argued that extraction of CO_2 from the air is now almost surely required to stabilize global temperatures and avoid disastrous consequences from climate change (Hansen et al. 2017; Hansen & Kharecha 2018).

Carbon capture and storage (CCS) involves capturing of CO_2 from large point emissions sources and storing the CO_2 underground in suitable geological formations or reusing it in the manufacture of basic materials (NRCan 2020). Carbon capture and storage is being pursued globally, and although not yet deployed at a large scale, there are many CCS technologies at various stages of development. The Canadian government has identified CCS as an important means to lessen the impact of Canadian fossil fuel combustion technologies and is leading research efforts on a number of aspects of this technology, including different capture methods and both short and long-term carbon storage options (NRCan 2020). Canada is in fact home to one of the first successful deployments of CCS technology at a coal-fired electricity generating station in Saskatchewan, the Boundary Dam Power Station (IEA 2015).

Although governments and researchers and private developers see great promise in CCS as a means to clean up fossil fuel combustion and prevent CO_2 emissions from reaching the atmosphere, as with many techno-fixes, there are also drawbacks which may result in additional emissions economy-wide that may partially offset or even exceed the amounts of captured emissions. At an operating level, CCS technologies require substantial amounts of energy to run, which can negatively affect the efficiency of the retrofitted power plant. In short, the power plant will be forced to direct a proportion of its power output to the CCS unit and will also become less efficient overall (Budinis et al. 2018). These energy and efficiency “penalties” can reduce the overall emissions reductions associated with deployment of the CCS unit.

The end use of the captured carbon can also influence the overall benefit of the system. Ironically, the Boundary Dam Power Station in Saskatchewan directs a proportion of its captured CO_2 to customers in the Saskatchewan oil and gas sector who inject the CO_2 to facilitate enhanced oil recovery (IEA 2015). So, CO_2 emissions captured to mitigate climate change are used to enhance the extraction of other fossil fuels which contribute to climate change. As counter-productive as this seems, the sale of these captured emissions to the oil and gas sector is an important factor in the economic viability of the CCS plant (IEA 2015). Lastly, the use of CCS units to capture emissions from fossil fuel combustion systems may contribute to further fossil fuel technology lock-in, as producers will be reluctant to remove them after the intensive capital and operating cost investments. This reinforced fossil fuel lock-in may serve to extend economic dependence on fossil fuels like coal, oil, and natural gas (Vergragt et al. 2011), something which is in direct contrast to guidance from policy developers and scientists when it comes to addressing climate change.

There are clear limitations to CCS, and the design and deployment of this technology illustrates many of the issues that have been highlighted in Chapter 7 for technology substitution. The deployment of CCS at the Boundary Dam site in Saskatchewan and the surrounding circumstances provide such a classic example of all the flaws identified in the Green Machine that the existence of this project almost does not seem believable.

Beyond CCS, the active removal of previously dissipated CO_2 from the atmosphere is also being explored but is less well-developed and uncertain at this point. What is perhaps most fascinating about these efforts to capture or remove already-emitted CO_2 from the atmosphere is that it is a return to what is known as “end-of-pipe” environmental management. End-of-pipe environmental management is the clean-up of emissions to the environment after they occur and is generally associated with environmental management approaches from the 1980s and early 1990s where environmental management was more of an afterthought. This end-of-pipe approach was actively replaced with approaches that sought to prevent pollution before it happens by way of technology and product design. There has been a prevalent shift away from end-of-pipe environmental management, which is seen as being a limited and reactive approach, towards more proactive approaches such as Design for Environment or Design for Sustainability (UNEP 2006). To see policy-makers and technology developers be forced to return to end-of-pipe management is a clear indication that the Green Machine has not succeeded in reducing the flow in the pipe.

The second of the three options outlined earlier in this section for addressing climate change is the development of geoengineering technologies to reduce incoming solar radiation in order to reduce global warming and subsequent climate change impacts. Geoengineering may be the most extreme manifestation of humankind's unfailing technological optimism. Geoengineering includes a group of technologies for counteracting climate change and whose potential for disruptive global environmental change may even exceed that of any conventional technologies that have been deployed to date. While the drastic global environmental changes brought on by technological development to date have been largely unintended or unanticipated, geoengineering technologies represent a deliberate intervention by humans to modify and permanently control the Earth's atmosphere and climate, and thereby controlling the fate of potentially all natural systems on the Earth which depend on the climate system.

Proposed geoengineering solutions include the floating of balloons or orbiting of massive mirrors in space to deflect solar radiation, the fertilization of the world's oceans with iron (Fe) to increase productivity and thus carbon sequestration, and the injection of aerosols or aerosol precursors (e.g. SO_2) into the atmosphere to reduce radiative forcing (Ciceronne 2006, Royal Society 2009, Goodell 2010, Hamilton 2013). These and other emerging geoengineering technologies represent mankind's most extreme attempt to resolve an environmental problem (global warming and climate change) with technology, and the potential side effects of such large-scale manipulation of Earth's most basic life support systems are unknown.

The relevance of the geoengineering story to this dissertation is not based in the technological and engineering design and execution, or even in assessing the potential unintended consequences of their deployment, but rather in what the pursuit of geoengineering reveals about the social and political aspects of technology in the context of sustainable development. In earlier sections of this thesis, it was established that the current global approach to resolving environmental issues such as climate change is to substitute eco-efficient technologies and products for conventional systems to reduce environmental impacts and maintain economic growth. However, the very pursuit of geoengineering solutions to climate change speaks volumes about our collective ignorance of the limitations and unanticipated environmental costs and negative social impacts that can arise from deployment of new technologies.

Indeed, the very rationale for the pursuit of geoengineering is that evidence is mounting to suggest our current technocratic approach to address climate change is not working quickly enough, or is failing altogether (Goodell 2010, Global Carbon Project 2012, Hamilton 2013). These solutions are therefore proposed to either act as a bridge technology to buy more time to allow for current technological approaches to lower GHG emissions sufficiently, or to provide a safeguard to mitigate climate change if GHG emissions continue to increase past critical thresholds and tipping points. Furthermore, despite the lack of confidence in eco-efficient technologies that the pursuit of geoengineering reveals, geoengineering itself is perhaps the ultimate example of our dedication to eco-efficiency.

One of the supporting arguments for pursuing geoengineering is that in terms of environmental benefit per dollar invested, geoengineering represents a far more efficient option to mitigate climate change than continued efforts to curtail global GHG emissions by way of government policy and regulation and education of consumers (Barrett 2008). It has also been proposed that rather than being a definitive long-term solution to the issue of climate change, geoengineering could simply be used to temporarily cool the planet to avoid the catastrophic effects from climate change long enough for humanity to complete its full transition to an economy based on eco-efficient technologies (Wigley 2006), which to date remains unrealized. Given what is known about the tendency of macro-systems of technology to remain locked-in over time, and the unknowns of what would happen to the climate and global ecosystems if geoengineering technologies were decommissioned, it is highly likely that once deployed, geoengineering technologies would become a necessary part of global environmental management and governance that could not easily be turned off or curtailed.

That fact that such extreme technological systems are being developed to combat climate change is a clear indicator that the prevailing ecomodern approach is failing. The Green Machine serves its purpose of going through the mechanisms of designing, deploying, and assessing eco-efficient technologies, and through methods such as LCA a great deal has been learned about what drives the environmental impacts and environmental trade-offs of many technologies and products. The Green Machine has built up tremendous momentum and increasing lock-in as the preferred, and to many the only, pathway to sustainability. An entire industry of professionals has been created in the process, including engineers and technology designers, government and corporate sustainability policy developers, and experts in modelling and quantifying the environmental performance of green technologies and products. It has evolved into a classic macro-technological system which is self-perpetuating and self-reinforcing, and the focus that is being reinforced is on how to do the mechanics better, how to design more and better eco-efficient technologies and products, and how to improve the accuracy and scope of our environmental impact assessment methods.

There are also risks in placing so much emphasis on models and measurement. There is a self-congratulatory element to quantitative models of technological systems which can divert attention away from the broader context, particularly when they are used to measure improvements in efficiency. As discussed, the ability to show efficiency improvements provides an instant legitimacy to any action or technology, such that the pursuit of efficiency becomes the primary goal and other matters of importance are overlooked. This pursuit of eco-efficiency for the sake of eco-efficiency is a hallmark of the ecomodern approach and the Green Machine, and the objective of Part III of this dissertation has been to take a step back from a career spent measuring things in the pursuit of eco-efficiency as a part of the Green Machine to take a broader, deeper reflection on why this pursuit has not had the intended results.

The three case studies in Part II of this dissertation were carried out to develop new insights on whether a shift from conventional fossil fuel systems to wood biomass energy systems in Nova Scotia could yield environmental benefits as is often promoted. The findings of this work were summarized in some detail in Chapter 6. These case studies were also intended to provide subject matter for the critical reflection in Part III. A key takeaway from the critical reflection is that many professionals working in the environmental management field are focused on the marginal improvement of eco-efficiency in technologies and consumer products, and this is largely because they are working within the broader Green Machine macro-system that is rooted in ecomodernism. Being inside the macro-system has a tendency to keep one's focus on perfecting the mechanics or the craft of designing, deploying, and assessing eco-efficient technologies. The engineer focuses on redesigning or creating new technologies, the government and corporate policy-makers focus on how to steer economic activity in this direction, and the impact assessment professional (e.g. LCA practitioner) pushes to improve the accuracy and scope of the assessment methods.

The wood biomass energy case studies in Part II are a good example of the mechanics of the Green Machine. Based on an assumption that burning wood provides environmental benefit over burning coal or oil, engineers and technology developers have been designing wood biomass energy systems for a number of applications in the hopes of reducing GHG emissions and combatting climate change. LCA practitioners and academic researchers have published hundreds of studies showing the potential changes in GHG emissions that could occur by the substitution of wood biomass energy systems for fossil fuel systems. Governments and corporations that are driven by meeting global targets and sustainable development goals have helped to fund this research and facilitate the uptake of biomass energy systems via policy and promotion. This is demonstrated clearly in the recent increase of adoption of wood biomass energy as a substitute for coal in the United Kingdom. All of these activities serve to reinforce the overall approach and to allow the Green Machine to continue its proliferation.

The critical reflection in Part III of this thesis was rooted in a need at least to intellectually detach from the Green Machine in order to be able to pursue other questions and objectives beyond just tweaking of the Green Machine mechanisms. This detachment and critical analysis was referred to as dismantling, an intellectual exercise to more closely examine the different elements of this macro-system of technology including its operating principles and components. One of the key findings of this critical reflection was that although macro-systems of technology tend to feel autonomous and impervious to questioning or changing direction, in fact they are ultimately driven by social and political forces and there should therefore be opportunity to steer the machine in other directions if needed. This would require the identification of key leverage points in the larger system. At present, the primary leverage point that many have tried to use to steer the Green Machine has been to use the results of the quantitative modelling of environmental impacts and benefits associated with green technologies relative to conventional technologies. For this leverage point, the application of tools like LCA has largely served to reinforce the flawed operating principles of the Green Machine.

8.2 Finding Leverage Points in Complex Systems

Part III of this thesis has been an effort to dismantle the Green Machine, to break down the elements of this macro technological system that has become the preferred means to achieve sustainable development. In Chapter 7, a number of elements of the Green Machine were broken down and critiqued, including the operating principles that originate in ecomodernism, and the more mechanical functions of designing, deploying, and assessing the eco-efficiency of green technologies. Another key part of this dismantling exercise is to identify leverage points in this macro system that one could use to change the structure and functioning of the Green Machine. There are many potential leverage points available in a macro-system and it can be difficult to determine which ones can create meaningful change.

Donella Meadows, the late systems thinker, provided a hierarchy of leverage points that are found in most complex systems and which provides a roadmap of sorts for identifying and understanding different leverage points in a macro-system like the Green Machine. In her 1999 essay, Meadows provided a list of 12 leverage points in complex systems and reflected on their relative importance and capacity for promoting change within the system (Meadows 1999). More recently, Abson et al. (2017) provided further interpretation of Meadows' hierarchy of leverage points within the context of sustainability, and how to direct sustainability science towards key leverage points in the global economic system to effect change. Meadows' original leverage points are summarized in Table 8-1 below, which also includes additions by Abson et al. to further categorize the leverage points.

Both Meadows (1999) and Abson et al. (2017) argued that issues pertaining to parameters and quantifying material stocks and flows are at the bottom of the leverage hierarchy in terms of their effectiveness at driving system change. Meadows argued that although about 99% of our attention goes to parameters, they are the points of least leverage in a complex system, likening them to "diddling with the details". Abson et al. also note that parameters are the relatively mechanistic characteristics that are typically targeted by policy-makers.

Table 8-1. Summary of leverage points in complex systems, shown in order from least effective to most effective at creating system change. Adapted from Meadows (1999) and Abson et al. (2017).

System Characteristics	Leverage Points	Effectiveness
Parameters	12. Constants, parameters, numbers	Shallow leverage points
	11. The size of buffer stocks, relative to their flows	
	10. The structure of material stocks and flows	
Feedbacks	9. The length of delays, relative to the rate of system change	
	8. The strength of negative feedback loops	
	7. The gain around driving positive feedback loops	
Design	6. The structure of information flows (access to information)	Deep leverage points
	5. The rules of the system (such as incentives & constraints)	
	4. The power to add, change or self-organize system structure	
Intent	3. The goals of the system	
	2. The mindset/paradigm out of which the system arises	
	1. The power to transcend paradigms	

In a sustainability context, Abson et al. (2017) argue that sustainability research and policy have primarily addressed the relatively shallow leverage points (see points 7 through 12) through a policy approach focused on setting targets and providing financial incentives, and that although these are important and can generate positive outcomes, they are unlikely to lead to transformational change (Abson et al. 2017).

These observations are certainly supported by the results of the critical reflection on the Green Machine in this thesis. The target of ecomodern policies is to work at the margins promoting eco-efficiency gains in using the stocks and flows of resources and emissions in technological systems. The role of LCA practitioners and other impact assessment researchers has also been largely targeted at quantifying and promoting eco-efficiency gains. With this focus on parameters as the means to move society towards sustainability, and the lack of positive results to this effect to-date, the argument that using parameters as a leverage point is the least effective approach to promote change is well supported. In reflecting on the I=PAT equation which was explored in Chapter 7, the current approach to use technology (T) to lower impacts is based almost entirely on modifying the eco-efficiency factor (T = 1/eco-efficiency) to lower impacts, but in reality this is not a strong leverage point for promoting large-scale impact reductions. Abson et al. (2017) argue that policy interventions and dominant scientific discourses mutually reinforce one another, meaning that these types of shallower interventions are favoured in both science and policy.

At the other end of the hierarchy are leverage points with greater effectiveness, or deep leverage points as classified by Abson et al. (2017). According to Meadows (1999), these include the goals of the broader system, the paradigm out of which the system arises, and the ability to transcend paradigms to understand how a system must change. The goal of the system is what other elements of the system generally fall in line with, so that stocks and flows and feedback loops and self-organizing behaviour will largely conform to the goal. In many instances, people working within the macro-system do not even recognize what the whole-system goal is that they are working towards (Meadows 1999).

Paradigms, according to Meadows, are the shared ideas in the minds of society that drive systems, unstated assumptions and deep beliefs. They are the sources of systems, and from them, shared social agreements about the nature of reality lead to development of system goals and everything else within systems (Meadows 1999). Lastly, Meadows lists the ability to transcend paradigms as the most effective leverage point for changing complex systems. She argues that this requires one to keep oneself unattached and flexible when it comes to paradigms, and to recognize that there are many paradigms depending on the situation, and not to remain tied to a particular paradigm. This suggestion is akin to Winner's suggestion that we detach ourselves from technologies and dismantle them.

In applying these concepts to the Green Machine, it is clear that although the emphasis has been on the parameters, or the controller mechanisms used for impact assessment such as LCA which reinforce the focus on eco-efficient technologies, these are weak leverage points, and the leverage points for effecting sustainable change are really at the level of the operating principles of the Green Machine. These were defined in Chapter 7, and include technological optimism, eco-efficiency, and pursuit of continued economic growth. These principles have been examined and critiqued in Chapter 7 using insights from ecological economics and generally shown to be flawed principles for achieving sustainable development. In the following section, a final reflection on the wood biomass energy case studies is provided using these deeper leverage points and trying to understand the role that wood biomass energy systems may or may not play in driving change towards sustainability, and the limitations around that contribution.

THE GREEN MACHINE AND LEVERAGE POINTS FOR SUSTAINABILITY

The Green Machine uses eco-efficient technology development to achieve its objective of sustainability of the human enterprise. The way that many impact assessment practitioners and researchers seek to guide the Green Machine is through impact assessment to optimize and/or select the most appropriate technologies. These assessments are largely based on eco-efficiency as well, following in line with this key operating principle of the Green Machine. As an LCA practitioner, I have sought to contribute to achieving the goal of sustainability by being a part of the Green Machine and using LCA to assess technology substitutions and development of green products. As a part of that effort, I and many other LCA practitioners have tried to refine and improve the methods used in LCA to increase the accuracy and scope of the methods and deliver better information and insights to technology developers, product designers, and policy makers.

The Green Machine is directed at improving the sustainability of the human enterprise, and in particular this effort is to sustain and expand upon the existing economic system, which is driven primarily by neo-classical economic principles. The Green Machine is not designed to question whether the system or paradigm being sustained is itself sustainable, or if it is worth sustaining, but rather it is directed at sustaining this system by "greening" it with eco-efficient technologies so that economic growth can continue and even be increased, but with less impact to the environment. One of the most recent objectives that has been outlined for the Green Machine is decoupling. The concept of decoupling is essentially an iteration of the concept of eco-efficiency, and in its plainest terms can be described as deriving more economic good with less environmental impact. Although not a new concept (see Gouldson & Murphy 1996; Mol & Sonnenfeld 2000), decoupling has recently been adopted as an official objective of the United Nations Environment Program (UNEP), which defines decoupling in two ways: 1) Resource decoupling, which means reducing the rate of use of primary resources per unit of economic activity; and 2) Impact decoupling, which means increasing economic output while reducing negative environmental impacts (UNEP 2011).

The UNEP language and strategy around decoupling is consistent with the founding language of sustainability from the Brundtland Report of the late 1980's. They indicate that in a world that will reach 9 billion in population by 2050, economic growth is clearly needed to lift people out of poverty and generate sufficient employment. The strategy to achieve decoupling is technological and systemic innovation, combined with rapid urbanization. Furthermore, UNEP argues that LCA, in combination with various economic input-output methods, should be used to estimate the environmental impacts of technologies and products to enable the tracking of decoupling trends (UNEP 2011). In essence, the concept of decoupling has all of the elements of the Green Machine: it is another way of describing the objectives and the mechanisms of the Green Machine. Again, after over 30 years of this approach with still decreasing environmental conditions, policy-makers are doubling down on ecomodernism and eco-efficiency under a new name (but old concept).

Decoupling as an objective has significant limitations from a biophysical perspective (see Section 7.3). Even within the recent UNEP report on decoupling, there is an admission to this effect. They describe "relative decoupling", which is basically eco-efficiency, a reduction in resource use or impacts per unit of activity or product. This is the most commonly cited form of decoupling and can be observed in the data; however, it faces the same limitations as eco-efficiency. The UNEP report also defines "absolute decoupling", which is when economic output continues to increase while the total amount of resource use or the total amount of environmental impact decrease. According to the UNEP report, absolute reductions in resource use are rare (UNEP 2011), and a review of current trends in resource use, emissions, and environmental impacts shows that although relative decoupling can be observed, absolute decoupling has not occurred. Based on the principles of ecological economics around technology substitution and critical natural capital, the concept of absolute decoupling is not achievable.

This objective of decoupling is another way of framing the application of the Green Machine. It is still an attempt to apply the Green Machine to create fundamental changes in the sustainability of a macro-system, the human enterprise, by improving eco-efficiency. In linking this idea to Meadows' hierarchy of leverage points in a system, then ecomodernism in the form of the Green Machine is still pulling on the "parameters" lever and other shallow leverage points of the economic system. This is the leverage point with the least amount of influence to create change towards sustainability. The leverage point with the greatest potential to move the system towards sustainability is at the level of the paradigm, in this case the neo-classical economic paradigm.

In viewing things this way, the eco-efficiency objective of the Green Machine is using the parameters lever, and is operating essentially at the margins of the system, or “rearranging the deck chairs on the Titanic” as Meadows put it when describing the effectiveness of different leverage points on the hierarchy (Meadows 1999, pg. 6). This is a key reason why, after 30-40 years of this eco-efficiency effort, the environmental impacts of the human enterprise continue to rise and the journey to sustainable development remains elusive.

LEVERAGE POINTS WITHIN THE GREEN MACHINE

By working at the level of parameters, efforts to improve the functioning of the Green Machine which are targeted at technology design or improving the accuracy of LCA models and methods are not leveraging the system in the correct areas to create meaningful change. There is value in undertaking this methodological development and improving the ability to quantify and communicate LCA results, but this work still lies at the level of parameters in the systems hierarchy, and work in this area does not help to understand or change the fact that 30-40 years of the Green Machine has not led to a more sustainable human society. To achieve meaningful change in the structure and functioning of the Green Machine, there is a need to engage the system at the level of paradigm, or the operating principles of the Green Machine.

Meadows’ argument that paradigm change provides the greatest leverage point for changing the course of a macro-system makes sense in theory, but creating paradigm change is not something that can be achieved in a simple policy statement or by publishing the results of an LCA. Paradigm change represents a large-scale shift in thinking and approach and values that spans jurisdictional boundaries, and that requires pushing back against well-established norms. Perhaps one of the reasons we are drawn to working at the parameter level is because that type of mechanistic work is feasible, understandable, and when completed it provides a sense of accomplishment that we’ve moved the ball forward on the issue at hand. There is value in this type of work, and in some ways it is necessary work to develop some of the data and insights that are needed to support recommendations for paradigm change. However, the more mechanistic work on parameters must not be allowed to distract us from efforts to create paradigm change when it is needed.

8.2.2 Recommendations for Reassembly of the Green Machine

The process of dismantling the Green Machine reveals theories on the deficiencies of its current configuration, and about why its objectives are not being fulfilled. This was the primary objective of Part III of this thesis, and the critical reflection has provided answers to many of the questions raised in Chapters 1 and 2. In the true spirit of a dismantling process, the intent is to eventually determine if the machine should be scrapped, or if it can be reassembled and redesigned to correct for the deficiencies that were identified in the dismantling process.

A full reassembly of the Green Machine is beyond the scope of this dissertation. Despite the deficiencies identified, there is clearly a need for technological innovation in some form to transition to a more sustainable society, and there is clearly a need for tools such as LCA to provide the insights needed to make decisions about appropriate technologies and to inform the needed paradigm shifts. However, any effort to pursue sustainability must clearly place more emphasis on points of greater leverage in the system, in particular the neoclassical paradigm which currently underpins the economy and the Green Machine. In the following sections, some final conclusions and recommendations are provided on Parts II and III of the dissertation, including some initial thoughts on how to proceed following dismantling of the Green Machine.

CONCLUSIONS AND RECOMMENDATIONS ON THE GREEN MACHINE

The concept of the Green Machine was developed using insights from the philosophy of technology and provided an alternative macro-system framework to the traditional artefact-based approach for critical reflection on ecomodernism and eco-efficient technologies. Using insights from ecological economics, the operating principles of the Green Machine were challenged and shown to consist of a weak sustainability approach. This weak sustainability approach permeates government and corporate policy, technology development, and environmental systems tools used for assessing the impacts and benefits of alternative technologies. As a result of the deficiencies of the Green Machine, the ongoing deployment of eco-efficient technologies has not led to the expected reduction in environmental impacts that were anticipated, and data indicate that environmental degradation is worsening on nearly all fronts.

To date, those working within the Green Machine who have sought to influence and improve its effectiveness have done so by using and refining tools like LCA to demonstrate the environmental costs and benefits of competing technologies and products and to provide more robust criteria for optimizing and selecting the most eco-efficient technologies. This approach is working at a level with the least amount of leverage to effect change in the system.

Any efforts to reassemble and redesign the Green Machine should be directed at the level of the foundational paradigm, which is ecomodernism. More specifically, the operating principles of the Green Machine should be revised to reflect the biophysical reality of the world into which green technologies are deployed. For example:

- Technological optimism should be replaced with technological pessimism, or as Costanza labeled it in the founding article of ecological economics, “prudent pessimism” about technology, or a critical theory of technology as described by Feenberg (2003). This principle is based on the knowledge that technology will be needed for a transition to a more sustainable society, but that policies and technologies should be developed in full acknowledgment of the negative environmental impacts of technologies, and in full acknowledgement of the limitations of technology relative to other approaches.
- The pursuit of infinite economic growth should be replaced with the pursuit of human progress within the boundaries of a biophysically-constrained planet. This principle acknowledges that technology substitution cannot bring about sustainability without corresponding policies to limit overall economic throughput in the economy. Technologies and technology assessment methods should be reconciled with planetary boundaries.

- Eco-efficiency should be replaced with appropriate technology development, and decisions to pursue greater eco-efficiency for specific technologies and products should be done in light of their broader sustainability implications. The unfailing belief in eco-efficiency for all things at all times has led to a general approach in which if we simply “green” all of our systems and products, we will achieve sustainability. Under this approach, there is very little differentiation between the importance of greening critical products and infrastructure such as energy systems relative to greening less-critical products. There is also a tendency to reward eco-efficiency improvements even when they are related to products and systems that are ultimately unsustainable in the broader context. The continued production and use of just about any consumer product can be validated by showing even the slightest eco-efficiency improvement.

CONCLUSIONS AND RECOMMENDATIONS ON LIFE CYCLE ASSESSMENT

The continued use of LCA to measure only eco-efficiency and to support the “greening” of all products and technologies should be curtailed. The use of LCA in this capacity has largely served to reinforce the flawed operating principles of the Green Machine. Many of the practitioners and researchers that are applying LCA may not even know or understand the paradigm under which they are serving and why it is flawed. As a result, their work is not used to challenge the paradigm, nor are the correct paradigms used to put their work in proper context. At present for many LCA practitioners it is enough to use LCA to either prove or disprove eco-efficiency measures to optimize and select green technologies and products. This work ends up reinforcing the flawed paradigm of the Green Machine. At a minimum, more effort should be placed on educating LCA practitioners and users of other environmental systems assessment tools about the deficiencies of the current ecomodern paradigm such that their research can address and reflect these issues more fully.

This is not to suggest that there is no value in pursuing LCA research and using LCA results to learn and inform decisions. In fact, Meadows indicates that there are instances where working at this parameter level of the leverage hierarchy can effect change in the broader system. According to Meadows, parameters become leverage points when they connect with and set off one of the other leverage points that is higher up in the hierarchy (Meadows 1999). Abson et al. (2017) argue that it is possible that parameter adjustments or changes in feedback can challenge or shift the mindset of actors in the system and therefore alter the intent (or paradigm and objectives) of the given system. In light of this, LCA could be used more effectively to drive change if applied correctly and if directed towards triggering other leverage points in the system.

Given the importance of the paradigm or operating principles of the Green Machine, efforts to connect LCA with the revised operating principles are worthwhile. Efforts have already begun in the LCA community to better connect LCA methods with the concept of planetary boundaries (Sala et al. 2016; Bjorn et al. 2015), in particular to develop metrics and methods for normalizing LCA results relative to estimated global thresholds for emissions and resource consumption. The limitations of LCA in terms of the scope of impacts that can be quantified will limit these efforts, but there is value in pushing the LCA methods in this direction.

Incorporation of assumptions which better reflect biophysical realities could also help to improve the relevance and insights to be gained from LCA research. The issues with assumptions of 1:1 replacement of fossil energy with renewable energy, or of virgin material replaced by recycled material, are assumptions that could be easily revised in LCA research. At a minimum, the use of sensitivity analysis to assess how the results would be different if full displacement is not achieved would lead to LCA results that are more in line with reality. At present the 1:1 displacement assumption is too idealistic in the context of climate change, with the IPCC providing guidance that the number of years available to reduce emissions is perhaps on the order of 10 years. How likely is it that renewable energy will replace fossil energy on a 1:1 basis within this timeframe? More realistic results would include lower displacement assumptions.

Lastly, it is recommended that LCA be used as more of a learning tool than a final decision-making tool. Due to its appearance of being comprehensive and the authority it gains from being quantitative, LCA has assumed a role in decision-making which may be above its capabilities. It has been argued since the early days of LCA as an emerging method that due to its limitations, the results of an LCA do not provide sufficient information to make universal claims, or to say that a given product or technology is environmental preferable to another. As argued by Finnveden (2000), this is primarily because not all relevant environmental impacts are considered, and there can be large uncertainties in the results due to data quality and impact assessment methods. It is also the case that although LCA is granted authority by being a quantitative tool, unlike other scientific methods, the predicted impacts in the world cannot be connected to the products by an experimental method, and so models must be used. These models are based on postulated properties, definitions, and axioms which cannot be proven either. As a result, equally valid models, giving equally valid results, can be developed from different starting points, and it cannot be shown which method or which result is the correct one (Finnveden 2000).

This is not unique to LCA and is the case for most environmental systems analysis tools (e.g. risk analysis, ecological footprinting, etc.), but can be a limiting factor when using LCA as a decision-support tool. This is also the reason that LCA can be used as a defensive tool to protect a policy or product by confusing the debate it can be both a sword and a shield on a given issue. These types of conflicting results can lead to paralysis in decision-making, which is why some have argued that LCA should be used more as a learning tool than a decision-making tool (Baumann 1998; Finvedden 2000).

CONCLUSIONS AND RECOMMENDATIONS ON WOOD BIOMASS ENERGY SYSTEMS

In Part II of the thesis, LCA was used to quantify the environmental impacts and benefits of substituting wood biomass for fossil fuels in a range of energy applications in Canada. A detailed summary of key findings and limitations of these studies was provided in Chapter 6. Throughout Part III of the thesis, various elements of the wood biomass case studies were re-examined as part of the critical reflection on the Green Machine. The critical reflection highlighted a number of potential deficiencies in the LCA methods and results for wood biomass energy and these are summarized in Section 7.4.

Based on the quantitative findings of the wood biomass case studies, and the uncertainties raised about the potential benefits of these systems in the critical reflection, it is recommended that wood biomass energy systems should be deployed in a smaller, more complementary role as opposed to current efforts to develop wood biomass energy systems at much larger scales such as national-level electricity generation. Large-scale deployment of wood biomass energy systems which may end up relying on significant increases to incremental forest harvesting may not yield the anticipated GHG emissions reductions shown in the literature, and may put increasing pressures on global forest ecosystems, which are an important stock of critical natural capital that underpins global environmental and human health. Energy policy development should focus on developing a wood biomass energy industry that complements and enhances existing forest industry activities at a smaller-scale, providing beneficial use of wastes and co-products and working within the biophysical and economic boundaries that exist.

Related to this, biomass energy should be accounted for in government forest management planning, including estimates of feedstock availability that consider the physical and economic availability of wood residues in the given jurisdiction, and the ecological implications of using wood residues for bioenergy. This is particularly relevant for the use of forest harvest residues which are more typically left in the forest. Forest management planners should develop estimates of the amount of biomass of any type that can be removed for the forest to support bioenergy and not undercut forest ecosystem health.

8.3 Final Reflections

When I began work on this dissertation, I was already an established professional in the environmental management field working as an LCA and sustainability consultant for clients in a wide range of industrial sectors. The use of LCA in this context is heavily dictated by the needs of the client such that the scope of the project is designed to answer the immediate technical questions at hand. For example, if recycled plastic is used to manufacture a given product, will the life cycle impacts of this product be decreased? The experience of always being limited in this way and repeatedly carrying out these mechanistic assessments was frustrating when I had bigger-picture questions about sustainability in my mind.

My decision to step away from my professional work to pursue doctoral studies was based on an underlying instinct that if I could remove myself from the confines of environmental consulting work, I could more freely explore the broader questions I had about our current approaches to sustainability. This has proven to be the case, and over the course of this PhD process I have been able to answer many of the more fundamental questions that I had about the broader context that surrounds me as an environmental consultant, and that surrounds all of us in our attempts to develop a more sustainable society.

Using insights from the philosophy of technology to conceptualize the Green Machine and then applying this metaphor to my research has proven to be of great value. Although the various principles and components of the Green Machine (e.g. ecomodernism) and the concepts that I used to critique it (e.g. the rebound effect) have already been individually identified and explored in the literature, there was something about bringing them together inside this conceptual framework that really resonated with me and that opened up new insights and understanding.

Interestingly, over the course of my PhD research, I maintained my consulting career and at times was more engaged with that work than with my dissertation. This was done out of necessity, but the challenges that it presented intellectually were notable. I came to view my PhD studies as being outside the Green Machine, where I had the space to think more broadly and critically about my use of LCA in the context of sustainability. At times when I was working for longer periods as a consultant, I could feel myself getting caught up in the momentum and the more mechanistic and confined approach. It was a feeling of being a cog in the Green Machine, or as an LCA practitioner it felt like being an inspector on the end of an assembly line, doing quality control for new products and technologies and signing off on their sustainability attributes as they rolled out of the factory.

As I reach the conclusion of my PhD research, this way of conceptualizing the various social, political, economic, and technological forces that shape our approaches to sustainability has been of great value for me both as an academic and as a consultant. I am finding ways of integrating my new perspective into my consulting work and looking for ways to share it with my clients. For example, prompting clients to consider the change in impacts that may result from scaling up production of their technologies and products. The intellectual detachment from the Green Machine that my PhD studies afforded me has been integral in opening up new insights that I can bring to bear on my work. It would be of great value for more professionals working in LCA and environmental management to at least briefly detach and view their work and their role in this broader context. The forces exerted on us by these macro-technological systems are strong yet often unperceivable when we are inside of them. The Green Machine has tremendous momentum, so my hope is that more colleagues can free themselves from these forces long enough to steer it in the right direction.

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APPENDIX A: SUPPORTING INFORMATION FOR CHAPTER 3 – LIFE CYCLE ASSESSMENT OF THERMAL ENERGY PRODUCTION FROM SHORT-ROTATION WILLOW BIOMASS IN SOUTHERN ONTARIO, CANADA.

Table A1. Fuel use by equipment during various short-rotation willow biomass production activities. All values calculated based on amount of time equipment used for and fuel calculator from Government of Alberta (2014), except for harvesting and baling, which is based on actual fuel use.

Activity	Amount (L/ha)	Type of equipment (e.g. tractor and hp)	Number of Passes per application	Total passes over plantation lifetime
Tillage, weeding, etc.	20.8	JD 7830/7930; 165-180 hp	1	1
Planting cuttings	5.2	Salix Maskiner Step Planter with JD 7830/7930; 165-180 hp	1	1
Fertilizer application	2.3	JD 7430; 140 hp	1	6
Pesticide application	3.3	JD 6700 Sprayer; 106 hp	2	6
Coppicing activities	13.6	Gaspardo Sickele Bar Mower with JD 7830/7930; 165-180 hp	1	1
Harvesting and baling*	84	Biobaler assuming 4 L/t DM and 21 t DM/ha (3-year cycle)	1	6

Unless otherwise mentioned, all values calculated based on amount of time equipment used for and fuel calculator from Government of Alberta (2014) http://www.agric.gov.ab.ca/app24/costcalculators/machinery/getmachimpls.jsp

Table A2. Emission factors used to estimate indicators for short-rotation willow production based on fertilizer application rates.

Substance	Value	Units	Source / Comment
Nitrous Oxide	1.7%	kg N2O-N/kg N	
Ammonia	194	kg NH_3/tonne N	EPA (2004); Based on urea
Nitric oxide	69.7	g NO/ kg N	MRI (1998); Based on urea
Phosphorus	2.9	% of P_2O_5	MAFRI

Table A3. Introductory Carbon Balance Model parameters used to model soil organic carbon accumulation over lifetime of short-rotation willow plantation.

Model Parameters	Value	Source
Average re_crop for Ontario (dimensionless)	1.305	Bolinder et al. (2008); Average of Lake Erie and St. Lawrence Lowlands)
ky (1/year)	0.8	Andrén and Kätterer (1997)
Total initial C mass (t/ha)	34.3	VandenBygart et al. (2003) (Based on assumption that healthy Ontario soil has 3.0 % SOM)
Annual C input, i (t C/ha.year)	2.65	Field measurement at GARS site
Y_0 = i/re.ky (t C/ha)	2.5	Andrén and Kätterer (1997)
O_0 = Tot C_0 - Y_0 (t C/ha)	31.8	Kätterer et al. (2008)
h	1.2	Andrén and Kätterer (1997)

Table A4. Contribution analysis for the production of 1 GJ of heat in a furnace using short-rotation willow pellets as a fuel for TRACI indicators. GWP=global warming potential, POFP= photochemical ozone formation potential, RE=respiratory effects, EP=eutrophication potential, AP= acidification potential, and ODP=Ozone depletion potential.

