Wood Heat and Biopower Life-Cycle Assessment Literature Review

Final Report

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Advance innovative energy solutions in ways that improve New York's economy and environment.

Vision Statement:

Serve as a catalyst — advancing energy innovation, technology, and investment; transforming New York's economy; and empowering people to choose clean and efficient energy as part of their everyday lives.

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Final Report

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Acronyms and Abbreviations List

aLCA	attributional LCA
BAF	Biomass Accounting Factor
BAU	Business as Usual
C&D	Construction and Demolition
CES	Clean Energy Standard
CHP	Combined Heat and Power
cLCA	consequential LCA
CPP	Clean Power Plan
DEC	New York State Department of Environmental Conservation
DPS	New York State Department of Public Service
EPA	Environmental Protection Agency
GHG	Greenhouse Gas
GWP	Global Warming Potential
IGCC	Integrated Gasification Combined Cycle
iLUC	indirect Land Use Change
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCFS	Low Carbon Fuel Standard (California policy)
LUC	Land Use Change
ODT	Oven Dry Ton
PSC	New York Public Service Commission
RED	Renewable Energy Directive (European policy)
RFS	Renewable Fuel Standard (U.S. policy)
RPS	Renewable Portfolio Standard
SAB	Science Advisory Board
SUNY	State University of New York

1 Introduction

This report summarizes the results of a literature review prepared for NYSERDA. The purpose of this effort is to review the different approaches and methodologies for life cycle assessments (LCAs) of woody biomass heat and power, particularly in the context of assessing the climate effects of bioenergy, and to provide recommendations on additional analysis or research needed to support policy considerations for New York State.

NYSERDA's goal is not to determine best use of biomass resources, but rather to understand how existing resources, if used to their potential, will help NYS achieve statewide goals such as renewable electricity mandates under the Clean Energy Standard, and greenhouse gas (GHG) reduction goals (e.g., New York City's 80 x 50). This effort is intended to help NYSERDA determine how to treat biomass in energy guidance and understand the related issues associated with carbon accounting for bioenergy. In particular, to provide a primer on the issues and methods for bioenergy LCA to identify what is needed regarding bioenergy LCA guidance for NYS and any gaps to be addressed through additional research and/or analysis.

There is an enormous amount of publicly available information on bioenergy LCAs spanning several decades. In order to cull the material to a manageable and useful level, the review is focused on information relevant to NYSERDA's current needs. The first consideration is gearing NYSERDA's work in this area toward policy and decision-making efforts. Furthermore, since this is intended as a guidance document for shaping additional analysis, it is important to focus on the approaches that make sense for the State. That said, other approaches and options are still considered and summarized for context. Although LCAs can include a wide range of environmental and social factors, GHGs are the primary component of interest to NYSERDA. The focus is on applicable technologies and feedstocks that are, or will be, commercially available in the near-term (five to 10 years), although policy relevance may extend further (20 years or more).

The report is based on a review of publicly available documents including journal articles and academic papers, research papers, governmental reports, and sustainability standards. In addition to the considerations described above, the documents reviewed were generally limited by the following criteria:

- Publicly available documents in English, published 2005 or later (although some older documents were included if relevant).
- Documents specifically discuss LCAs for bioenergy, and include evaluation of GHGs.
- Applicable feedstocks are woody biomass resources, particularly the types of resources with significant near-term availability in NYS.
- Applicable conversion technologies are commercially available biomass power and heat conversion technologies pertinent to NYS. Biofuel conversion technologies are not included in this report. However, since there is overlap in the biomass feedstock components, some of the literature does discuss biofuels.

Selected papers are a comprehensive cross section of available documentation meeting the criteria above. These materials were identified from searches in the following sources: ANTARES internal library, internet (Google, Google Scholar), and publisher databases (e.g., Wiley). Additional documents were included based on recommendations from subcontractors who are experts in the field.

Chapter 2 provides a summary of biomass resources and bioenergy technologies applicable to NYS for context. Chapter 3 summarizes the relevant policy considerations for bioenergy life cycle impacts in the State and the U.S., including an overview of the U.S. Environmental Protection Agency (EPA) Framework for Assessing Biogenic CO_2 Emissions from Stationary Sources, which is under development. A qualitative discussion of the approaches, methodologies, and inputs for LCA studies is provided in Chapter 4. The extensive variation in analysis methods and inputs contributes to the differences in results seen in LCA studies. Analysis inputs that can have a tremendous impact in results include the geographic scope and spatial scale, timeframe for analysis, bioenergy technology mix and counterfactual energy system, biomass feedstock, land use impacts, and local forest management and industry practices. These are characterized and discussed throughout the report. Chapter 5 provides a summary of the LCA considerations that have general agreement as well as those that do not, and a discussion of the areas with ongoing debate. Recommendations are provided in Chapter 6.

1.1   Limitations and Exceptions

As previously noted, this study was completed by reviewing existing literature on biomass and bioenergy LCAs. No original analyses were performed in this effort, and no attempt was made to compile or align LCA results from various sources.

Only woody biomass resources were considered in the study—other feedstock types are not included. Furthermore, the review was focused on consideration of direct GHG impacts associated with bioenergy (particularly CO_2, CH_4, and N_2O), following NYSERDA's objectives and direction. Other types of emissions (e.g., GHG precursors, black carbon, or criteria pollutants) are not often factored into LCAs and therefore not covered in detail. This study also does not cover other impact categories that are periodically included in LCAs, such as other environmental factors, biodiversity, or socioeconomic considerations.

It is important to note that results from specific papers are included in a few of the sections for illustrative purposes. Such examples not intended as an endorsement of a particular analysis or a critique of the methods or results presented.

2   New York State Context

This chapter reviews the current policy environment supporting biomass heat and power generation in the State, provides an overview of available biomass fuels, and describes commercial energy conversion technologies.

2.1   Policies Related to Biomass Energy Development in New York State

Governor Andrew M. Cuomo's Reforming the Energy Vision Initiative is a comprehensive energy strategy designed to spur clean energy innovation and align energy markets with the regulatory landscape to promote more efficient energy use, increase reliance on renewable energy resources, and deploy distributed energy resources and energy storage technologies (NYS Department of Public Service 2016).