Impact category	ODP	GWP	POFP	AP	EP	RE
Unit	kg CFC-11 eq	kg CO_2 eq	kg O_3 eq	kg SO_2 eq	kg N eq	kg $PM_{2.5}$ eq
Combustion	0.0E+00	1.0E+00	2.5E+00	7.7E-02	5.1E-03	2.8E-02
Electricity Production and Use	2.5E-07	4.5E-01	8.2E-03	3.7E-03	1.8E-04	3.2E-04
Pelletization	5.3E-07	1.8E+00	1.4E-01	1.2E-02	6.3E-04	7.4E-04
SRW Biomass Production	6.0E-07	9.8E+00	1.3E+00	1.8E-01	5.5E-02	7.6E-03
SRW Pellet Transport	2.5E-07	1.2E+00	2.9E-01	9.1E-03	9.6E-04	5.5E-04
Ash Disposal - Municipal	3.7E-10	2.0E-03	1.6E-03	4.9E-05	4.7E-04	2.3E-06
Ash Disposal-Land Application	2.6E-11	1.3E-04	3.8E-05	1.2E-06	1.2E-07	1.6E-07
Total	1.6E-06	1.4E+01	4.2E+00	2.9E-01	6.2E-02	3.7E-02

Table A5. Cumulative energy demand for production of 1 GJ of heat in an industrial furnace using short-rotation willow pellets as a fuel

Activity	-Non-Renewable-	----------Renewable----------		Total
	All	*Biomass*	*Other*	
Unit		**MJ**		
Combustion	0.00E+00	1.7E+00	0.0E+00	1.7E+00
Electricity Production and Use	6.2E-02	2.3E-06	6.3E-03	6.8E-02
Pelletization	1.5E-01	4.8E-06	1.3E-02	1.6E-01
SRW Biomass Production	5.2E-02	1.0E-04	3.3E-04	5.3E-02
SRW Pellet Transport	1.8E-02	4.0E-06	2.1E-05	1.8E-02
Ash Disposal - Municipal	3.1E-05	1.4E-08	7.8E-08	3.1E-05
Ash Disposal - Land Application	1.8E-06	4.1E-10	2.1E-09	1.8E-06
Total	2.8E-01	1.7E+00	2.0E-02	2.0E+00

Table A6. Cumulative energy demand for production of 1 oven dry tonne of short-rotation willow biomass

Activity	-Non-Renewable-	----------Renewable----------		Total
	All	*Biomass*	*Other*	
Unit		**MJ**		
Pesticide Production	7.1E+00	5.3E-02	1.9E-01	7.3E+00
Fertilizer Production	2.9E+02	8.9E-01	2.6E+00	2.9E+02
Equipment Operation	1.9E+02	4.3E-02	2.3E-01	1.9E+02
Transport	7.2E+00	0.0E+00	0.0E+00	7.2E+00
Cutting Production	7.0E-06	9.9E-08	3.0E-06	1.0E-05
Total	4.9E+02	9.9E-01	3.1E+00	5.0E+02

Table A7. Life cycle impact assessment for production of 1 GJ of heat in a furnace using short-rotation will pellets, light fuel oil, and natural gas for TRACI indicators.

Impact category	Unit	SRW Pellets	Light Fuel Oil	Natural Gas
Ozone depletion	kg CFC-11 eq	1.6E-06	1.7E-05	1.4E-05
Global warming	kg CO_2 eq	1.4E+01	8.7E+01	7.5E+01
Smog	kg O_3 eq	4.2E+00	1.8E+00	9.9E-01
Acidification	kg SO_2 eq	2.9E-01	1.7E-01	6.3E-02
Eutrophication	kg N eq	6.2E-02	3.9E-02	1.5E-02
Respiratory effects	kg $PM_{2.5}$ eq	3.7E-02	1.1E-02	3.0E-03

APPENDIX B: SUPPORTING DATA TABLES AND BACKGROUND INFORMATION FOR CHAPTER 5 - LIFE CYCLE ENVIRONMENTAL CONSIDERATIONS FOR DOMESTIC AND EXPORT BIOENERGY PATHWAYS FOR NOVA SCOTIA WOOD PELLETS

B1. Wood Pellet Pathway Assumptions

Forest carbon modelling was conducted by the Canadian Forest Service (CFS) using Nova Scotia forest inventory data provided by the Department of Natural Resources and a number of assumptions based on the specifics of the wood biomass LCA project. The forest inventory data were provided at the county-level, and for the purposes of this analysis the data were organized into three Nova Scotia regions, including Eastern, Central, and Western (See Appendix B2). Forest carbon modelling was done using the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) (Kurz et al. 2009; Kull et al. 2011).

The forest carbon analysis was run for a business-as-usual scenario (BAU) where a typical annual harvest regime for Nova Scotia was assumed with no incremental harvest for bioenergy. The analysis calculated changes in forest carbon stocks over a 100-year time horizon. Projected harvest levels and locations for the BAU scenario were based on a 5-year average of harvest data from the Nova Scotia Registry of Buyers (NSDNR 2013). Effects of natural disturbances (e.g., forest fires, insect infestation, hurricanes, etc.) were excluded from the forest carbon analysis as some of these events are not as common in Nova Scotia.

The wood pellet bioenergy scenarios were then modeled in the forest carbon analysis based on the incremental harvest required to provide the wood biomass feedstocks (harvest that occurs beyond the BAU). These scenarios are described below.

Residential Space Heating

Homeowners were assumed to switch from heating oil to burning wood pellets for residential space heating. Two pathways were modeled: 1) feedstock used to produce wood pellets was entirely made up of sawdust and shavings from existing sawmill activities; and 2) a portion of the feedstock is obtained from the harvest of unmerchantable roundwood. Under the first scenario, all wood fibre used to make pellets would be obtained within the BAU harvesting scenario for saw logs. In the second scenario, 100% of the feedstock would come from incremental harvest of roundwood.

Data and assumptions on the heat output of an average residential pellet stove were provided by the Nova Scotia Department of Energy. A standard residential wood pellet stove was assumed to have an output of 40,000 BTU and operate at a capacity of 50% (4,380 hours/year) and an average efficiency of 80%. The pellet stove was assumed to operate at peak thermal output (40,000 BTU) 10% of operation time, 50% of peak (20,000 BTU) for 30% of operating time, 25% of peak (10,000 BTU) for 50% of the time, and 10% of time for maintenance (0 BTU). The average annual thermal energy output was 65,700,000 BTU, requiring an input of approximately 82,125,000 BTU of wood pellets (at 80% efficiency).

For the residential heating scenarios, an annual wood pellet production of 45,000 tonnes was modelled. The energy content of the wood pellets was assumed to be 18.5 MJ/kg (Magelli et al. 2009), which is equivalent to approximately 17,535 BTU/kg. The total available energy in the pellets was approximately 789,100 MMBTU, and assuming an average efficiency of 80% for the pellet stoves. At an average annual output of 82,125,000 BTU per pellet stove, the annual production amount of 45,000 tonnes of wood pellets could heat approximately 9,600 homes in Nova Scotia.

Forest Carbon Model Input

Pellet Heat Pathway 1 – Feedstock is 100% sawmill residues

- All sawmill residues will fall within the BAU harvest, no incremental harvest

Pellet Heat Pathway 2 – Feedstock is 100% roundwood

- Incremental harvest for roundwood would be 86,670 m^3
    - 45,000 tonnes of pellets = 90,000 tonnes of hardwood (green)
    - 90,000 * 0.963 = 86,670 m^3 of hardwood (oven-dry) leaving the forest (conversion factor from Registry of Buyers pg. 37)
- Incremental harvest would be spread over the 3 regions equally

Incremental carbon harvest = (86,670 m^3/1000)*1.151*424.44*0.5 = 21,170 t C

Carbon harvest broken down by region:

- Eastern Region: 7,057 t C
- Central Region: 7,057 t C
- Western Region: 7,057 t C

Export and Co-Firing for Electricity Generation

Wood pellets are assumed to be produced for export to European ports via container ship and to ultimately be used for co-fired electricity generation in Europe. The wood pellets are assumed to be manufactured from a mixture of sawmill residues and wood chips from unmerchantable roundwood. The residues are obtained from existing sawmill activities, so that no new harvest beyond the BAU saw log harvest is required for this portion of the feedstock. Wood chips would be obtained from new harvest of unmerchantable hardwood trees that would have otherwise remained in the forest. The ratio of sawdust to chipped roundwood in the feedstock fluctuates over time due to various factors such as feedstock availability, pellet quality requirements, and financial reasons. Two scenarios were run for the forest carbon analysis, one with a high-level of residue inputs (80%) and one with a lower-level of residue inputs (20%).

The coal-fired power plant model was based on a study by Ehrig & Behrendt (2013) in which they modeled the import of wood pellets for co-firing with coal in the Netherlands. The power plant is assumed to be an 800 MW plant operating for 5,000 hours per year at 46% efficiency (Ehrig & Behrendt 2013). At this level of efficiency and capacity, the plant produces 1,840,000 MWh of electricity annually from coal, requiring an input of 14,400,000 GJ of energy from coal.

The wood pellet export model was based on annual export of 50,000 tonnes of wood pellets from Nova Scotia. At an energy content of 18.5 MJ/kg, this amount of wood pellets contains 925,000 GJ of energy. It is assumed that all of these wood pellets are co-fired with coal in the 800 MW coal-fired generation plant. AT 46% conversion efficiency, this input of wood pellets could produce approximately 425,500 GJ of electricity, or 118,000 MWh. In the co-firing scenario, there would still be approximately 1,722,000 MWh produced from coal.

Forest Carbon Model Input

Pellet Co-Fire Pathway 1 (CF1) – Feedstock is 20% residues/80% roundwood

- 20% residues scenario: Incremental harvest of 77,040 m^3 (oven-dry) of hardwood
    - 50,000 tonnes of pellets = 100,000 tonnes of wood fibre input (green)
    - 100,000 tonnes * 0.8 = 80,000 tonnes of hardwood (green)
    - 80,000 * 0.963 = 77,040 m^3 of hardwood (oven-dry) leaving the forest (conversion factor from Registry of Buyers pg. 37)
- All incremental harvest is assumed to be from the Central Region

Incremental carbon harvest = (70,040 m^3/1000)*1.151*424.44*0.5 = 18,818 t C

Pellet Co-Fire Pathway 2 (CF2) – Feedstock is 80% residues/20% roundwood

- 80% residues scenario: Incremental harvest of 19,260 m^3/year (oven-dry) of hardwood leaving the forest
    - 50,000 tonnes of pellets = 100,000 tonnes of wood fibre input (green)
    - 100,000 tonnes *0.2 = 20,000 tonnes of hardwood (green)
    - 20,000 * 0.963 = 19,260 m^3 of hardwood (oven-dry) leaving the forest (conversion factor from Registry of Buyers pg.37)
- Residues will come from the BAU harvest
- All incremental harvest assumed to be from Central Region

Incremental carbon harvest = (19,260 m^3/1000)*1.151*424.44*0.5 = 4,705 t C

B2. Supporting Information for the Nova Scotia Forest Carbon Modelling and Simulations

Forest Carbon Modelling

The forest inventory data provided for the forest carbon modelling was at the county-level, and for the purposes of this analysis the data were organized into three Nova Scotia regions, including Eastern, Central, and Western (Table B1).

For the BAU, the forest carbon analysis was run for a typical annual harvest regime based on data from the Nova Scotia Registry of Buyers and assuming no incremental harvest for bioenergy. The analysis calculated changes in the forest carbon cycle over a 100-year time horizon. Projected harvest levels and locations for the BAU scenario were based on a 5-year average of harvest data from the Registry of Buyers (Forest et al. 2011; NSDNR 2013). Effects of natural disturbances (e.g., forest fires, insect infestation, hurricanes, etc.) were excluded from the forest carbon analysis. The various bioenergy scenarios were then modeled in the forest carbon analysis based on the incremental harvest required to provide the wood biomass feedstocks (harvest that occurs beyond the BAU).

The focus of the forest carbon modeling was to quantify net ecosystem production (NEP) on an annual basis for both the BAU and the wood pellet pathways. Net ecosystem production is a measure of the net amount of carbon taken up in the forest through primary production. It is calculated by subtracting heterotrophic respiration (Rh) from net primary productivity (NPP) (Kirschbaum et al. 2001).

Eq. 1. $NEP = NPP - Rh$

Table B1. Summary of forest areas included in each of the harvesting regions including Eastern, Central, and Western regions. Source: Nova Scotia Department of Lands and Forestry.

Eastern Region – 1,281,788 ha			Central Region – 1,219,531 ha			Western Region – 1,611,389 ha		
Admin No.	Boundary Name	Area (ha)	Admin No.	Boundary Name	Area (ha)	Admin No.	Boundary Name	Area (ha)
100	INVERNESS	11,083	440	GUYEAST	38,526	720	ANNAPOLIS	176,279
100	VICTORIA	9,855	440	HANTS	21,188	720	DIGBY	74,570
210	INVERNESS	120,615	440	HFXEAST	70,862	720	HANTS	36,029
210	VICTORIA	147,264	440	HFXWEST	84,596	720	HFXWEST	2,984
220	INVERNESS	108	440	STMARYS	54,944	720	KINGS	57,671
220	VICTORIA	9,299	450	COLCHESTER	1,146	720	LUNENBURG	13,175
310	CAPE_BRETO	52,625	450	HFXEAST	29,778	720	QUEENS	11,265
310	INVERNESS	126,739	450	HFXWEST	469	720	SHELBURNE	9,390
310	RICHMOND	11,673	450	PICTOU	323	720	YARMOUTH	1,077
310	VICTORIA	27,494	450	STMARYS	20,282	730	DIGBY	86,535
320	INVERNESS	22,700	510	CAPE_BRETO	94,403	730	YARMOUTH	53,082
320	VICTORIA	3,167	510	INVERNESS	26,757	740	ANNAPOLIS	17,369
330	ANTIGONISH	43,724	510	RICHMOND	45,092	740	HANTS	1,324
330	PICTOU	70,650	510	VICTORIA	28,746	740	HFXWEST	285
330	STMARYS	1,973	520	ANTIGONISH	48,370	740	KINGS	11,149
340	COLCHESTER	86,552	520	GUYEAST	2,565	740	LUNENBURG	128,275
340	CUMBERLAND	56,729	520	INVERNESS	7,759	740	QUEENS	43,959
340	PICTOU	24,958	520	PICTOU	9	750	LUNENBURG	5,586
350	COLCHESTER	31,129	530	COLCHESTER	20,470	750	QUEENS	75,721
360	ANTIGONISH	16,517	530	CUMBERLAND	106,172	750	SHELBURNE	1,053
360	GUYEAST	64,010	530	PICTOU	68,712	760	QUEENS	48,129
360	STMARYS	1,591	540	COLCHESTER	850	760	SHELBURNE	120,060
370	GUYEAST	11,321	540	CUMBERLAND	73,715	760	YARMOUTH	46,220
370	PICTOU	18,644	550	CUMBERLAND	5,095	770	DIGBY	19,840
370	STMARYS	39,879	560	CUMBERLAND	63,228	770	QUEENS	638
380	COLCHESTER	71,175	610	ANNAPOLIS	13,176	770	SHELBURNE	9,005
380	PICTOU	38,343	610	DIGBY	3,285	770	YARMOUTH	24,732
410	COLCHESTER	13,934	610	KINGS	12,999	780	HANTS	25,559
410	HANTS	22,468	620	COLCHESTER	16,767	780	HFXWEST	51,733
410	HFXEAST	3,257	620	HANTS	1,669	780	LUNENBURG	65,286
410	HFXWEST	11,718	630	COLCHESTER	39,775	810	CAPE_BRETO	33,488
420	HANTS	3,424	630	HANTS	126,916	810	GUYEAST	6,786
420	HFXEAST	39,012	630	HFXEAST	681	810	RICHMOND	39,695
420	HFXWEST	6,755	630	HFXWEST	23,027	820	GUYEAST	28,892
420	STMARYS	15,791	630	KINGS	1	820	HFXEAST	24,783
430	HFXEAST	19,254	710	ANNAPOLIS	29,597	820	HFXWEST	24,963
430	HFXWEST	26,357	710	DIGBY	7,887	820	STMARYS	20,514
			710	HANTS	2,272	830	LUNENBURG	21,081
			710	KINGS	27,419	830	QUEENS	16,412
						830	SHELBURNE	42,876
						830	YARMOUTH	1,859
						840	YARMOUTH	20,640
						910	COLCHESTER	3,896
						910	CUMBERLAND	28,483
						920	ANNAPOLIS	31,122
						920	CUMBERLAND	71
						920	DIGBY	14,111
						920	KINGS	33,737

NPP was quantified in the forest carbon model by using average tree growth rates linked to harvesting sites in a Geographic Information System (GIS). It was assumed that the forest management approach across Nova Scotia was to harvest by clearcutting and to allow natural re-growth with no active silviculture being undertaken. Each year of the analysis, NPP was calculated by adding primary productivity (in tonnes of carbon) across the province and subtracting carbon lost to the atmosphere via plant respiration (Kirschbaum et al. 2001).

Eq. 2. $NPP = GPP - R_a$

In some forest carbon analyses, net biome production (NBP) is calculated, which is NEP minus disturbance emissions (Kirschbaum et al. 2001), which include carbon removed from the forest due to harvesting activities. In this calculation of NBP it is assumed that all carbon removed from the forest in harvesting activities is released to the atmosphere during the year of harvest. In the present analysis, the carbon residency time for typical Nova Scotia forest products from the BAU harvest was modeled, such that only a portion of carbon from each year's harvest was assumed to be emitted to the atmosphere. In this case, carbon leaving the forest via harvest can either be stored in various types of wood products (paper, lumber, other wood products), landfilled, or released directly to the atmosphere via combustion or rapid decay. Carbon residency times vary according to the type of wood product, for example carbon stored in lumber products has a longer residency time than carbon stored in paper products. Carbon harvested in wood used for bioenergy is assumed to go directly to the atmosphere in the given year. Each year, some harvested carbon is released directly to the atmosphere (e.g. bioenergy) and some carbon is released to the atmosphere via decay of forest products (FP_{dec}). The amount for FP_{dec} was calculated each year based on the fate of softwood, hardwood, and pulpwood in common forest products in Nova Scotia and carbon decay rates for each type of product and according to the following formula. Carbon decay and residency rates for wood products were obtained from the Canadian Forest Service and are summarized in Tables B2 and B3.

Eq. 3. $FP_{dec} = C_{hard} + C_{soft} + C_{pulp} + C_{bioe}$

C_{hard}, C_{soft}, and C_{pulp} are the amounts of carbon released to the atmosphere by decay of forest products from hardwood, softwood, and pulpwood (respectively) expressed in CO_2 equivalents. C_{bioe} is carbon released to the atmosphere through the combustion of any newly harvested roundwood used to produce wood pellets. The only difference in FP_{dec} between the BAU and the bioenergy pathways is that in Pellet Pathway 2 and Co-Fire Pathway 1 and Co-Fire Pathway 2 there is incremental harvesting resulting in an amount of C_{bioe}. For Pellet Pathway 1 there is no incremental harvesting, so C_{bioe} is 0 and FP_{dec} is therefore equivalent between the BAU and Pellet Pathway 1.

Table B2. Carbon residency and decay fractions for wood products – Part 1. Data show the fraction of each unit of carbon that is sequestered in wood products or released to the atmosphere for each year after harvest. Carbon fractions are shown relative to end use and to harvested wood type.

	Paper Products			Other Wood Products		Lumber	Landfill - Slow		
Year	HW	SW	PW	HW	SW	SW	HW	SW	PW
1	0.034	0.024	0.077	0.186	0.118	0.285	0.118	0.093	0.153
2	0.034	0.024	0.077	0.186	0.118	0.285	0.118	0.093	0.153
3	0.034	0.024	0.077	0.186	0.118	0.285	0.118	0.093	0.153
4	0.034	0.024	0.077	0.186	0.118	0.285	0.118	0.093	0.153
5	0.034	0.024	0.077	0.186	0.118	0.285	0.118	0.093	0.153
6	0.019	0.013	0.044	0.169	0.107	0.274	0.132	0.108	0.169
7	0.019	0.013	0.044	0.169	0.107	0.274	0.132	0.108	0.169
8	0.019	0.013	0.044	0.169	0.107	0.274	0.132	0.108	0.169
9	0.019	0.013	0.044	0.169	0.107	0.274	0.132	0.108	0.169
10	0.019	0.013	0.044	0.169	0.107	0.274	0.132	0.108	0.169
11	0.018	0.013	0.04	0.154	0.098	0.263	0.14	0.117	0.171
12	0.018	0.013	0.04	0.154	0.098	0.263	0.14	0.117	0.171
13	0.018	0.013	0.04	0.154	0.098	0.263	0.14	0.117	0.171
14	0.018	0.013	0.04	0.154	0.098	0.263	0.14	0.117	0.171
15	0.018	0.013	0.04	0.154	0.098	0.263	0.14	0.117	0.171
16	0.017	0.012	0.037	0.139	0.088	0.252	0.147	0.127	0.172
17	0.017	0.012	0.037	0.139	0.088	0.252	0.147	0.127	0.172
18	0.017	0.012	0.037	0.139	0.088	0.252	0.147	0.127	0.172
19	0.017	0.012	0.037	0.139	0.088	0.252	0.147	0.127	0.172
20	0.017	0.012	0.037	0.139	0.088	0.252	0.147	0.127	0.172
21	0.015	0.011	0.035	0.124	0.079	0.241	0.154	0.136	0.173
22	0.015	0.011	0.035	0.124	0.079	0.241	0.154	0.136	0.173
23	0.015	0.011	0.035	0.124	0.079	0.241	0.154	0.136	0.173
24	0.015	0.011	0.035	0.124	0.079	0.241	0.154	0.136	0.173
25	0.015	0.011	0.035	0.124	0.079	0.241	0.154	0.136	0.173
26	0.015	0.01	0.033	0.110	0.069	0.23	0.161	0.146	0.174
27	0.015	0.01	0.033	0.110	0.069	0.23	0.161	0.146	0.174
28	0.015	0.01	0.033	0.110	0.069	0.23	0.161	0.146	0.174
29	0.015	0.01	0.033	0.110	0.069	0.23	0.161	0.146	0.174
30	0.015	0.01	0.033	0.110	0.069	0.23	0.161	0.146	0.174

	Paper Products			Other Wood Products		Lumber	Landfill - Slow		
Year	HW	SW	PW	HW	SW	SW	HW	SW	PW
31	0.013	0.009	0.031	0.094	0.06	0.219	0.169	0.155	0.175
32	0.013	0.009	0.031	0.094	0.06	0.219	0.169	0.155	0.175
33	0.013	0.009	0.031	0.094	0.06	0.219	0.169	0.155	0.175
34	0.013	0.009	0.031	0.094	0.06	0.219	0.169	0.155	0.175
35	0.013	0.009	0.031	0.094	0.06	0.219	0.169	0.155	0.175
36	0.012	0.009	0.028	0.079	0.05	0.208	0.176	0.165	0.176
37	0.012	0.009	0.028	0.079	0.05	0.208	0.176	0.165	0.176
38	0.012	0.009	0.028	0.079	0.05	0.208	0.176	0.165	0.176
39	0.012	0.009	0.028	0.079	0.05	0.208	0.176	0.165	0.176
40	0.012	0.009	0.028	0.079	0.05	0.208	0.176	0.165	0.176
41	0.012	0.008	0.026	0.064	0.041	0.197	0.183	0.175	0.177
42	0.012	0.008	0.026	0.064	0.041	0.197	0.183	0.175	0.177
43	0.012	0.008	0.026	0.064	0.041	0.197	0.183	0.175	0.177
44	0.012	0.008	0.026	0.064	0.041	0.197	0.183	0.175	0.177
45	0.012	0.008	0.026	0.064	0.041	0.197	0.183	0.175	0.177
46	0.01	0.007	0.024	0.049	0.031	0.186	0.19	0.184	0.178
47	0.01	0.007	0.024	0.049	0.031	0.186	0.19	0.184	0.178
48	0.01	0.007	0.024	0.049	0.031	0.186	0.19	0.184	0.178
49	0.01	0.007	0.024	0.049	0.031	0.186	0.19	0.184	0.178
50	0.01	0.007	0.024	0.049	0.031	0.186	0.19	0.184	0.178
51	0.009	0.007	0.022	0.034	0.022	0.174	0.198	0.194	0.179
52	0.009	0.007	0.022	0.034	0.022	0.174	0.198	0.194	0.179
53	0.009	0.007	0.022	0.034	0.022	0.174	0.198	0.194	0.179
54	0.009	0.007	0.022	0.034	0.022	0.174	0.198	0.194	0.179
55	0.009	0.007	0.022	0.034	0.022	0.174	0.198	0.194	0.179
56	0.008	0.006	0.019	0.019	0.012	0.163	0.205	0.204	0.18
57	0.008	0.006	0.019	0.019	0.012	0.163	0.205	0.204	0.18
58	0.008	0.006	0.019	0.019	0.012	0.163	0.205	0.204	0.18
59	0.008	0.006	0.019	0.019	0.012	0.163	0.205	0.204	0.18
60	0.008	0.006	0.019	0.019	0.012	0.163	0.205	0.204	0.18
61	0.007	0.005	0.017	0.016	0.01	0.146	0.206	0.212	0.181
62	0.007	0.005	0.017	0.016	0.01	0.146	0.206	0.212	0.181
63	0.007	0.005	0.017	0.016	0.01	0.146	0.206	0.212	0.181
64	0.007	0.005	0.017	0.016	0.01	0.146	0.206	0.212	0.181
65	0.007	0.005	0.017	0.016	0.01	0.146	0.206	0.212	0.181
66	0.006	0.004	0.014	0.014	0.009	0.129	0.208	0.221	0.183
67	0.006	0.004	0.014	0.014	0.009	0.129	0.208	0.221	0.183
68	0.006	0.004	0.014	0.014	0.009	0.129	0.208	0.221	0.183
69	0.006	0.004	0.014	0.014	0.009	0.129	0.208	0.221	0.183
70	0.006	0.004	0.014	0.014	0.009	0.129	0.208	0.221	0.183
71	0.005	0.004	0.012	0.012	0.007	0.111	0.209	0.23	0.184
72	0.005	0.004	0.012	0.012	0.007	0.111	0.209	0.23	0.184
73	0.005	0.004	0.012	0.012	0.007	0.111	0.209	0.23	0.184
74	0.005	0.004	0.012	0.012	0.007	0.111	0.209	0.23	0.184
75	0.005	0.004	0.012	0.012	0.007	0.111	0.209	0.23	0.184
76	0.004	0.003	0.01	0.010	0.006	0.094	0.211	0.238	0.185
77	0.004	0.003	0.01	0.010	0.006	0.094	0.211	0.238	0.185
78	0.004	0.003	0.01	0.010	0.006	0.094	0.211	0.238	0.185
79	0.004	0.003	0.01	0.010	0.006	0.094	0.211	0.238	0.185
80	0.004	0.003	0.01	0.010	0.006	0.094	0.211	0.238	0.185
81	0.003	0.002	0.008	0.007	0.005	0.077	0.212	0.247	0.186
82	0.003	0.002	0.008	0.007	0.005	0.077	0.212	0.247	0.186
83	0.003	0.002	0.008	0.007	0.005	0.077	0.212	0.247	0.186
84	0.003	0.002	0.008	0.007	0.005	0.077	0.212	0.247	0.186
85	0.003	0.002	0.008	0.007	0.005	0.077	0.212	0.247	0.186
86	0.002	0.002	0.005	0.005	0.003	0.059	0.214	0.256	0.187
87	0.002	0.002	0.005	0.005	0.003	0.059	0.214	0.256	0.187
88	0.002	0.002	0.005	0.005	0.003	0.059	0.214	0.256	0.187

	Paper Products			Other Wood Products		Lumber	Landfill - Slow		
Year	HW	SW	PW	HW	SW	SW	HW	SW	PW
89	0.002	0.002	0.005	0.005	0.003	0.059	0.214	0.256	0.187
90	0.002	0.002	0.005	0.005	0.003	0.059	0.214	0.256	0.187
91	0.001	0.001	0.003	0.003	0.002	0.042	0.215	0.265	0.188
92	0.001	0.001	0.003	0.003	0.002	0.042	0.215	0.265	0.188
93	0.001	0.001	0.003	0.003	0.002	0.042	0.215	0.265	0.188
94	0.001	0.001	0.003	0.003	0.002	0.042	0.215	0.265	0.188
95	0.001	0.001	0.003	0.003	0.002	0.042	0.215	0.265	0.188
96	0	0	0.001	0.001	0	0.024	0.217	0.273	0.189
97	0	0	0.001	0.001	0	0.024	0.217	0.273	0.189
98	0	0	0.001	0.001	0	0.024	0.217	0.273	0.189
99	0	0	0.001	0.001	0	0.024	0.217	0.273	0.189
100	0	0	0.001	0.001	0	0.024	0.217	0.273	0.189

Table B3. Carbon residency and decay fractions for wood products – Part 2. Data show the fraction of each unit of carbon that is sequestered in wood products or released to the atmosphere for each year after harvest. Carbon fractions are shown relative to end use and to harvested wood type.

	Landfill - Fast			To Atmosphere		
Year	HW	SW	PW	HW	SW	PW
1	0.112	0.088	0.145	0.549	0.391	0.622
2	0.112	0.088	0.145	0.551	0.393	0.624
3	0.112	0.088	0.145	0.553	0.395	0.626
4	0.112	0.088	0.145	0.554	0.396	0.628
5	0.112	0.088	0.145	0.556	0.398	0.63
6	0.12	0.098	0.153	0.558	0.399	0.632
7	0.12	0.098	0.153	0.56	0.401	0.634
8	0.12	0.098	0.153	0.561	0.403	0.636
9	0.12	0.098	0.153	0.563	0.404	0.637
10	0.12	0.098	0.153	0.564	0.406	0.639
11	0.12	0.102	0.146	0.566	0.407	0.641
12	0.12	0.102	0.146	0.568	0.409	0.643
13	0.12	0.102	0.146	0.57	0.411	0.645
14	0.12	0.102	0.146	0.571	0.412	0.646
15	0.12	0.102	0.146	0.573	0.414	0.648
16	0.12	0.105	0.139	0.575	0.415	0.65
17	0.12	0.105	0.139	0.577	0.417	0.652
18	0.12	0.105	0.139	0.579	0.419	0.653
19	0.12	0.105	0.139	0.58	0.42	0.655
20	0.12	0.105	0.139	0.582	0.422	0.656
21	0.12	0.107	0.131	0.584	0.424	0.658
22	0.12	0.107	0.131	0.586	0.426	0.66
23	0.12	0.107	0.131	0.588	0.428	0.662
24	0.12	0.107	0.131	0.59	0.429	0.663
25	0.12	0.107	0.131	0.592	0.431	0.665
26	0.119	0.11	0.123	0.594	0.433	0.667
27	0.119	0.11	0.123	0.596	0.435	0.669
28	0.119	0.11	0.123	0.598	0.437	0.671
29	0.119	0.11	0.123	0.6	0.439	0.672
30	0.119	0.11	0.123	0.602	0.441	0.675
31	0.118	0.111	0.116	0.604	0.443	0.676
32	0.118	0.111	0.116	0.606	0.445	0.678
33	0.118	0.111	0.116	0.608	0.447	0.68
34	0.118	0.111	0.116	0.61	0.449	0.681
35	0.118	0.111	0.116	0.612	0.451	0.683
36	0.116	0.113	0.108	0.614	0.453	0.685

	Landfill - Fast			To Atmosphere		
Year	HW	SW	PW	HW	SW	PW
37	0.116	0.113	0.108	0.616	0.455	0.687
38	0.116	0.113	0.108	0.618	0.457	0.689
39	0.116	0.113	0.108	0.621	0.46	0.69
40	0.116	0.113	0.108	0.623	0.462	0.692
41	0.114	0.114	0.1	0.625	0.464	0.694
42	0.114	0.114	0.1	0.627	0.466	0.696
43	0.114	0.114	0.1	0.629	0.468	0.698
44	0.114	0.114	0.1	0.632	0.471	0.699
45	0.114	0.114	0.1	0.634	0.473	0.701
46	0.112	0.114	0.092	0.636	0.475	0.703
47	0.112	0.114	0.092	0.638	0.477	0.705
48	0.112	0.114	0.092	0.64	0.48	0.707
49	0.112	0.114	0.092	0.643	0.482	0.708
50	0.112	0.114	0.092	0.645	0.485	0.71
51	0.109	0.114	0.084	0.647	0.487	0.712
52	0.109	0.114	0.084	0.649	0.489	0.714
53	0.109	0.114	0.084	0.652	0.492	0.716
54	0.109	0.114	0.084	0.654	0.494	0.717
55	0.109	0.114	0.084	0.657	0.497	0.719
56	0.106	0.114	0.077	0.659	0.499	0.721
57	0.106	0.114	0.077	0.661	0.502	0.723
58	0.106	0.114	0.077	0.663	0.504	0.725
59	0.106	0.114	0.077	0.667	0.507	0.726
60	0.106	0.114	0.077	0.669	0.509	0.728
61	0.097	0.111	0.068	0.67	0.512	0.73
62	0.097	0.111	0.068	0.672	0.515	0.732
63	0.097	0.111	0.068	0.674	0.517	0.734
64	0.097	0.111	0.068	0.677	0.52	0.736
65	0.097	0.111	0.068	0.679	0.522	0.738
66	0.089	0.109	0.061	0.68	0.525	0.74
67	0.089	0.109	0.061	0.682	0.528	0.742
68	0.089	0.109	0.061	0.684	0.53	0.744
69	0.089	0.109	0.061	0.687	0.533	0.745
70	0.089	0.109	0.061	0.689	0.535	0.747
71	0.08	0.106	0.052	0.691	0.538	0.749
72	0.08	0.106	0.052	0.693	0.541	0.751
73	0.08	0.106	0.052	0.695	0.544	0.753
74	0.08	0.106	0.052	0.698	0.546	0.754
75	0.08	0.106	0.052	0.7	0.549	0.756
76	0.07	0.103	0.044	0.702	0.552	0.758
77	0.07	0.103	0.044	0.704	0.555	0.76
78	0.07	0.103	0.044	0.706	0.558	0.762
79	0.07	0.103	0.044	0.709	0.56	0.764
80	0.07	0.103	0.044	0.711	0.563	0.766
81	0.061	0.099	0.036	0.713	0.566	0.768
82	0.061	0.099	0.036	0.715	0.569	0.77
83	0.061	0.099	0.036	0.717	0.572	0.772
84	0.061	0.099	0.036	0.72	0.575	0.773
85	0.061	0.099	0.036	0.722	0.578	0.775
86	0.052	0.096	0.028	0.724	0.581	0.777
87	0.052	0.096	0.028	0.726	0.584	0.779
88	0.052	0.096	0.028	0.728	0.587	0.781
89	0.052	0.096	0.028	0.731	0.59	0.783
90	0.052	0.096	0.028	0.733	0.593	0.785
91	0.043	0.091	0.019	0.735	0.596	0.787
92	0.043	0.091	0.019	0.737	0.599	0.789
93	0.043	0.091	0.019	0.739	0.602	0.791
94	0.043	0.091	0.019	0.742	0.606	0.792
95	0.043	0.091	0.019	0.744	0.609	0.794
96	0.033	0.086	0.011	0.746	0.612	0.796

	Landfill - Fast			To Atmosphere		
Year	HW	SW	PW	HW	SW	PW
97	0.033	0.086	0.011	0.747	0.614	0.797
98	0.033	0.086	0.011	0.748	0.616	0.798
99	0.033	0.086	0.011	0.75	0.618	0.799
100	0.033	0.086	0.011	0.751	0.62	0.8

Simulation of growth causes carbon to enter the forest ecosystem and it is distributed among 10 different biomass pools. Simulation of turnover and disturbance processes causes the transfers of carbon from biomass to DOM pools. Disturbances can also cause the loss of carbon from the ecosystem as gaseous emissions or to the forestry sector. Carbon is transferred between DOM pools by a variety of mechanisms: decay, transfer, and disturbance. Carbon that remains in the ecosystem eventually ends up in the belowground slow DOM pool. In the diagram, rectangles represent pools, rounded rectangles represent groups of pools, arrows represent the movement of C between groups of pools, ovals represent the simulated processes and circles represent losses from the ecosystem. SW= softwood, HW= hardwood. (Source: Kurz et al. 2009).

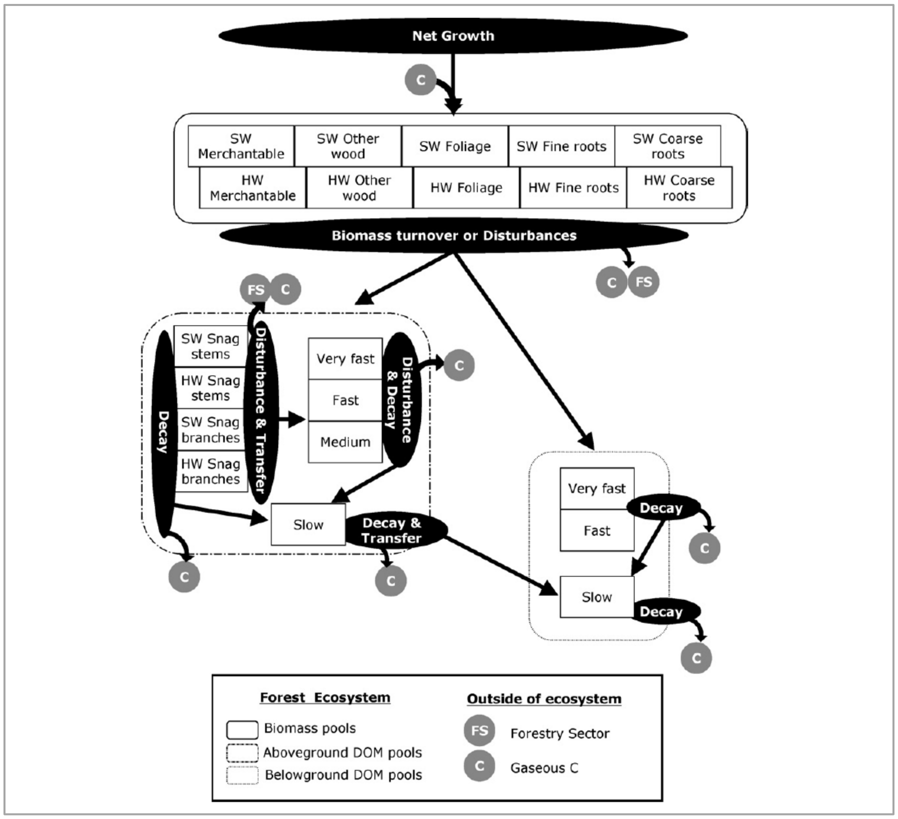

Figure B1. Conceptual design of CBM-CFS3 (Kurz et al. 2009).

B3. Forest Carbon Simulation Results for the Reference Case Business as Usual (BAU)

Table B4. BAU forest carbon simulation data broken down by region of Nova Scotia, expressed in tonnes of carbon.

Legend:
NPP = net primary productivity (Net growth + litterfall); Rh = heterotrophic respiration; NEP = net ecosystem productivity (NPP – Rh); Litterfall = carbon in litter layer on forest floor; Harvest = carbon in harvested wood; Bio2DOM = carbon in dead organic matter; Net Growth = carbon in forest growth; NBP = net biome production (NEP – Harvest)

Year	NPP	Rh	NEP	Litterfall	Harvest	Bio2DOM	Net Growth	NBP
Central Region								
2011	5,125,538	4,812,836	312,703	3,935,420	431,570	614,159	1,190,118	-118,867
2012	5,149,336	4,827,942	321,394	3,925,591	576,872	797,223	1,223,745	-255,478
2013	5,085,079	4,835,715	249,364	3,922,681	555,105	787,082	1,162,398	-305,741
2014	5,117,529	4,831,593	285,936	3,918,496	537,329	721,121	1,199,033	-251,392
2015	5,145,437	4,829,664	315,773	3,911,979	530,057	748,973	1,233,458	-214,285
2016	5,176,962	4,826,019	350,943	3,908,991	526,187	741,375	1,267,971	-175,244
2017	5,205,091	4,819,863	385,229	3,905,406	545,110	738,987	1,299,686	-159,881
2018	5,158,761	4,814,430	344,331	3,912,882	538,758	732,911	1,245,879	-194,427
2019	5,191,848	4,806,745	385,104	3,913,881	535,489	710,709	1,277,967	-150,385
2020	5,222,536	4,801,187	421,349	3,912,947	535,121	723,664	1,309,590	-113,771
2021	5,252,520	4,796,851	455,670	3,913,756	536,133	726,570	1,338,764	-80,463
2022	5,280,771	4,794,494	486,276	3,914,353	538,121	739,425	1,366,417	-51,845
2023	5,243,944	4,789,068	454,877	3,925,115	536,725	712,630	1,318,829	-81,848
2024	5,273,966	4,786,188	487,779	3,923,990	536,318	730,479	1,349,977	-48,539
2025	5,296,972	4,781,363	515,609	3,924,198	536,483	717,822	1,372,774	-20,874
2026	5,318,757	4,781,685	537,073	3,920,572	536,756	757,527	1,398,185	316
2027	5,340,970	4,780,229	560,742	3,919,050	536,881	749,951	1,421,920	23,861
2028	5,299,762	4,774,808	524,954	3,927,373	536,632	721,122	1,372,389	-11,679
2029	5,321,697	4,767,230	554,467	3,927,450	536,614	701,666	1,394,247	17,853
2030	5,342,534	4,762,374	580,159	3,929,920	536,673	703,842	1,412,614	43,486
2031	5,357,482	4,763,009	594,474	3,926,606	536,711	748,939	1,430,876	57,762
2032	5,367,981	4,764,622	603,359	3,922,264	536,703	765,143	1,445,717	66,656
2033	5,325,581	4,757,988	567,593	3,932,440	536,666	703,260	1,393,141	30,927
2034	5,340,507	4,755,930	584,576	3,929,160	536,673	734,952	1,411,347	47,903
2035	5,362,284	4,751,068	611,216	3,931,607	536,685	707,683	1,430,677	74,531
2036	5,384,656	4,744,792	639,864	3,934,756	536,688	689,988	1,449,900	103,176
2037	5,391,913	4,748,911	643,002	3,931,010	536,683	764,788	1,460,903	106,318
2038	5,345,384	4,752,162	593,222	3,933,669	536,679	770,002	1,411,714	56,543
2039	5,366,849	4,749,983	616,866	3,934,921	536,681	733,527	1,431,928	80,184
2040	5,387,872	4,746,363	641,509	3,933,365	536,684	728,985	1,454,507	104,825
2041	5,410,428	4,741,121	669,307	3,934,679	536,683	711,726	1,475,750	132,624
2042	5,433,448	4,738,279	695,169	3,937,822	536,682	714,193	1,495,626	158,487
2043	5,365,366	4,732,532	632,834	3,949,051	536,681	683,911	1,416,315	96,153
2044	5,389,608	4,731,154	658,454	3,952,500	536,683	700,153	1,437,108	121,771
2045	5,409,731	4,734,462	675,269	3,950,043	536,683	744,197	1,459,688	138,587
2046	5,431,280	4,738,811	692,469	3,949,871	536,683	754,175	1,481,409	155,786
2047	5,453,971	4,738,263	715,708	3,951,418	536,683	728,056	1,502,553	179,026
2048	5,356,795	4,732,473	624,321	3,958,553	536,683	694,338	1,398,242	87,639
2049	5,380,617	4,731,278	649,339	3,960,766	536,683	705,793	1,419,851	112,656
2050	5,403,954	4,727,408	676,546	3,963,213	536,683	688,786	1,440,741	139,863
2051	5,426,053	4,730,103	695,949	3,966,848	536,683	719,266	1,459,205	159,267
2052	5,445,252	4,735,945	709,307	3,967,405	536,683	750,171	1,477,847	172,624
2053	5,342,778	4,736,076	606,701	3,973,341	536,683	721,855	1,369,436	70,019
2054	5,364,312	4,732,287	632,025	3,975,767	536,683	688,795	1,388,545	95,343

Year	NPP	Rh	NEP	Litterfall	Harvest	Bio2DOM	Net Growth	NBP
2055	5,383,722	4,731,777	651,945	3,976,831	536,683	705,143	1,406,890	115,262
2056	5,404,218	4,734,924	669,294	3,980,286	536,683	720,612	1,423,932	132,611
2057	5,422,871	4,736,148	686,723	3,981,427	536,683	719,961	1,441,444	150,041
2058	5,332,152	4,734,147	598,005	3,989,995	536,683	693,247	1,342,157	61,323
2059	5,349,235	4,737,323	611,913	3,988,456	536,683	727,344	1,360,779	75,230
2060	5,366,772	4,741,197	625,575	3,988,004	536,683	737,390	1,378,768	88,892
2061	5,381,798	4,740,765	641,033	3,987,534	536,683	717,932	1,394,264	104,350
2062	5,401,954	4,741,007	660,948	3,992,829	536,683	705,572	1,409,126	124,265
2063	5,331,997	4,739,809	592,187	4,007,301	536,683	683,888	1,324,695	55,505
2064	5,355,068	4,738,476	616,592	4,014,869	536,683	671,679	1,340,198	79,909
2065	5,374,676	4,741,472	633,204	4,020,019	536,683	697,804	1,354,657	96,522
2066	5,393,430	4,742,062	651,367	4,028,710	536,683	672,197	1,364,720	114,685
2067	5,420,685	4,740,401	680,284	4,048,189	536,683	621,822	1,372,496	143,601
2068	5,357,020	4,749,599	607,421	4,055,853	536,683	715,302	1,301,168	70,739
2069	5,378,983	4,751,042	627,941	4,066,783	536,683	649,094	1,312,200	91,258
2070	5,398,220	4,753,894	644,326	4,075,270	536,683	658,986	1,322,951	107,643
2071	5,413,288	4,756,609	656,679	4,084,185	536,683	654,339	1,329,103	119,996
2072	5,438,902	4,755,562	683,340	4,107,542	536,683	585,601	1,331,360	146,657
2073	5,388,797	4,768,205	620,592	4,116,816	536,683	696,402	1,271,981	83,909
2074	5,407,390	4,770,131	637,259	4,131,937	536,683	610,593	1,275,453	100,576
2075	5,416,333	4,780,482	635,851	4,132,784	536,683	690,025	1,283,549	99,168
2076	5,437,288	4,779,429	657,858	4,152,616	536,683	581,950	1,284,672	121,176
2077	5,443,776	4,787,899	655,877	4,156,305	536,683	668,224	1,287,471	119,194
2078	5,411,450	4,796,079	615,371	4,163,685	536,683	672,120	1,247,765	78,688
2079	5,420,258	4,802,319	617,939	4,168,110	536,683	658,739	1,252,148	81,257
2080	5,428,888	4,807,164	621,724	4,174,356	536,683	648,262	1,254,531	85,041
2081	5,431,484	4,816,511	614,973	4,172,953	536,683	696,182	1,258,531	78,290
2082	5,449,662	4,810,948	638,714	4,194,708	536,683	558,094	1,254,954	102,031
2083	5,450,633	4,808,257	642,376	4,225,263	536,683	528,341	1,225,370	105,693
2084	5,456,386	4,821,231	635,155	4,232,354	536,683	649,689	1,224,032	98,472
2085	5,456,612	4,834,777	621,835	4,232,497	536,683	682,363	1,224,115	85,153
2086	5,456,148	4,845,205	610,943	4,232,840	536,683	679,274	1,223,309	74,261
2087	5,457,677	4,852,698	604,979	4,236,710	536,683	664,580	1,220,967	68,296
2088	5,447,559	4,860,270	587,289	4,239,243	536,683	683,700	1,208,316	50,607
2089	5,456,054	4,860,027	596,027	4,248,797	536,683	615,026	1,207,258	59,344
2090	5,456,928	4,865,128	591,800	4,249,405	536,683	660,630	1,207,523	55,118
2091	5,469,878	4,862,752	607,125	4,266,495	536,683	573,799	1,203,383	70,443
2092	5,466,412	4,874,941	591,471	4,260,899	536,683	699,614	1,205,513	54,788
2093	5,472,722	4,872,230	600,492	4,277,552	536,683	575,502	1,195,170	63,810
2094	5,473,990	4,878,070	595,921	4,279,746	536,683	643,649	1,194,244	59,238
2095	5,473,321	4,887,619	585,703	4,279,002	536,683	679,302	1,194,320	49,020
2096	5,475,399	4,892,688	582,711	4,281,429	536,683	654,172	1,193,969	46,028
2097	5,481,173	4,894,648	586,526	4,289,432	536,683	624,806	1,191,741	49,843
2098	5,475,938	4,901,823	574,115	4,288,477	536,683	678,553	1,187,461	37,432
2099	5,483,874	4,901,014	582,859	4,298,233	536,683	606,312	1,185,641	46,177
2100	5,477,712	4,908,977	568,735	4,291,513	536,683	696,445	1,186,199	32,052
2101	5,490,539	4,902,049	588,490	4,309,236	536,683	552,361	1,181,303	51,808
2102	5,509,424	4,897,784	611,641	4,331,659	536,683	529,429	1,177,766	74,958
2103	5,515,001	4,903,827	611,174	4,342,684	536,683	598,013	1,172,317	74,491
2104	5,504,361	4,919,981	584,380	4,333,678	536,683	705,318	1,170,683	47,698
2105	5,493,696	4,928,899	564,797	4,323,118	536,683	697,364	1,170,578	28,114
2106	5,512,082	4,921,019	591,064	4,343,913	536,683	529,606	1,168,170	54,381
2107	5,518,525	4,924,179	594,346	4,354,446	536,683	597,042	1,164,079	57,663
2108	5,514,389	4,937,396	576,993	4,348,268	536,683	696,076	1,166,121	40,310
2109	5,502,051	4,949,899	552,152	4,336,293	536,683	734,413	1,165,758	15,469
2110	5,483,847	4,959,619	524,228	4,319,649	536,683	757,890	1,164,197	-12,455
Eastern Region								
2011	4,359,558	3,854,578	504,980	3,457,137	195,529	291,256	902,421	309,451
2012	4,397,744	3,857,949	539,795	3,471,951	224,567	323,313	925,792	315,228
2013	4,347,202	3,862,653	484,549	3,496,721	217,749	324,092	850,481	266,801
2014	4,380,237	3,866,308	513,929	3,509,781	216,719	315,938	870,455	297,209

Year	NPP	Rh	NEP	Litterfall	Harvest	Bio2DOM	Net Growth	NBP
2015	4,411,862	3,870,881	540,981	3,522,328	220,157	321,642	889,534	320,824
2016	4,444,923	3,874,930	569,993	3,536,724	214,944	310,957	908,199	355,049
2017	4,480,605	3,880,024	600,581	3,549,479	218,827	318,940	931,126	381,755
2018	4,432,749	3,884,313	548,437	3,576,039	217,679	298,184	856,710	330,757
2019	4,460,805	3,891,566	569,239	3,588,966	217,666	314,715	871,840	351,574
2020	4,487,252	3,896,480	590,772	3,601,092	217,854	302,671	886,160	372,918
2021	4,510,860	3,903,711	607,148	3,613,893	217,394	310,106	896,967	389,754
2022	4,532,506	3,909,398	623,108	3,625,247	217,884	305,359	907,259	405,224
2023	4,494,822	3,918,223	576,599	3,648,031	217,695	319,339	846,791	358,903
2024	4,518,768	3,923,359	595,409	3,659,886	217,699	294,371	858,882	377,710
2025	4,534,658	3,929,625	605,033	3,668,436	217,705	305,050	866,222	387,328
2026	4,543,558	3,938,385	605,172	3,675,751	217,676	323,479	867,807	387,497
2027	4,563,444	3,944,268	619,176	3,684,813	217,731	307,196	878,630	401,445
2028	4,524,128	3,949,559	574,569	3,706,528	217,701	294,418	817,599	356,869
2029	4,539,925	3,955,582	584,343	3,713,385	217,702	303,019	826,539	366,641
2030	4,554,830	3,964,077	590,753	3,719,445	217,703	323,139	835,385	373,050
2031	4,570,232	3,972,069	598,163	3,726,247	217,703	322,634	843,985	380,460
2032	4,586,148	3,977,180	608,968	3,736,220	217,709	301,270	849,928	391,260
2033	4,547,968	3,979,867	568,100	3,756,953	217,704	280,533	791,014	350,396
2034	4,563,155	3,984,472	578,683	3,764,855	217,704	287,608	798,300	360,979
2035	4,577,673	3,990,345	587,328	3,770,589	217,704	298,785	807,084	369,624
2036	4,590,655	4,000,235	590,419	3,774,071	217,704	331,835	816,584	372,715
2037	4,604,464	4,007,281	597,184	3,779,754	217,705	318,010	824,711	379,479
2038	4,549,870	4,012,198	537,671	3,795,604	217,704	302,788	754,266	319,967
2039	4,564,080	4,018,157	545,923	3,800,997	217,704	307,015	763,084	328,219
2040	4,579,995	4,024,172	555,823	3,808,085	217,704	305,411	771,911	338,119
2041	4,592,762	4,030,993	561,770	3,812,614	217,704	317,575	780,148	344,065
2042	4,607,679	4,035,108	572,571	3,820,752	217,704	295,273	786,927	354,867
2043	4,539,998	4,041,908	498,090	3,833,447	217,704	318,211	706,551	280,386
2044	4,551,407	4,047,859	503,549	3,836,968	217,704	312,807	714,439	285,844
2045	4,563,599	4,052,758	510,841	3,840,131	217,704	310,644	723,469	293,136
2046	4,577,085	4,055,754	521,331	3,845,014	217,704	296,437	732,071	303,627
2047	4,590,624	4,059,982	530,643	3,849,909	217,704	300,882	740,715	312,938
2048	4,522,282	4,064,802	457,480	3,861,486	217,704	304,011	660,796	239,775
2049	4,531,801	4,068,702	463,099	3,862,191	217,704	304,948	669,610	245,395
2050	4,541,042	4,073,861	467,181	3,862,380	217,704	316,705	678,662	249,477
2051	4,549,267	4,077,392	471,875	3,862,147	217,704	313,718	687,120	254,171
2052	4,559,885	4,083,052	476,833	3,864,053	217,704	323,148	695,831	259,129
2053	4,501,262	4,086,935	414,326	3,874,012	217,704	310,403	627,249	196,622
2054	4,511,834	4,090,391	421,444	3,876,537	217,704	306,393	635,297	203,739
2055	4,524,855	4,090,645	434,210	3,881,992	217,704	282,292	642,863	216,506
2056	4,536,628	4,090,236	446,391	3,886,583	217,704	273,758	650,045	228,687
2057	4,547,725	4,092,592	455,134	3,889,888	217,704	286,690	657,838	237,430
2058	4,492,481	4,095,711	396,770	3,899,471	217,704	290,170	593,010	179,066
2059	4,498,385	4,101,403	396,983	3,897,409	217,704	314,231	600,976	179,278
2060	4,502,920	4,107,426	395,494	3,893,069	217,704	331,413	609,851	177,789
2061	4,509,626	4,112,248	397,378	3,891,945	217,704	325,374	617,681	179,674
2062	4,518,004	4,114,447	403,556	3,892,550	217,704	310,161	625,454	185,852
2063	4,462,696	4,116,638	346,057	3,900,087	217,704	307,974	562,609	128,353
2064	4,470,437	4,117,969	352,469	3,900,522	217,704	300,632	569,916	134,764
2065	4,475,923	4,120,912	355,012	3,897,933	217,704	318,223	577,990	137,307
2066	4,480,567	4,123,432	357,135	3,895,474	217,704	320,248	585,093	139,431
2067	4,487,812	4,126,883	360,929	3,895,509	217,704	322,363	592,302	143,225
2068	4,419,181	4,129,194	289,987	3,903,145	217,704	314,451	516,036	72,283
2069	4,427,122	4,128,633	298,489	3,904,214	217,704	293,562	522,908	80,785
2070	4,435,219	4,126,075	309,144	3,905,835	217,704	277,349	529,383	91,439
2071	4,438,840	4,127,742	311,098	3,903,984	217,704	304,574	534,855	93,394
2072	4,438,617	4,133,783	304,834	3,897,528	217,704	346,512	541,089	87,130
2073	4,413,254	4,133,367	279,886	3,905,283	217,704	299,560	507,970	62,182
2074	4,416,523	4,135,086	281,437	3,902,828	217,704	314,846	513,695	63,733
2075	4,421,500	4,135,197	286,303	3,901,944	217,704	303,232	519,556	68,599

Year	NPP	Rh	NEP	Litterfall	Harvest	Bio2DOM	Net Growth	NBP
2076	4,426,848	4,134,578	292,270	3,902,526	217,704	294,171	524,322	74,566
2077	4,429,593	4,137,612	291,981	3,899,086	217,704	324,283	530,507	74,277
2078	4,409,194	4,139,509	269,685	3,904,039	217,704	317,536	505,155	51,981
2079	4,413,410	4,142,616	270,794	3,901,814	217,704	325,952	511,596	53,090
2080	4,419,948	4,140,381	279,567	3,902,887	217,704	290,711	517,061	61,863
2081	4,420,770	4,140,590	280,180	3,900,517	217,704	309,293	520,253	62,476
2082	4,420,837	4,144,900	275,937	3,895,191	217,704	342,553	525,646	58,233
2083	4,408,965	4,144,323	264,642	3,899,223	217,704	311,108	509,742	46,938
2084	4,413,516	4,144,527	268,989	3,897,913	217,704	312,002	515,603	51,285
2085	4,418,627	4,142,555	276,072	3,898,930	217,704	292,903	519,697	58,368
2086	4,417,087	4,144,822	272,265	3,894,221	217,704	329,790	522,866	54,560
2087	4,420,099	4,145,997	274,102	3,894,256	217,704	316,285	525,843	56,398
2088	4,412,937	4,148,225	264,712	3,898,245	217,704	322,397	514,692	47,008
2089	4,417,290	4,144,935	272,355	3,898,761	217,704	289,164	518,529	54,651
2090	4,415,623	4,148,221	267,402	3,892,749	217,704	339,649	522,874	49,698
2091	4,416,630	4,149,089	267,541	3,891,002	217,704	323,390	525,628	49,836
2092	4,419,035	4,148,371	270,664	3,890,467	217,704	311,230	528,568	52,960
2093	4,415,954	4,146,561	269,392	3,894,275	217,704	298,696	521,679	51,688
2094	4,413,882	4,150,449	263,433	3,887,135	217,704	349,917	526,747	45,729
2095	4,414,992	4,153,902	261,090	3,884,046	217,704	346,834	530,945	43,386
2096	4,417,476	4,150,910	266,566	3,884,336	217,704	305,692	533,141	48,862
2097	4,414,760	4,153,247	261,512	3,878,403	217,704	349,471	536,357	43,808
2098	4,410,124	4,152,916	257,209	3,878,082	217,704	329,982	532,043	39,505
2099	4,414,908	4,148,014	266,894	3,880,623	217,704	289,314	534,285	49,190
2100	4,413,710	4,149,915	263,796	3,877,303	217,704	335,961	536,407	46,091
2101	4,415,007	4,150,621	264,386	3,876,865	217,704	325,436	538,141	46,682
2102	4,417,633	4,148,745	268,888	3,877,799	217,704	307,510	539,833	51,183
2103	4,411,269	4,149,916	261,353	3,874,694	217,704	334,519	536,575	43,649
2104	4,410,918	4,150,956	259,962	3,871,740	217,704	334,924	539,178	42,257
2105	4,415,235	4,149,624	265,611	3,872,633	217,704	313,680	542,603	47,907
2106	4,416,059	4,151,609	264,450	3,871,017	217,704	338,818	545,042	46,745
2107	4,415,530	4,152,615	262,915	3,868,929	217,704	337,311	546,601	45,210
2108	4,408,869	4,154,260	254,609	3,865,088	217,704	349,392	543,781	36,905
2109	4,409,675	4,154,128	255,548	3,862,990	217,704	337,930	546,685	37,843
2110	4,420,130	4,148,429	271,701	3,872,287	217,704	274,181	547,844	53,997
Western Region								
2011	5,205,073	4,517,145	687,929	4,442,704	326,531	423,126	762,370	361,397
2012	5,209,640	4,545,970	663,669	4,437,852	305,080	399,581	771,788	358,589
2013	5,101,278	4,568,652	532,626	4,442,154	298,492	392,489	659,125	234,134
2014	5,104,841	4,585,651	519,190	4,433,880	292,910	389,691	670,962	226,280
2015	5,108,002	4,601,115	506,887	4,425,871	304,466	406,728	682,131	202,421
2016	5,113,102	4,612,715	500,386	4,419,930	305,495	399,501	693,171	194,891
2017	5,117,677	4,622,405	495,273	4,413,512	301,289	402,751	704,165	193,984
2018	5,024,542	4,629,738	394,804	4,418,301	300,531	396,210	606,241	94,273
2019	5,027,574	4,636,453	391,121	4,408,645	300,938	408,022	618,929	90,183
2020	5,031,418	4,640,460	390,957	4,401,387	302,543	398,312	630,031	88,414
2021	5,036,822	4,643,317	393,505	4,394,788	302,159	396,630	642,034	91,346
2022	5,041,974	4,646,046	395,927	4,388,867	301,492	398,102	653,106	94,435
2023	4,968,468	4,646,665	321,803	4,397,263	301,533	380,130	571,205	20,271
2024	4,973,942	4,646,993	326,949	4,390,389	301,733	383,652	583,553	25,216
2025	4,972,817	4,647,650	325,168	4,382,455	301,891	390,992	590,362	23,276
2026	4,975,589	4,648,196	327,393	4,375,695	301,762	392,121	599,894	25,631
2027	4,973,550	4,650,198	323,352	4,364,602	301,682	415,943	608,947	21,670
2028	4,911,184	4,651,342	259,842	4,366,836	301,720	416,221	544,348	-41,878
2029	4,914,257	4,648,976	265,281	4,358,993	301,758	392,921	555,264	-36,477
2030	4,913,939	4,647,961	265,978	4,350,307	301,763	403,564	563,632	-35,786
2031	4,916,175	4,644,398	271,777	4,342,063	301,737	391,443	574,113	-29,960
2032	4,912,703	4,640,178	272,525	4,332,571	301,732	390,549	580,132	-29,207
2033	4,873,306	4,638,014	235,292	4,338,246	301,742	394,153	535,060	-66,450
2034	4,877,520	4,636,010	241,511	4,330,772	301,746	394,544	546,749	-60,235
2035	4,883,197	4,633,461	249,735	4,325,416	301,744	388,043	557,781	-52,009

Year	NPP	Rh	NEP	Litterfall	Harvest	Bio2DOM	Net Growth	NBP
2036	4,885,140	4,632,944	252,196	4,315,304	301,741	413,609	569,836	-49,545
2037	4,886,939	4,631,368	255,571	4,305,478	301,741	413,566	581,461	-46,169
2038	4,849,983	4,629,127	220,856	4,309,544	301,743	407,418	540,439	-80,887
2039	4,855,909	4,624,397	231,512	4,303,652	301,743	386,055	552,257	-70,231
2040	4,860,836	4,621,622	239,214	4,298,577	301,742	391,568	562,260	-62,527
2041	4,866,302	4,617,831	248,472	4,293,597	301,742	386,081	572,705	-53,270
2042	4,870,603	4,614,590	256,013	4,287,018	301,742	391,432	583,584	-45,729
2043	4,833,478	4,612,332	221,146	4,289,313	301,742	400,197	544,165	-80,596
2044	4,837,200	4,610,285	226,915	4,281,667	301,742	399,879	555,533	-74,827
2045	4,844,099	4,606,644	237,454	4,277,447	301,742	384,239	566,652	-64,288
2046	4,851,331	4,603,699	247,632	4,272,262	301,742	388,098	579,069	-54,110
2047	4,854,930	4,603,957	250,972	4,263,867	301,742	416,195	591,063	-50,770
2048	4,822,159	4,601,115	221,044	4,269,550	301,742	389,841	552,610	-80,698
2049	4,829,761	4,597,442	232,319	4,265,926	301,742	381,017	563,835	-69,423
2050	4,837,128	4,594,718	242,410	4,262,442	301,742	382,599	574,687	-59,332
2051	4,845,452	4,591,925	253,527	4,262,419	301,742	371,868	583,033	-48,215
2052	4,850,940	4,590,258	260,682	4,257,122	301,742	389,803	593,819	-41,060
2053	4,817,189	4,588,587	228,602	4,259,590	301,742	387,623	557,599	-73,140
2054	4,821,166	4,586,726	234,440	4,252,723	301,742	389,649	568,443	-67,302
2055	4,825,699	4,585,636	240,062	4,247,872	301,742	391,953	577,827	-61,679
2056	4,828,049	4,583,689	244,360	4,241,113	301,742	394,160	586,936	-57,381
2057	4,831,642	4,581,711	249,931	4,235,545	301,742	393,305	596,097	-51,811
2058	4,802,773	4,579,067	223,705	4,242,660	301,742	374,287	560,113	-78,037
2059	4,806,587	4,577,089	229,498	4,236,642	301,742	387,578	569,945	-72,244
2060	4,811,563	4,575,061	236,501	4,231,194	301,742	387,064	580,369	-65,240
2061	4,811,167	4,577,427	233,740	4,221,019	301,742	428,239	590,148	-68,002
2062	4,807,823	4,577,057	230,766	4,209,311	301,742	427,279	598,512	-70,976
2063	4,777,011	4,575,942	201,069	4,208,024	301,742	420,157	568,987	-100,673
2064	4,778,882	4,573,091	205,791	4,199,764	301,742	413,531	579,118	-95,951
2065	4,785,507	4,568,037	217,470	4,197,259	301,742	387,808	588,248	-84,272
2066	4,789,238	4,564,531	224,707	4,192,766	301,742	396,379	596,472	-77,035
2067	4,795,646	4,560,506	235,140	4,191,383	301,742	384,000	604,264	-66,602
2068	4,762,801	4,557,331	205,470	4,190,553	301,742	394,219	572,248	-96,272
2069	4,764,347	4,554,294	210,052	4,183,123	301,742	397,393	581,224	-91,689
2070	4,768,770	4,552,501	216,269	4,179,332	301,742	398,008	589,438	-85,472
2071	4,769,984	4,548,621	221,362	4,173,434	301,742	392,043	596,549	-80,379
2072	4,773,391	4,545,504	227,888	4,169,864	301,742	389,239	603,527	-73,854
2073	4,753,803	4,544,081	209,722	4,169,310	301,742	400,334	584,493	-92,020
2074	4,754,916	4,542,168	212,748	4,164,185	301,742	399,109	590,731	-88,994
2075	4,757,551	4,539,372	218,179	4,159,381	301,742	394,911	598,170	-83,563
2076	4,755,593	4,539,402	216,191	4,149,983	301,742	423,903	605,610	-85,551
2077	4,755,277	4,536,693	218,583	4,142,497	301,742	410,670	612,780	-83,159
2078	4,734,974	4,537,919	197,055	4,132,411	301,742	452,060	602,563	-104,687
2079	4,732,865	4,535,831	197,034	4,122,027	301,742	436,957	610,838	-104,708
2080	4,736,445	4,531,453	204,992	4,117,725	301,742	413,673	618,720	-96,750
2081	4,738,865	4,527,317	211,548	4,112,083	301,742	415,794	626,782	-90,194
2082	4,742,735	4,521,885	220,850	4,109,288	301,742	399,648	633,448	-80,891
2083	4,740,058	4,517,318	222,740	4,112,593	301,742	392,315	627,465	-79,001
2084	4,741,944	4,513,419	228,525	4,107,658	301,742	401,961	634,286	-73,217
2085	4,745,659	4,509,956	235,703	4,104,353	301,742	399,005	641,307	-66,038
2086	4,746,707	4,509,275	237,432	4,098,740	301,742	421,399	647,968	-64,310
2087	4,748,710	4,506,058	242,652	4,095,699	301,742	403,403	653,011	-59,090
2088	4,746,116	4,503,130	242,986	4,095,764	301,742	400,549	650,352	-58,756
2089	4,749,569	4,500,569	249,000	4,092,784	301,742	402,241	656,784	-52,742
2090	4,747,358	4,502,796	244,562	4,084,027	301,742	447,040	663,331	-57,180
2091	4,753,583	4,497,779	255,804	4,084,250	301,742	390,009	669,333	-45,938
2092	4,748,126	4,499,548	248,578	4,072,268	301,742	456,693	675,859	-53,164
2093	4,744,189	4,499,495	244,694	4,068,607	301,742	443,385	675,582	-57,048
2094	4,745,608	4,496,406	249,203	4,063,302	301,742	428,315	682,306	-52,539
2095	4,751,505	4,491,073	260,432	4,063,407	301,742	400,625	688,098	-41,310
2096	4,755,498	4,489,167	266,332	4,061,435	301,742	419,463	694,063	-35,410

Year	NPP	Rh	NEP	Litterfall	Harvest	Bio2DOM	Net Growth	NBP
2097	4,756,992	4,485,470	271,522	4,058,352	301,742	411,487	698,640	-30,220
2098	4,754,281	4,483,765	270,517	4,057,079	301,742	420,232	697,202	-31,225
2099	4,757,297	4,480,855	276,442	4,054,792	301,742	411,780	702,505	-25,300
2100	4,761,383	4,477,880	283,503	4,054,904	301,742	402,942	706,480	-18,238
2101	4,761,249	4,477,621	283,628	4,050,686	301,742	427,408	710,563	-18,114
2102	4,763,073	4,475,062	288,011	4,050,677	301,742	406,385	712,397	-13,731
2103	4,754,899	4,479,353	275,546	4,041,908	301,742	470,672	712,992	-26,196
2104	4,753,873	4,479,507	274,366	4,036,965	301,742	448,900	716,908	-27,376
2105	4,761,152	4,474,664	286,488	4,039,646	301,742	401,816	721,506	-15,254
2106	4,763,932	4,473,398	290,534	4,039,251	301,742	423,611	724,681	-11,208
2107	4,765,522	4,470,351	295,171	4,037,988	301,742	414,663	727,534	-6,570
2108	4,765,229	4,469,652	295,577	4,037,938	301,742	424,749	727,291	-6,165
2109	4,769,089	4,467,411	301,678	4,038,390	301,742	411,636	730,699	-64
2110	4,776,038	4,464,206	311,832	4,042,137	301,742	393,316	733,902	10,091

B4. Life Cycle GHG Emissions for the Reference Case Business as Usual Harvesting

Table B5. BAU forest carbon emissions data for all three regions of Nova Scotia combined, and life cycle GHG emissions for residential space heating with conventional oil furnaces. Results expressed in tonnes of CO_2 equivalents.