Governor Cuomo's Office initiated a number of programs and policies designed to help meet the goals outlined in the Reforming the Energy Vision. Among these is the Clean Energy Standard (CES). The New York Public Service Commission (PSC) recently approved the CES, which requires that 50% of the State's electricity come from renewable energy resources by 2030. Tier 1 of the program requires load serving entities to procure new renewable resources on an incremental basis. The PSC order adopting the CES suggests that resources eligible to meet the Tier 1 requirement will mirror eligibility rules for the main Tier of the Renewable Portfolio Standard (RPS), which includes biogas, biomass, and liquid biofuels (Voegele 2016). Section 2.2 summarizes the eligibility rules related to biomass technology/fuel combinations. Note that for cogeneration projects, only the renewable electric generation is eligible, as the CES does not include thermal energy resources.

The New York Department of Public Service (DPS) issued a white paper analyzing the cost implications of the State's CES on electric prices in April 2016 (New York State Department of Public Service 2016). Projections of the post-2015 Tier 1 deployment of large-scale renewable power generation by technology, including biomass, were key elements used to estimate the costs and benefits of implementation of the CES. The study evaluated possible scenarios for repowered fossil fuel power plants and greenfield biomass Integrated Gasification Combined Cycle (IGCC) projects. Figure 1 shows a projected increase in biomass power capacity of 89 MW by 2023 in New York State.

Figure 1. Projected Post-2015 Tier 1 Bioenergy Technology Deployment – Cumulative Increase (MW)
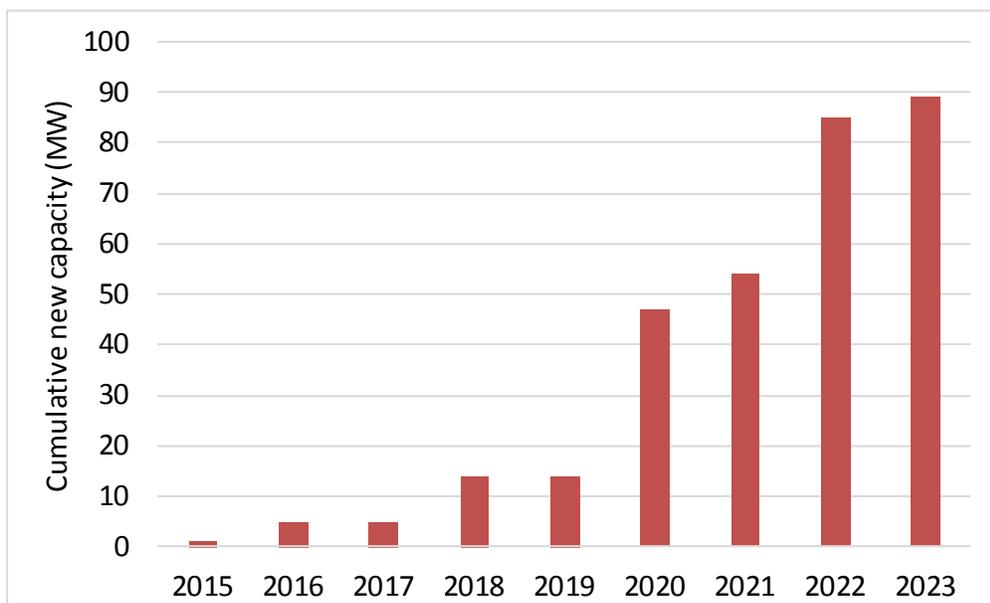
The scenarios examined model project locations within individual NYISO regions, taking into account access to biomass fuels, locations of potential repowering projects, development lead times and other factors. New biomass power plants under this projection would produce an estimated 590 gigawatt-hours (GWh) of new renewable electric generation. This represents 5% of the 12,365 GWh targeted for the Tier 1 program by 2023 (New York State Department of Public Service 2016). Therefore, biomass energy is expected to play a small but significant role in meeting overall renewable energy goals for New York State.

The biomass technologies chosen in the DPS study on large-scale renewable deployment differ from those that make up the bulk of existing biomass power capacity today, and were selected on the assumption that these options have a greater likelihood to be permitted and be economically viable. For greenfield projects, the study focused on gasification technologies, specifically IGCC. Direct-fired biomass projects were also considered for repowering. This does not preclude development of projects using other, currently commercial technologies that may meet permitting/regulatory requirements and provide reliable and economical power. Among these other technologies are greenfield direct-fired or

fluidized bed combustion, cofiring, and Combined Heat and Power (CHP) projects. These technologies are currently eligible for participation under the New York State RPS program, subject to eligibility requirements promulgated by the PSC, and appear likely to remain eligible under the CES, at least in the short term.

NYSERDA also supports the development of biomass thermal energy applications through research and development and market conditioning programs such as the Renewable Heat New York Program. This program seeks to recruit installers to participate in an incentive program (Program Opportunity Notice 3010) designed to install pellet and advanced cordwood boilers with thermal storage to residential and commercial customers (NYSERDA 2015). NYSERDA also offers incentives for installation of qualified wood pellet stoves.

Municipal governments in NYS have also enacted policies that affect the potential for biomass and other renewable energy sources. New York City's announced commitment for an 80% reduction in GHG emissions by 2050 relative to 2005 (known as 80 x 50) could have implications for the deployment of new, advanced technology biomass power and CHP systems to replace older in-city power stations.[1] The City is in the process of evaluating ways in which the efficiency, reliability, and GHG benefits of new in-city power generation may be valued under NYISO, State and federal regulations to eliminate financial hurdles to implementing these types of projects (City of New York).

While there are no federal requirements imposed on energy service providers to sell or generate heat or power using biomass, there are federal agency requirements to utilize renewable energy (including biomass) and decrease GHG intensity. These policies have direct roles in the development of biomass energy facilities, such as the ReEnergy-owned and operated 60 MW biomass power facility in Fort Drum, NY. The U.S. Defense Logistics Agency signed a 20-year contract with ReEnergy in 2014 to supply power to their military installation at Fort Drum (ReEnergy Holdings 2014). The 2007 National Defense Authorization Act called for a quarter of the energy used by the U.S. Department of Defense to come from renewable sources by 2025 (Block 2015).

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[1] Note that strict emissions regulations in NYC would likely limit development of direct fired solid biomass projects, but gasification technologies with low emissions may be feasible to some extent. Furthermore, other types of biomass such as anaerobic digestion of recovered organic waste materials and wastewater could be used to address multiple goals simultaneously (distributed renewable energy generation, GHG emissions reductions, and resource recovery), although they are outside of the scope of this study.