Year	C_{atm} (BAU)	NEP_{bau}	FP_{dec}	LCE_{fos}	Cumulative C_{atm} (BAU)
2011	-3,643,779	-5,525,592	1,784,704	97,110	-3,643,779
2012	-3,416,479	-5,596,227	2,082,639	97,110	-7,060,257
2013	-2,525,367	-4,648,201	2,025,724	97,110	-9,585,624
2014	-2,757,549	-4,840,932	1,986,273	97,110	-12,343,174
2015	-2,900,253	-5,004,558	2,007,195	97,110	-15,243,427
2016	-3,121,460	-5,216,253	1,997,683	97,110	-18,364,887
2017	-3,297,651	-5,435,573	2,040,812	97,110	-21,662,538
2018	-2,595,130	-4,725,387	2,033,146	97,110	-24,257,669
2019	-2,808,684	-4,937,853	2,032,059	97,110	-27,066,353
2020	-3,010,575	-5,149,299	2,041,614	97,110	-30,076,928
2021	-3,199,451	-5,344,704	2,048,143	97,110	-33,276,379
2022	-3,368,151	-5,524,494	2,059,233	97,110	-36,644,530
2023	-2,805,286	-4,966,533	2,064,137	97,110	-39,449,816
2024	-3,010,041	-5,175,201	2,068,050	97,110	-42,459,857
2025	-3,133,256	-5,306,122	2,075,756	97,110	-45,593,113
2026	-3,214,218	-5,393,571	2,082,243	97,110	-48,807,332
2027	-3,329,863	-5,516,999	2,090,026	97,110	-52,137,195
2028	-2,796,111	-4,988,869	2,095,648	97,110	-54,933,306
2029	-2,954,461	-5,153,014	2,101,443	97,110	-57,887,767
2030	-3,068,988	-5,273,386	2,107,288	97,110	-60,956,755
2031	-3,162,355	-5,374,400	2,114,935	97,110	-64,119,110
2032	-3,229,550	-5,449,409	2,122,750	97,110	-67,348,660
2033	-2,803,908	-5,031,514	2,130,496	97,110	-70,152,568
2034	-2,923,539	-5,155,506	2,134,857	97,110	-73,076,107
2035	-3,075,990	-5,315,187	2,142,087	97,110	-76,152,097
2036	-3,193,633	-5,440,699	2,149,956	97,110	-79,345,730
2037	-3,234,514	-5,489,427	2,157,803	97,110	-82,580,244
2038	-2,698,284	-4,960,918	2,165,523	97,110	-85,278,528
2039	-2,848,395	-5,117,085	2,171,580	97,110	-88,126,924
2040	-2,994,316	-5,272,127	2,180,702	97,110	-91,121,239
2041	-3,145,723	-5,429,944	2,187,110	97,110	-94,266,963
2042	-3,300,496	-5,592,173	2,194,567	97,110	-97,567,458
2043	-2,662,668	-4,962,098	2,202,319	97,110	-100,230,126
2044	-2,791,793	-5,097,326	2,208,422	97,110	-103,021,920
2045	-2,911,553	-5,224,480	2,215,818	97,110	-105,933,472
2046	-3,042,643	-5,363,456	2,223,703	97,110	-108,976,115
2047	-3,166,611	-5,495,176	2,231,455	97,110	-112,142,726
2048	-2,445,130	-4,781,441	2,239,201	97,110	-114,587,856
2049	-2,591,113	-4,935,257	2,247,034	97,110	-117,178,969
2050	-2,735,281	-5,087,122	2,254,731	97,110	-119,914,251
2051	-2,856,752	-5,216,360	2,262,498	97,110	-122,771,002
2052	-2,942,481	-5,309,838	2,270,248	97,110	-125,713,483
2053	-2,211,028	-4,586,142	2,278,004	97,110	-127,924,511
2054	-2,343,696	-4,726,624	2,285,817	97,110	-130,268,207
2055	-2,476,560	-4,867,218	2,293,548	97,110	-132,744,768
2056	-2,592,961	-4,991,367	2,301,296	97,110	-135,337,728
2057	-2,701,705	-5,107,862	2,309,047	97,110	-138,039,433
2058	-2,056,248	-4,471,822	2,318,465	97,110	-140,095,681
2059	-2,122,933	-4,544,902	2,324,859	97,110	-142,218,615
2060	-2,184,225	-4,615,281	2,333,946	97,110	-144,402,840

Year	C_{atm} (BAU)	NEP_{bau}	FP_{dec}	LCE_{fos}	Cumulative C_{atm} (BAU)
2061	-2,229,730	-4,668,795	2,341,955	97,110	-146,632,570
2062	-2,306,829	-4,753,640	2,349,701	97,110	-148,939,399
2063	-1,725,007	-4,181,283	2,359,166	97,110	-150,664,405
2064	-1,849,063	-4,311,703	2,365,531	97,110	-152,513,468
2065	-1,953,108	-4,424,867	2,374,649	97,110	-154,466,576
2066	-2,046,041	-4,525,879	2,382,728	97,110	-156,512,617
2067	-2,194,980	-4,684,216	2,392,126	97,110	-158,707,596
2068	-1,550,412	-4,047,565	2,400,042	97,110	-160,258,008
2069	-1,665,803	-4,170,891	2,407,978	97,110	-161,923,811
2070	-1,780,198	-4,292,942	2,415,634	97,110	-163,704,009
2071	-1,842,046	-4,364,140	2,424,984	97,110	-165,546,055
2072	-1,931,255	-4,462,946	2,434,581	97,110	-167,477,310
2073	-1,534,790	-4,074,436	2,442,535	97,110	-169,012,100
2074	-1,603,337	-4,152,400	2,451,953	97,110	-170,615,437
2075	-1,627,966	-4,185,021	2,459,946	97,110	-172,243,403
2076	-1,714,093	-4,280,392	2,469,189	97,110	-173,957,496
2077	-1,704,953	-4,280,838	2,478,775	97,110	-175,662,449
2078	-1,387,498	-3,971,347	2,486,738	97,110	-177,049,948
2079	-1,393,249	-3,984,768	2,494,410	97,110	-178,443,196
2080	-1,460,793	-4,060,058	2,502,155	97,110	-179,903,989
2081	-1,452,924	-4,061,594	2,511,560	97,110	-181,356,914
2082	-1,548,957	-4,167,288	2,521,221	97,110	-182,905,871
2083	-1,518,273	-4,146,215	2,530,832	97,110	-184,424,143
2084	-1,522,688	-4,156,895	2,537,097	97,110	-185,946,831
2085	-1,517,078	-4,160,351	2,546,162	97,110	-187,463,910
2086	-1,459,799	-4,112,749	2,555,840	97,110	-188,923,709
2087	-1,454,145	-4,116,762	2,565,507	97,110	-190,377,853
2088	-1,346,451	-4,018,604	2,575,043	97,110	-191,724,304
2089	-1,420,595	-4,100,790	2,583,085	97,110	-193,144,899
2090	-1,361,323	-4,050,814	2,592,382	97,110	-194,506,221
2091	-1,449,675	-4,148,823	2,602,038	97,110	-195,955,896
2092	-1,367,552	-4,076,318	2,611,656	97,110	-197,323,448
2093	-1,372,199	-4,090,504	2,621,195	97,110	-198,695,648
2094	-1,342,128	-4,068,404	2,629,166	97,110	-200,037,776
2095	-1,327,959	-4,063,515	2,638,447	97,110	-201,365,734
2096	-1,349,081	-4,094,281	2,648,090	97,110	-202,714,816
2097	-1,353,976	-4,108,787	2,657,701	97,110	-204,068,792
2098	-1,279,395	-4,043,754	2,667,248	97,110	-205,348,187
2099	-1,359,083	-4,133,138	2,676,946	97,110	-206,707,270
2100	-1,312,225	-4,095,844	2,686,510	97,110	-208,019,495
2101	-1,377,771	-4,170,971	2,696,090	97,110	-209,397,265
2102	-1,485,773	-4,288,540	2,705,657	97,110	-210,883,038
2103	-1,401,100	-4,213,428	2,715,218	97,110	-212,284,138
2104	-1,283,709	-4,105,657	2,724,839	97,110	-213,567,847
2105	-1,267,507	-4,099,008	2,734,391	97,110	-214,835,354
2106	-1,364,930	-4,205,993	2,743,952	97,110	-216,200,284
2107	-1,382,300	-4,229,425	2,750,015	97,110	-217,582,584
2108	-1,284,113	-4,136,747	2,755,524	97,110	-218,866,696
2109	-1,213,025	-4,071,414	2,761,279	97,110	-220,079,721
2110	-1,201,344	-4,065,486	2,767,031	97,110	-221,281,065

B5. Forest Carbon Simulation Results for Pellet Heat Pathway 1

Forest carbon simulation data for wood pellets made from 100% residues are equivalent to the BAU since there is no incremental harvesting. See Table B4 in Appendix B4.

B6. Life Cycle GHG Emissions for Pellet Heat Pathway 1

Table B6: Life cycle GHG emissions for Pellet Heat Pathway 1, including forest carbon emissions data and life cycle emissions for wood pellet production for residential space heating with wood pellets made from 100% residues. Results are expressed in tonnes of CO_2 equivalents and includes forest carbon simulation results for all three regions of Nova Scotia.

Year	C_{atm} (pellets)	NEP_{bau}	FP_{dec}	LCE_{pel}	C_{atm} (pellets) (Relative to BAU)	C_{atm} (pellets) Cumulative (Relative to BAU)
2011	-3,720,226	-5,525,592	1,784,704	21,930	-75,180	-75,180
2012	-3,492,926	-5,596,227	2,082,639	21,930	-75,180	-150,360
2013	-2,601,814	-4,648,201	2,025,724	21,930	-75,180	-225,540
2014	-2,833,996	-4,840,932	1,986,273	21,930	-75,180	-300,720
2015	-2,976,700	-5,004,558	2,007,195	21,930	-75,180	-375,900
2016	-3,197,907	-5,216,253	1,997,683	21,930	-75,180	-451,080
2017	-3,374,098	-5,435,573	2,040,812	21,930	-75,180	-526,260
2018	-2,671,577	-4,725,387	2,033,146	21,930	-75,180	-601,440
2019	-2,885,131	-4,937,853	2,032,059	21,930	-75,180	-676,620
2020	-3,087,022	-5,149,299	2,041,614	21,930	-75,180	-751,800
2021	-3,275,898	-5,344,704	2,048,143	21,930	-75,180	-826,980
2022	-3,444,598	-5,524,494	2,059,233	21,930	-75,180	-902,160
2023	-2,881,733	-4,966,533	2,064,137	21,930	-75,180	-977,340
2024	-3,086,488	-5,175,201	2,068,050	21,930	-75,180	-1,052,520
2025	-3,209,703	-5,306,122	2,075,756	21,930	-75,180	-1,127,700
2026	-3,290,665	-5,393,571	2,082,243	21,930	-75,180	-1,202,880
2027	-3,406,310	-5,516,999	2,090,026	21,930	-75,180	-1,278,060
2028	-2,872,558	-4,988,869	2,095,648	21,930	-75,180	-1,353,240
2029	-3,030,908	-5,153,014	2,101,443	21,930	-75,180	-1,428,420
2030	-3,145,435	-5,273,386	2,107,288	21,930	-75,180	-1,503,600
2031	-3,238,802	-5,374,400	2,114,935	21,930	-75,180	-1,578,780
2032	-3,305,997	-5,449,409	2,122,750	21,930	-75,180	-1,653,960
2033	-2,880,355	-5,031,514	2,130,496	21,930	-75,180	-1,729,140
2034	-2,999,986	-5,155,506	2,134,857	21,930	-75,180	-1,804,320
2035	-3,152,437	-5,315,187	2,142,087	21,930	-75,180	-1,879,500
2036	-3,270,080	-5,440,699	2,149,956	21,930	-75,180	-1,954,680
2037	-3,310,961	-5,489,427	2,157,803	21,930	-75,180	-2,029,860
2038	-2,774,731	-4,960,918	2,165,523	21,930	-75,180	-2,105,040
2039	-2,924,842	-5,117,085	2,171,580	21,930	-75,180	-2,180,220
2040	-3,070,763	-5,272,127	2,180,702	21,930	-75,180	-2,255,400
2041	-3,222,170	-5,429,944	2,187,110	21,930	-75,180	-2,330,580
2042	-3,376,943	-5,592,173	2,194,567	21,930	-75,180	-2,405,760
2043	-2,739,115	-4,962,098	2,202,319	21,930	-75,180	-2,480,940
2044	-2,868,240	-5,097,326	2,208,422	21,930	-75,180	-2,556,120
2045	-2,988,000	-5,224,480	2,215,818	21,930	-75,180	-2,631,300
2046	-3,119,090	-5,363,456	2,223,703	21,930	-75,180	-2,706,480
2047	-3,243,058	-5,495,176	2,231,455	21,930	-75,180	-2,781,660
2048	-2,521,577	-4,781,441	2,239,201	21,930	-75,180	-2,856,840
2049	-2,667,560	-4,935,257	2,247,034	21,930	-75,180	-2,932,020

Year	C_{atm} (pellets)	NEP_{bau}	FP_{dec}	LCE_{pel}	C_{atm} (pellets) (Relative to BAU)	C_{atm} (pellets) Cumulative (Relative to BAU)
2050	-2,811,728	-5,087,122	2,254,731	21,930	-75,180	-3,007,200
2051	-2,933,199	-5,216,360	2,262,498	21,930	-75,180	-3,082,380
2052	-3,018,928	-5,309,838	2,270,248	21,930	-75,180	-3,157,560
2053	-2,287,475	-4,586,142	2,278,004	21,930	-75,180	-3,232,740
2054	-2,420,143	-4,726,624	2,285,817	21,930	-75,180	-3,307,920
2055	-2,553,007	-4,867,218	2,293,548	21,930	-75,180	-3,383,100
2056	-2,669,408	-4,991,367	2,301,296	21,930	-75,180	-3,458,280
2057	-2,778,152	-5,107,862	2,309,047	21,930	-75,180	-3,533,460
2058	-2,132,695	-4,471,822	2,318,465	21,930	-75,180	-3,608,640
2059	-2,199,380	-4,544,902	2,324,859	21,930	-75,180	-3,683,820
2060	-2,260,672	-4,615,281	2,333,946	21,930	-75,180	-3,759,000
2061	-2,306,177	-4,668,795	2,341,955	21,930	-75,180	-3,834,180
2062	-2,383,276	-4,753,640	2,349,701	21,930	-75,180	-3,909,360
2063	-1,801,454	-4,181,283	2,359,166	21,930	-75,180	-3,984,540
2064	-1,925,510	-4,311,703	2,365,531	21,930	-75,180	-4,059,720
2065	-2,029,555	-4,424,867	2,374,649	21,930	-75,180	-4,134,900
2066	-2,122,488	-4,525,879	2,382,728	21,930	-75,180	-4,210,080
2067	-2,271,427	-4,684,216	2,392,126	21,930	-75,180	-4,285,260
2068	-1,626,859	-4,047,565	2,400,042	21,930	-75,180	-4,360,440
2069	-1,742,250	-4,170,891	2,407,978	21,930	-75,180	-4,435,620
2070	-1,856,645	-4,292,942	2,415,634	21,930	-75,180	-4,510,800
2071	-1,918,493	-4,364,140	2,424,984	21,930	-75,180	-4,585,980
2072	-2,007,702	-4,462,946	2,434,581	21,930	-75,180	-4,661,160
2073	-1,611,237	-4,074,436	2,442,535	21,930	-75,180	-4,736,340
2074	-1,679,784	-4,152,400	2,451,953	21,930	-75,180	-4,811,520
2075	-1,704,413	-4,185,021	2,459,946	21,930	-75,180	-4,886,700
2076	-1,790,540	-4,280,392	2,469,189	21,930	-75,180	-4,961,880
2077	-1,781,400	-4,280,838	2,478,775	21,930	-75,180	-5,037,060
2078	-1,463,945	-3,971,347	2,486,738	21,930	-75,180	-5,112,240
2079	-1,469,696	-3,984,768	2,494,410	21,930	-75,180	-5,187,420
2080	-1,537,240	-4,060,058	2,502,155	21,930	-75,180	-5,262,600
2081	-1,529,371	-4,061,594	2,511,560	21,930	-75,180	-5,337,780
2082	-1,625,404	-4,167,288	2,521,221	21,930	-75,180	-5,412,960
2083	-1,594,720	-4,146,215	2,530,832	21,930	-75,180	-5,488,140
2084	-1,599,135	-4,156,895	2,537,097	21,930	-75,180	-5,563,320
2085	-1,593,525	-4,160,351	2,546,162	21,930	-75,180	-5,638,500
2086	-1,536,246	-4,112,749	2,555,840	21,930	-75,180	-5,713,680
2087	-1,530,592	-4,116,762	2,565,507	21,930	-75,180	-5,788,860
2088	-1,422,898	-4,018,604	2,575,043	21,930	-75,180	-5,864,040
2089	-1,497,042	-4,100,790	2,583,085	21,930	-75,180	-5,939,220
2090	-1,437,770	-4,050,814	2,592,382	21,930	-75,180	-6,014,400
2091	-1,526,122	-4,148,823	2,602,038	21,930	-75,180	-6,089,580
2092	-1,443,999	-4,076,318	2,611,656	21,930	-75,180	-6,164,760
2093	-1,448,646	-4,090,504	2,621,195	21,930	-75,180	-6,239,940
2094	-1,418,575	-4,068,404	2,629,166	21,930	-75,180	-6,315,120
2095	-1,404,406	-4,063,515	2,638,447	21,930	-75,180	-6,390,300
2096	-1,425,528	-4,094,281	2,648,090	21,930	-75,180	-6,465,480
2097	-1,430,423	-4,108,787	2,657,701	21,930	-75,180	-6,540,660
2098	-1,355,842	-4,043,754	2,667,248	21,930	-75,180	-6,615,840
2099	-1,435,530	-4,133,138	2,676,946	21,930	-75,180	-6,691,020
2100	-1,388,672	-4,095,844	2,686,510	21,930	-75,180	-6,766,200
2101	-1,454,218	-4,170,971	2,696,090	21,930	-75,180	-6,841,380
2102	-1,562,220	-4,288,540	2,705,657	21,930	-75,180	-6,916,560
2103	-1,477,547	-4,213,428	2,715,218	21,930	-75,180	-6,991,740
2104	-1,360,156	-4,105,657	2,724,839	21,930	-75,180	-7,066,920
2105	-1,343,954	-4,099,008	2,734,391	21,930	-75,180	-7,142,100
2106	-1,441,377	-4,205,993	2,743,952	21,930	-75,180	-7,217,280
2107	-1,458,747	-4,229,425	2,750,015	21,930	-75,180	-7,292,460

Year	C_{atm} (pellets)	NEP_{bau}	FP_{dec}	LCE_{pel}	C_{atm} (pellets) (Relative to BAU)	C_{atm} (pellets) Cumulative (Relative to BAU)
2108	-1,360,560	-4,136,747	2,755,524	21,930	-75,180	-7,367,640
2109	-1,289,472	-4,071,414	2,761,279	21,930	-75,180	-7,442,820
2110	-1,277,791	-4,065,486	2,767,031	21,930	-75,180	-7,518,000

B7. Forest Carbon Simulation Data for Pellet Heat Pathway 2

Table B7. Forest carbon simulation results for Pellet Heat Pathway 2, broken down by region of Nova Scotia, expressed in tonnes of carbon.

Legend:
NPP = net primary productivity (Net growth + litterfall); Rh = heterotrophic respiration; NEP = net ecosystem productivity (NPP – Rh); Litterfall = carbon in litter layer on forest floor; Harvest = carbon in harvested wood; Bio2DOM = carbon in dead organic matter; Net Growth = carbon in forest growth; NBP = net biome production (NEP – Harvest)

Year	NPP	Rh	NEP	Litterfall	Harvest	Bio2DOM	Net Growth	NBP
Central Region								
2011	5,124,901	4,813,460	311,441	3,934,885	438,627	621,605	1,190,015	-127,186
2012	5,147,846	4,829,105	318,741	3,924,362	583,929	805,522	1,223,484	-265,188
2013	5,082,861	4,837,214	245,648	3,920,903	562,162	794,873	1,161,958	-316,515
2014	5,114,509	4,833,336	281,173	3,916,097	544,386	729,234	1,198,412	-263,213
2015	5,141,382	4,831,503	309,878	3,908,837	537,114	757,041	1,232,545	-227,236
2016	5,172,103	4,827,899	344,205	3,905,413	533,244	748,903	1,266,690	-189,039
2017	5,199,021	4,822,072	376,950	3,900,639	552,167	750,631	1,298,382	-175,217
2018	5,152,602	4,815,969	336,633	3,908,183	545,815	736,278	1,244,419	-209,182
2019	5,184,641	4,808,408	376,233	3,908,381	542,546	719,867	1,276,260	-166,313
2020	5,214,563	4,802,419	412,143	3,907,032	542,178	729,643	1,307,531	-130,034
2021	5,243,611	4,798,263	445,347	3,907,022	543,190	736,562	1,336,589	-97,842
2022	5,271,179	4,795,290	475,889	3,907,100	545,178	745,208	1,364,079	-69,290
2023	5,234,417	4,789,933	444,484	3,917,391	543,782	721,660	1,317,027	-99,297
2024	5,263,553	4,786,884	476,669	3,915,523	543,375	739,360	1,348,030	-66,706
2025	5,286,167	4,781,607	504,560	3,915,578	543,540	723,498	1,370,589	-38,981
2026	5,306,607	4,782,493	524,114	3,910,461	543,813	772,707	1,396,145	-19,700
2027	5,329,246	4,779,685	549,561	3,909,591	543,938	750,280	1,419,655	5,623
2028	5,288,190	4,774,404	513,786	3,916,797	543,689	731,932	1,371,393	-29,903
2029	5,310,083	4,766,344	543,738	3,917,103	543,671	706,305	1,392,979	67
2030	5,330,383	4,760,806	569,577	3,919,170	543,730	709,208	1,411,213	25,847
2031	5,344,076	4,761,664	582,412	3,914,590	543,768	760,534	1,429,485	38,644
2032	5,354,795	4,762,506	592,289	3,910,834	543,760	767,744	1,443,961	48,530
2033	5,311,991	4,757,011	554,980	3,919,309	543,723	721,648	1,392,682	11,257
2034	5,327,864	4,752,904	574,960	3,917,151	543,730	729,784	1,410,713	31,230
2035	5,349,252	4,748,519	600,733	3,919,000	543,742	717,793	1,430,252	56,991
2036	5,370,849	4,741,618	629,232	3,921,599	543,745	695,827	1,449,250	85,487
2037	5,377,533	4,746,200	631,334	3,917,068	543,740	776,898	1,460,466	87,593
2038	5,332,050	4,749,075	582,975	3,919,721	543,736	776,084	1,412,329	39,239
2039	5,352,982	4,746,161	606,821	3,920,250	543,738	739,580	1,432,731	63,083
2040	5,374,426	4,742,906	631,520	3,919,394	543,741	737,098	1,455,032	87,779
2041	5,396,377	4,736,233	660,144	3,919,982	543,740	713,192	1,476,394	116,404
2042	5,419,508	4,734,038	685,471	3,922,820	543,739	725,002	1,496,689	141,732
2043	5,352,040	4,727,353	624,686	3,933,749	543,738	687,396	1,418,291	80,948
2044	5,376,581	4,726,105	650,476	3,937,231	543,740	707,689	1,439,350	106,737
2045	5,396,464	4,730,216	666,248	3,934,239	543,740	757,296	1,462,225	122,509
2046	5,418,493	4,733,640	684,853	3,934,419	543,740	756,610	1,484,074	141,113
2047	5,440,630	4,733,354	707,276	3,935,050	543,740	739,554	1,505,580	163,536
2048	5,345,236	4,726,819	618,417	3,942,640	543,740	696,451	1,402,596	74,677
2049	5,368,808	4,724,856	643,953	3,944,492	543,740	709,584	1,424,316	100,213
2050	5,392,725	4,721,621	671,104	3,947,215	543,740	698,037	1,445,509	127,364
2051	5,413,408	4,725,240	688,168	3,948,735	543,740	737,730	1,464,673	144,428
2052	5,433,221	4,730,110	703,110	3,949,942	543,740	752,873	1,483,279	159,371
2053	5,331,858	4,728,749	603,109	3,955,933	543,740	721,411	1,375,926	59,369
2054	5,353,273	4,725,099	628,174	3,957,817	543,740	697,415	1,395,456	84,435
2055	5,373,606	4,725,405	648,201	3,959,341	543,740	715,887	1,414,265	104,461
2056	5,393,819	4,728,566	665,253	3,962,337	543,740	730,389	1,431,482	121,513
2057	5,412,384	4,728,370	684,014	3,963,204	543,740	720,619	1,449,180	140,274

Year	NPP	Rh	NEP	Litterfall	Harvest	Bio2DOM	Net Growth	NBP
2058	5,322,509	4,726,265	596,244	3,971,715	543,740	699,675	1,350,794	52,505
2059	5,339,773	4,731,000	608,773	3,969,776	543,740	744,045	1,369,996	65,033
2060	5,356,870	4,733,934	622,936	3,968,760	543,740	743,406	1,388,110	79,196
2061	5,372,233	4,732,703	639,530	3,968,635	543,740	720,953	1,403,598	95,790
2062	5,392,490	4,733,730	658,761	3,973,787	543,740	718,283	1,418,703	115,021
2063	5,320,592	4,733,465	587,128	3,984,429	543,740	707,971	1,336,164	43,388
2064	5,346,789	4,729,537	617,252	3,996,103	543,740	659,213	1,350,686	73,512
2065	5,366,553	4,732,585	633,968	4,001,045	543,740	704,561	1,365,508	90,228
2066	5,388,009	4,731,156	656,853	4,013,761	543,740	654,247	1,374,248	113,113
2067	5,406,635	4,736,281	670,354	4,022,173	543,740	695,779	1,384,462	126,614
2068	5,346,261	4,741,035	605,226	4,032,707	543,740	699,529	1,313,554	61,487
2069	5,366,941	4,742,473	624,469	4,041,850	543,740	664,749	1,325,092	80,729
2070	5,384,563	4,746,015	638,548	4,047,175	543,740	686,611	1,337,388	94,808
2071	5,409,152	4,741,197	667,955	4,069,475	543,740	587,264	1,339,677	124,215
2072	5,425,181	4,749,355	675,826	4,080,543	543,740	670,415	1,344,638	132,087
2073	5,375,160	4,758,999	616,161	4,089,323	543,740	698,918	1,285,836	72,421
2074	5,392,801	4,761,552	631,250	4,102,161	543,740	633,764	1,290,640	87,510
2075	5,409,426	4,765,061	644,365	4,112,988	543,740	637,664	1,296,438	100,625
2076	5,420,073	4,770,309	649,764	4,119,926	543,740	660,730	1,300,147	106,025
2077	5,429,471	4,775,094	654,377	4,127,008	543,740	656,155	1,302,462	110,637
2078	5,399,718	4,782,183	617,535	4,137,222	543,740	666,892	1,262,496	73,795
2079	5,409,340	4,788,372	620,968	4,142,819	543,740	662,055	1,266,521	77,228
2080	5,412,633	4,797,146	615,487	4,141,548	543,740	702,665	1,271,085	71,748
2081	5,425,636	4,796,750	628,887	4,154,235	543,740	619,553	1,271,401	85,147
2082	5,448,138	4,791,389	656,749	4,181,825	543,740	534,613	1,266,312	113,009
2083	5,438,727	4,799,269	639,459	4,200,132	543,740	616,678	1,238,596	95,719
2084	5,438,009	4,815,045	622,964	4,198,844	543,740	704,582	1,239,165	79,225
2085	5,437,645	4,826,855	610,789	4,196,428	543,740	703,505	1,241,216	67,050
2086	5,442,410	4,831,477	610,933	4,203,836	543,740	650,711	1,238,574	67,193
2087	5,440,720	4,839,204	601,516	4,204,590	543,740	689,056	1,236,130	57,776
2088	5,437,158	4,841,858	595,300	4,213,572	543,740	648,645	1,223,586	51,561
2089	5,438,417	4,846,568	591,850	4,213,676	543,740	672,451	1,224,741	48,110
2090	5,450,757	4,844,870	605,887	4,228,842	543,740	595,684	1,221,915	62,148
2091	5,447,620	4,855,987	591,633	4,223,790	543,740	707,342	1,223,830	47,894
2092	5,459,090	4,852,805	606,285	4,238,906	543,740	586,879	1,220,184	62,546
2093	5,455,744	4,857,994	597,750	4,243,434	543,740	651,929	1,212,310	54,010
2094	5,456,483	4,865,729	590,755	4,244,703	543,740	673,606	1,211,780	47,015
2095	5,455,145	4,873,569	581,576	4,243,125	543,740	689,247	1,212,020	37,836
2096	5,460,869	4,875,961	584,908	4,249,779	543,740	646,374	1,211,090	41,168
2097	5,465,558	4,877,269	588,289	4,256,768	543,740	636,614	1,208,790	44,550
2098	5,460,787	4,883,131	577,656	4,256,519	543,740	678,409	1,204,268	33,916
2099	5,461,222	4,885,225	575,996	4,256,711	543,740	660,246	1,204,510	32,257
2100	5,477,629	4,877,455	600,173	4,279,860	543,740	537,728	1,197,769	56,434
2101	5,497,133	4,874,351	622,782	4,303,536	543,740	534,530	1,193,597	79,043
2102	5,493,889	4,889,436	604,453	4,300,907	543,740	687,478	1,192,982	60,713
2103	5,484,940	4,902,661	582,280	4,291,191	543,740	715,346	1,193,749	38,540
2104	5,486,153	4,902,796	583,357	4,296,287	543,740	621,364	1,189,866	39,618
2105	5,501,301	4,896,741	604,560	4,318,483	543,740	534,366	1,182,818	60,821
2106	5,499,154	4,907,553	591,602	4,317,651	543,740	666,774	1,181,503	47,862
2107	5,489,731	4,924,286	565,445	4,305,643	543,740	754,535	1,184,088	21,706
2108	5,480,745	4,933,685	547,060	4,291,830	543,740	748,492	1,188,916	3,320
2109	5,462,005	4,940,770	521,236	4,275,413	543,740	765,453	1,186,592	-22,504
2110	5,451,817	4,940,135	511,681	4,263,806	543,740	728,952	1,188,010	-32,058
Eastern Region								
2011	4,358,815	3,855,407	503,409	3,456,338	202,585	301,574	902,478	300,823
2012	4,395,910	3,859,905	536,004	3,469,977	231,623	337,767	925,933	304,381
2013	4,344,527	3,864,542	479,985	3,493,821	224,805	331,367	850,706	255,180
2014	4,376,298	3,868,411	507,888	3,505,507	223,776	327,950	870,791	284,112
2015	4,406,949	3,873,152	533,797	3,516,879	227,213	333,228	890,070	306,584
2016	4,439,283	3,876,743	562,540	3,530,533	222,000	318,655	908,750	340,540
2017	4,474,315	3,882,240	592,075	3,542,338	225,883	332,250	931,977	366,192

Year	NPP	Rh	NEP	Litterfall	Harvest	Bio2DOM	Net Growth	NBP
2018	4,425,474	3,886,254	539,221	3,568,018	224,735	309,722	857,456	314,485
2019	4,453,097	3,892,029	561,068	3,580,345	224,722	317,214	872,752	336,346
2020	4,478,755	3,898,222	580,533	3,591,281	224,911	321,521	887,474	355,623
2021	4,501,646	3,904,054	597,592	3,603,262	224,450	315,928	898,384	373,142
2022	4,522,434	3,909,706	612,728	3,613,675	224,940	317,603	908,760	387,788
2023	4,484,829	3,917,583	567,245	3,636,174	224,752	325,284	848,655	342,493
2024	4,507,379	3,921,827	585,551	3,646,572	224,755	302,944	860,807	360,796
2025	4,522,572	3,928,960	593,611	3,654,170	224,761	322,120	868,401	368,850
2026	4,531,585	3,936,176	595,409	3,661,311	224,732	327,208	870,274	370,677
2027	4,551,355	3,942,179	609,177	3,669,906	224,788	319,626	881,449	384,389
2028	4,509,031	3,947,920	561,111	3,688,287	224,757	317,807	820,744	336,354
2029	4,524,917	3,952,713	572,204	3,695,389	224,758	308,867	829,528	347,446
2030	4,540,197	3,961,363	578,835	3,701,202	224,760	336,664	838,995	354,075
2031	4,556,260	3,967,495	588,764	3,708,526	224,760	323,264	847,734	364,005
2032	4,571,788	3,969,246	602,542	3,718,720	224,765	291,580	853,068	377,777
2033	4,532,913	3,973,172	559,741	3,738,023	224,760	297,281	794,890	334,981
2034	4,545,454	3,979,348	566,106	3,742,728	224,761	313,958	802,726	341,345
2035	4,559,404	3,986,805	572,599	3,747,363	224,761	323,265	812,041	347,838
2036	4,573,823	3,994,484	579,339	3,752,302	224,761	331,449	821,521	354,578
2037	4,588,434	3,998,790	589,644	3,758,611	224,762	313,830	829,823	364,883
2038	4,533,983	4,004,738	529,245	3,773,769	224,761	317,608	760,214	304,484
2039	4,547,981	4,010,725	537,257	3,779,510	224,761	317,360	768,471	312,496
2040	4,561,819	4,017,571	544,249	3,783,570	224,761	328,958	778,250	319,488
2041	4,576,573	4,021,076	555,496	3,790,271	224,761	306,316	786,302	330,736
2042	4,589,181	4,026,598	562,583	3,795,090	224,761	319,375	794,092	337,823
2043	4,522,369	4,032,771	489,598	3,809,079	224,761	324,383	713,290	264,838
2044	4,533,177	4,038,397	494,780	3,811,095	224,761	326,376	722,083	270,020
2045	4,546,492	4,041,278	505,213	3,815,151	224,761	309,544	731,340	280,453
2046	4,559,362	4,045,293	514,070	3,818,864	224,761	314,014	740,498	289,309
2047	4,572,089	4,049,414	522,675	3,822,552	224,761	316,095	749,538	297,914
2048	4,501,236	4,052,831	448,405	3,831,773	224,761	314,607	669,463	223,644
2049	4,510,446	4,057,694	452,752	3,831,584	224,761	326,187	678,862	227,992
2050	4,520,217	4,060,414	459,804	3,832,631	224,761	313,275	687,586	235,043
2051	4,529,550	4,067,653	461,896	3,832,316	224,761	346,019	697,233	237,136
2052	4,541,602	4,070,471	471,130	3,835,465	224,761	318,609	706,137	246,370
2053	4,485,005	4,072,549	412,456	3,847,703	224,761	304,982	637,303	187,695
2054	4,495,604	4,072,683	422,921	3,850,973	224,761	293,803	644,630	198,160
2055	4,506,417	4,073,338	433,079	3,853,431	224,761	294,157	652,986	208,318
2056	4,517,339	4,075,699	441,640	3,856,467	224,761	299,241	660,872	216,879
2057	4,526,208	4,078,527	447,680	3,857,699	224,761	305,653	668,509	222,920
2058	4,469,468	4,082,798	386,669	3,865,141	224,761	315,967	604,326	161,908
2059	4,475,239	4,088,291	386,947	3,862,711	224,761	330,603	612,528	162,187
2060	4,482,616	4,094,778	387,838	3,860,298	224,761	344,485	622,319	163,078
2061	4,490,844	4,095,854	394,990	3,860,315	224,761	316,629	630,528	170,229
2062	4,498,922	4,098,030	400,893	3,860,795	224,761	320,080	638,127	176,132
2063	4,443,812	4,099,835	343,977	3,868,370	224,761	314,102	575,443	119,216
2064	4,448,771	4,101,339	347,432	3,865,554	224,761	321,545	583,217	122,671
2065	4,456,233	4,104,515	351,717	3,864,582	224,761	327,379	591,651	126,957
2066	4,462,378	4,108,769	353,609	3,862,804	224,761	338,566	599,575	128,849
2067	4,470,507	4,109,490	361,016	3,864,091	224,761	317,133	606,416	136,256
2068	4,403,323	4,106,699	296,624	3,873,767	224,761	290,541	529,556	71,863
2069	4,409,249	4,106,559	302,690	3,872,774	224,761	303,509	536,475	77,929
2070	4,412,896	4,110,423	302,472	3,868,450	224,761	332,395	544,445	77,712
2071	4,416,887	4,112,546	304,341	3,866,884	224,761	324,722	550,002	79,580
2072	4,420,788	4,114,390	306,398	3,864,827	224,761	326,296	555,960	81,637
2073	4,395,412	4,114,333	281,079	3,871,829	224,761	312,185	523,583	56,318
2074	4,400,878	4,114,890	285,988	3,871,092	224,761	312,129	529,787	61,227
2075	4,404,194	4,116,192	288,003	3,868,577	224,761	321,329	535,617	63,242
2076	4,407,208	4,118,502	288,706	3,866,057	224,761	329,595	541,151	63,945
2077	4,411,762	4,122,020	289,742	3,863,891	224,761	338,327	547,871	64,982
2078	4,394,381	4,119,804	274,577	3,871,865	224,761	302,250	522,516	49,816