Federal efforts under the EPA Clean Power Plan (CPP) to reduce carbon emissions from power plants also have implications for the future of biomass energy. While the implementation of the CPP stalled while State-sponsored litigation against it is being resolved, the EPA developed a draft accounting framework that would factor in the impacts of biomass utilization on above- and below-ground carbon sequestration and link that to the net atmospheric carbon benefits of biomass energy. Section 3 discusses this effort and the future of the rulemaking process in detail.

2.2 Biomass Fuels – an Overview

Specific biomass feedstocks used for energy production have a big impact on the LCA results and GHG emissions profiles. This section provides a summary of the types of resources considered in this study –feedstocks applicable to bioenergy production in New York State in the near term.

2.2.1 Resource Types of Interest

There are a variety of wood biomass resources that contribute to a reliable, sustainable biomass fuel supply for biomass heating and power generation. These include various forest-derived biomass materials as well as urban wood that meets eligibility criteria with some restrictions under the New York RPS/CES. Energy crops such as short-rotation woody crops (e.g., willow and poplar) are also of interest, but due to the time required to develop a willow supply, it is unlikely these resources could be available in significant quantities within the five to 10 year timeframe of interest for this study.[2]

The specific eligible unadulterated wood biomass sources under the above policy regime includes (NYSERDA 2014):

- Harvested wood (from commercial harvesting)
- Silvicultural waste wood
- Mill residues
- Site conversion waste wood (wood from clearing forestland for development)
- Unadulterated source-separated wood from municipal solid waste or Construction and Demolition (C&D) debris
- Clean recovered C&D wood from a material recovery facility or C&D processing facility
- Energy crops

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[2] Although there are already some existing willow biomass resources in the State that are used for energy generation, they make up a very small proportion of the total current resource.

Harvested wood or silvicultural waste wood must be harvested in accordance with the end user facility's forest management plan to be considered eligible biomass under the RPS. According to the New York State RPS Biomass Power Guide, the plan must specify how the forest management practices contribute to conservation of biological diversity, maintain forest productivity and promote forest health (NYSERDA 2014). There are also additional hurdles that must be met for clean wood separated from C&D waste materials from a material recovery facility or C&D facility to be categorized as an unadulterated biomass resource.

Adulterated biomass, including paper, paperboard, yard waste, plywood and particle board, and other adulterated wood waste must undergo a primary conversion to a liquid or gaseous fuel in order to be eligible (NYSERDA 2014). As this effort is focused on unadulterated biomass, these other wood waste materials will not be covered in detail here.

2.2.2 Characterization of NY Forests and Resources in Context of LCAs

New York State's forest resource includes 19 million acres of forest land, about 63% of the total area of the State of New York. Approximately 16 million acres of forest land (84%) in New York is classified as timberland (i.e., "forest land that is producing or is capable of producing crops of industrial wood and not withdrawn from timber utilization by statute or administrative regulation," as defined by (USDA Forest Service 2016), while approximately 3 million acres (16%) are reserved from harvest, primarily in the Adirondack and Catskill Preserve. Areas in the Adirondacks have the highest proportion of forest land (>70%) while the largely agricultural Lake Plain region of the State has the lowest percent forest cover at 40% (U.S. Department of Agriculture Forest Service 2015). Hardwood forests make up the majority of the forested area in the State. The most common forest type group is maple/beech/birch, making up 53% of the forest land area while oak/hickory forest type groups make up 19% of the forest land area (U.S. Department of Agriculture Forest Service 2015). Important conifer species include eastern white and red pine and hemlock.

Most active forest management that results in the generation of forest products including biomass comes from private land. According to the latest forest inventory report for NYS from the U.S. Department of Agriculture Forest Service, approximately 75% of the forest land in the State is privately owned (U.S. Department of Agriculture Forest Service 2015).

Figure 2. Forest Ownership Distribution Map

Image Source: (U.S. Department of Agriculture Forest Service 2015)
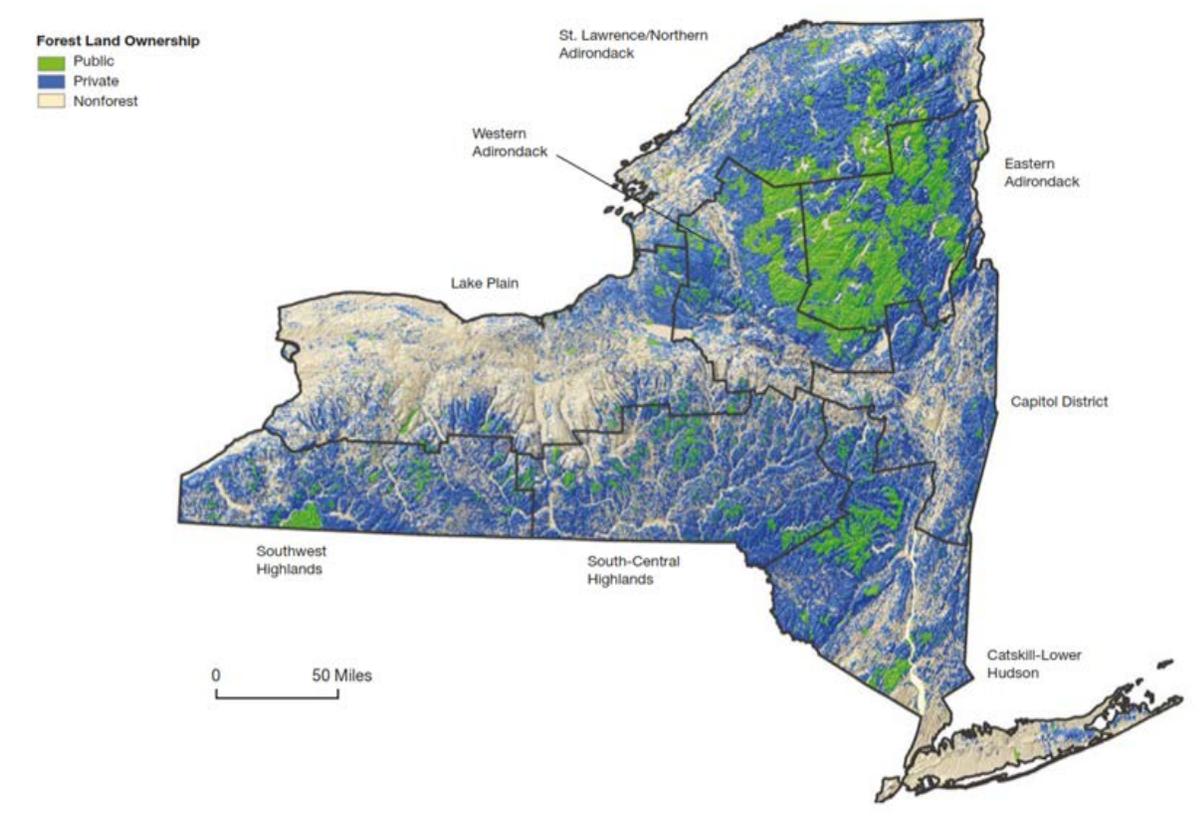
Landowner preferences and parcel size affect the likelihood that timber harvesting will take place on forest land in the State. While there is no absolute cut-off point in terms of parcel sizes for which active management can be performed cost-effectively, forests owned by large corporations and larger parcels are more likely to be managed for timber production. Based on information from U.S. Department of Agriculture Forest Service (2015), corporations own about 2.7 million acres of forest land (14% of the total) and family forest owners own 10.8 million acres (57% of the total). An additional 4% of private forest land is owned by nonfamily partnerships, non-governmental organizations, and tribal land. The remainder (25%) is public land. The majority of the private landowners in the State (588,000 +/- 133,000) are small landowners owning at least one, but less than 10 acres. Combined, these small landowners own only 1.6 million acres (+/- 249,000) of forest land, which is about 5% of the total in NYS. There are another 200,000 landowners that each own at least 10 acres of forest land; their combined total ownership covers 9.3 million acres, which is about half of the forest land in the State.

About 24% of forest landowners in the State rate timber production as important or very important reasons for owning forest land. Forest land near urban areas often is owned for other reasons such as recreation, wildlife habitat, water resources protection etc. In these areas, urban wood from construction debris and tree trimming can be significant potential sources of biomass feedstocks. In many cases, biomass fuel users would need to compete with landscaping markets for these materials.

Of the 4.1 million acres of forest land owned by the State, 2.6 million acres are contained within the Adirondack Park, part of a six-million-acre patchwork of public and private lands in Northern New York known as the Adirondack Preserve. The Catskill Park consists of another 286,000 acres within a larger area known as the Catskill Preserve. The remaining public land is held by the State or federal government and is professionally managed. Together the Adirondack Forest Preserve and Catskill Forest Preserve (the State-owned portions of the respective Parks) make up the State's Forest Preserve and are protected as forever wild due to their ecological, scenic, and recreational value (New York State Department of Environmental Conservation n.d.). However, a significant amount of active forest management occurs on private land in the Adirondack Preserve.

Overall, annual forest growth is 2.1 times current annual removals on timberland in NYS (U.S. Department of Agriculture Forest Service 2015). There is potential for forest management to improve value and increase the sustainable flow of timber products from forests in the State. Only 9% of family forest owners with parcels greater than 10 acres have forest management plans in place (U.S. Department of Agriculture Forest Service 2015). This is an indication of significant potential for improved forest management. However, there are site-specific technical and other challenges to improving forest management in NYS. Topography can be uneven and steep, increasing logging costs and posing challenges for pre-commercial thinning designed to optimize growth. Topography also limits the extent of plantation forestry. Landowner preferences also play a significant role in determining the realistic potential for improved forest management in NYS. Not all landowners are willing to pay extra to optimize forest productivity on their land for a variety of reasons, among them the long payback period on this investment. Revenue from the sales of forest products may not cover all of the up-front costs of forest management.

Analysis of the life-cycle carbon impacts of different timberland management strategies in the Southeastern U.S. suggests that forest management designed to increase forest productivity on commercial timberland while providing a steady stream of biomass has the potential to improve forest carbon sequestration compared to other biomass sources (Stephenson 2014). Timberland improvement activities could also improve the carbon implications of forest biomass utilization, although there are significant differences between the two regions in terms of forest types, climate, management regimes and other factors that combined make the potential for greater forest productivity in the Southern U.S. greater overall than in NYS.

Management strategies need to be tailored to specific forest types and forest management practices. Additional work is needed to develop guidance on which management practices can optimize both GHG and economic outcomes for forest landowners and managers in the U.S. Northeast. Realizing this opportunity is likely a long-term effort. Investment in forest productivity also pays dividends in terms of maintaining forest land values. This helps keep land in forest cover and can reduce the rate of forest land conversion to other uses (Miner 2014). An estimated 331,000 acres of forestland was lost to non-forest uses between 2007 and 2012 in the State (U.S. Department of Agriculture Forest Service 2015).

Comparing NYS to other areas of the U.S. where industrial timber management is the norm helps put the opportunity for improved management in the State in context. The percentage of forest landowners in the U.S. Southeast that view timber management as a primary purpose for owning land is approximately 80%. By comparison, the value for NYS is 24%. Forest landowner motivations and drivers for managing their land are significantly different than in areas like the southeastern U.S., which has an impact on forestry investments. A significant commitment and effort would be needed to convince large numbers of small forest landowners, who manage land for other purposes, that increased carbon sequestration fits in with their management vision for their property. In the past, universities and the New York State Department of Environmental Conservation (DEC) had limited success with this type of outreach, in part due to limited resources and a lack of financial incentives for landowners. There is no guarantee of success even with an increase in commitment of resources, and outcomes will only be evident over the long term.

Existing biomass fuel consumers include residential and commercial firewood and pellet fuel users and biomass power and combined heat and power generation facilities. Firewood is produced using smaller low-grade trees that are harvested along with higher value timber or from land clearing operations. While some pellet fuels are sourced from out-of-state, a majority of the demand for pellet fuels and firewood is met using wood sourced from NYS. Figure 3 shows nine pellet mill operations, four of which border the Adirondack Preserve, and the rest distributed in the southern portion of the State. Note that the production capacities of these pellet mills vary significantly, ranging from around 1,000 tons per year up to more than 100,000 tons/year (Biomass Magazine 2016). The majority of the pellets produced in the State are hardwood pellets destined for residential markets, although mills with access to port facilities have the potential for export as well. Pellet mills rely largely on a combination of mill residuals, including sawdust and chips, and forest biomass for their feedstock supply. Biomass power generation and CHP generation facilities in the State rely on residues from sawmills, logging operations, and chipped or ground noncommercial[3] trees for their fuel supplies.