Year	NPP	Rh	NEP	Litterfall	Harvest	Bio2DOM	Net Growth	NBP
2079	4,397,598	4,120,090	277,508	3,869,176	224,761	319,334	528,423	52,748
2080	4,399,287	4,123,071	276,216	3,865,275	224,761	340,018	534,012	51,456
2081	4,400,954	4,123,418	277,536	3,862,570	224,761	326,972	538,384	52,775
2082	4,405,212	4,123,834	281,379	3,861,411	224,761	323,880	543,801	56,618
2083	4,396,519	4,122,358	274,161	3,867,896	224,761	306,069	528,623	49,400
2084	4,396,277	4,124,196	272,081	3,862,353	224,761	339,137	533,924	47,320
2085	4,401,147	4,125,941	275,206	3,862,823	224,761	326,396	538,324	50,445
2086	4,404,329	4,126,655	277,674	3,862,417	224,761	323,956	541,912	52,913
2087	4,404,764	4,125,254	279,510	3,860,378	224,761	317,627	544,386	54,749
2088	4,397,267	4,125,735	271,532	3,863,535	224,761	322,399	533,732	46,772
2089	4,399,311	4,127,917	271,394	3,859,923	224,761	340,353	539,388	46,633
2090	4,401,789	4,128,014	273,774	3,858,656	224,761	325,690	543,132	49,014
2091	4,404,998	4,126,553	278,445	3,859,023	224,761	312,248	545,975	53,684
2092	4,402,490	4,132,227	270,263	3,851,769	224,761	373,892	550,721	45,502
2093	4,398,662	4,133,074	265,587	3,853,604	224,761	338,447	545,058	40,827
2094	4,399,957	4,130,757	269,200	3,851,014	224,761	326,380	548,943	44,440
2095	4,399,493	4,132,823	266,670	3,846,995	224,761	352,376	552,499	41,910
2096	4,402,455	4,131,240	271,215	3,846,834	224,761	326,660	555,622	46,455
2097	4,406,622	4,127,736	278,886	3,848,306	224,761	307,986	558,317	54,125
2098	4,400,348	4,130,469	269,879	3,846,862	224,761	349,207	553,486	45,118
2099	4,403,364	4,130,778	272,586	3,846,648	224,761	331,350	556,716	47,825
2100	4,402,581	4,129,486	273,095	3,844,611	224,761	328,915	557,970	48,334
2101	4,402,710	4,131,079	271,631	3,842,043	224,761	345,097	560,666	46,870
2102	4,405,856	4,130,390	275,466	3,841,811	224,761	329,363	564,045	50,705
2103	4,401,812	4,131,706	270,106	3,840,599	224,761	344,936	561,213	45,345
2104	4,405,954	4,131,406	274,548	3,841,402	224,761	329,571	564,552	49,788
2105	4,404,268	4,134,174	270,094	3,836,733	224,761	362,026	567,535	45,334
2106	4,404,872	4,134,754	270,118	3,834,858	224,761	348,358	570,014	45,358
2107	4,411,040	4,131,179	279,862	3,840,586	224,761	305,050	570,454	55,101
2108	4,411,004	4,130,347	280,657	3,843,780	224,761	319,690	567,224	55,897
2109	4,414,799	4,130,918	283,881	3,846,568	224,761	321,300	568,231	59,121
2110	4,416,233	4,132,727	283,506	3,846,594	224,761	335,369	569,639	58,745
Western Region								
2011	5,204,424	4,517,802	686,621	4,442,088	333,588	431,019	762,336	353,033
2012	5,208,296	4,547,135	661,162	4,436,564	312,137	407,830	771,732	349,025
2013	5,099,346	4,570,118	529,228	4,440,287	305,549	400,242	659,059	223,679
2014	5,102,255	4,587,355	514,900	4,431,359	299,967	397,888	670,895	214,933
2015	5,104,769	4,602,944	501,825	4,422,682	311,523	414,976	682,087	190,302
2016	5,109,280	4,614,590	494,691	4,416,151	312,552	407,555	693,129	182,138
2017	5,113,180	4,624,240	488,940	4,409,054	308,346	410,979	704,126	180,594
2018	5,019,495	4,631,538	387,957	4,413,157	307,588	404,796	606,338	80,369
2019	5,022,026	4,638,177	383,849	4,402,968	307,995	416,401	619,058	75,854
2020	5,025,189	4,641,961	383,228	4,395,074	309,600	406,337	630,115	73,628
2021	5,030,250	4,644,612	385,638	4,388,092	309,216	404,213	642,158	76,422
2022	5,034,843	4,647,226	387,617	4,381,659	308,549	406,495	653,184	79,068
2023	4,960,652	4,647,651	313,001	4,389,336	308,590	388,754	571,316	4,412
2024	4,965,565	4,647,563	318,002	4,381,789	308,790	391,284	583,776	9,212
2025	4,964,060	4,648,145	315,915	4,373,512	308,948	399,795	590,548	6,967
2026	4,966,169	4,648,418	317,751	4,365,922	308,819	401,231	600,247	8,932
2027	4,963,691	4,650,241	313,450	4,354,435	308,739	424,858	609,256	4,711
2028	4,901,305	4,651,100	250,205	4,356,546	308,777	423,520	544,759	-58,572
2029	4,903,918	4,648,348	255,569	4,348,031	308,815	401,267	555,886	-53,246
2030	4,903,402	4,646,843	256,559	4,339,571	308,820	408,488	563,831	-52,261
2031	4,904,505	4,643,200	261,306	4,330,353	308,794	401,628	574,152	-47,488
2032	4,900,271	4,638,619	261,653	4,320,130	308,789	398,742	580,141	-47,136
2033	4,860,881	4,636,367	224,514	4,325,384	308,799	403,477	535,497	-84,285
2034	4,864,686	4,634,295	230,391	4,317,833	308,803	403,355	546,853	-78,412
2035	4,870,027	4,631,022	239,005	4,312,083	308,801	394,115	557,944	-69,796
2036	4,870,667	4,630,430	240,237	4,300,652	308,798	424,787	570,015	-68,561
2037	4,871,809	4,628,282	243,527	4,290,218	308,798	421,278	581,591	-65,270
2038	4,835,479	4,625,593	209,886	4,294,695	308,800	412,928	540,784	-98,913

Year	NPP	Rh	NEP	Litterfall	Harvest	Bio2DOM	Net Growth	NBP
2039	4,841,878	4,620,295	221,583	4,289,882	308,800	387,449	551,996	-87,217
2040	4,845,788	4,618,032	227,756	4,283,992	308,799	404,229	561,796	-81,043
2041	4,849,576	4,613,940	235,635	4,276,992	308,799	397,731	572,584	-73,163
2042	4,853,322	4,609,770	243,552	4,269,955	308,799	396,567	583,368	-65,246
2043	4,817,809	4,607,814	209,994	4,272,510	308,799	410,309	545,298	-98,804
2044	4,822,254	4,605,171	217,083	4,266,227	308,799	401,452	556,027	-91,716
2045	4,827,768	4,601,312	226,455	4,260,324	308,799	394,679	567,443	-82,343
2046	4,834,562	4,598,093	236,469	4,254,527	308,799	396,617	580,036	-72,330
2047	4,837,932	4,599,124	238,808	4,246,047	308,799	429,569	591,884	-69,991
2048	4,808,556	4,594,595	213,960	4,252,899	308,799	386,683	555,657	-94,838
2049	4,816,364	4,590,780	225,584	4,249,577	308,799	385,111	566,787	-83,214
2050	4,823,608	4,588,351	235,257	4,245,664	308,799	392,349	577,944	-73,542
2051	4,831,360	4,585,760	245,601	4,244,541	308,799	383,826	586,820	-63,198
2052	4,836,785	4,583,664	253,121	4,239,041	308,799	395,451	597,744	-55,678
2053	4,804,231	4,581,801	222,430	4,241,349	308,799	394,790	562,882	-86,369
2054	4,807,474	4,579,697	227,777	4,233,239	308,799	399,529	574,234	-81,022
2055	4,811,389	4,578,224	233,165	4,227,364	308,799	401,352	584,025	-75,634
2056	4,814,615	4,576,981	237,634	4,221,175	308,799	406,087	593,440	-71,164
2057	4,819,168	4,574,022	245,147	4,216,190	308,799	395,426	602,979	-63,652
2058	4,791,439	4,571,092	220,347	4,223,323	308,799	381,023	568,116	-88,452
2059	4,795,862	4,569,024	226,839	4,217,974	308,799	392,554	577,888	-81,960
2060	4,798,085	4,568,304	229,781	4,208,818	308,799	411,584	589,267	-79,018
2061	4,798,606	4,569,233	229,372	4,199,418	308,799	430,098	599,187	-79,426
2062	4,795,533	4,569,543	225,990	4,187,905	308,799	440,957	607,628	-82,808
2063	4,765,708	4,566,452	199,255	4,186,847	308,799	417,854	578,860	-109,543
2064	4,769,249	4,563,710	205,539	4,179,978	308,799	418,079	589,271	-103,259
2065	4,775,328	4,558,512	216,816	4,176,825	308,799	395,184	598,504	-91,983
2066	4,779,227	4,555,403	223,824	4,172,156	308,799	406,358	607,071	-84,974
2067	4,784,200	4,550,936	233,265	4,169,167	308,799	393,874	615,033	-75,534
2068	4,752,027	4,547,710	204,316	4,168,634	308,799	401,253	583,393	-104,483
2069	4,752,498	4,546,365	206,133	4,159,351	308,799	421,933	593,147	-102,666
2070	4,760,439	4,541,316	219,122	4,159,572	308,799	380,439	600,866	-89,677
2071	4,760,962	4,537,846	223,116	4,153,156	308,799	399,878	607,806	-85,682
2072	4,763,307	4,535,897	227,411	4,148,560	308,799	404,840	614,748	-81,388
2073	4,744,111	4,533,465	210,646	4,147,376	308,799	404,567	596,735	-98,153
2074	4,746,260	4,531,399	214,861	4,142,837	308,799	404,258	603,423	-93,938
2075	4,747,289	4,529,329	217,960	4,136,462	308,799	409,597	610,828	-90,839
2076	4,743,923	4,529,899	214,024	4,125,483	308,799	441,463	618,440	-94,775
2077	4,739,192	4,529,816	209,376	4,112,809	308,799	452,449	626,383	-99,423
2078	4,724,260	4,526,692	197,567	4,109,172	308,799	429,273	615,088	-111,231
2079	4,722,541	4,524,440	198,102	4,098,578	308,799	445,011	623,964	-110,697
2080	4,727,928	4,518,320	209,607	4,096,365	308,799	405,534	631,563	-99,191
2081	4,731,230	4,514,341	216,889	4,092,380	308,799	416,308	638,850	-91,910
2082	4,735,139	4,510,019	225,120	4,089,647	308,799	409,192	645,492	-83,679
2083	4,730,095	4,505,627	224,468	4,089,721	308,799	406,861	640,375	-84,331
2084	4,733,379	4,501,423	231,956	4,086,531	308,799	403,296	646,847	-76,843
2085	4,735,302	4,499,953	235,349	4,081,207	308,799	423,173	654,095	-73,450
2086	4,737,089	4,497,322	239,767	4,076,972	308,799	416,195	660,117	-69,032
2087	4,739,842	4,494,587	245,255	4,075,183	308,799	409,335	664,660	-63,544
2088	4,736,625	4,491,611	245,014	4,073,300	308,799	411,808	663,325	-63,785
2089	4,735,604	4,491,892	243,712	4,065,528	308,799	440,687	670,075	-65,087
2090	4,738,475	4,489,404	249,070	4,062,437	308,799	418,593	676,038	-59,728
2091	4,740,235	4,486,712	253,524	4,057,610	308,799	422,126	682,626	-55,275
2092	4,737,486	4,487,796	249,690	4,048,885	308,799	456,774	688,601	-59,108
2093	4,732,910	4,486,868	246,042	4,043,566	308,799	450,886	689,344	-62,757
2094	4,738,200	4,482,466	255,733	4,042,589	308,799	418,023	695,610	-53,065
2095	4,741,708	4,479,236	262,472	4,040,073	308,799	423,325	701,635	-46,327
2096	4,745,793	4,475,908	269,885	4,038,772	308,799	418,060	707,021	-38,914
2097	4,745,761	4,473,454	272,307	4,034,048	308,799	429,106	711,713	-36,492
2098	4,745,279	4,470,878	274,401	4,034,063	308,799	421,005	711,216	-34,398
2099	4,750,380	4,467,453	282,927	4,034,195	308,799	408,951	716,185	-25,871

Year	NPP	Rh	NEP	Litterfall	Harvest	Bio2DOM	Net Growth	NBP
2100	4,753,366	4,464,942	288,423	4,033,051	308,799	413,829	720,314	-20,375
2101	4,752,947	4,465,574	287,373	4,029,017	308,799	438,540	723,930	-21,425
2102	4,748,361	4,467,002	281,359	4,021,503	308,799	458,699	726,857	-27,440
2103	4,745,159	4,467,879	277,280	4,017,331	308,799	457,350	727,828	-31,519
2104	4,749,122	4,464,398	284,724	4,017,241	308,799	423,949	731,881	-24,075
2105	4,752,237	4,462,762	289,475	4,015,748	308,799	433,737	736,489	-19,323
2106	4,757,022	4,459,012	298,011	4,017,703	308,799	412,010	739,319	-10,788
2107	4,755,958	4,458,957	297,002	4,013,387	308,799	444,529	742,571	-11,797
2108	4,760,592	4,454,631	305,961	4,017,535	308,799	402,209	743,056	-2,838
2109	4,765,741	4,452,843	312,899	4,019,734	308,799	411,615	746,007	4,100
2110	4,766,535	4,452,861	313,674	4,017,433	308,799	431,120	749,102	4,876

B8. Life Cycle GHG Emissions for Pellet Heat Pathway 2

Table B8. Life cycle GHG emissions for Pellet Heat Pathway 2, including forest carbon emissions data and life cycle emissions for wood pellet production for residential space heating with wood pellets made from 100% unmerchantable roundwood. Results are expressed in tonnes of CO_2 equivalents and include forest carbon simulation results for all three regions of Nova Scotia.

Year	C_{atm} (pellets)	NEP_{pel}	FP_{dec}	PEL_{comb}	LCE_{pel}	C_{atm} (pellets) (Relative to BAU)	C_{atm} (pellets) Cumulative (Relative to BAU)
2011	-3,632,438	-5,510,398	1,784,704	77,695	16,700	12,479	12,479
2012	-3,387,483	-5,563,379	2,082,639	77,695	16,700	30,134	42,613
2013	-2,486,358	-4,605,339	2,025,724	77,695	16,700	40,147	82,759
2014	-2,706,004	-4,785,534	1,986,273	77,695	16,700	52,683	135,442
2015	-2,837,534	-4,937,986	2,007,195	77,695	16,700	63,857	199,299
2016	-3,052,329	-5,143,269	1,997,683	77,695	16,700	70,269	269,569
2017	-3,216,658	-5,350,727	2,040,812	77,695	16,700	82,131	351,700
2018	-2,511,781	-4,638,184	2,033,146	77,695	16,700	84,488	436,187
2019	-2,723,302	-4,848,618	2,032,059	77,695	16,700	86,520	522,708
2020	-2,914,700	-5,049,571	2,041,614	77,695	16,700	97,013	619,721
2021	-3,101,477	-5,242,878	2,048,143	77,695	16,700	99,112	718,832
2022	-3,265,288	-5,417,778	2,059,233	77,695	16,700	104,000	822,833
2023	-2,704,367	-4,861,762	2,064,137	77,695	16,700	102,057	924,889
2024	-2,904,108	-5,065,416	2,068,050	77,695	16,700	107,071	1,031,960
2025	-3,020,684	-5,189,697	2,075,756	77,695	16,700	113,710	1,145,670
2026	-3,099,295	-5,274,795	2,082,243	77,695	16,700	116,061	1,261,731
2027	-3,219,645	-5,402,928	2,090,026	77,695	16,700	111,356	1,373,088
2028	-2,674,217	-4,863,122	2,095,648	77,695	16,700	123,031	1,496,119
2029	-2,838,748	-5,033,449	2,101,443	77,695	16,700	116,851	1,612,970
2030	-2,955,696	-5,156,240	2,107,288	77,695	16,700	114,431	1,727,401
2031	-3,049,016	-5,257,209	2,114,935	77,695	16,700	114,477	1,841,877
2032	-3,129,289	-5,345,295	2,122,750	77,695	16,700	101,399	1,943,277
2033	-2,691,241	-4,914,994	2,130,496	77,695	16,700	113,805	2,057,082
2034	-2,805,133	-5,033,248	2,134,857	77,695	16,700	119,543	2,176,625
2035	-2,947,934	-5,183,278	2,142,087	77,695	16,700	129,194	2,305,819
2036	-3,073,910	-5,317,122	2,149,956	77,695	16,700	120,862	2,426,680
2037	-3,123,673	-5,374,733	2,157,803	77,695	16,700	111,979	2,538,659
2038	-2,593,348	-4,852,129	2,165,523	77,695	16,700	106,074	2,644,733
2039	-2,747,138	-5,011,975	2,171,580	77,695	16,700	102,395	2,747,129
2040	-2,876,975	-5,150,933	2,180,702	77,695	16,700	118,479	2,865,607
2041	-3,045,814	-5,326,181	2,187,110	77,695	16,700	101,047	2,966,655
2042	-3,186,371	-5,474,195	2,194,567	77,695	16,700	115,263	3,081,917
2043	-2,564,527	-4,860,103	2,202,319	77,695	16,700	99,279	3,181,196
2044	-2,698,106	-4,999,785	2,208,422	77,695	16,700	94,826	3,276,022
2045	-2,821,280	-5,130,355	2,215,818	77,695	16,700	91,410	3,367,432
2046	-2,950,927	-5,267,887	2,223,703	77,695	16,700	92,853	3,460,286
2047	-3,065,631	-5,390,343	2,231,455	77,695	16,700	102,118	3,562,404
2048	-2,368,012	-4,700,470	2,239,201	77,695	16,700	78,256	3,640,660
2049	-2,512,510	-4,852,801	2,247,034	77,695	16,700	79,741	3,720,401
2050	-2,665,835	-5,013,822	2,254,731	77,695	16,700	70,585	3,790,986
2051	-2,766,334	-5,122,089	2,262,498	77,695	16,700	91,555	3,882,541
2052	-2,874,911	-5,238,415	2,270,248	77,695	16,700	68,708	3,951,249
2053	-2,172,179	-4,543,440	2,278,004	77,695	16,700	39,987	3,991,236
2054	-2,314,385	-4,693,460	2,285,817	77,695	16,700	30,449	4,021,685
2055	-2,437,207	-4,824,012	2,293,548	77,695	16,700	40,491	4,062,176
2056	-2,539,862	-4,934,416	2,301,296	77,695	16,700	54,237	4,116,413
2057	-2,650,702	-5,053,006	2,309,047	77,695	16,700	52,141	4,168,553
2058	-2,004,244	-4,415,965	2,318,465	77,695	16,700	53,142	4,221,695

Year	C_{atm} (pellets)	NEP_{pel}	FP_{dec}	PEL_{comb}	LCE_{pel}	C_{atm} (pellets) (Relative to BAU)	C_{atm} (pellets) Cumulative (Relative to BAU)
2059	-2,068,674	-4,486,790	2,324,859	77,695	16,700	55,397	4,277,092
2060	-2,125,635	-4,552,837	2,333,946	77,695	16,700	59,728	4,336,821
2061	-2,203,270	-4,638,482	2,341,955	77,695	16,700	27,598	4,364,418
2062	-2,275,355	-4,718,313	2,349,701	77,695	16,700	32,612	4,397,030
2063	-1,695,998	-4,148,421	2,359,166	77,695	16,700	30,147	4,427,177
2064	-1,835,930	-4,294,718	2,365,531	77,695	16,700	14,271	4,441,448
2065	-1,945,273	-4,413,180	2,374,649	77,695	16,700	8,973	4,450,420
2066	-2,053,847	-4,529,832	2,382,728	77,695	16,700	-6,668	4,443,752
2067	-2,155,824	-4,641,208	2,392,126	77,695	16,700	40,293	4,484,045
2068	-1,566,330	-4,059,630	2,400,042	77,695	16,700	-14,780	4,469,265
2069	-1,657,946	-4,159,181	2,407,978	77,695	16,700	8,995	4,478,260
2070	-1,748,831	-4,257,722	2,415,634	77,695	16,700	32,505	4,510,765
2071	-1,868,921	-4,387,162	2,424,984	77,695	16,700	-25,738	4,485,027
2072	-1,911,522	-4,439,360	2,434,581	77,695	16,700	20,871	4,505,898
2073	-1,530,145	-4,065,937	2,442,535	77,695	16,700	5,784	4,511,682
2074	-1,609,592	-4,154,802	2,451,953	77,695	16,700	-5,117	4,506,565
2075	-1,668,499	-4,221,702	2,459,946	77,695	16,700	-39,395	4,467,169
2076	-1,667,206	-4,229,652	2,469,189	77,695	16,700	48,025	4,515,194
2077	-1,661,295	-4,233,327	2,478,775	77,695	16,700	44,796	4,559,991
2078	-1,419,127	-3,999,122	2,486,738	77,695	16,700	-30,491	4,529,500
2079	-1,436,774	-4,024,440	2,494,410	77,695	16,700	-42,387	4,487,113
2080	-1,446,399	-4,041,811	2,502,155	77,695	16,700	15,532	4,502,644
2081	-1,517,737	-4,122,554	2,511,560	77,695	16,700	-63,675	4,438,970
2082	-1,654,640	-4,269,118	2,521,221	77,695	16,700	-104,545	4,334,425
2083	-1,552,692	-4,176,781	2,530,832	77,695	16,700	-33,281	4,301,143
2084	-1,505,740	-4,136,094	2,537,097	77,695	16,700	18,086	4,319,230
2085	-1,475,913	-4,115,333	2,546,162	77,695	16,700	42,303	4,361,533
2086	-1,492,034	-4,141,131	2,555,840	77,695	16,700	-31,097	4,330,436
2087	-1,474,686	-4,133,450	2,565,507	77,695	16,700	-19,403	4,311,033
2088	-1,412,175	-4,080,475	2,575,043	77,695	16,700	-64,586	4,246,447
2089	-1,386,186	-4,062,528	2,583,085	77,695	16,700	35,547	4,281,994
2090	-1,456,808	-4,142,447	2,592,382	77,695	16,700	-94,347	4,187,647
2091	-1,428,324	-4,123,619	2,602,038	77,695	16,700	22,489	4,210,136
2092	-1,428,383	-4,133,296	2,611,656	77,695	16,700	-59,694	4,150,442
2093	-1,356,971	-4,071,423	2,621,195	77,695	16,700	16,366	4,166,808
2094	-1,372,155	-4,094,578	2,629,166	77,695	16,700	-28,889	4,137,919
2095	-1,344,632	-4,076,336	2,638,447	77,695	16,700	-15,535	4,122,384
2096	-1,391,103	-4,132,451	2,648,090	77,695	16,700	-40,884	4,081,500
2097	-1,430,944	-4,181,901	2,657,701	77,695	16,700	-75,830	4,005,670
2098	-1,356,999	-4,117,505	2,667,248	77,695	16,700	-76,466	3,929,204
2099	-1,382,437	-4,152,639	2,676,946	77,695	16,700	-22,216	3,906,988
2100	-1,483,642	-4,263,409	2,686,510	77,695	16,700	-170,279	3,736,709
2101	-1,547,808	-4,337,155	2,696,090	77,695	16,700	-168,899	3,567,810
2102	-1,462,973	-4,261,887	2,705,657	77,695	16,700	23,938	3,591,748
2103	-1,337,397	-4,145,872	2,715,218	77,695	16,700	64,841	3,656,589
2104	-1,375,356	-4,193,452	2,724,839	77,695	16,700	-90,510	3,566,079
2105	-1,444,708	-4,272,356	2,734,391	77,695	16,700	-176,063	3,390,016
2106	-1,419,002	-4,256,211	2,743,952	77,695	16,700	-52,933	3,337,083
2107	-1,348,999	-4,192,272	2,750,015	77,695	16,700	34,438	3,371,521
2108	-1,311,819	-4,160,600	2,755,524	77,695	16,700	-26,568	3,344,953
2109	-1,248,582	-4,103,118	2,761,279	77,695	16,700	-34,419	3,310,535
2110	-1,209,233	-4,069,522	2,767,031	77,695	16,700	-6,751	3,303,784

B9. Life Cycle GHG Emissions for the Reference Case Business as Usual: Sensitivity Analysis with Electric Heat

Table B9. Life cycle GHG emissions for the reference case business as usual scenario, including forest carbon emissions data and life cycle emissions for residential space heating with Nova Scotia grid electricity. Results are expressed in tonnes of CO_2 equivalents and include forest carbon simulation results for all three regions of Nova Scotia.

Year	C_{atm} (BAU)	NEP_{bau}	FP_{dec}	LCE_{elec}	Cumulative C_{atm}
2011	-3,647,416	-5,525,592	1,784,704	295,700	-3,445,189
2012	-3,420,116	-5,596,227	2,082,639	295,700	-6,663,077
2013	-2,529,004	-4,648,201	2,025,724	295,700	-8,989,854
2014	-2,761,186	-4,840,932	1,986,273	295,700	-11,548,814
2015	-2,903,890	-5,004,558	2,007,195	295,700	-14,250,477
2016	-3,125,097	-5,216,253	1,997,683	295,700	-17,173,347
2017	-3,301,288	-5,435,573	2,040,812	295,700	-20,272,408
2018	-2,598,767	-4,725,387	2,033,146	295,700	-22,668,949
2019	-2,812,321	-4,937,853	2,032,059	295,700	-25,279,043
2020	-3,014,212	-5,149,299	2,041,614	295,700	-28,091,028
2021	-3,203,088	-5,344,704	2,048,143	295,700	-31,091,889
2022	-3,371,788	-5,524,494	2,059,233	295,700	-34,261,450
2023	-2,808,923	-4,966,533	2,064,137	295,700	-36,868,146
2024	-3,013,678	-5,175,201	2,068,050	295,700	-39,679,597
2025	-3,136,893	-5,306,122	2,075,756	295,700	-42,614,263
2026	-3,217,855	-5,393,571	2,082,243	295,700	-45,629,892
2027	-3,333,500	-5,516,999	2,090,026	295,700	-48,761,165
2028	-2,799,748	-4,988,869	2,095,648	295,700	-51,358,686
2029	-2,958,098	-5,153,014	2,101,443	295,700	-54,114,557
2030	-3,072,625	-5,273,386	2,107,288	295,700	-56,984,955
2031	-3,165,992	-5,374,400	2,114,935	295,700	-59,948,720
2032	-3,233,187	-5,449,409	2,122,750	295,700	-62,979,680
2033	-2,807,545	-5,031,514	2,130,496	295,700	-65,584,998
2034	-2,927,176	-5,155,506	2,134,857	295,700	-68,309,947
2035	-3,079,627	-5,315,187	2,142,087	295,700	-71,187,347
2036	-3,197,270	-5,440,699	2,149,956	295,700	-74,182,390
2037	-3,238,151	-5,489,427	2,157,803	295,700	-77,218,314
2038	-2,701,921	-4,960,918	2,165,523	295,700	-79,718,008
2039	-2,852,032	-5,117,085	2,171,580	295,700	-82,367,814
2040	-2,997,953	-5,272,127	2,180,702	295,700	-85,163,539
2041	-3,149,360	-5,429,944	2,187,110	295,700	-88,110,673
2042	-3,304,133	-5,592,173	2,194,567	295,700	-91,212,578
2043	-2,666,305	-4,962,098	2,202,319	295,700	-93,676,656
2044	-2,795,430	-5,097,326	2,208,422	295,700	-96,269,860
2045	-2,915,190	-5,224,480	2,215,818	295,700	-98,982,822
2046	-3,046,280	-5,363,456	2,223,703	295,700	-101,826,875
2047	-3,170,248	-5,495,176	2,231,455	295,700	-104,794,896
2048	-2,448,767	-4,781,441	2,239,201	295,700	-107,041,436
2049	-2,594,750	-4,935,257	2,247,034	295,700	-109,433,959
2050	-2,738,918	-5,087,122	2,254,731	295,700	-111,970,651
2051	-2,860,389	-5,216,360	2,262,498	295,700	-114,628,812
2052	-2,946,118	-5,309,838	2,270,248	295,700	-117,372,703
2053	-2,214,665	-4,586,142	2,278,004	295,700	-119,385,141
2054	-2,347,333	-4,726,624	2,285,817	295,700	-121,530,247
2055	-2,480,197	-4,867,218	2,293,548	295,700	-123,808,218
2056	-2,596,598	-4,991,367	2,301,296	295,700	-126,202,588
2057	-2,705,342	-5,107,862	2,309,047	295,700	-128,705,703
2058	-2,059,885	-4,471,822	2,318,465	295,700	-130,563,361

Year	C_{atm} (BAU)	NEP_{bau}	FP_{dec}	LCE_{elec}	Cumulative C_{atm}
2059	-2,126,570	-4,544,902	2,324,859	295,700	-132,487,705
2060	-2,187,862	-4,615,281	2,333,946	295,700	-134,473,340
2061	-2,233,367	-4,668,795	2,341,955	295,700	-136,504,480
2062	-2,310,466	-4,753,640	2,349,701	295,700	-138,612,719
2063	-1,728,644	-4,181,283	2,359,166	295,700	-140,139,135
2064	-1,852,700	-4,311,703	2,365,531	295,700	-141,789,608
2065	-1,956,745	-4,424,867	2,374,649	295,700	-143,544,126
2066	-2,049,678	-4,525,879	2,382,728	295,700	-145,391,577
2067	-2,198,617	-4,684,216	2,392,126	295,700	-147,387,966
2068	-1,554,049	-4,047,565	2,400,042	295,700	-148,739,788
2069	-1,669,440	-4,170,891	2,407,978	295,700	-150,207,001
2070	-1,783,835	-4,292,942	2,415,634	295,700	-151,788,609
2071	-1,845,683	-4,364,140	2,424,984	295,700	-153,432,065
2072	-1,934,892	-4,462,946	2,434,581	295,700	-155,164,730
2073	-1,538,427	-4,074,436	2,442,535	295,700	-156,500,930
2074	-1,606,974	-4,152,400	2,451,953	295,700	-157,905,677
2075	-1,631,603	-4,185,021	2,459,946	295,700	-159,335,053
2076	-1,717,730	-4,280,392	2,469,189	295,700	-160,850,556
2077	-1,708,590	-4,280,838	2,478,775	295,700	-162,356,919
2078	-1,391,135	-3,971,347	2,486,738	295,700	-163,545,828
2079	-1,396,886	-3,984,768	2,494,410	295,700	-164,740,486
2080	-1,464,430	-4,060,058	2,502,155	295,700	-166,002,689
2081	-1,456,561	-4,061,594	2,511,560	295,700	-167,257,024
2082	-1,552,594	-4,167,288	2,521,221	295,700	-168,607,391
2083	-1,521,910	-4,146,215	2,530,832	295,700	-169,927,073
2084	-1,526,325	-4,156,895	2,537,097	295,700	-171,251,171
2085	-1,520,715	-4,160,351	2,546,162	295,700	-172,569,660
2086	-1,463,436	-4,112,749	2,555,840	295,700	-173,830,869
2087	-1,457,782	-4,116,762	2,565,507	295,700	-175,086,423
2088	-1,350,088	-4,018,604	2,575,043	295,700	-176,234,284
2089	-1,424,232	-4,100,790	2,583,085	295,700	-177,456,289
2090	-1,364,960	-4,050,814	2,592,382	295,700	-178,619,021
2091	-1,453,312	-4,148,823	2,602,038	295,700	-179,870,106
2092	-1,371,189	-4,076,318	2,611,656	295,700	-181,039,068
2093	-1,375,836	-4,090,504	2,621,195	295,700	-182,212,678
2094	-1,345,765	-4,068,404	2,629,166	295,700	-183,356,216
2095	-1,331,596	-4,063,515	2,638,447	295,700	-184,485,584
2096	-1,352,718	-4,094,281	2,648,090	295,700	-185,636,076
2097	-1,357,613	-4,108,787	2,657,701	295,700	-186,791,462
2098	-1,283,032	-4,043,754	2,667,248	295,700	-187,872,267
2099	-1,362,720	-4,133,138	2,676,946	295,700	-189,032,760
2100	-1,315,862	-4,095,844	2,686,510	295,700	-190,146,395
2101	-1,381,408	-4,170,971	2,696,090	295,700	-191,325,575
2102	-1,489,410	-4,288,540	2,705,657	295,700	-192,612,758
2103	-1,404,737	-4,213,428	2,715,218	295,700	-193,815,268
2104	-1,287,346	-4,105,657	2,724,839	295,700	-194,900,387
2105	-1,271,144	-4,099,008	2,734,391	295,700	-195,969,304
2106	-1,368,567	-4,205,993	2,743,952	295,700	-197,135,644
2107	-1,385,937	-4,229,425	2,750,015	295,700	-198,319,354
2108	-1,287,750	-4,136,747	2,755,524	295,700	-199,404,876
2109	-1,216,662	-4,071,414	2,761,279	295,700	-200,419,311
2110	-1,204,981	-4,065,486	2,767,031	295,700	-201,422,065

B10. Life Cycle GHG Emissions for Pellet Heat Pathway 1: Sensitivity Analysis with Electric Heat

Table B10. Life cycle GHG emissions for Pellet Heat Pathway 1, including forest carbon emissions data and life cycle emissions for residential space heating with wood pellets from 100% residues. Sensitivity analysis for residential space heating with Nova Scotia grid electricity. Results are expressed in tonnes of CO_2 equivalents and include forest carbon simulation results for all three regions of Nova Scotia.