Figure 3. Existing Pellet Mill Operations in NYS

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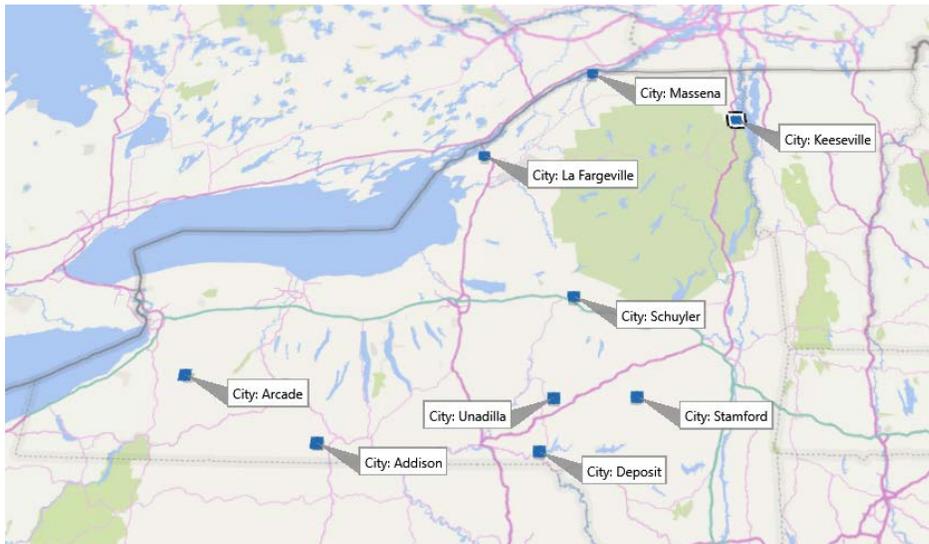
3   Noncommercial in this context refers to trees that are unsuitable for higher-value uses such as lumber.

2.2.3 Biomass Resource Availability

In 2013, NYSERDA published an assessment of biomass availability that considered forest and urban resources by county, including the following:

- Forest based biomass (hardwood and softwood)
- C&D wood
- Willow (future cultivated crop)

Forest Biomass. Potentially available forest biomass includes: logging residues, biomass from land clearing operations, harvest of noncommercial tree species, and commercial timber. Cornell University and SUNY College of Environmental Science and Forestry developed estimates of the total potential forest biomass resource in support of the Renewable Fuels Roadmap. That roadmap effort was led by Pace University under contract to NYSERDA (Pace University Energy and Climate Center 2010). Each biomass category is available at different price points. Merchantable biomass includes pulpwood, which is at the high end of value for this supply.

The results of the Pace 2013 study indicated that there are 15.8 million acres in the state where wood biomass could be harvested. Further, a total of 8.1 million oven dry tons (ODT)[4] are technically available and could be sustainably harvested per year in NYS, but when an estimate of landowner interest in forest management is factored in, the potentially harvestable biomass in NYS drops to 4.3 million ODT (Table 1). Though shown in terms of ODT, forest resources are typically sold as a green wood fuel, with an estimated moisture content of 45%.

Table 1. New York Total Potentially Harvestable Forest Biomass

Forest Biomass	Million ODT per Year (2012)
Total Potentially Available	4.3
Portion from merchantable wood (up to pulpwood quality)	2.3
Portion from noncommercial species	1.4
Portion from logging residue and other recoverable	0.5

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[4] Oven dry tons is used to indicate a 0% moisture content. This unit is used so that biomass materials are compared on an equal level, since the moisture content affects weight and energy value of the material.

Construction and Demolition (C&D) Wood. The C&D Wood waste stream composition was estimated based on the DEC Beyond Waste materials management study (New York State Climate Action Council 2010) as well as the DEC C&D Composition Analysis (NYSERDA 2015). The total NYS C&D waste stream has been estimated by these studies at 13 million as-received tons (11 million ODT assuming 15% moisture content) per year. The wood waste portion of this C&D stream has been characterized as roughly 15 to 20% statewide, or 1.9 to 2.6 million as-received tons per year (1.6 to 2.2 million ODT per year assuming 15% moisture content) based on the same studies. The detailed makeup of the wood waste stream in Figure 4 was taken from a study conducted by DSM Environmental for the Massachusetts Department of Environmental Protection (DSM Environmental Services, Inc. 2008). This study includes a detailed characterization of both the C&D waste stream and a breakdown of the wood component of this stream for Massachusetts; NYS is assumed to have a similar C&D composition.

Figure 4. Characterization of C&D Waste Stream and Woody Sub-Segment by Weight

% of Total C&D	Wood Type	% of Waste Wood Only
9.1%	Untreated/Unpainted	27%
2.4%	Pallets & Crates	7%
8.1%	Engineered	24%
6.5%	Painted/Stained	19%
1.6%	Pressure-Treated	5%
0.3%	Wood Furniture	1%
6.0%	Other Wood	18%
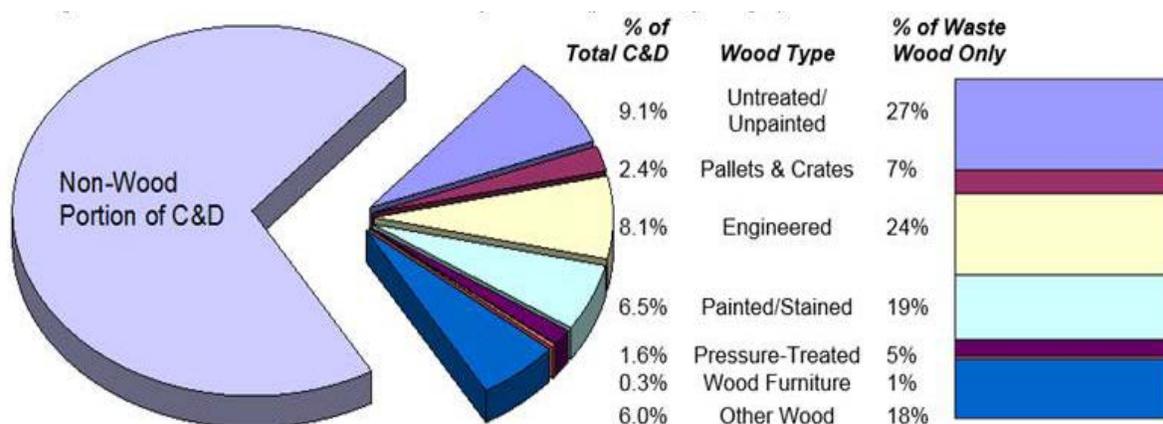
It is assumed that the eligible portions of the wood waste stream that contribute to the eligible biomass resources in NYS include "untreated/unpainted" wood and "pallets & crates," which make up 34% of the wood waste stream combined. This would be approximately 0.56 to 0.75 million ODT of C&D wood. Additional material could potentially be used for gasification, as the current RPS regulation allows for a wider range of fuels to be used in these facilities, subject to a specific comparative emission test. Therefore, some additional portion of the approximately 42% of the C&D wood waste could potentially be utilized for energy generation if gasification technology is commercialized (e.g., IGCC), which represents approximately 0.7 to 0.9 million ODT of potential biomass fuel per year. The average as-received moisture content of C&D wood is approximately 15%. Not all of this material can be considered recoverable and available for use due to potential issues with commingling with other waste.