Year	C_{atm} (pellets)	NEP_{bau}	FP_{dec}	LCE_{pel}	C_{atm} (pellets) (Relative to BAU)	C_{atm} (pellets) Cumulative (Relative to BAU)
2011	-3,720,226	-5,525,592	1,784,704	21,930	-273,770	-273,770
2012	-3,492,926	-5,596,227	2,082,639	21,930	-273,770	-547,540
2013	-2,601,814	-4,648,201	2,025,724	21,930	-273,770	-821,310
2014	-2,833,996	-4,840,932	1,986,273	21,930	-273,770	-1,095,080
2015	-2,976,700	-5,004,558	2,007,195	21,930	-273,770	-1,368,850
2016	-3,197,907	-5,216,253	1,997,683	21,930	-273,770	-1,642,620
2017	-3,374,098	-5,435,573	2,040,812	21,930	-273,770	-1,916,390
2018	-2,671,577	-4,725,387	2,033,146	21,930	-273,770	-2,190,160
2019	-2,885,131	-4,937,853	2,032,059	21,930	-273,770	-2,463,930
2020	-3,087,022	-5,149,299	2,041,614	21,930	-273,770	-2,737,700
2021	-3,275,898	-5,344,704	2,048,143	21,930	-273,770	-3,011,470
2022	-3,444,598	-5,524,494	2,059,233	21,930	-273,770	-3,285,240
2023	-2,881,733	-4,966,533	2,064,137	21,930	-273,770	-3,559,010
2024	-3,086,488	-5,175,201	2,068,050	21,930	-273,770	-3,832,780
2025	-3,209,703	-5,306,122	2,075,756	21,930	-273,770	-4,106,550
2026	-3,290,665	-5,393,571	2,082,243	21,930	-273,770	-4,380,320
2027	-3,406,310	-5,516,999	2,090,026	21,930	-273,770	-4,654,090
2028	-2,872,558	-4,988,869	2,095,648	21,930	-273,770	-4,927,860
2029	-3,030,908	-5,153,014	2,101,443	21,930	-273,770	-5,201,630
2030	-3,145,435	-5,273,386	2,107,288	21,930	-273,770	-5,475,400
2031	-3,238,802	-5,374,400	2,114,935	21,930	-273,770	-5,749,170
2032	-3,305,997	-5,449,409	2,122,750	21,930	-273,770	-6,022,940
2033	-2,880,355	-5,031,514	2,130,496	21,930	-273,770	-6,296,710
2034	-2,999,986	-5,155,506	2,134,857	21,930	-273,770	-6,570,480
2035	-3,152,437	-5,315,187	2,142,087	21,930	-273,770	-6,844,250
2036	-3,270,080	-5,440,699	2,149,956	21,930	-273,770	-7,118,020
2037	-3,310,961	-5,489,427	2,157,803	21,930	-273,770	-7,391,790
2038	-2,774,731	-4,960,918	2,165,523	21,930	-273,770	-7,665,560
2039	-2,924,842	-5,117,085	2,171,580	21,930	-273,770	-7,939,330
2040	-3,070,763	-5,272,127	2,180,702	21,930	-273,770	-8,213,100
2041	-3,222,170	-5,429,944	2,187,110	21,930	-273,770	-8,486,870
2042	-3,376,943	-5,592,173	2,194,567	21,930	-273,770	-8,760,640
2043	-2,739,115	-4,962,098	2,202,319	21,930	-273,770	-9,034,410
2044	-2,868,240	-5,097,326	2,208,422	21,930	-273,770	-9,308,180
2045	-2,988,000	-5,224,480	2,215,818	21,930	-273,770	-9,581,950
2046	-3,119,090	-5,363,456	2,223,703	21,930	-273,770	-9,855,720
2047	-3,243,058	-5,495,176	2,231,455	21,930	-273,770	-10,129,490
2048	-2,521,577	-4,781,441	2,239,201	21,930	-273,770	-10,403,260
2049	-2,667,560	-4,935,257	2,247,034	21,930	-273,770	-10,677,030
2050	-2,811,728	-5,087,122	2,254,731	21,930	-273,770	-10,950,800
2051	-2,933,199	-5,216,360	2,262,498	21,930	-273,770	-11,224,570
2052	-3,018,928	-5,309,838	2,270,248	21,930	-273,770	-11,498,340
2053	-2,287,475	-4,586,142	2,278,004	21,930	-273,770	-11,772,110
2054	-2,420,143	-4,726,624	2,285,817	21,930	-273,770	-12,045,880
2055	-2,553,007	-4,867,218	2,293,548	21,930	-273,770	-12,319,650
2056	-2,669,408	-4,991,367	2,301,296	21,930	-273,770	-12,593,420

Year	C_{atm} (pellets)	NEP_{bau}	FP_{dec}	LCE_{pel}	C_{atm} (pellets) (Relative to BAU)	C_{atm} (pellets) Cumulative (Relative to BAU)
2057	-2,778,152	-5,107,862	2,309,047	21,930	-273,770	-12,867,190
2058	-2,132,695	-4,471,822	2,318,465	21,930	-273,770	-13,140,960
2059	-2,199,380	-4,544,902	2,324,859	21,930	-273,770	-13,414,730
2060	-2,260,672	-4,615,281	2,333,946	21,930	-273,770	-13,688,500
2061	-2,306,177	-4,668,795	2,341,955	21,930	-273,770	-13,962,270
2062	-2,383,276	-4,753,640	2,349,701	21,930	-273,770	-14,236,040
2063	-1,801,454	-4,181,283	2,359,166	21,930	-273,770	-14,509,810
2064	-1,925,510	-4,311,703	2,365,531	21,930	-273,770	-14,783,580
2065	-2,029,555	-4,424,867	2,374,649	21,930	-273,770	-15,057,350
2066	-2,122,488	-4,525,879	2,382,728	21,930	-273,770	-15,331,120
2067	-2,271,427	-4,684,216	2,392,126	21,930	-273,770	-15,604,890
2068	-1,626,859	-4,047,565	2,400,042	21,930	-273,770	-15,878,660
2069	-1,742,250	-4,170,891	2,407,978	21,930	-273,770	-16,152,430
2070	-1,856,645	-4,292,942	2,415,634	21,930	-273,770	-16,426,200
2071	-1,918,493	-4,364,140	2,424,984	21,930	-273,770	-16,699,970
2072	-2,007,702	-4,462,946	2,434,581	21,930	-273,770	-16,973,740
2073	-1,611,237	-4,074,436	2,442,535	21,930	-273,770	-17,247,510
2074	-1,679,784	-4,152,400	2,451,953	21,930	-273,770	-17,521,280
2075	-1,704,413	-4,185,021	2,459,946	21,930	-273,770	-17,795,050
2076	-1,790,540	-4,280,392	2,469,189	21,930	-273,770	-18,068,820
2077	-1,781,400	-4,280,838	2,478,775	21,930	-273,770	-18,342,590
2078	-1,463,945	-3,971,347	2,486,738	21,930	-273,770	-18,616,360
2079	-1,469,696	-3,984,768	2,494,410	21,930	-273,770	-18,890,130
2080	-1,537,240	-4,060,058	2,502,155	21,930	-273,770	-19,163,900
2081	-1,529,371	-4,061,594	2,511,560	21,930	-273,770	-19,437,670
2082	-1,625,404	-4,167,288	2,521,221	21,930	-273,770	-19,711,440
2083	-1,594,720	-4,146,215	2,530,832	21,930	-273,770	-19,985,210
2084	-1,599,135	-4,156,895	2,537,097	21,930	-273,770	-20,258,980
2085	-1,593,525	-4,160,351	2,546,162	21,930	-273,770	-20,532,750
2086	-1,536,246	-4,112,749	2,555,840	21,930	-273,770	-20,806,520
2087	-1,530,592	-4,116,762	2,565,507	21,930	-273,770	-21,080,290
2088	-1,422,898	-4,018,604	2,575,043	21,930	-273,770	-21,354,060
2089	-1,497,042	-4,100,790	2,583,085	21,930	-273,770	-21,627,830
2090	-1,437,770	-4,050,814	2,592,382	21,930	-273,770	-21,901,600
2091	-1,526,122	-4,148,823	2,602,038	21,930	-273,770	-22,175,370
2092	-1,443,999	-4,076,318	2,611,656	21,930	-273,770	-22,449,140
2093	-1,448,646	-4,090,504	2,621,195	21,930	-273,770	-22,722,910
2094	-1,418,575	-4,068,404	2,629,166	21,930	-273,770	-22,996,680
2095	-1,404,406	-4,063,515	2,638,447	21,930	-273,770	-23,270,450
2096	-1,425,528	-4,094,281	2,648,090	21,930	-273,770	-23,544,220
2097	-1,430,423	-4,108,787	2,657,701	21,930	-273,770	-23,817,990
2098	-1,355,842	-4,043,754	2,667,248	21,930	-273,770	-24,091,760
2099	-1,435,530	-4,133,138	2,676,946	21,930	-273,770	-24,365,530
2100	-1,388,672	-4,095,844	2,686,510	21,930	-273,770	-24,639,300
2101	-1,454,218	-4,170,971	2,696,090	21,930	-273,770	-24,913,070
2102	-1,562,220	-4,288,540	2,705,657	21,930	-273,770	-25,186,840
2103	-1,477,547	-4,213,428	2,715,218	21,930	-273,770	-25,460,610
2104	-1,360,156	-4,105,657	2,724,839	21,930	-273,770	-25,734,380
2105	-1,343,954	-4,099,008	2,734,391	21,930	-273,770	-26,008,150
2106	-1,441,377	-4,205,993	2,743,952	21,930	-273,770	-26,281,920
2107	-1,458,747	-4,229,425	2,750,015	21,930	-273,770	-26,555,690
2108	-1,360,560	-4,136,747	2,755,524	21,930	-273,770	-26,829,460
2109	-1,289,472	-4,071,414	2,761,279	21,930	-273,770	-27,103,230
2110	-1,277,791	-4,065,486	2,767,031	21,930	-273,770	-27,377,000

B11. Life Cycle GHG Emissions for Pellet Heat Pathway 2: Sensitivity Analysis with Electric Heat

Table B11. Life cycle GHG emissions for Pellet Heat Pathway 2, including forest carbon emissions data and life cycle emissions for residential space heating with wood pellets from 100% unmerchantable roundwood. Sensitivity analysis for residential space heating with Nova Scotia grid electricity. Results are expressed in tonnes of CO_2 equivalents and include forest carbon simulation results for all three regions of Nova Scotia.

Year	C_{atm} (pellets)	NEP_{pel}	FP_{dec}	PEL_{comb}	LCE_{pel}	C_{atm} (pellets) (Relative to BAU)	C_{atm} (pellets) Cumulative (Relative to BAU)
2011	-3,632,438	-5,510,398	1,784,704	77,695	16,700	-186,111	-186,111
2012	-3,387,483	-5,563,379	2,082,639	77,695	16,700	-168,456	-354,567
2013	-2,486,358	-4,605,339	2,025,724	77,695	16,700	-158,443	-513,011
2014	-2,706,004	-4,785,534	1,986,273	77,695	16,700	-145,907	-658,918
2015	-2,837,534	-4,937,986	2,007,195	77,695	16,700	-134,733	-793,651
2016	-3,052,329	-5,143,269	1,997,683	77,695	16,700	-128,321	-921,971
2017	-3,216,658	-5,350,727	2,040,812	77,695	16,700	-116,459	-1,038,430
2018	-2,511,781	-4,638,184	2,033,146	77,695	16,700	-114,102	-1,152,533
2019	-2,723,302	-4,848,618	2,032,059	77,695	16,700	-112,070	-1,264,602
2020	-2,914,700	-5,049,571	2,041,614	77,695	16,700	-101,577	-1,366,179
2021	-3,101,477	-5,242,878	2,048,143	77,695	16,700	-99,478	-1,465,658
2022	-3,265,288	-5,417,778	2,059,233	77,695	16,700	-94,590	-1,560,247
2023	-2,704,367	-4,861,762	2,064,137	77,695	16,700	-96,533	-1,656,781
2024	-2,904,108	-5,065,416	2,068,050	77,695	16,700	-91,519	-1,748,300
2025	-3,020,684	-5,189,697	2,075,756	77,695	16,700	-84,880	-1,833,180
2026	-3,099,295	-5,274,795	2,082,243	77,695	16,700	-82,529	-1,915,709
2027	-3,219,645	-5,402,928	2,090,026	77,695	16,700	-87,234	-2,002,942
2028	-2,674,217	-4,863,122	2,095,648	77,695	16,700	-75,559	-2,078,501
2029	-2,838,748	-5,033,449	2,101,443	77,695	16,700	-81,739	-2,160,240
2030	-2,955,696	-5,156,240	2,107,288	77,695	16,700	-84,159	-2,244,399
2031	-3,049,016	-5,257,209	2,114,935	77,695	16,700	-84,113	-2,328,513
2032	-3,129,289	-5,345,295	2,122,750	77,695	16,700	-97,191	-2,425,703
2033	-2,691,241	-4,914,994	2,130,496	77,695	16,700	-84,785	-2,510,488
2034	-2,805,133	-5,033,248	2,134,857	77,695	16,700	-79,047	-2,589,535
2035	-2,947,934	-5,183,278	2,142,087	77,695	16,700	-69,396	-2,658,931
2036	-3,073,910	-5,317,122	2,149,956	77,695	16,700	-77,728	-2,736,660
2037	-3,123,673	-5,374,733	2,157,803	77,695	16,700	-86,611	-2,823,271
2038	-2,593,348	-4,852,129	2,165,523	77,695	16,700	-92,516	-2,915,787
2039	-2,747,138	-5,011,975	2,171,580	77,695	16,700	-96,195	-3,011,981
2040	-2,876,975	-5,150,933	2,180,702	77,695	16,700	-80,111	-3,092,093
2041	-3,045,814	-5,326,181	2,187,110	77,695	16,700	-97,543	-3,189,635
2042	-3,186,371	-5,474,195	2,194,567	77,695	16,700	-83,327	-3,272,963
2043	-2,564,527	-4,860,103	2,202,319	77,695	16,700	-99,311	-3,372,274
2044	-2,698,106	-4,999,785	2,208,422	77,695	16,700	-103,764	-3,476,038
2045	-2,821,280	-5,130,355	2,215,818	77,695	16,700	-107,180	-3,583,218
2046	-2,950,927	-5,267,887	2,223,703	77,695	16,700	-105,737	-3,688,954
2047	-3,065,631	-5,390,343	2,231,455	77,695	16,700	-96,472	-3,785,426
2048	-2,368,012	-4,700,470	2,239,201	77,695	16,700	-120,334	-3,905,760
2049	-2,512,510	-4,852,801	2,247,034	77,695	16,700	-118,849	-4,024,609
2050	-2,665,835	-5,013,822	2,254,731	77,695	16,700	-128,005	-4,152,614
2051	-2,766,334	-5,122,089	2,262,498	77,695	16,700	-107,035	-4,259,649
2052	-2,874,911	-5,238,415	2,270,248	77,695	16,700	-129,882	-4,389,531
2053	-2,172,179	-4,543,440	2,278,004	77,695	16,700	-158,603	-4,548,134
2054	-2,314,385	-4,693,460	2,285,817	77,695	16,700	-168,141	-4,716,275

Year	**C_{atm} (pellets)**	**NEP_{pel}**	**FP_{dec}**	**PEL_{comb}**	**LCE_{pel}**	**C_{atm} (pellets) (Relative to BAU)**	**C_{atm} (pellets) Cumulative (Relative to BAU)**
2055	-2,437,207	-4,824,012	2,293,548	77,695	16,700	-158,099	-4,874,374
2056	-2,539,862	-4,934,416	2,301,296	77,695	16,700	-144,353	-5,018,727
2057	-2,650,702	-5,053,006	2,309,047	77,695	16,700	-146,449	-5,165,177
2058	-2,004,244	-4,415,965	2,318,465	77,695	16,700	-145,448	-5,310,625
2059	-2,068,674	-4,486,790	2,324,859	77,695	16,700	-143,193	-5,453,818
2060	-2,125,635	-4,552,837	2,333,946	77,695	16,700	-138,862	-5,592,679
2061	-2,203,270	-4,638,482	2,341,955	77,695	16,700	-170,992	-5,763,672
2062	-2,275,355	-4,718,313	2,349,701	77,695	16,700	-165,978	-5,929,650
2063	-1,695,998	-4,148,421	2,359,166	77,695	16,700	-168,443	-6,098,093
2064	-1,835,930	-4,294,718	2,365,531	77,695	16,700	-184,319	-6,282,412
2065	-1,945,273	-4,413,180	2,374,649	77,695	16,700	-189,617	-6,472,030
2066	-2,053,847	-4,529,832	2,382,728	77,695	16,700	-205,258	-6,677,288
2067	-2,155,824	-4,641,208	2,392,126	77,695	16,700	-158,297	-6,835,585
2068	-1,566,330	-4,059,630	2,400,042	77,695	16,700	-213,370	-7,048,955
2069	-1,657,946	-4,159,181	2,407,978	77,695	16,700	-189,595	-7,238,550
2070	-1,748,831	-4,257,722	2,415,634	77,695	16,700	-166,085	-7,404,635
2071	-1,868,921	-4,387,162	2,424,984	77,695	16,700	-224,328	-7,628,963
2072	-1,911,522	-4,439,360	2,434,581	77,695	16,700	-177,719	-7,806,682
2073	-1,530,145	-4,065,937	2,442,535	77,695	16,700	-192,806	-7,999,488
2074	-1,609,592	-4,154,802	2,451,953	77,695	16,700	-203,707	-8,203,195
2075	-1,668,499	-4,221,702	2,459,946	77,695	16,700	-237,985	-8,441,181
2076	-1,667,206	-4,229,652	2,469,189	77,695	16,700	-150,565	-8,591,746
2077	-1,661,295	-4,233,327	2,478,775	77,695	16,700	-153,794	-8,745,539
2078	-1,419,127	-3,999,122	2,486,738	77,695	16,700	-229,081	-8,974,620
2079	-1,436,774	-4,024,440	2,494,410	77,695	16,700	-240,977	-9,215,597
2080	-1,446,399	-4,041,811	2,502,155	77,695	16,700	-183,058	-9,398,656
2081	-1,517,737	-4,122,554	2,511,560	77,695	16,700	-262,265	-9,660,920
2082	-1,654,640	-4,269,118	2,521,221	77,695	16,700	-303,135	-9,964,055
2083	-1,552,692	-4,176,781	2,530,832	77,695	16,700	-231,871	-10,195,927
2084	-1,505,740	-4,136,094	2,537,097	77,695	16,700	-180,504	-10,376,430
2085	-1,475,913	-4,115,333	2,546,162	77,695	16,700	-156,287	-10,532,717
2086	-1,492,034	-4,141,131	2,555,840	77,695	16,700	-229,687	-10,762,404
2087	-1,474,686	-4,133,450	2,565,507	77,695	16,700	-217,993	-10,980,397
2088	-1,412,175	-4,080,475	2,575,043	77,695	16,700	-263,176	-11,243,573
2089	-1,386,186	-4,062,528	2,583,085	77,695	16,700	-163,043	-11,406,616
2090	-1,456,808	-4,142,447	2,592,382	77,695	16,700	-292,937	-11,699,553
2091	-1,428,324	-4,123,619	2,602,038	77,695	16,700	-176,101	-11,875,654
2092	-1,428,383	-4,133,296	2,611,656	77,695	16,700	-258,284	-12,133,938
2093	-1,356,971	-4,071,423	2,621,195	77,695	16,700	-182,224	-12,316,162
2094	-1,372,155	-4,094,578	2,629,166	77,695	16,700	-227,479	-12,543,641
2095	-1,344,632	-4,076,336	2,638,447	77,695	16,700	-214,125	-12,757,766
2096	-1,391,103	-4,132,451	2,648,090	77,695	16,700	-239,474	-12,997,240
2097	-1,430,944	-4,181,901	2,657,701	77,695	16,700	-274,420	-13,271,660
2098	-1,356,999	-4,117,505	2,667,248	77,695	16,700	-275,056	-13,546,716
2099	-1,382,437	-4,152,639	2,676,946	77,695	16,700	-220,806	-13,767,522
2100	-1,483,642	-4,263,409	2,686,510	77,695	16,700	-368,869	-14,136,391
2101	-1,547,808	-4,337,155	2,696,090	77,695	16,700	-367,489	-14,503,880
2102	-1,462,973	-4,261,887	2,705,657	77,695	16,700	-174,652	-14,678,532
2103	-1,337,397	-4,145,872	2,715,218	77,695	16,700	-133,749	-14,812,281
2104	-1,375,356	-4,193,452	2,724,839	77,695	16,700	-289,100	-15,101,381
2105	-1,444,708	-4,272,356	2,734,391	77,695	16,700	-374,653	-15,476,034
2106	-1,419,002	-4,256,211	2,743,952	77,695	16,700	-251,523	-15,727,557
2107	-1,348,999	-4,192,272	2,750,015	77,695	16,700	-164,152	-15,891,709
2108	-1,311,819	-4,160,600	2,755,524	77,695	16,700	-225,158	-16,116,867
2109	-1,248,582	-4,103,118	2,761,279	77,695	16,700	-233,009	-16,349,875
2110	-1,209,233	-4,069,522	2,767,031	77,695	16,700	-205,341	-16,555,216

B12. Forest Carbon Simulation Data - Pellet Co-Fire Pathway 1

Table B12. Forest carbon simulation data for Pellet Co-Fire Pathway 1, broken down by region of harvest. Values expressed in tonnes of carbon.

Legend:
NPP = net primary productivity (Net growth + litterfall); Rh = heterotrophic respiration; NEP = net ecosystem productivity (NPP – Rh); Litterfall = carbon in litter layer on forest floor; Harvest = carbon in harvested wood; Bio2DOM = carbon in dead organic matter; Net Growth = carbon in forest growth; NBP = net biome production (NEP – Harvest)

Year	NPP	Rh	NEP	Litterfall	Harvest	Bio2DOM	Net Growth	NBP
Central Region								
2011	5,123,628	4,814,516	309,112	3,933,944	450,388	634,153	1,189,685	-141,276
2012	5,145,428	4,831,006	314,422	3,922,277	595,690	819,251	1,223,152	-281,268
2013	5,079,323	4,839,692	239,631	3,917,619	573,923	808,588	1,161,704	-334,292
2014	5,108,967	4,836,335	272,632	3,911,673	556,147	743,908	1,197,294	-283,515
2015	5,134,133	4,835,043	299,090	3,902,993	548,876	773,818	1,231,140	-249,785
2016	5,163,689	4,830,863	332,826	3,898,609	545,005	759,594	1,265,081	-212,179
2017	5,189,204	4,825,295	363,909	3,892,736	563,928	766,268	1,296,468	-200,019
2018	5,142,271	4,818,627	323,644	3,899,902	557,576	745,986	1,242,369	-233,932
2019	5,172,425	4,811,457	360,968	3,898,433	554,307	738,146	1,273,992	-193,339
2020	5,200,596	4,804,453	396,144	3,895,883	553,939	739,974	1,304,713	-157,795
2021	5,227,389	4,801,361	426,028	3,893,816	554,951	761,074	1,333,574	-128,923
2022	5,254,425	4,796,281	458,144	3,893,962	556,939	748,754	1,360,463	-98,796
2023	5,217,464	4,790,755	426,709	3,903,231	555,542	735,712	1,314,232	-128,834
2024	5,244,455	4,787,245	457,210	3,899,324	555,136	755,644	1,345,130	-97,926
2025	5,266,652	4,781,416	485,236	3,899,520	555,301	734,057	1,367,133	-70,065
2026	5,285,122	4,782,671	502,451	3,892,656	555,574	793,519	1,392,466	-53,123
2027	5,306,823	4,777,820	529,003	3,891,681	555,699	754,452	1,415,142	-26,696
2028	5,265,597	4,772,377	493,220	3,897,613	555,450	746,706	1,367,984	-62,231
2029	5,288,003	4,764,166	523,837	3,898,426	555,432	718,314	1,389,577	-31,595
2030	5,305,481	4,757,132	548,349	3,898,072	555,491	719,988	1,407,409	-7,142
2031	5,318,024	4,760,164	557,860	3,892,376	555,529	790,215	1,425,648	2,330
2032	5,329,140	4,757,774	571,365	3,889,443	555,521	763,524	1,439,697	15,845
2033	5,287,538	4,752,578	534,960	3,896,873	555,484	737,886	1,390,665	-20,524
2034	5,302,357	4,748,169	554,188	3,894,116	555,491	743,654	1,408,242	-1,303
2035	5,323,636	4,742,405	581,231	3,896,574	555,503	721,976	1,427,062	25,728
2036	5,342,167	4,737,831	604,336	3,895,648	555,506	730,390	1,446,519	48,830
2037	5,348,270	4,740,943	607,327	3,890,593	555,501	787,648	1,457,678	51,826
2038	5,306,880	4,742,281	564,599	3,894,558	555,497	780,750	1,412,322	9,102
2039	5,326,230	4,739,278	586,952	3,892,987	555,499	757,711	1,433,243	31,453
2040	5,347,700	4,734,748	612,952	3,892,237	555,502	744,652	1,455,462	57,450
2041	5,370,042	4,727,012	643,029	3,893,666	555,501	717,244	1,476,376	87,528
2042	5,392,638	4,724,356	668,282	3,896,160	555,500	733,896	1,496,478	112,782
2043	5,327,638	4,717,738	609,900	3,907,213	555,500	697,754	1,420,425	54,400
2044	5,350,010	4,716,661	633,349	3,908,293	555,501	727,642	1,441,717	77,849
2045	5,368,944	4,722,656	646,288	3,904,444	555,501	784,566	1,464,500	90,787
2046	5,390,735	4,723,455	667,280	3,904,731	555,501	758,245	1,486,003	111,779
2047	5,412,556	4,721,659	690,898	3,904,659	555,501	745,719	1,507,898	135,397
2048	5,322,394	4,715,147	607,246	3,913,994	555,501	703,322	1,408,400	51,746
2049	5,344,495	4,711,275	633,221	3,914,727	555,501	712,677	1,429,768	77,720
2050	5,369,828	4,709,706	660,121	3,918,343	555,501	713,520	1,451,485	104,621
2051	5,388,661	4,714,764	673,897	3,917,664	555,501	764,258	1,470,997	118,397
2052	5,408,205	4,718,539	689,666	3,918,446	555,501	763,474	1,489,758	134,165
2053	5,310,634	4,714,659	595,976	3,925,670	555,501	716,678	1,384,964	40,475
2054	5,331,955	4,711,178	620,777	3,926,951	555,501	709,220	1,405,004	65,277
2055	5,352,705	4,712,777	639,928	3,928,281	555,501	735,143	1,424,424	84,428
2056	5,372,812	4,715,946	656,866	3,930,863	555,501	744,356	1,441,948	101,366
2057	5,391,918	4,714,743	677,176	3,932,048	555,501	726,911	1,459,871	121,675

Year	NPP	Rh	NEP	Litterfall	Harvest	Bio2DOM	Net Growth	NBP
2058	5,303,665	4,712,940	590,724	3,939,522	555,501	715,271	1,364,143	35,224
2059	5,321,017	4,718,313	602,704	3,937,758	555,501	760,954	1,383,259	47,203
2060	5,337,136	4,719,106	618,030	3,936,069	555,501	747,215	1,401,068	62,530
2061	5,354,595	4,718,573	636,022	3,936,932	555,501	732,943	1,417,664	80,522
2062	5,373,780	4,719,753	654,027	3,940,921	555,501	735,400	1,432,859	98,526
2063	5,300,460	4,720,580	579,881	3,947,151	555,501	739,194	1,353,310	24,380
2064	5,326,570	4,716,659	609,912	3,959,006	555,501	678,098	1,367,564	54,411
2065	5,343,916	4,718,946	624,971	3,960,590	555,501	728,018	1,383,326	69,470
2066	5,369,176	4,715,336	653,839	3,977,705	555,501	650,121	1,391,471	98,339
2067	5,382,329	4,722,352	659,977	3,979,119	555,501	741,159	1,403,210	104,476
2068	5,328,066	4,723,327	604,739	3,994,604	555,501	683,846	1,333,462	49,239
2069	5,346,630	4,724,718	621,912	4,000,960	555,501	689,499	1,345,670	66,412
2070	5,368,780	4,724,198	644,582	4,012,454	555,501	660,222	1,356,326	89,081
2071	5,391,054	4,724,432	666,622	4,032,124	555,501	631,494	1,358,930	111,121
2072	5,403,317	4,733,869	669,447	4,038,348	555,501	706,197	1,364,969	113,947
2073	5,359,774	4,737,016	622,758	4,055,026	555,501	656,686	1,304,748	67,257
2074	5,373,311	4,742,133	631,178	4,062,475	555,501	669,563	1,310,836	75,677
2075	5,385,983	4,747,004	638,979	4,068,503	555,501	680,284	1,317,480	83,479
2076	5,396,271	4,750,965	645,306	4,074,865	555,501	674,229	1,321,406	89,805
2077	5,405,005	4,756,951	648,055	4,080,480	555,501	683,827	1,324,525	92,554
2078	5,379,352	4,761,779	617,573	4,092,248	555,501	669,108	1,287,104	62,072
2079	5,383,836	4,770,303	613,533	4,091,888	555,501	714,597	1,291,948	58,033
2080	5,397,409	4,770,215	627,194	4,103,082	555,501	640,703	1,294,327	71,693
2081	5,421,115	4,764,162	656,953	4,131,102	555,501	546,354	1,290,013	101,452
2082	5,431,109	4,772,764	658,345	4,143,515	555,501	643,531	1,287,595	102,844
2083	5,410,915	4,787,760	623,155	4,147,180	555,501	717,458	1,263,736	67,655
2084	5,412,265	4,798,127	614,138	4,146,695	555,501	707,348	1,265,570	58,637
2085	5,418,035	4,803,933	614,102	4,152,750	555,501	675,278	1,265,284	58,601
2086	5,417,043	4,810,979	606,064	4,153,735	555,501	701,315	1,263,308	50,563
2087	5,417,476	4,815,051	602,426	4,155,963	555,501	683,407	1,261,513	46,925
2088	5,417,276	4,814,990	602,286	4,167,501	555,501	641,398	1,249,774	46,785
2089	5,423,999	4,818,891	605,108	4,174,068	555,501	658,987	1,249,930	49,607
2090	5,423,825	4,826,098	597,727	4,172,542	555,501	698,736	1,251,283	42,226
2091	5,432,575	4,825,426	607,149	4,183,836	555,501	626,304	1,248,739	51,648
2092	5,435,410	4,829,507	605,902	4,189,668	555,501	660,836	1,245,742	50,402
2093	5,427,863	4,839,406	588,456	4,187,477	555,501	716,519	1,240,386	32,956
2094	5,434,152	4,840,785	593,367	4,195,510	555,501	649,104	1,238,642	37,866
2095	5,432,154	4,847,970	584,183	4,194,445	555,501	706,440	1,237,709	28,683
2096	5,438,162	4,849,011	589,151	4,200,755	555,501	655,735	1,237,407	33,651
2097	5,432,276	4,854,750	577,526	4,195,110	555,501	714,890	1,237,166	22,025
2098	5,446,090	4,846,275	599,815	4,216,918	555,501	559,942	1,229,171	44,314
2099	5,465,542	4,841,365	624,177	4,241,018	555,501	546,103	1,224,524	68,676
2100	5,462,255	4,855,172	607,083	4,239,442	555,501	698,802	1,222,813	51,583
2101	5,458,906	4,867,506	591,401	4,231,728	555,501	725,539	1,227,178	35,900
2102	5,461,837	4,867,552	594,285	4,237,899	555,501	635,144	1,223,938	38,784
2103	5,469,587	4,867,110	602,477	4,251,021	555,501	606,161	1,218,566	46,977
2104	5,463,208	4,878,233	584,976	4,246,928	555,501	711,390	1,216,280	29,475
2105	5,452,522	4,889,777	562,745	4,237,113	555,501	751,901	1,215,409	7,244
2106	5,444,029	4,898,796	545,232	4,223,610	555,501	772,168	1,220,419	-10,268
2107	5,434,865	4,901,457	533,408	4,210,589	555,501	755,833	1,224,276	-22,092
2108	5,425,401	4,902,997	522,404	4,198,735	555,501	759,208	1,226,666	-33,096
2109	5,411,522	4,904,646	506,876	4,184,250	555,501	779,779	1,227,273	-48,625
2110	5,405,900	4,899,245	506,655	4,175,492	555,501	737,053	1,230,408	-48,846
Eastern Region								
2011	4,359,558	3,854,578	504,980	3,457,137	195,529	291,256	902,421	309,451
2012	4,397,744	3,857,949	539,795	3,471,951	224,567	323,313	925,792	315,228
2013	4,347,202	3,862,653	484,549	3,496,721	217,749	324,092	850,481	266,801
2014	4,380,237	3,866,308	513,929	3,509,781	216,719	315,938	870,455	297,209
2015	4,411,862	3,870,881	540,981	3,522,328	220,157	321,642	889,534	320,824
2016	4,444,923	3,874,930	569,993	3,536,724	214,944	310,957	908,199	355,049
2017	4,480,605	3,880,024	600,581	3,549,479	218,827	318,940	931,126	381,755

Year	NPP	Rh	NEP	Litterfall	Harvest	Bio2DOM	Net Growth	NBP
2018	4,432,749	3,884,313	548,437	3,576,039	217,679	298,184	856,710	330,757
2019	4,460,805	3,891,566	569,239	3,588,966	217,666	314,715	871,840	351,574
2020	4,487,252	3,896,480	590,772	3,601,092	217,854	302,671	886,160	372,918
2021	4,510,860	3,903,711	607,148	3,613,893	217,394	310,106	896,967	389,754
2022	4,532,506	3,909,398	623,108	3,625,247	217,884	305,359	907,259	405,224
2023	4,494,822	3,918,223	576,599	3,648,031	217,695	319,339	846,791	358,903
2024	4,518,768	3,923,359	595,409	3,659,886	217,699	294,371	858,882	377,710
2025	4,534,658	3,929,625	605,033	3,668,436	217,705	305,050	866,222	387,328
2026	4,543,558	3,938,385	605,172	3,675,751	217,676	323,479	867,807	387,497
2027	4,563,444	3,944,268	619,176	3,684,813	217,731	307,196	878,630	401,445
2028	4,524,128	3,949,559	574,569	3,706,528	217,701	294,418	817,599	356,869
2029	4,539,925	3,955,582	584,343	3,713,385	217,702	303,019	826,539	366,641
2030	4,554,830	3,964,077	590,753	3,719,445	217,703	323,139	835,385	373,050
2031	4,570,232	3,972,069	598,163	3,726,247	217,703	322,634	843,985	380,460
2032	4,586,148	3,977,180	608,968	3,736,220	217,709	301,270	849,928	391,260
2033	4,547,968	3,979,867	568,100	3,756,953	217,704	280,533	791,014	350,396
2034	4,563,155	3,984,472	578,683	3,764,855	217,704	287,608	798,300	360,979
2035	4,577,673	3,990,345	587,328	3,770,589	217,704	298,785	807,084	369,624
2036	4,590,655	4,000,235	590,419	3,774,071	217,704	331,835	816,584	372,715
2037	4,604,464	4,007,281	597,184	3,779,754	217,705	318,010	824,711	379,479
2038	4,549,870	4,012,198	537,671	3,795,604	217,704	302,788	754,266	319,967
2039	4,564,080	4,018,157	545,923	3,800,997	217,704	307,015	763,084	328,219
2040	4,579,995	4,024,172	555,823	3,808,085	217,704	305,411	771,911	338,119
2041	4,592,762	4,030,993	561,770	3,812,614	217,704	317,575	780,148	344,065
2042	4,607,679	4,035,108	572,571	3,820,752	217,704	295,273	786,927	354,867
2043	4,539,998	4,041,908	498,090	3,833,447	217,704	318,211	706,551	280,386
2044	4,551,407	4,047,859	503,549	3,836,968	217,704	312,807	714,439	285,844
2045	4,563,599	4,052,758	510,841	3,840,131	217,704	310,644	723,469	293,136
2046	4,577,085	4,055,754	521,331	3,845,014	217,704	296,437	732,071	303,627
2047	4,590,624	4,059,982	530,643	3,849,909	217,704	300,882	740,715	312,938
2048	4,522,282	4,064,802	457,480	3,861,486	217,704	304,011	660,796	239,775
2049	4,531,801	4,068,702	463,099	3,862,191	217,704	304,948	669,610	245,395
2050	4,541,042	4,073,861	467,181	3,862,380	217,704	316,705	678,662	249,477
2051	4,549,267	4,077,392	471,875	3,862,147	217,704	313,718	687,120	254,171
2052	4,559,885	4,083,052	476,833	3,864,053	217,704	323,148	695,831	259,129
2053	4,501,262	4,086,935	414,326	3,874,012	217,704	310,403	627,249	196,622
2054	4,511,834	4,090,391	421,444	3,876,537	217,704	306,393	635,297	203,739
2055	4,524,855	4,090,645	434,210	3,881,992	217,704	282,292	642,863	216,506
2056	4,536,628	4,090,236	446,391	3,886,583	217,704	273,758	650,045	228,687
2057	4,547,725	4,092,592	455,134	3,889,888	217,704	286,690	657,838	237,430
2058	4,492,481	4,095,711	396,770	3,899,471	217,704	290,170	593,010	179,066
2059	4,498,385	4,101,403	396,983	3,897,409	217,704	314,231	600,976	179,278
2060	4,502,920	4,107,426	395,494	3,893,069	217,704	331,413	609,851	177,789
2061	4,509,626	4,112,248	397,378	3,891,945	217,704	325,374	617,681	179,674
2062	4,518,004	4,114,447	403,556	3,892,550	217,704	310,161	625,454	185,852
2063	4,462,696	4,116,638	346,057	3,900,087	217,704	307,974	562,609	128,353
2064	4,470,437	4,117,969	352,469	3,900,522	217,704	300,632	569,916	134,764
2065	4,475,923	4,120,912	355,012	3,897,933	217,704	318,223	577,990	137,307
2066	4,480,567	4,123,432	357,135	3,895,474	217,704	320,248	585,093	139,431
2067	4,487,812	4,126,883	360,929	3,895,509	217,704	322,363	592,302	143,225
2068	4,419,181	4,129,194	289,987	3,903,145	217,704	314,451	516,036	72,283
2069	4,427,122	4,128,633	298,489	3,904,214	217,704	293,562	522,908	80,785
2070	4,435,219	4,126,075	309,144	3,905,835	217,704	277,349	529,383	91,439
2071	4,438,840	4,127,742	311,098	3,903,984	217,704	304,574	534,855	93,394
2072	4,438,617	4,133,783	304,834	3,897,528	217,704	346,512	541,089	87,130
2073	4,413,254	4,133,367	279,886	3,905,283	217,704	299,560	507,970	62,182
2074	4,416,523	4,135,086	281,437	3,902,828	217,704	314,846	513,695	63,733
2075	4,421,500	4,135,197	286,303	3,901,944	217,704	303,232	519,556	68,599
2076	4,426,848	4,134,578	292,270	3,902,526	217,704	294,171	524,322	74,566
2077	4,429,593	4,137,612	291,981	3,899,086	217,704	324,283	530,507	74,277
2078	4,409,194	4,139,509	269,685	3,904,039	217,704	317,536	505,155	51,981