Wood Energy Crops. Short rotation willow and poplar crops are a potential future resource for bioenergy production. Based on the results of an assessment performed by Cornell University and SUNY College of Environmental Science and Forestry for the Renewable Fuels Roadmap (Pace University Energy and Climate Center 2010), the total annual wood energy crop potential in New York statewide is 2.1 million ODT. These results are based on an assessment of sustainable production of willow on potentially available lands currently in herbaceous (non-forest) cover, with yields applicable to local soil and climate data, assuming a three-year harvest cycle. There are currently only 1,200 acres of willow being grown in NYS. Biomass from these fields is being used in the Black River and Lyonsdale power plants. Extensive landowner outreach and education would be required to deploy wood energy crop systems. It is likely that it would take more than five years before wood energy crops could be available in any significant quantity, and as many as 10 years or longer for wood energy crop systems to be fully commercialized. As such, the 2.1 million ODT per year production can be considered the high-end of potential development over a long time frame.

Summary of Wood Biomass Resource Availability. Table 2 summarizes total wood biomass resource potential and associated power generation potential for the State, based on the results from the DPS 2016 study. Note that this does not include mill residues, which are currently completely utilized for fuel and fiber by existing consumers.

Table 2. Summary of Long Term Wood Biomass Resource Availability in New York State

Type	Quantity (Million ODT/year)	Potential Power Generation (GWh/year)*
Forest biomass	4.3	6,431
Clean C&D wood	0.7	1,086
Wood energy crops	2.1	3,141
Total unadulterated biomass (subtotal)	7.1	10,658
Adulterated C&D wood (gasification only)	0.9	1,398
Total all wood biomass	8.0	12,056

*   Based on a wood heat content of 17.2 MMBtu/ODT (8,600 Btu/dry pound) and plant heat rate of 11,500 Btu/kWh. The plant heat rate is consistent with projections based on biomass IGCC technology (New York State Department of Public Service 2016)

2.3 Biomass Energy Conversion Technologies

While much of the preceding discussion of biomass deals with large-scale biomass power applications, there is a wide spectrum of biomass energy conversion technologies and sizes that are feasible in New York State, ranging from efficient residential and small commercial pellet and cordwood heating systems to industrial CHP and utility-scale biomass power. The following discussion provides an overview of the various biomass energy conversion technologies currently in use, and near-commercial technologies that have the potential to play a role in the CES program. The energy conversion technology impacts the type of feedstock that can be used as well as the selection of counterfactual energy systems considered for LCA studies. The conversion efficiency of the bioenergy technology also has a significant impact on associated GHG emissions.

2.3.1 Residential and Small Commercial Pellet and Cordwood Heating Systems

Increased deployment of modern residential and commercial wood heating systems can support expanded reliance on renewable sources of thermal energy, save homeowners and businesses money, and reduce air emissions especially when compared to older wood burning appliances.

The types of systems that NYSERDA is currently promoting include:

- Residential pellet stoves and pellet stove inserts
- Residential and small commercial advanced cordwood boilers
- Residential and commercial pellet boilers with thermal storage

Table 3 summarizes wood heating system sizes and efficiencies for systems eligible for incentives under the Renewable Heat NY Program. Additional discussion of the system types is provided below.

Table 3. Wood Heating System Sizes and Efficiency for Systems Eligible for Renewable Heat NY Incentives

Technology	Sample system size range (Btu/hour), based on currently qualified systems	Minimum thermal efficiency (% HHV)
Pellet stoves*	10,800 – 50,000 (pellet stove) 16,700 – 45,500 (pellet stove insert)	58%
Cordwood boiler	70,000 - 200,000	60%
Pellet boiler	34,800 - 273,000 (small) 300,000 – 2,470,000 (large)	85%

*   System sizes shown for pellet stoves are based on high output range. The minimum efficiency is based on reported efficiencies for the systems currently approved for the program. For the other system, the minimum efficiency is based on the lower limit to be eligible for incentives.

Pellet Stoves

Pellet stove heating systems have higher efficiencies and lower emissions than traditional wood stoves and boilers. For example, the residential pellet stoves and pellet stove insert systems that are eligible for incentives under the NY Renewable Heat program must have particulate matter emissions of 2.0 grams per hour or less, and must also be on the EPA Certified Wood Heater list (NYSERDA, Residential Pellet Stoves n.d.).

Cordwood

Advanced cordwood boiler systems with full thermal storage for residential and small commercial applications offer significant improvements in efficiency and emissions over older wood boilers or furnaces. Modern systems can exceed seasonal efficiencies of 60% based on the higher heating value of the fuel. Thermal storage is provided by water storage tanks that can be pressurized or non-pressurized. Note that cordwood boiler systems eligible for incentives under the Renewable Heat NY Program are limited in size to 300,000 Btu/hour (NYSERDA 2015).

Pellet Boilers

Residential and commercial pellet boiler systems can reach thermal efficiencies of greater than 85% based on fuel higher heating value. System that are currently on the approved Renewable Heat NY list range from about 30,000 Btu/hour to more than 2 million Btu/hour in maximum heat output. Modern pellet boilers are generally equipped with fully automatic feed systems and thermal storage, which are required for eligibility for incentives under the Renewable Heat NY Program (NYSERDA 2015).

2.3.2 Direct Combustion—Thermal, CHP, and Power Applications

Direct combustion of solid fuel biomass in a boiler to generate steam for industrial process heating and power generation remains the most common way of converting biomass into a usable form of energy. The technology is well established, with a variety of combustors and boilers on the market to choose from.

Stoker and fluidized bed furnaces combined with steam turbines represent the most widely used biomass power technology combination in the U.S. They are both mature technologies. The heat rates are mainly determined by the fuel moisture content, steam pressure, temperature and turbine selection.

Table 4 shows the two predominant types of boiler technologies available on the market today. Each boiler is capable of handling a range of fuel moisture contents and fuel particle sizes. Each technology has its advantages and disadvantages in terms of complexity, efficiency, and cost. The added cost for higher-pressure boilers must be compensated by the improved efficiency—this is mainly implemented in larger facilities. Fluidized bed systems have similar efficiencies, but tend to cost 15 to 20% more than stoker units of similar capacity.

Table 4. Summary of Direct Combustion Technologies

Source: (U.S. Environmental Protection Agency 2013)

	Stoker Grate	Fluidized Bed
Relative Cost	Less costly	More costly
Complexity	Simple	Complex
Thermal Efficiency (%)*	63-71	67-75
Biomass Size Requirement	0.25" - 2"	1.5" - 3"
Biomass Max. Moisture Content Requirement	10-50%, depending on manufacturer	up to 60%, depending on manufacturer

2.3.3   Biomass Gasification—Thermal and CHP Applications

Gasifiers convert biomass into a syngas containing carbon monoxide and hydrogen (and other components) by reacting the raw material at high temperatures (1,800°F) with a controlled amount of oxygen and/or steam. This low- to medium-Btu gas[5] can be used as a fuel to replace natural gas in many applications, depending on purity requirements. Char is often a coproduct of the gasification process, but it is usually used directly or indirectly to improve overall energy recovery.

Gasification technologies are compared in Table 5. The overall efficiency of a gasifier project depends on whether the project is used for heating, power generation only, or CHP. The choice of combustion technology and prime mover (e.g., steam turbine, reciprocating engine) affects the overall system conversion efficiency. Section 2.3 discusses some of the efficiency issues for different gasifier, combustor, and prime mover configurations.

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[5]   Gas with less than 700 Btu per standard cubic foot (scf).

Table 5. Summary of Gasification Technologies

	Fixed Bed	Fluidized Bed
Relative Cost	Less costly	More costly
Complexity	Simple	Complex
Biomass Size	<= 0.25"	<= 3"
Biomass Maximum Moisture Content	20%	Typically 20% to 30%, depending on manufacturer
Applications	Boiler fuel, process or space heat, reciprocating engine after cleanup	Boiler fuel, process or space heat, gas turbine or reciprocating engine after cleanup

The fixed bed gasifier is similar to a stoker grate furnace while the fluidized bed gasifier has a similar design as the fluidized bed furnace. Fixed bed systems are commercially dominant (across all scales), but tend to be limited to smaller district heating and CHP projects, generally less than 5 MWe in capacity. When used as gasifiers, fixed beds produce a lower Btu syngas than fluidized beds, though at lower complexity and cost. Fluidized bed gasifiers can be designed to handle a wider range of biomass fuels. Fluidized bed gasifiers have been used in larger utility-scale projects to generate electricity in conjunction with gas boilers and steam turbines.

The potential to use biomass-derived syngas in biomass IGCC systems can result in an increase overall system efficiencies. The system replaces the traditional biomass combustor with a gasifier and a gas turbine. Exhaust heat from the gas turbine is used to produce steam that can be used in a conventional steam turbine. This technology is of potential importance in this discussion as at least one developer of this technology, Taylor Biomass Energy, has actively been persuing an IGCC/CHP project in the State for more than a decade.

There are also several other less conventional gasification technologies currently in a demonstration phase, which are unlikely to make a significant market impact over the next ten years, but are worth mentioning. These include plasma arc gasification (currently applied only to small-scale commercial waste or medical waste processing units) and low temperature hydrothermal gasification, which uses high-moisture fuels in the presence of water and a catalyst.

2.3.4 Biomass Cofiring with Fossil Fuel

Cofiring biomass with a fossil fuel, such as coal, is the most efficient and inexpensive method of combustion. This is because moderate cofiring percentages (up to 10%) can be achieved with relatively few changes to existing plant infrastructure. However, with the decline of coal-fired power in the State and nationwide, this technology is not expected to contribute significantly to future biomass energy production and is not discussed further in this report.

2.3.5 Comparison of Different Conversion Technologies

Table 6 shows the typical overall conversion efficiencies associated with the different types of technologies that have been discussed. Biomass power generation technologies have typical electrical conversion efficiencies ranging from 10 to 30% when used in power-only mode, meaning that approximately 10 to 30% of the energy that is put into the system leaves the system as usable energy. The rest of it is lost to the environment through the form of waste heat, emissions, incomplete combustion, and other process inefficiencies (Ecofys 2010). However, using a biomass combustion system in CHP mode can improve system efficiency to as much as 75% (NYSERDA 2009). Note that incoming biomass fuel may need to be resized and/or dried to work with the energy conversion technology. Biomass IGCC applications have the potential for significantly higher electrical conversion efficiencies than large-scale direct combustion applications.

Table 6. Conversion Efficiencies for Various Technologies

Technology	Type of energy	Wood fuel types	Overall thermal efficiency (%)	Thermal energy percent (%) of total output	Electric energy percent (%) of total output
Pellet stove/insert[1]	Heating	Pellets	58-73%	100%	0%
Cordwood boiler with thermal storage[1]	Heating	Cordwood	60-69%	100%	0%
Pellet boiler with thermal storage[1]	Heating	Pellets	85-90%	100%	0%
Small Scale CHP (Gasification + engine)[2]	Heat and power	Hog fuel, bark, chips, pellets, sawdust	69%	60%	40%
Large Scale Power (Fluid bed boiler + turbine)[3]	Power	Hog fuel, bark, chips, pellets, sawdust	25%	0%	100%
Gasification + turbine (IGCC)[2]	Power	Hog fuel, bark, chips, pellets, sawdust	31%	0%	100%

Notes: (1) Systems eligible for participation in Renewable Heat NY Program. (2) Source is (EPRI 2007). (3) Source is (NYSERDA 2009)

2.4   Current Status of Biomass Energy Technology Deployment in New York State

Biomass energy currently represents a significant component of renewable energy production including heat and power in the New York State, exceeded only by hydropower as source of renewable energy production (U.S. Department of Energy Energy Information Administration 2009).