Year	NPP	Rh	NEP	Litterfall	Harvest	Bio2DOM	Net Growth	NBP
2079	4,413,410	4,142,616	270,794	3,901,814	217,704	325,952	511,596	53,090
2080	4,419,948	4,140,381	279,567	3,902,887	217,704	290,711	517,061	61,863
2081	4,420,770	4,140,590	280,180	3,900,517	217,704	309,293	520,253	62,476
2082	4,420,837	4,144,900	275,937	3,895,191	217,704	342,553	525,646	58,233
2083	4,408,965	4,144,323	264,642	3,899,223	217,704	311,108	509,742	46,938
2084	4,413,516	4,144,527	268,989	3,897,913	217,704	312,002	515,603	51,285
2085	4,418,627	4,142,555	276,072	3,898,930	217,704	292,903	519,697	58,368
2086	4,417,087	4,144,822	272,265	3,894,221	217,704	329,790	522,866	54,560
2087	4,420,099	4,145,997	274,102	3,894,256	217,704	316,285	525,843	56,398
2088	4,412,937	4,148,225	264,712	3,898,245	217,704	322,397	514,692	47,008
2089	4,417,290	4,144,935	272,355	3,898,761	217,704	289,164	518,529	54,651
2090	4,415,623	4,148,221	267,402	3,892,749	217,704	339,649	522,874	49,698
2091	4,416,630	4,149,089	267,541	3,891,002	217,704	323,390	525,628	49,836
2092	4,419,035	4,148,371	270,664	3,890,467	217,704	311,230	528,568	52,960
2093	4,415,954	4,146,561	269,392	3,894,275	217,704	298,696	521,679	51,688
2094	4,413,882	4,150,449	263,433	3,887,135	217,704	349,917	526,747	45,729
2095	4,414,992	4,153,902	261,090	3,884,046	217,704	346,834	530,945	43,386
2096	4,417,476	4,150,910	266,566	3,884,336	217,704	305,692	533,141	48,862
2097	4,414,760	4,153,247	261,512	3,878,403	217,704	349,471	536,357	43,808
2098	4,410,124	4,152,916	257,209	3,878,082	217,704	329,982	532,043	39,505
2099	4,414,908	4,148,014	266,894	3,880,623	217,704	289,314	534,285	49,190
2100	4,413,710	4,149,915	263,796	3,877,303	217,704	335,961	536,407	46,091
2101	4,415,007	4,150,621	264,386	3,876,865	217,704	325,436	538,141	46,682
2102	4,417,633	4,148,745	268,888	3,877,799	217,704	307,510	539,833	51,183
2103	4,411,269	4,149,916	261,353	3,874,694	217,704	334,519	536,575	43,649
2104	4,410,918	4,150,956	259,962	3,871,740	217,704	334,924	539,178	42,257
2105	4,415,235	4,149,624	265,611	3,872,633	217,704	313,680	542,603	47,907
2106	4,416,059	4,151,609	264,450	3,871,017	217,704	338,818	545,042	46,745
2107	4,415,530	4,152,615	262,915	3,868,929	217,704	337,311	546,601	45,210
2108	4,408,869	4,154,260	254,609	3,865,088	217,704	349,392	543,781	36,905
2109	4,409,675	4,154,128	255,548	3,862,990	217,704	337,930	546,685	37,843
2110	4,420,130	4,148,429	271,701	3,872,287	217,704	274,181	547,844	53,997
Western Region								
2011	5,205,073	4,517,145	687,929	4,442,704	326,531	423,126	762,370	361,397
2012	5,209,640	4,545,970	663,669	4,437,852	305,080	399,581	771,788	358,589
2013	5,101,278	4,568,652	532,626	4,442,154	298,492	392,489	659,125	234,134
2014	5,104,841	4,585,651	519,190	4,433,880	292,910	389,691	670,962	226,280
2015	5,108,002	4,601,115	506,887	4,425,871	304,466	406,728	682,131	202,421
2016	5,113,102	4,612,715	500,386	4,419,930	305,495	399,501	693,171	194,891
2017	5,117,677	4,622,405	495,273	4,413,512	301,289	402,751	704,165	193,984
2018	5,024,542	4,629,738	394,804	4,418,301	300,531	396,210	606,241	94,273
2019	5,027,574	4,636,453	391,121	4,408,645	300,938	408,022	618,929	90,183
2020	5,031,418	4,640,460	390,957	4,401,387	302,543	398,312	630,031	88,414
2021	5,036,822	4,643,317	393,505	4,394,788	302,159	396,630	642,034	91,346
2022	5,041,974	4,646,046	395,927	4,388,867	301,492	398,102	653,106	94,435
2023	4,968,468	4,646,665	321,803	4,397,263	301,533	380,130	571,205	20,271
2024	4,973,942	4,646,993	326,949	4,390,389	301,733	383,652	583,553	25,216
2025	4,972,817	4,647,650	325,168	4,382,455	301,891	390,992	590,362	23,276
2026	4,975,589	4,648,196	327,393	4,375,695	301,762	392,121	599,894	25,631
2027	4,973,550	4,650,198	323,352	4,364,602	301,682	415,943	608,947	21,670
2028	4,911,184	4,651,342	259,842	4,366,836	301,720	416,221	544,348	-41,878
2029	4,914,257	4,648,976	265,281	4,358,993	301,758	392,921	555,264	-36,477
2030	4,913,939	4,647,961	265,978	4,350,307	301,763	403,564	563,632	-35,786
2031	4,916,175	4,644,398	271,777	4,342,063	301,737	391,443	574,113	-29,960
2032	4,912,703	4,640,178	272,525	4,332,571	301,732	390,549	580,132	-29,207
2033	4,873,306	4,638,014	235,292	4,338,246	301,742	394,153	535,060	-66,450
2034	4,877,520	4,636,010	241,511	4,330,772	301,746	394,544	546,749	-60,235
2035	4,883,197	4,633,461	249,735	4,325,416	301,744	388,043	557,781	-52,009
2036	4,885,140	4,632,944	252,196	4,315,304	301,741	413,609	569,836	-49,545
2037	4,886,939	4,631,368	255,571	4,305,478	301,741	413,566	581,461	-46,169
2038	4,849,983	4,629,127	220,856	4,309,544	301,743	407,418	540,439	-80,887

Year	NPP	Rh	NEP	Litterfall	Harvest	Bio2DOM	Net Growth	NBP
2039	4,855,909	4,624,397	231,512	4,303,652	301,743	386,055	552,257	-70,231
2040	4,860,836	4,621,622	239,214	4,298,577	301,742	391,568	562,260	-62,527
2041	4,866,302	4,617,831	248,472	4,293,597	301,742	386,081	572,705	-53,270
2042	4,870,603	4,614,590	256,013	4,287,018	301,742	391,432	583,584	-45,729
2043	4,833,478	4,612,332	221,146	4,289,313	301,742	400,197	544,165	-80,596
2044	4,837,200	4,610,285	226,915	4,281,667	301,742	399,879	555,533	-74,827
2045	4,844,099	4,606,644	237,454	4,277,447	301,742	384,239	566,652	-64,288
2046	4,851,331	4,603,699	247,632	4,272,262	301,742	388,098	579,069	-54,110
2047	4,854,930	4,603,957	250,972	4,263,867	301,742	416,195	591,063	-50,770
2048	4,822,159	4,601,115	221,044	4,269,550	301,742	389,841	552,610	-80,698
2049	4,829,761	4,597,442	232,319	4,265,926	301,742	381,017	563,835	-69,423
2050	4,837,128	4,594,718	242,410	4,262,442	301,742	382,599	574,687	-59,332
2051	4,845,452	4,591,925	253,527	4,262,419	301,742	371,868	583,033	-48,215
2052	4,850,940	4,590,258	260,682	4,257,122	301,742	389,803	593,819	-41,060
2053	4,817,189	4,588,587	228,602	4,259,590	301,742	387,623	557,599	-73,140
2054	4,821,166	4,586,726	234,440	4,252,723	301,742	389,649	568,443	-67,302
2055	4,825,699	4,585,636	240,062	4,247,872	301,742	391,953	577,827	-61,679
2056	4,828,049	4,583,689	244,360	4,241,113	301,742	394,160	586,936	-57,381
2057	4,831,642	4,581,711	249,931	4,235,545	301,742	393,305	596,097	-51,811
2058	4,802,773	4,579,067	223,705	4,242,660	301,742	374,287	560,113	-78,037
2059	4,806,587	4,577,089	229,498	4,236,642	301,742	387,578	569,945	-72,244
2060	4,811,563	4,575,061	236,501	4,231,194	301,742	387,064	580,369	-65,240
2061	4,811,167	4,577,427	233,740	4,221,019	301,742	428,239	590,148	-68,002
2062	4,807,823	4,577,057	230,766	4,209,311	301,742	427,279	598,512	-70,976
2063	4,777,011	4,575,942	201,069	4,208,024	301,742	420,157	568,987	-100,673
2064	4,778,882	4,573,091	205,791	4,199,764	301,742	413,531	579,118	-95,951
2065	4,785,507	4,568,037	217,470	4,197,259	301,742	387,808	588,248	-84,272
2066	4,789,238	4,564,531	224,707	4,192,766	301,742	396,379	596,472	-77,035
2067	4,795,646	4,560,506	235,140	4,191,383	301,742	384,000	604,264	-66,602
2068	4,762,801	4,557,331	205,470	4,190,553	301,742	394,219	572,248	-96,272
2069	4,764,347	4,554,294	210,052	4,183,123	301,742	397,393	581,224	-91,689
2070	4,768,770	4,552,501	216,269	4,179,332	301,742	398,008	589,438	-85,472
2071	4,769,984	4,548,621	221,362	4,173,434	301,742	392,043	596,549	-80,379
2072	4,773,391	4,545,504	227,888	4,169,864	301,742	389,239	603,527	-73,854
2073	4,753,803	4,544,081	209,722	4,169,310	301,742	400,334	584,493	-92,020
2074	4,754,916	4,542,168	212,748	4,164,185	301,742	399,109	590,731	-88,994
2075	4,757,551	4,539,372	218,179	4,159,381	301,742	394,911	598,170	-83,563
2076	4,755,593	4,539,402	216,191	4,149,983	301,742	423,903	605,610	-85,551
2077	4,755,277	4,536,693	218,583	4,142,497	301,742	410,670	612,780	-83,159
2078	4,734,974	4,537,919	197,055	4,132,411	301,742	452,060	602,563	-104,687
2079	4,732,865	4,535,831	197,034	4,122,027	301,742	436,957	610,838	-104,708
2080	4,736,445	4,531,453	204,992	4,117,725	301,742	413,673	618,720	-96,750
2081	4,738,865	4,527,317	211,548	4,112,083	301,742	415,794	626,782	-90,194
2082	4,742,735	4,521,885	220,850	4,109,288	301,742	399,648	633,448	-80,891
2083	4,740,058	4,517,318	222,740	4,112,593	301,742	392,315	627,465	-79,001
2084	4,741,944	4,513,419	228,525	4,107,658	301,742	401,961	634,286	-73,217
2085	4,745,659	4,509,956	235,703	4,104,353	301,742	399,005	641,307	-66,038
2086	4,746,707	4,509,275	237,432	4,098,740	301,742	421,399	647,968	-64,310
2087	4,748,710	4,506,058	242,652	4,095,699	301,742	403,403	653,011	-59,090
2088	4,746,116	4,503,130	242,986	4,095,764	301,742	400,549	650,352	-58,756
2089	4,749,569	4,500,569	249,000	4,092,784	301,742	402,241	656,784	-52,742
2090	4,747,358	4,502,796	244,562	4,084,027	301,742	447,040	663,331	-57,180
2091	4,753,583	4,497,779	255,804	4,084,250	301,742	390,009	669,333	-45,938
2092	4,748,126	4,499,548	248,578	4,072,268	301,742	456,693	675,859	-53,164
2093	4,744,189	4,499,495	244,694	4,068,607	301,742	443,385	675,582	-57,048
2094	4,745,608	4,496,406	249,203	4,063,302	301,742	428,315	682,306	-52,539
2095	4,751,505	4,491,073	260,432	4,063,407	301,742	400,625	688,098	-41,310
2096	4,755,498	4,489,167	266,332	4,061,435	301,742	419,463	694,063	-35,410
2097	4,756,992	4,485,470	271,522	4,058,352	301,742	411,487	698,640	-30,220
2098	4,754,281	4,483,765	270,517	4,057,079	301,742	420,232	697,202	-31,225
2099	4,757,297	4,480,855	276,442	4,054,792	301,742	411,780	702,505	-25,300

Year	NPP	Rh	NEP	Litterfall	Harvest	Bio2DOM	Net Growth	NBP
2100	4,761,383	4,477,880	283,503	4,054,904	301,742	402,942	706,480	-18,238
2101	4,761,249	4,477,621	283,628	4,050,686	301,742	427,408	710,563	-18,114
2102	4,763,073	4,475,062	288,011	4,050,677	301,742	406,385	712,397	-13,731
2103	4,754,899	4,479,353	275,546	4,041,908	301,742	470,672	712,992	-26,196
2104	4,753,873	4,479,507	274,366	4,036,965	301,742	448,900	716,908	-27,376
2105	4,761,152	4,474,664	286,488	4,039,646	301,742	401,816	721,506	-15,254
2106	4,763,932	4,473,398	290,534	4,039,251	301,742	423,611	724,681	-11,208
2107	4,765,522	4,470,351	295,171	4,037,988	301,742	414,663	727,534	-6,570
2108	4,765,229	4,469,652	295,577	4,037,938	301,742	424,749	727,291	-6,165
2109	4,769,089	4,467,411	301,678	4,038,390	301,742	411,636	730,699	-64
2110	4,776,038	4,464,206	311,832	4,042,137	301,742	393,316	733,902	10,091

B13. Life Cycle GHG Emissions for the Business as Usual Reference Case for Pellet Co-Fire Pathway 1

Table B13. Life cycle GHG emissions for business as usual forest harvesting in Nova Scotia and business as usual electricity generation with coal in the Netherlands, expressed in tonnes of CO_2 equivalents.

Year	C_{atm} (BAU)	NEP_{bau}	FP_{dec}	LCE_{fos}
2011	-1,895,349	-5,525,592	1,784,704	1,845,540
2012	-1,668,049	-5,596,227	2,082,639	1,845,540
2013	-776,937	-4,648,201	2,025,724	1,845,540
2014	-1,009,119	-4,840,932	1,986,273	1,845,540
2015	-1,151,823	-5,004,558	2,007,195	1,845,540
2016	-1,373,030	-5,216,253	1,997,683	1,845,540
2017	-1,549,221	-5,435,573	2,040,812	1,845,540
2018	-846,700	-4,725,387	2,033,146	1,845,540
2019	-1,060,254	-4,937,853	2,032,059	1,845,540
2020	-1,262,145	-5,149,299	2,041,614	1,845,540
2021	-1,451,021	-5,344,704	2,048,143	1,845,540
2022	-1,619,721	-5,524,494	2,059,233	1,845,540
2023	-1,056,856	-4,966,533	2,064,137	1,845,540
2024	-1,261,611	-5,175,201	2,068,050	1,845,540
2025	-1,384,826	-5,306,122	2,075,756	1,845,540
2026	-1,465,788	-5,393,571	2,082,243	1,845,540
2027	-1,581,433	-5,516,999	2,090,026	1,845,540
2028	-1,047,681	-4,988,869	2,095,648	1,845,540
2029	-1,206,031	-5,153,014	2,101,443	1,845,540
2030	-1,320,558	-5,273,386	2,107,288	1,845,540
2031	-1,413,925	-5,374,400	2,114,935	1,845,540
2032	-1,481,120	-5,449,409	2,122,750	1,845,540
2033	-1,055,478	-5,031,514	2,130,496	1,845,540
2034	-1,175,109	-5,155,506	2,134,857	1,845,540
2035	-1,327,560	-5,315,187	2,142,087	1,845,540
2036	-1,445,203	-5,440,699	2,149,956	1,845,540
2037	-1,486,084	-5,489,427	2,157,803	1,845,540
2038	-949,854	-4,960,918	2,165,523	1,845,540
2039	-1,099,965	-5,117,085	2,171,580	1,845,540
2040	-1,245,886	-5,272,127	2,180,702	1,845,540
2041	-1,397,293	-5,429,944	2,187,110	1,845,540
2042	-1,552,066	-5,592,173	2,194,567	1,845,540
2043	-914,238	-4,962,098	2,202,319	1,845,540
2044	-1,043,363	-5,097,326	2,208,422	1,845,540
2045	-1,163,123	-5,224,480	2,215,818	1,845,540
2046	-1,294,213	-5,363,456	2,223,703	1,845,540
2047	-1,418,181	-5,495,176	2,231,455	1,845,540
2048	-696,700	-4,781,441	2,239,201	1,845,540
2049	-842,683	-4,935,257	2,247,034	1,845,540
2050	-986,851	-5,087,122	2,254,731	1,845,540
2051	-1,108,322	-5,216,360	2,262,498	1,845,540
2052	-1,194,051	-5,309,838	2,270,248	1,845,540
2053	-462,598	-4,586,142	2,278,004	1,845,540
2054	-595,266	-4,726,624	2,285,817	1,845,540
2055	-728,130	-4,867,218	2,293,548	1,845,540
2056	-844,531	-4,991,367	2,301,296	1,845,540
2057	-953,275	-5,107,862	2,309,047	1,845,540
2058	-307,818	-4,471,822	2,318,465	1,845,540
2059	-374,503	-4,544,902	2,324,859	1,845,540
2060	-435,795	-4,615,281	2,333,946	1,845,540
2061	-481,300	-4,668,795	2,341,955	1,845,540

Year	C_{atm} (BAU)	NEP_{bau}	FP_{dec}	LCE_{fos}
2062	-558,399	-4,753,640	2,349,701	1,845,540
2063	23,423	-4,181,283	2,359,166	1,845,540
2064	-100,633	-4,311,703	2,365,531	1,845,540
2065	-204,678	-4,424,867	2,374,649	1,845,540
2066	-297,611	-4,525,879	2,382,728	1,845,540
2067	-446,550	-4,684,216	2,392,126	1,845,540
2068	198,018	-4,047,565	2,400,042	1,845,540
2069	82,627	-4,170,891	2,407,978	1,845,540
2070	-31,768	-4,292,942	2,415,634	1,845,540
2071	-93,616	-4,364,140	2,424,984	1,845,540
2072	-182,825	-4,462,946	2,434,581	1,845,540
2073	213,640	-4,074,436	2,442,535	1,845,540
2074	145,093	-4,152,400	2,451,953	1,845,540
2075	120,464	-4,185,021	2,459,946	1,845,540
2076	34,337	-4,280,392	2,469,189	1,845,540
2077	43,477	-4,280,838	2,478,775	1,845,540
2078	360,932	-3,971,347	2,486,738	1,845,540
2079	355,181	-3,984,768	2,494,410	1,845,540
2080	287,637	-4,060,058	2,502,155	1,845,540
2081	295,506	-4,061,594	2,511,560	1,845,540
2082	199,473	-4,167,288	2,521,221	1,845,540
2083	230,157	-4,146,215	2,530,832	1,845,540
2084	225,742	-4,156,895	2,537,097	1,845,540
2085	231,352	-4,160,351	2,546,162	1,845,540
2086	288,631	-4,112,749	2,555,840	1,845,540
2087	294,285	-4,116,762	2,565,507	1,845,540
2088	401,979	-4,018,604	2,575,043	1,845,540
2089	327,835	-4,100,790	2,583,085	1,845,540
2090	387,107	-4,050,814	2,592,382	1,845,540
2091	298,755	-4,148,823	2,602,038	1,845,540
2092	380,878	-4,076,318	2,611,656	1,845,540
2093	376,231	-4,090,504	2,621,195	1,845,540
2094	406,302	-4,068,404	2,629,166	1,845,540
2095	420,471	-4,063,515	2,638,447	1,845,540
2096	399,349	-4,094,281	2,648,090	1,845,540
2097	394,454	-4,108,787	2,657,701	1,845,540
2098	469,035	-4,043,754	2,667,248	1,845,540
2099	389,347	-4,133,138	2,676,946	1,845,540
2100	436,205	-4,095,844	2,686,510	1,845,540
2101	370,659	-4,170,971	2,696,090	1,845,540
2102	262,657	-4,288,540	2,705,657	1,845,540
2103	347,330	-4,213,428	2,715,218	1,845,540
2104	464,721	-4,105,657	2,724,839	1,845,540
2105	480,923	-4,099,008	2,734,391	1,845,540
2106	383,500	-4,205,993	2,743,952	1,845,540
2107	366,130	-4,229,425	2,750,015	1,845,540
2108	464,317	-4,136,747	2,755,524	1,845,540
2109	535,405	-4,071,414	2,761,279	1,845,540
2110	547,086	-4,065,486	2,767,031	1,845,540

B14. Life Cycle GHG Emissions Data - Pellet Co-Fire Pathway 1

Table B14. Life cycle GHG emissions for Pellet Co-Fire Pathway 1, including forest carbon emissions data for all three regions of Nova Scotia and life cycle emissions for co-firing of wood pellets (80% from chipped hardwood) with coal in the Netherlands, expressed in tonnes of CO_2 equivalents.

Year	C_{atm} (pellets)	NEP_{pel}	FP_{dec}	PEL_{comb}	LCE_{pel}	C_{atm} (pellets) (Relative to BAU)	C_{atm} (pellets) Cumulative (Relative to BAU)
2011	-1,914,459	-5,512,415	1,784,704	69,062	1,744,190	-19,110	-19,110
2012	-1,674,752	-5,570,643	2,082,639	69,062	1,744,190	-6,703	-25,813
2013	-773,503	-4,612,479	2,025,724	69,062	1,744,190	3,434	-22,380
2014	-992,581	-4,792,106	1,986,273	69,062	1,744,190	16,538	-5,841
2015	-1,122,886	-4,943,334	2,007,195	69,062	1,744,190	28,937	23,096
2016	-1,338,829	-5,149,764	1,997,683	69,062	1,744,190	34,201	57,297
2017	-1,503,265	-5,357,330	2,040,812	69,062	1,744,190	45,956	103,253
2018	-803,069	-4,649,467	2,033,146	69,062	1,744,190	43,631	146,884
2019	-1,003,964	-4,849,275	2,032,059	69,062	1,744,190	56,290	203,175
2020	-1,201,928	-5,056,794	2,041,614	69,062	1,744,190	60,217	263,392
2021	-1,374,524	-5,235,920	2,048,143	69,062	1,744,190	76,496	339,888
2022	-1,548,763	-5,421,248	2,059,233	69,062	1,744,190	70,958	410,846
2023	-985,768	-4,863,157	2,064,137	69,062	1,744,190	71,088	481,934
2024	-1,181,712	-5,063,014	2,068,050	69,062	1,744,190	79,899	561,833
2025	-1,305,645	-5,194,654	2,075,756	69,062	1,744,190	79,181	641,014
2026	-1,371,017	-5,266,511	2,082,243	69,062	1,744,190	94,772	735,786
2027	-1,497,240	-5,400,518	2,090,026	69,062	1,744,190	84,193	819,979
2028	-963,506	-4,872,406	2,095,648	69,062	1,744,190	84,175	904,154
2029	-1,125,907	-5,040,602	2,101,443	69,062	1,744,190	80,124	984,278
2030	-1,236,103	-5,156,643	2,107,288	69,062	1,744,190	84,455	1,068,733
2031	-1,311,840	-5,240,027	2,114,935	69,062	1,744,190	102,085	1,170,818
2032	-1,395,991	-5,331,993	2,122,750	69,062	1,744,190	85,129	1,255,947
2033	-968,005	-4,911,753	2,130,496	69,062	1,744,190	87,473	1,343,420
2034	-1,095,873	-5,043,983	2,134,857	69,062	1,744,190	79,235	1,422,655
2035	-1,249,804	-5,205,142	2,142,087	69,062	1,744,190	77,756	1,500,412
2036	-1,347,103	-5,310,311	2,149,956	69,062	1,744,190	98,100	1,598,512
2037	-1,387,447	-5,358,503	2,157,803	69,062	1,744,190	98,636	1,697,148
2038	-877,097	-4,855,872	2,165,523	69,062	1,744,190	72,757	1,769,905
2039	-1,022,470	-5,007,302	2,171,580	69,062	1,744,190	77,495	1,847,401
2040	-1,173,370	-5,167,323	2,180,702	69,062	1,744,190	72,516	1,919,917
2041	-1,333,141	-5,333,504	2,187,111	69,062	1,744,190	64,152	1,984,069
2042	-1,485,678	-5,493,497	2,194,567	69,062	1,744,190	66,387	2,050,456
2043	-862,357	-4,877,928	2,202,319	69,062	1,744,190	51,881	2,102,337
2044	-983,517	-5,005,191	2,208,422	69,062	1,744,190	59,846	2,162,184
2045	-1,089,049	-5,118,119	2,215,818	69,062	1,744,190	74,074	2,236,258
2046	-1,234,056	-5,271,011	2,223,703	69,062	1,744,190	60,156	2,296,414
2047	-1,359,413	-5,404,120	2,231,455	69,062	1,744,190	58,768	2,355,182
2048	-666,323	-4,718,776	2,239,201	69,062	1,744,190	30,378	2,385,560
2049	-815,817	-4,876,104	2,247,034	69,062	1,744,190	26,866	2,412,426
2050	-958,860	-5,026,843	2,254,731	69,062	1,744,190	27,991	2,440,417
2051	-1,059,678	-5,135,428	2,262,498	69,062	1,744,190	48,644	2,489,061
2052	-1,154,256	-5,237,756	2,270,247	69,062	1,744,190	39,794	2,528,855
2053	-455,523	-4,546,779	2,278,004	69,062	1,744,190	7,075	2,535,930
2054	-586,275	-4,685,345	2,285,818	69,062	1,744,190	8,991	2,544,922
2055	-716,318	-4,823,118	2,293,548	69,062	1,744,190	11,813	2,556,734
2056	-831,209	-4,945,758	2,301,296	69,062	1,744,190	13,321	2,570,056
2057	-950,523	-5,072,822	2,309,047	69,062	1,744,190	2,752	2,572,808
2058	-313,385	-4,445,101	2,318,465	69,062	1,744,190	-5,567	2,567,241
2059	-372,995	-4,511,105	2,324,858	69,062	1,744,190	1,509	2,568,749

Year	C_{atm} (pellets)	NEP_{pel}	FP_{dec}	PEL_{comb}	LCE_{pel}	C_{atm} (pellets) (Relative to BAU)	C_{atm} (pellets) Cumulative (Relative to BAU)
2060	-440,396	-4,587,594	2,333,946	69,062	1,744,190	-4,601	2,564,148
2061	-495,198	-4,650,405	2,341,955	69,062	1,744,190	-13,898	2,550,250
2062	-565,288	-4,728,241	2,349,701	69,062	1,744,190	-6,889	2,543,361
2063	36,302	-4,136,117	2,359,166	69,062	1,744,190	12,878	2,556,239
2064	-108,404	-4,287,187	2,365,531	69,062	1,744,190	-7,771	2,548,468
2065	-206,749	-4,394,650	2,374,649	69,062	1,744,190	-2,071	2,546,397
2066	-338,970	-4,534,950	2,382,728	69,062	1,744,190	-41,359	2,505,038
2067	-404,311	-4,609,690	2,392,126	69,062	1,744,190	42,238	2,547,276
2068	175,574	-4,037,720	2,400,042	69,062	1,744,190	-22,444	2,524,832
2069	72,464	-4,148,766	2,407,978	69,062	1,744,190	-10,164	2,514,669
2070	-64,995	-4,293,881	2,415,634	69,062	1,744,190	-33,227	2,481,441
2071	-162,395	-4,400,632	2,424,984	69,062	1,744,190	-68,779	2,412,662
2072	-164,127	-4,411,960	2,434,581	69,062	1,744,190	18,698	2,431,360
2073	173,404	-4,082,383	2,442,535	69,062	1,744,190	-40,236	2,391,124
2074	135,124	-4,130,081	2,451,953	69,062	1,744,190	-9,969	2,381,155
2075	76,694	-4,196,504	2,459,945	69,062	1,744,190	-43,770	2,337,385
2076	48,117	-4,234,324	2,469,189	69,062	1,744,190	13,780	2,351,165
2077	39,895	-4,252,132	2,478,775	69,062	1,744,190	-3,582	2,347,583
2078	320,562	-3,979,428	2,486,738	69,062	1,744,190	-40,370	2,307,214
2079	339,063	-3,968,598	2,494,410	69,062	1,744,190	-16,118	2,291,096
2080	235,275	-4,080,132	2,502,155	69,062	1,744,190	-52,362	2,238,734
2081	109,151	-4,215,661	2,511,560	69,062	1,744,190	-186,354	2,052,380
2082	95,139	-4,239,334	2,521,221	69,062	1,744,190	-104,335	1,948,045
2083	268,409	-4,075,675	2,530,832	69,062	1,744,190	38,251	1,986,296
2084	270,585	-4,079,764	2,537,097	69,062	1,744,190	44,844	2,031,140
2085	227,447	-4,131,968	2,546,163	69,062	1,744,190	-3,905	2,027,235
2086	274,251	-4,094,842	2,555,840	69,062	1,744,190	-14,380	2,012,855
2087	271,369	-4,107,391	2,565,507	69,062	1,744,190	-22,917	1,989,938
2088	314,655	-4,073,640	2,575,043	69,062	1,744,190	-87,324	1,902,614
2089	262,221	-4,134,116	2,583,085	69,062	1,744,190	-65,614	1,837,000
2090	333,070	-4,072,564	2,592,382	69,062	1,744,190	-54,038	1,782,962
2091	266,381	-4,148,910	2,602,039	69,062	1,744,190	-32,374	1,750,588
2092	295,627	-4,129,281	2,611,656	69,062	1,744,190	-85,251	1,665,336
2093	388,115	-4,046,332	2,621,195	69,062	1,744,190	11,885	1,677,221
2094	383,387	-4,059,031	2,629,166	69,062	1,744,190	-22,915	1,654,306
2095	393,758	-4,057,940	2,638,446	69,062	1,744,190	-26,713	1,627,593
2096	343,423	-4,117,919	2,648,090	69,062	1,744,190	-55,925	1,571,667
2097	395,197	-4,075,756	2,657,701	69,062	1,744,190	743	1,572,411
2098	342,427	-4,138,073	2,667,248	69,062	1,744,190	-126,607	1,445,803
2099	205,424	-4,284,773	2,676,945	69,062	1,744,190	-183,923	1,261,880
2100	263,180	-4,236,582	2,686,510	69,062	1,744,190	-173,026	1,088,855
2101	327,690	-4,181,652	2,696,090	69,062	1,744,190	-42,969	1,045,885
2102	294,065	-4,224,844	2,705,657	69,062	1,744,190	31,409	1,077,294
2103	346,958	-4,181,512	2,715,218	69,062	1,744,190	-372	1,076,922
2104	430,247	-4,107,843	2,724,839	69,062	1,744,190	-34,474	1,042,448
2105	456,165	-4,091,478	2,734,391	69,062	1,744,190	-24,758	1,017,689
2106	519,412	-4,037,793	2,743,952	69,062	1,744,190	135,912	1,153,602
2107	557,483	-4,005,784	2,750,015	69,062	1,744,190	191,353	1,344,954
2108	632,369	-3,936,407	2,755,524	69,062	1,744,190	168,052	1,513,006
2109	669,279	-3,905,252	2,761,279	69,062	1,744,190	133,873	1,646,880
2110	579,292	-4,000,992	2,767,031	69,062	1,744,190	32,206	1,679,086

B15. Forest Carbon Simulation Data - Pellet Co-Fire Pathway 2

Table B15. Forest carbon results for harvesting for business as usual and wood pellet export and cofiring in Europe for Pellet Co-Fire Pathway 2. Values expressed in tonnes of carbon.

Legend:
NPP = net primary productivity (Net growth + litterfall); Rh = heterotrophic respiration; NEP = net ecosystem productivity (NPP – Rh); Litterfall = carbon in litter layer on forest floor; Harvest = carbon in harvested wood; Bio2DOM = carbon in dead organic matter; Net Growth = carbon in forest growth; NBP = net biome production (NEP – Harvest)

Year	NPP	Rh	NEP	Litterfall	Harvest	Bio2DOM	Net Growth	NBP
Central Region								
2011	5,125,115	4,813,251	311,863	3,935,063	436,275	619,121	1,190,051	-124,412
2012	5,148,358	4,828,712	319,647	3,924,764	581,577	802,751	1,223,594	-261,930
2013	5,083,668	4,836,723	246,945	3,921,512	559,810	792,290	1,162,155	-312,866
2014	5,115,570	4,832,774	282,796	3,916,898	542,034	726,628	1,198,671	-259,238
2015	5,142,765	4,830,909	311,856	3,909,878	534,763	754,412	1,232,887	-222,906
2016	5,173,743	4,827,297	346,447	3,906,603	530,892	746,447	1,267,141	-184,445
2017	5,201,042	4,821,406	379,636	3,902,208	549,815	747,149	1,298,833	-170,179
2018	5,154,715	4,815,398	339,318	3,909,890	543,463	733,975	1,244,826	-204,145
2019	5,187,101	4,807,829	379,271	3,910,212	540,194	717,180	1,276,889	-160,923
2020	5,217,317	4,801,983	415,334	3,909,145	539,826	727,255	1,308,171	-124,491
2021	5,246,717	4,797,723	448,994	3,909,490	540,838	732,676	1,337,227	-91,844
2022	5,274,438	4,795,065	479,373	3,909,616	542,827	743,864	1,364,822	-63,453
2023	5,237,750	4,789,670	448,080	3,920,131	541,430	718,347	1,317,619	-93,350
2024	5,267,304	4,786,615	480,689	3,918,677	541,023	735,497	1,348,628	-60,334
2025	5,289,764	4,781,636	508,128	3,918,497	541,188	722,834	1,371,267	-33,060
2026	5,310,516	4,782,403	528,113	3,913,686	541,461	768,725	1,396,830	-13,349
2027	5,333,268	4,779,818	553,450	3,912,969	541,586	748,115	1,420,299	11,864
2028	5,292,246	4,774,428	517,818	3,920,539	541,337	727,636	1,371,707	-23,520
2029	5,314,148	4,766,732	547,416	3,920,606	541,319	706,033	1,393,543	6,097
2030	5,334,751	4,761,369	573,382	3,923,031	541,378	706,601	1,411,720	32,004
2031	5,348,788	4,762,099	586,689	3,918,763	541,416	756,568	1,430,026	45,272
2032	5,359,630	4,763,437	596,194	3,914,905	541,408	767,748	1,444,725	54,786
2033	5,316,691	4,757,709	558,982	3,923,776	541,371	717,020	1,392,915	17,611
2034	5,332,375	4,753,930	578,444	3,921,330	541,378	729,714	1,411,045	37,066
2035	5,353,873	4,749,431	604,442	3,923,224	541,390	714,766	1,430,649	63,052
2036	5,376,035	4,742,897	633,138	3,926,257	541,393	694,189	1,449,779	91,746
2037	5,382,808	4,747,059	635,750	3,921,955	541,388	771,480	1,460,853	94,361
2038	5,336,494	4,750,259	586,235	3,924,196	541,384	775,959	1,412,298	44,851
2039	5,357,786	4,747,482	610,304	3,925,218	541,386	736,577	1,432,569	68,918
2040	5,379,408	4,743,938	635,470	3,924,435	541,389	732,444	1,454,973	94,081
2041	5,401,295	4,738,008	663,288	3,925,024	541,388	714,558	1,476,271	121,900
2042	5,424,350	4,735,405	688,945	3,927,893	541,387	720,524	1,496,457	147,558
2043	5,356,795	4,729,343	627,453	3,938,964	541,386	687,739	1,417,831	86,067
2044	5,381,344	4,728,053	653,291	3,942,558	541,388	705,162	1,438,786	111,904
2045	5,401,326	4,731,909	669,417	3,939,744	541,388	753,120	1,461,582	128,029
2046	5,423,108	4,735,548	687,559	3,939,707	541,388	755,603	1,483,401	146,172
2047	5,445,592	4,735,119	710,473	3,940,703	541,388	735,406	1,504,889	169,085
2048	5,349,329	4,728,586	620,744	3,947,994	541,388	694,660	1,401,336	79,356
2049	5,373,145	4,727,154	645,991	3,950,081	541,388	709,407	1,423,064	104,603
2050	5,396,739	4,723,658	673,081	3,952,613	541,388	695,071	1,444,126	131,693
2051	5,417,853	4,726,713	691,140	3,954,804	541,388	729,935	1,463,049	149,753
2052	5,437,469	4,732,311	705,158	3,955,711	541,388	754,455	1,481,758	163,770
2053	5,335,491	4,731,342	604,149	3,961,723	541,388	721,303	1,373,768	62,761
2054	5,356,927	4,727,609	629,318	3,963,751	541,388	694,686	1,393,176	87,931
2055	5,376,847	4,727,618	649,229	3,964,883	541,388	713,022	1,411,964	107,841
2056	5,397,383	4,730,505	666,878	3,968,368	541,388	724,929	1,429,015	125,490

Year	NPP	Rh	NEP	Litterfall	Harvest	Bio2DOM	Net Growth	NBP
2057	5,415,788	4,731,008	684,780	3,969,167	541,388	721,869	1,446,620	143,392
2058	5,325,755	4,728,978	596,778	3,977,752	541,388	697,799	1,348,004	55,390
2059	5,343,031	4,733,340	609,691	3,975,928	541,388	739,435	1,367,103	68,303
2060	5,359,983	4,736,200	623,783	3,974,957	541,388	740,250	1,385,026	82,396
2061	5,375,336	4,735,299	640,037	3,974,732	541,388	720,110	1,400,604	98,649
2062	5,395,506	4,736,391	659,115	3,979,931	541,388	716,034	1,415,575	117,728
2063	5,324,262	4,735,937	588,325	3,991,654	541,388	701,485	1,332,608	46,937
2064	5,350,838	4,731,548	619,291	4,003,961	541,388	651,081	1,346,877	77,903
2065	5,370,161	4,735,035	635,127	4,008,600	541,388	703,091	1,361,562	93,739
2066	5,389,652	4,735,358	654,294	4,018,615	541,388	668,051	1,371,037	112,906
2067	5,410,574	4,738,523	672,052	4,029,910	541,388	676,776	1,380,665	130,664
2068	5,347,994	4,744,934	603,060	4,037,940	541,388	712,725	1,310,054	61,673
2069	5,369,315	4,745,834	623,480	4,047,947	541,388	659,387	1,321,368	82,093
2070	5,388,642	4,747,688	640,954	4,055,970	541,388	666,704	1,332,672	99,567
2071	5,410,796	4,745,485	665,311	4,074,597	541,388	606,595	1,336,199	123,924
2072	5,430,052	4,751,179	678,873	4,089,745	541,388	644,300	1,340,307	137,485
2073	5,379,322	4,762,316	617,005	4,097,914	541,388	703,068	1,281,408	75,618
2074	5,397,124	4,763,931	633,193	4,111,370	541,388	622,742	1,285,755	91,806
2075	5,413,550	4,768,345	645,206	4,122,084	541,388	636,979	1,291,467	103,818
2076	5,424,626	4,774,045	650,580	4,129,481	541,388	656,666	1,295,144	109,193
2077	5,433,406	4,779,689	653,717	4,135,830	541,388	659,900	1,297,576	112,330
2078	5,401,124	4,787,743	613,381	4,142,922	541,388	679,386	1,258,202	71,993
2079	5,413,980	4,790,872	623,108	4,152,476	541,388	634,043	1,261,504	81,721
2080	5,417,452	4,800,827	616,626	4,151,541	541,388	701,127	1,265,911	75,238
2081	5,426,320	4,803,507	622,813	4,158,605	541,388	648,036	1,267,715	81,425
2082	5,449,030	4,796,966	652,064	4,186,358	541,388	532,009	1,262,672	110,677
2083	5,444,486	4,800,586	643,900	4,210,620	541,388	577,232	1,233,866	102,513
2084	5,443,792	4,817,438	626,355	4,209,513	541,388	701,223	1,234,280	84,967
2085	5,444,275	4,829,520	614,755	4,208,654	541,388	693,177	1,235,622	73,367
2086	5,447,882	4,835,047	612,835	4,214,696	541,388	651,921	1,233,186	71,447
2087	5,446,050	4,844,199	601,851	4,215,266	541,388	690,668	1,230,784	60,464
2088	5,444,091	4,846,152	597,938	4,226,581	541,388	634,583	1,217,510	56,551
2089	5,441,969	4,853,920	588,049	4,222,582	541,388	695,383	1,219,387	46,662
2090	5,457,666	4,847,941	609,725	4,242,320	541,388	558,703	1,215,346	68,337
2091	5,455,137	4,859,710	595,427	4,238,735	541,388	698,963	1,216,402	54,040
2092	5,461,101	4,861,558	599,543	4,245,911	541,388	629,220	1,215,190	58,156
2093	5,457,994	4,865,507	592,487	4,250,523	541,388	645,864	1,207,471	51,099
2094	5,462,283	4,870,355	591,928	4,256,471	541,388	647,249	1,205,812	50,541
2095	5,461,978	4,877,571	584,407	4,256,399	541,388	674,348	1,205,580	43,019
2096	5,468,826	4,879,635	589,191	4,263,981	541,388	632,746	1,204,846	47,804
2097	5,466,078	4,887,663	578,414	4,262,003	541,388	692,895	1,204,074	37,027
2098	5,470,593	4,886,017	584,575	4,273,049	541,388	609,154	1,197,544	43,188
2099	5,465,706	4,894,134	571,572	4,266,634	541,388	702,036	1,199,072	30,185
2100	5,476,522	4,887,954	588,568	4,282,597	541,388	569,498	1,193,925	47,180
2101	5,494,956	4,883,325	611,631	4,305,307	541,388	534,862	1,189,649	70,243
2102	5,503,941	4,888,711	615,230	4,317,744	541,388	599,291	1,186,197	73,842
2103	5,495,580	4,904,804	590,776	4,309,323	541,388	710,403	1,186,257	49,388
2104	5,485,151	4,913,742	571,409	4,299,707	541,388	701,146	1,185,444	30,021
2105	5,499,445	4,906,195	593,251	4,319,981	541,388	537,936	1,179,464	51,863
2106	5,506,713	4,909,346	597,367	4,330,250	541,388	601,832	1,176,463	55,980
2107	5,501,132	4,923,059	578,073	4,324,543	541,388	705,635	1,176,589	36,685
2108	5,493,826	4,935,448	558,379	4,312,473	541,388	739,569	1,181,354	16,991
2109	5,474,849	4,945,316	529,533	4,296,525	541,388	763,991	1,178,323	-11,855
2110	5,462,549	4,947,163	515,386	4,282,307	541,388	736,751	1,180,242	-26,001
Eastern Region								
2011	4,359,558	3,854,578	504,980	3,457,137	195,529	291,256	902,421	309,451
2012	4,397,744	3,857,949	539,795	3,471,951	224,567	323,313	925,792	315,228
2013	4,347,202	3,862,653	484,549	3,496,721	217,749	324,092	850,481	266,801
2014	4,380,237	3,866,308	513,929	3,509,781	216,719	315,938	870,455	297,209
2015	4,411,862	3,870,881	540,981	3,522,328	220,157	321,642	889,534	320,824
2016	4,444,923	3,874,930	569,993	3,536,724	214,944	310,957	908,199	355,049

Year	NPP	Rh	NEP	Litterfall	Harvest	Bio2DOM	Net Growth	NBP
2017	4,480,605	3,880,024	600,581	3,549,479	218,827	318,940	931,126	381,755
2018	4,432,749	3,884,313	548,437	3,576,039	217,679	298,184	856,710	330,757
2019	4,460,805	3,891,566	569,239	3,588,966	217,666	314,715	871,840	351,574
2020	4,487,252	3,896,480	590,772	3,601,092	217,854	302,671	886,160	372,918
2021	4,510,860	3,903,711	607,148	3,613,893	217,394	310,106	896,967	389,754
2022	4,532,506	3,909,398	623,108	3,625,247	217,884	305,359	907,259	405,224
2023	4,494,822	3,918,223	576,599	3,648,031	217,695	319,339	846,791	358,903
2024	4,518,768	3,923,359	595,409	3,659,886	217,699	294,371	858,882	377,710
2025	4,534,658	3,929,625	605,033	3,668,436	217,705	305,050	866,222	387,328
2026	4,543,558	3,938,385	605,172	3,675,751	217,676	323,479	867,807	387,497
2027	4,563,444	3,944,268	619,176	3,684,813	217,731	307,196	878,630	401,445
2028	4,524,128	3,949,559	574,569	3,706,528	217,701	294,418	817,599	356,869
2029	4,539,925	3,955,582	584,343	3,713,385	217,702	303,019	826,539	366,641
2030	4,554,830	3,964,077	590,753	3,719,445	217,703	323,139	835,385	373,050
2031	4,570,232	3,972,069	598,163	3,726,247	217,703	322,634	843,985	380,460
2032	4,586,148	3,977,180	608,968	3,736,220	217,709	301,270	849,928	391,260
2033	4,547,968	3,979,867	568,100	3,756,953	217,704	280,533	791,014	350,396
2034	4,563,155	3,984,472	578,683	3,764,855	217,704	287,608	798,300	360,979
2035	4,577,673	3,990,345	587,328	3,770,589	217,704	298,785	807,084	369,624
2036	4,590,655	4,000,235	590,419	3,774,071	217,704	331,835	816,584	372,715
2037	4,604,464	4,007,281	597,184	3,779,754	217,705	318,010	824,711	379,479
2038	4,549,870	4,012,198	537,671	3,795,604	217,704	302,788	754,266	319,967
2039	4,564,080	4,018,157	545,923	3,800,997	217,704	307,015	763,084	328,219
2040	4,579,995	4,024,172	555,823	3,808,085	217,704	305,411	771,911	338,119
2041	4,592,762	4,030,993	561,770	3,812,614	217,704	317,575	780,148	344,065
2042	4,607,679	4,035,108	572,571	3,820,752	217,704	295,273	786,927	354,867
2043	4,539,998	4,041,908	498,090	3,833,447	217,704	318,211	706,551	280,386
2044	4,551,407	4,047,859	503,549	3,836,968	217,704	312,807	714,439	285,844
2045	4,563,599	4,052,758	510,841	3,840,131	217,704	310,644	723,469	293,136
2046	4,577,085	4,055,754	521,331	3,845,014	217,704	296,437	732,071	303,627
2047	4,590,624	4,059,982	530,643	3,849,909	217,704	300,882	740,715	312,938
2048	4,522,282	4,064,802	457,480	3,861,486	217,704	304,011	660,796	239,775
2049	4,531,801	4,068,702	463,099	3,862,191	217,704	304,948	669,610	245,395
2050	4,541,042	4,073,861	467,181	3,862,380	217,704	316,705	678,662	249,477
2051	4,549,267	4,077,392	471,875	3,862,147	217,704	313,718	687,120	254,171
2052	4,559,885	4,083,052	476,833	3,864,053	217,704	323,148	695,831	259,129
2053	4,501,262	4,086,935	414,326	3,874,012	217,704	310,403	627,249	196,622
2054	4,511,834	4,090,391	421,444	3,876,537	217,704	306,393	635,297	203,739
2055	4,524,855	4,090,645	434,210	3,881,992	217,704	282,292	642,863	216,506
2056	4,536,628	4,090,236	446,391	3,886,583	217,704	273,758	650,045	228,687
2057	4,547,725	4,092,592	455,134	3,889,888	217,704	286,690	657,838	237,430
2058	4,492,481	4,095,711	396,770	3,899,471	217,704	290,170	593,010	179,066
2059	4,498,385	4,101,403	396,983	3,897,409	217,704	314,231	600,976	179,278
2060	4,502,920	4,107,426	395,494	3,893,069	217,704	331,413	609,851	177,789
2061	4,509,626	4,112,248	397,378	3,891,945	217,704	325,374	617,681	179,674
2062	4,518,004	4,114,447	403,556	3,892,550	217,704	310,161	625,454	185,852
2063	4,462,696	4,116,638	346,057	3,900,087	217,704	307,974	562,609	128,353
2064	4,470,437	4,117,969	352,469	3,900,522	217,704	300,632	569,916	134,764
2065	4,475,923	4,120,912	355,012	3,897,933	217,704	318,223	577,990	137,307
2066	4,480,567	4,123,432	357,135	3,895,474	217,704	320,248	585,093	139,431
2067	4,487,812	4,126,883	360,929	3,895,509	217,704	322,363	592,302	143,225
2068	4,419,181	4,129,194	289,987	3,903,145	217,704	314,451	516,036	72,283
2069	4,427,122	4,128,633	298,489	3,904,214	217,704	293,562	522,908	80,785
2070	4,435,219	4,126,075	309,144	3,905,835	217,704	277,349	529,383	91,439
2071	4,438,840	4,127,742	311,098	3,903,984	217,704	304,574	534,855	93,394
2072	4,438,617	4,133,783	304,834	3,897,528	217,704	346,512	541,089	87,130
2073	4,413,254	4,133,367	279,886	3,905,283	217,704	299,560	507,970	62,182
2074	4,416,523	4,135,086	281,437	3,902,828	217,704	314,846	513,695	63,733
2075	4,421,500	4,135,197	286,303	3,901,944	217,704	303,232	519,556	68,599
2076	4,426,848	4,134,578	292,270	3,902,526	217,704	294,171	524,322	74,566
2077	4,429,593	4,137,612	291,981	3,899,086	217,704	324,283	530,507	74,277

Year	NPP	Rh	NEP	Litterfall	Harvest	Bio2DOM	Net Growth	NBP
2078	4,409,194	4,139,509	269,685	3,904,039	217,704	317,536	505,155	51,981
2079	4,413,410	4,142,616	270,794	3,901,814	217,704	325,952	511,596	53,090
2080	4,419,948	4,140,381	279,567	3,902,887	217,704	290,711	517,061	61,863
2081	4,420,770	4,140,590	280,180	3,900,517	217,704	309,293	520,253	62,476
2082	4,420,837	4,144,900	275,937	3,895,191	217,704	342,553	525,646	58,233
2083	4,408,965	4,144,323	264,642	3,899,223	217,704	311,108	509,742	46,938
2084	4,413,516	4,144,527	268,989	3,897,913	217,704	312,002	515,603	51,285
2085	4,418,627	4,142,555	276,072	3,898,930	217,704	292,903	519,697	58,368
2086	4,417,087	4,144,822	272,265	3,894,221	217,704	329,790	522,866	54,560
2087	4,420,099	4,145,997	274,102	3,894,256	217,704	316,285	525,843	56,398
2088	4,412,937	4,148,225	264,712	3,898,245	217,704	322,397	514,692	47,008
2089	4,417,290	4,144,935	272,355	3,898,761	217,704	289,164	518,529	54,651
2090	4,415,623	4,148,221	267,402	3,892,749	217,704	339,649	522,874	49,698
2091	4,416,630	4,149,089	267,541	3,891,002	217,704	323,390	525,628	49,836
2092	4,419,035	4,148,371	270,664	3,890,467	217,704	311,230	528,568	52,960
2093	4,415,954	4,146,561	269,392	3,894,275	217,704	298,696	521,679	51,688
2094	4,413,882	4,150,449	263,433	3,887,135	217,704	349,917	526,747	45,729
2095	4,414,992	4,153,902	261,090	3,884,046	217,704	346,834	530,945	43,386
2096	4,417,476	4,150,910	266,566	3,884,336	217,704	305,692	533,141	48,862
2097	4,414,760	4,153,247	261,512	3,878,403	217,704	349,471	536,357	43,808
2098	4,410,124	4,152,916	257,209	3,878,082	217,704	329,982	532,043	39,505
2099	4,414,908	4,148,014	266,894	3,880,623	217,704	289,314	534,285	49,190
2100	4,413,710	4,149,915	263,796	3,877,303	217,704	335,961	536,407	46,091
2101	4,415,007	4,150,621	264,386	3,876,865	217,704	325,436	538,141	46,682
2102	4,417,633	4,148,745	268,888	3,877,799	217,704	307,510	539,833	51,183
2103	4,411,269	4,149,916	261,353	3,874,694	217,704	334,519	536,575	43,649
2104	4,410,918	4,150,956	259,962	3,871,740	217,704	334,924	539,178	42,257
2105	4,415,235	4,149,624	265,611	3,872,633	217,704	313,680	542,603	47,907
2106	4,416,059	4,151,609	264,450	3,871,017	217,704	338,818	545,042	46,745
2107	4,415,530	4,152,615	262,915	3,868,929	217,704	337,311	546,601	45,210
2108	4,408,869	4,154,260	254,609	3,865,088	217,704	349,392	543,781	36,905
2109	4,409,675	4,154,128	255,548	3,862,990	217,704	337,930	546,685	37,843
2110	4,420,130	4,148,429	271,701	3,872,287	217,704	274,181	547,844	53,997
Western Region								
2011	5,205,073	4,517,145	687,929	4,442,704	326,531	423,126	762,370	361,397
2012	5,209,640	4,545,970	663,669	4,437,852	305,080	399,581	771,788	358,589
2013	5,101,278	4,568,652	532,626	4,442,154	298,492	392,489	659,125	234,134
2014	5,104,841	4,585,651	519,190	4,433,880	292,910	389,691	670,962	226,280
2015	5,108,002	4,601,115	506,887	4,425,871	304,466	406,728	682,131	202,421
2016	5,113,102	4,612,715	500,386	4,419,930	305,495	399,501	693,171	194,891
2017	5,117,677	4,622,405	495,273	4,413,512	301,289	402,751	704,165	193,984
2018	5,024,542	4,629,738	394,804	4,418,301	300,531	396,210	606,241	94,273
2019	5,027,574	4,636,453	391,121	4,408,645	300,938	408,022	618,929	90,183
2020	5,031,418	4,640,460	390,957	4,401,387	302,543	398,312	630,031	88,414
2021	5,036,822	4,643,317	393,505	4,394,788	302,159	396,630	642,034	91,346
2022	5,041,974	4,646,046	395,927	4,388,867	301,492	398,102	653,106	94,435
2023	4,968,468	4,646,665	321,803	4,397,263	301,533	380,130	571,205	20,271
2024	4,973,942	4,646,993	326,949	4,390,389	301,733	383,652	583,553	25,216
2025	4,972,817	4,647,650	325,168	4,382,455	301,891	390,992	590,362	23,276
2026	4,975,589	4,648,196	327,393	4,375,695	301,762	392,121	599,894	25,631
2027	4,973,550	4,650,198	323,352	4,364,602	301,682	415,943	608,947	21,670
2028	4,911,184	4,651,342	259,842	4,366,836	301,720	416,221	544,348	-41,878
2029	4,914,257	4,648,976	265,281	4,358,993	301,758	392,921	555,264	-36,477
2030	4,913,939	4,647,961	265,978	4,350,307	301,763	403,564	563,632	-35,786
2031	4,916,175	4,644,398	271,777	4,342,063	301,737	391,443	574,113	-29,960
2032	4,912,703	4,640,178	272,525	4,332,571	301,732	390,549	580,132	-29,207
2033	4,873,306	4,638,014	235,292	4,338,246	301,742	394,153	535,060	-66,450
2034	4,877,520	4,636,010	241,511	4,330,772	301,746	394,544	546,749	-60,235
2035	4,883,197	4,633,461	249,735	4,325,416	301,744	388,043	557,781	-52,009
2036	4,885,140	4,632,944	252,196	4,315,304	301,741	413,609	569,836	-49,545
2037	4,886,939	4,631,368	255,571	4,305,478	301,741	413,566	581,461	-46,169

Year	NPP	Rh	NEP	Litterfall	Harvest	Bio2DOM	Net Growth	NBP
2038	4,849,983	4,629,127	220,856	4,309,544	301,743	407,418	540,439	-80,887
2039	4,855,909	4,624,397	231,512	4,303,652	301,743	386,055	552,257	-70,231
2040	4,860,836	4,621,622	239,214	4,298,577	301,742	391,568	562,260	-62,527
2041	4,866,302	4,617,831	248,472	4,293,597	301,742	386,081	572,705	-53,270
2042	4,870,603	4,614,590	256,013	4,287,018	301,742	391,432	583,584	-45,729
2043	4,833,478	4,612,332	221,146	4,289,313	301,742	400,197	544,165	-80,596
2044	4,837,200	4,610,285	226,915	4,281,667	301,742	399,879	555,533	-74,827
2045	4,844,099	4,606,644	237,454	4,277,447	301,742	384,239	566,652	-64,288
2046	4,851,331	4,603,699	247,632	4,272,262	301,742	388,098	579,069	-54,110
2047	4,854,930	4,603,957	250,972	4,263,867	301,742	416,195	591,063	-50,770
2048	4,822,159	4,601,115	221,044	4,269,550	301,742	389,841	552,610	-80,698
2049	4,829,761	4,597,442	232,319	4,265,926	301,742	381,017	563,835	-69,423
2050	4,837,128	4,594,718	242,410	4,262,442	301,742	382,599	574,687	-59,332
2051	4,845,452	4,591,925	253,527	4,262,419	301,742	371,868	583,033	-48,215
2052	4,850,940	4,590,258	260,682	4,257,122	301,742	389,803	593,819	-41,060
2053	4,817,189	4,588,587	228,602	4,259,590	301,742	387,623	557,599	-73,140
2054	4,821,166	4,586,726	234,440	4,252,723	301,742	389,649	568,443	-67,302
2055	4,825,699	4,585,636	240,062	4,247,872	301,742	391,953	577,827	-61,679
2056	4,828,049	4,583,689	244,360	4,241,113	301,742	394,160	586,936	-57,381
2057	4,831,642	4,581,711	249,931	4,235,545	301,742	393,305	596,097	-51,811
2058	4,802,773	4,579,067	223,705	4,242,660	301,742	374,287	560,113	-78,037
2059	4,806,587	4,577,089	229,498	4,236,642	301,742	387,578	569,945	-72,244
2060	4,811,563	4,575,061	236,501	4,231,194	301,742	387,064	580,369	-65,240
2061	4,811,167	4,577,427	233,740	4,221,019	301,742	428,239	590,148	-68,002
2062	4,807,823	4,577,057	230,766	4,209,311	301,742	427,279	598,512	-70,976
2063	4,777,011	4,575,942	201,069	4,208,024	301,742	420,157	568,987	-100,673
2064	4,778,882	4,573,091	205,791	4,199,764	301,742	413,531	579,118	-95,951
2065	4,785,507	4,568,037	217,470	4,197,259	301,742	387,808	588,248	-84,272
2066	4,789,238	4,564,531	224,707	4,192,766	301,742	396,379	596,472	-77,035
2067	4,795,646	4,560,506	235,140	4,191,383	301,742	384,000	604,264	-66,602
2068	4,762,801	4,557,331	205,470	4,190,553	301,742	394,219	572,248	-96,272
2069	4,764,347	4,554,294	210,052	4,183,123	301,742	397,393	581,224	-91,689
2070	4,768,770	4,552,501	216,269	4,179,332	301,742	398,008	589,438	-85,472
2071	4,769,984	4,548,621	221,362	4,173,434	301,742	392,043	596,549	-80,379
2072	4,773,391	4,545,504	227,888	4,169,864	301,742	389,239	603,527	-73,854
2073	4,753,803	4,544,081	209,722	4,169,310	301,742	400,334	584,493	-92,020
2074	4,754,916	4,542,168	212,748	4,164,185	301,742	399,109	590,731	-88,994
2075	4,757,551	4,539,372	218,179	4,159,381	301,742	394,911	598,170	-83,563
2076	4,755,593	4,539,402	216,191	4,149,983	301,742	423,903	605,610	-85,551
2077	4,755,277	4,536,693	218,583	4,142,497	301,742	410,670	612,780	-83,159
2078	4,734,974	4,537,919	197,055	4,132,411	301,742	452,060	602,563	-104,687
2079	4,732,865	4,535,831	197,034	4,122,027	301,742	436,957	610,838	-104,708
2080	4,736,445	4,531,453	204,992	4,117,725	301,742	413,673	618,720	-96,750
2081	4,738,865	4,527,317	211,548	4,112,083	301,742	415,794	626,782	-90,194
2082	4,742,735	4,521,885	220,850	4,109,288	301,742	399,648	633,448	-80,891
2083	4,740,058	4,517,318	222,740	4,112,593	301,742	392,315	627,465	-79,001
2084	4,741,944	4,513,419	228,525	4,107,658	301,742	401,961	634,286	-73,217
2085	4,745,659	4,509,956	235,703	4,104,353	301,742	399,005	641,307	-66,038
2086	4,746,707	4,509,275	237,432	4,098,740	301,742	421,399	647,968	-64,310
2087	4,748,710	4,506,058	242,652	4,095,699	301,742	403,403	653,011	-59,090
2088	4,746,116	4,503,130	242,986	4,095,764	301,742	400,549	650,352	-58,756
2089	4,749,569	4,500,569	249,000	4,092,784	301,742	402,241	656,784	-52,742
2090	4,747,358	4,502,796	244,562	4,084,027	301,742	447,040	663,331	-57,180
2091	4,753,583	4,497,779	255,804	4,084,250	301,742	390,009	669,333	-45,938
2092	4,748,126	4,499,548	248,578	4,072,268	301,742	456,693	675,859	-53,164
2093	4,744,189	4,499,495	244,694	4,068,607	301,742	443,385	675,582	-57,048
2094	4,745,608	4,496,406	249,203	4,063,302	301,742	428,315	682,306	-52,539
2095	4,751,505	4,491,073	260,432	4,063,407	301,742	400,625	688,098	-41,310
2096	4,755,498	4,489,167	266,332	4,061,435	301,742	419,463	694,063	-35,410
2097	4,756,992	4,485,470	271,522	4,058,352	301,742	411,487	698,640	-30,220
2098	4,754,281	4,483,765	270,517	4,057,079	301,742	420,232	697,202	-31,225

Year	NPP	Rh	NEP	Litterfall	Harvest	Bio2DOM	Net Growth	NBP
2099	4,757,297	4,480,855	276,442	4,054,792	301,742	411,780	702,505	-25,300
2100	4,761,383	4,477,880	283,503	4,054,904	301,742	402,942	706,480	-18,238
2101	4,761,249	4,477,621	283,628	4,050,686	301,742	427,408	710,563	-18,114
2102	4,763,073	4,475,062	288,011	4,050,677	301,742	406,385	712,397	-13,731
2103	4,754,899	4,479,353	275,546	4,041,908	301,742	470,672	712,992	-26,196
2104	4,753,873	4,479,507	274,366	4,036,965	301,742	448,900	716,908	-27,376
2105	4,761,152	4,474,664	286,488	4,039,646	301,742	401,816	721,506	-15,254
2106	4,763,932	4,473,398	290,534	4,039,251	301,742	423,611	724,681	-11,208
2107	4,765,522	4,470,351	295,171	4,037,988	301,742	414,663	727,534	-6,570
2108	4,765,229	4,469,652	295,577	4,037,938	301,742	424,749	727,291	-6,165
2109	4,769,089	4,467,411	301,678	4,038,390	301,742	411,636	730,699	-64
2110	4,776,038	4,464,206	311,832	4,042,137	301,742	393,316	733,902	10,091

B16. Life Cycle GHG Emissions Results for Pellet Co-Fire Pathway 2

Table B16. Life cycle GHG emissions for Pellet Co-Fire Pathway 2, including forest carbon emissions data for all three regions of Nova Scotia and life cycle emissions for co-firing of wood pellets (80% from sawmill) with coal in the Netherlands, expressed in tonnes of CO_2 equivalents.

Year	C_{atm} (pellets)	NEP_{pel}	FP_{dec}	PEL_{comb}	LCE_{pel}	C_{atm} (pellets) (Relative to BAU)	C_{atm} (pellets) Cumulative (Relative to BAU)
2011	-2,012,874	-5,522,512	1,744,241	17,267	1,748,130	-117,525	-117,525
2012	-1,752,810	-5,589,816	2,071,609	17,267	1,748,130	-84,761	-202,286
2013	-855,483	-4,639,321	2,018,440	17,267	1,748,130	-78,546	-280,833
2014	-1,059,174	-4,829,407	2,004,835	17,267	1,748,130	-50,055	-330,887
2015	-1,216,058	-4,990,185	2,008,730	17,267	1,748,130	-64,235	-395,122
2016	-1,444,366	-5,199,751	1,989,988	17,267	1,748,130	-71,335	-466,458
2017	-1,610,049	-5,415,047	2,039,600	17,267	1,748,130	-60,828	-527,285
2018	-907,677	-4,706,988	2,033,914	17,267	1,748,130	-60,977	-588,262
2019	-1,116,553	-4,916,448	2,034,498	17,267	1,748,130	-56,299	-644,561
2020	-1,321,051	-5,127,224	2,040,776	17,267	1,748,130	-58,905	-703,466
2021	-1,507,933	-5,320,204	2,046,874	17,267	1,748,130	-56,912	-760,378
2022	-1,674,611	-5,499,161	2,059,152	17,267	1,748,130	-54,890	-815,269
2023	-1,111,874	-4,941,590	2,064,319	17,267	1,748,130	-55,018	-870,286
2024	-1,315,603	-5,149,184	2,068,183	17,267	1,748,130	-53,991	-924,278
2025	-1,437,892	-5,278,668	2,075,378	17,267	1,748,130	-53,066	-977,344
2026	-1,513,295	-5,360,688	2,081,996	17,267	1,748,130	-47,507	-1,024,850
2027	-1,634,953	-5,490,240	2,089,889	17,267	1,748,130	-53,520	-1,078,370
2028	-1,101,708	-4,962,680	2,095,575	17,267	1,748,130	-54,027	-1,132,397
2029	-1,260,424	-5,127,138	2,101,317	17,267	1,748,130	-54,393	-1,186,790
2030	-1,375,994	-5,248,513	2,107,122	17,267	1,748,130	-55,436	-1,242,226
2031	-1,465,676	-5,345,830	2,114,757	17,267	1,748,130	-51,751	-1,293,977
2032	-1,535,146	-5,423,112	2,122,569	17,267	1,748,130	-54,026	-1,348,003
2033	-1,104,205	-4,999,913	2,130,311	17,267	1,748,130	-48,727	-1,396,729
2034	-1,232,840	-5,133,001	2,134,764	17,267	1,748,130	-57,732	-1,454,461
2035	-1,382,996	-5,290,326	2,141,932	17,267	1,748,130	-55,436	-1,509,897
2036	-1,500,829	-5,416,016	2,149,789	17,267	1,748,130	-55,626	-1,565,523
2037	-1,539,828	-5,462,812	2,157,587	17,267	1,748,130	-53,744	-1,619,268
2038	-1,004,539	-4,935,277	2,165,341	17,267	1,748,130	-54,684	-1,673,952
2039	-1,156,153	-5,093,004	2,171,454	17,267	1,748,130	-56,188	-1,730,140
2040	-1,304,069	-5,249,964	2,180,498	17,267	1,748,130	-58,183	-1,788,322
2041	-1,455,493	-5,407,853	2,186,963	17,267	1,748,130	-58,199	-1,846,522
2042	-1,609,564	-5,569,331	2,194,369	17,267	1,748,130	-57,499	-1,904,021
2043	-974,787	-4,942,349	2,202,165	17,267	1,748,130	-60,549	-1,964,569
2044	-1,104,707	-5,078,379	2,208,275	17,267	1,748,130	-61,343	-2,025,913
2045	-1,221,962	-5,203,001	2,215,641	17,267	1,748,130	-58,840	-2,084,752
2046	-1,356,505	-5,345,438	2,223,535	17,267	1,748,130	-62,292	-2,147,044
2047	-1,479,306	-5,475,961	2,231,258	17,267	1,748,130	-61,125	-2,208,169
2048	-763,890	-4,768,311	2,239,023	17,267	1,748,130	-67,190	-2,275,359
2049	-910,719	-4,922,971	2,246,855	17,267	1,748,130	-68,036	-2,343,395
2050	-1,054,456	-5,074,404	2,254,550	17,267	1,748,130	-67,605	-2,411,000
2051	-1,170,995	-5,198,710	2,262,318	17,267	1,748,130	-62,673	-2,473,673
2052	-1,259,145	-5,294,612	2,270,069	17,267	1,748,130	-65,094	-2,538,767
2053	-533,549	-4,576,773	2,277,826	17,267	1,748,130	-70,951	-2,609,719
2054	-665,660	-4,716,690	2,285,632	17,267	1,748,130	-70,394	-2,680,113
2055	-798,485	-4,857,249	2,293,367	17,267	1,748,130	-70,354	-2,750,467
2056	-915,987	-4,982,501	2,301,116	17,267	1,748,130	-71,456	-2,821,923
2057	-1,026,461	-5,100,729	2,308,871	17,267	1,748,130	-73,186	-2,895,109

Year	C_{atm} (pellets)	NEP_{pel}	FP_{dec}	PEL_{comb}	LCE_{pel}	C_{atm} (pellets) (Relative to BAU)	C_{atm} (pellets) Cumulative (Relative to BAU)
2058	-383,678	-4,467,318	2,318,242	17,267	1,748,130	-75,861	-2,970,969
2059	-446,645	-4,536,747	2,324,704	17,267	1,748,130	-72,142	-3,043,111
2060	-509,585	-4,608,707	2,333,725	17,267	1,748,130	-73,790	-3,116,901
2061	-557,950	-4,665,139	2,341,791	17,267	1,748,130	-76,650	-3,193,551
2062	-632,018	-4,746,915	2,349,500	17,267	1,748,130	-73,619	-3,267,170
2063	-42,756	-4,167,108	2,358,954	17,267	1,748,130	-66,180	-3,333,350
2064	-190,825	-4,321,608	2,365,385	17,267	1,748,130	-90,193	-3,423,542
2065	-292,103	-4,431,923	2,374,423	17,267	1,748,130	-87,425	-3,510,967
2066	-388,655	-4,536,617	2,382,565	17,267	1,748,130	-91,044	-3,602,011
2067	-496,728	-4,654,004	2,391,878	17,267	1,748,130	-50,179	-3,652,190
2068	133,702	-4,031,559	2,399,864	17,267	1,748,130	-64,315	-3,716,505
2069	18,669	-4,154,521	2,407,793	17,267	1,748,130	-63,958	-3,780,463
2070	-99,704	-4,280,568	2,415,467	17,267	1,748,130	-67,936	-3,848,399
2071	-205,662	-4,395,822	2,424,763	17,267	1,748,130	-112,046	-3,960,445
2072	-246,814	-4,446,550	2,434,339	17,267	1,748,130	-63,989	-4,024,434
2073	146,464	-4,061,273	2,442,339	17,267	1,748,130	-67,176	-4,091,610
2074	79,662	-4,137,478	2,451,743	17,267	1,748,130	-65,431	-4,157,041
2075	5,822	-4,219,354	2,459,779	17,267	1,748,130	-114,642	-4,271,683
2076	-19,332	-4,253,680	2,468,951	17,267	1,748,130	-53,669	-4,325,352
2077	-28,965	-4,272,912	2,478,550	17,267	1,748,130	-72,441	-4,397,793
2078	287,895	-3,964,044	2,486,542	17,267	1,748,130	-73,036	-4,470,830
2079	255,892	-4,003,738	2,494,233	17,267	1,748,130	-99,290	-4,570,119
2080	226,048	-4,041,347	2,501,998	17,267	1,748,130	-61,589	-4,631,708
2081	186,360	-4,090,366	2,511,329	17,267	1,748,130	-109,146	-4,740,854
2082	70,094	-4,216,285	2,520,981	17,267	1,748,130	-129,379	-4,870,234
2083	144,178	-4,151,809	2,530,590	17,267	1,748,130	-85,980	-4,956,213
2084	177,757	-4,124,598	2,536,958	17,267	1,748,130	-47,985	-5,004,198
2085	176,998	-4,134,366	2,545,966	17,267	1,748,130	-54,354	-5,058,552
2086	201,332	-4,119,690	2,555,625	17,267	1,748,130	-87,299	-5,145,851
2087	225,354	-4,105,283	2,565,240	17,267	1,748,130	-68,931	-5,214,782
2088	282,524	-4,057,685	2,574,812	17,267	1,748,130	-119,455	-5,334,237
2089	276,805	-4,071,512	2,582,919	17,267	1,748,130	-51,030	-5,385,267
2090	240,969	-4,116,598	2,592,169	17,267	1,748,130	-146,138	-5,531,406
2091	261,322	-4,105,891	2,601,816	17,267	1,748,130	-37,433	-5,568,839
2092	270,857	-4,105,943	2,611,403	17,267	1,748,130	-110,021	-5,678,860
2093	325,241	-4,061,124	2,620,968	17,267	1,748,130	-50,990	-5,729,850
2094	340,634	-4,053,750	2,628,987	17,267	1,748,130	-65,668	-5,795,518
2095	344,868	-4,058,760	2,638,230	17,267	1,748,130	-75,604	-5,871,121
2096	295,199	-4,118,066	2,647,868	17,267	1,748,130	-104,150	-5,975,271
2097	343,833	-4,079,017	2,657,453	17,267	1,748,130	-50,621	-6,025,892
2098	350,274	-4,082,144	2,667,021	17,267	1,748,130	-118,760	-6,144,652
2099	350,410	-4,091,714	2,676,727	17,267	1,748,130	-38,937	-6,183,589
2100	283,049	-4,168,631	2,686,283	17,267	1,748,130	-153,156	-6,336,745
2101	205,364	-4,255,895	2,695,861	17,267	1,748,130	-165,296	-6,502,041
2102	169,112	-4,301,713	2,705,428	17,267	1,748,130	-93,545	-6,595,586
2103	341,823	-4,138,566	2,714,992	17,267	1,748,130	-5,507	-6,601,093
2104	431,951	-4,058,053	2,724,606	17,267	1,748,130	-32,771	-6,633,864
2105	296,125	-4,203,435	2,734,162	17,267	1,748,130	-184,799	-6,818,663
2106	279,993	-4,229,128	2,743,724	17,267	1,748,130	-103,507	-6,922,170
2107	345,567	-4,169,703	2,749,872	17,267	1,748,130	-20,563	-6,942,733
2108	452,366	-4,068,432	2,755,401	17,267	1,748,130	-11,951	-6,954,684
2109	538,162	-3,988,403	2,761,168	17,267	1,748,130	2,757	-6,951,927
2110	499,244	-4,033,037	2,766,884	17,267	1,748,130	-47,841	-6,999,768