NYSERDA published the "New York Wood Heat Report" in 2016.[6] This report presents detailed information on current wood heating use, trends, and potential. Key summary statistics from that report provide a good overview of the extent of wood heating use in residential and commercial applications. New York State is currently the second largest consumer of wood for residential heating, exceeded only by California. About one million wood-burning heating appliances are currently installed in homes across NYS, but the U.S. Census Bureau American Community Survey (five-year period from 2006–2010) reports that about 127,000 homes (approximately 2% of total households) in the State relied on wood as their primary heating source (Bureau 2011). In 2011, households burned approximately 1.5 million tons of wood in NYS, inclusive of pellet fuel and cordwood systems. Other states including Maine, New Hampshire, and Vermont have a significantly higher proportion of households that use wood for their primary heating source. There are a limited number of wood-fired commercial and industrial boilers in the State, mostly at wood processing facilities and some schools. The best indication of where wood-fired boilers are most likely to be installed is where there is a large concentration of oil-fired boilers and limited access to natural gas. There are a large number of boilers in heavily urban areas such as New York City; many of these are located in areas with access to natural gas and would be likely to be replaced with natural gas at the end of their useful life. More rural areas with limited natural gas availability that are located in areas with active forest removals are much more likely targets (Figure 5).

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[6]   Available on-line: https://www.nyserda.ny.gov/-/media/Files/Publications/Research/Biomass-Solar-Wind/ 15-26-NYS-Wood-Heat-Report.pdf

Figure 5. Percentage of Industrial and Commercial Oil- and Propane-Fired Boilers, by County, Located Near Natural Gas Lines

Source: (NYSERDA, New York State Wood Heat Report 2016)
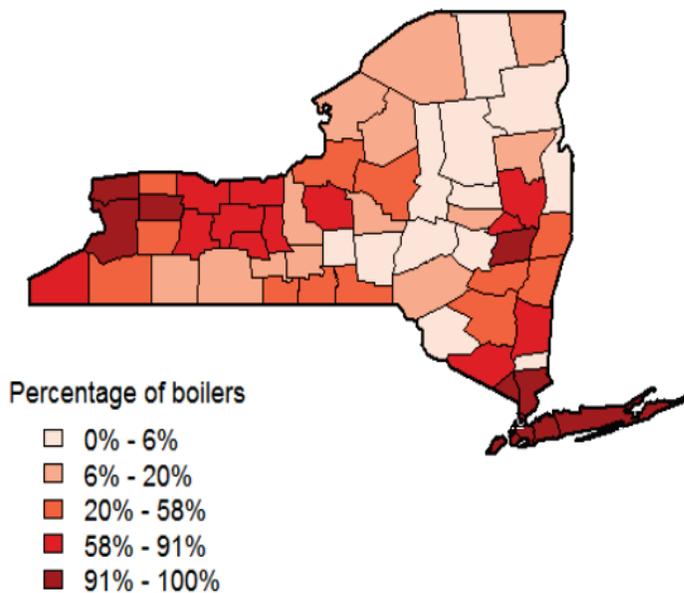
The cost-effectiveness of transitioning to wood fuel depends on trends in heating oil prices, the age of the existing boiler, and also on the cost differential between an oil-fired and wood-fired unit.

Table 7 summarizes existing biomass power generation capacity with contracts under the State's RPS Program. The Main Tier of the New York RPS includes two biomass power projects with a combined 69.3 MW of electricity capacity. Two other projects with a total of 43 MW of wood-fired power generation capacity are included under the Tier 2 Maintenance program (NYSERDA 2016).

Table 7. Summary of New York RPS Program Biomass Project Capacity

Source: (NYSERDA 2016)

Plant Name	Fuel Type	City	County	Program Tier	Capacity MW
ReEnergy Chateaugay	Forest residues	Chateaugay	Franklin	Tier 2	21.0
ReEnergy Lyonsdale	Forest residues	Lyonsdale	Lewis	Tier 2	22.0
ReEnergy Fort Drum	Mill residues, forest residues, urban wood	Fort Drum	Jefferson	Main Tier	43.3
Niagara Generating Facility*	Wood and tire-derived fuel	Niagara Falls	Niagara	Main Tier	26.0
Total					112.3

* The capacity value is for wood-fired capacity only. The total capacity with wood and tire-derived fuel is 48 MW.

3   Relevant Policy Considerations for Life Cycle Impacts of Bioenergy

Biomass energy is unique among renewable energy resources in that it requires conversion of a solid fuel through combustion or other energy recovery process. Wood fuel has implications for land use and biogenic carbon sequestration that should be taken into account in GHG life cycle analysis, in addition to emissions associated with the production, harvest, transport, and conversion of wood biomass to energy.

The current policy environment in NYS considers that not all biomass is carbon neutral, but stops short of advocating a specific carbon accounting framework. In Part 242 of the State's Air Resources codes, rules and regulations that govern the CO_2 budget trading program, the DEC clarifies that "*The premise of biomass carbon neutrality, or low carbon intensity, cannot hold true over time without adequate future re-growth and attendant carbon sequestration to offset the CO2 emissions from biomass combustion*" (New York State Department of Environmental Conservation 2010). The New York Climate Action Plan assumes that biomass is carbon neutral and can provide meaningful carbon emissions reductions but acknowledged that consensus on how to appropriately assign carbon intensity is lacking (New York State Climate Action Council 2010, 5-5). The Regional Greenhouse Gas Initiative has eligibility requirements for biomass to ensure that the CO_2 emitted from the burning of biomass is re-sequestered as the forest grows. The burgeoning need to ensure that renewable energy resources contribute to stabilization and eventual reduction of GHG emissions is broadly driving pressures to adopt more explicit carbon accounting methods that verify GHG emissions reductions claims made by projects.

There are many existing GHG protocols that address some or all of the biogenic and land-use factors that affect the GHG profile of biomass energy facilities. The definition of supply shed boundaries,[7] estimates for baseline emissions and measurement protocols for change in carbon stocks are important elements of any biomass GHG accounting method. Decisions about these elements affect the extent to which an accounting framework creates increased or decreased value for biomass projects in NYS relative to other

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[7]   The term supply shed refers to the geographic area where biomass resources may come from to serve a project or group of projects.

compliance measures (wind, solar, energy efficiency, conversions to natural gas, etc.). New York RPS/CES bioenergy projects have a stake in the decisions on reporting and accounting for CO_2 emissions. How the boundaries for accounting are drawn and the methods for carbon stocks measurement are applied will be the key determinant of whether projects are perceived as offering renewable energy benefits and carbon emissions reductions in a given policy portfolio.

The most recent effort by the EPA under the auspices of the CPP addresses a wide range of variables that affect the GHG profile of a biomass energy project. The draft "Framework for Assessing Biogenic CO_2 Emissions from Stationary Sources" released in November 2014 factors in the impacts of biomass feedstock production on land use, in addition to aboveground and belowground carbon sequestration on the net atmospheric carbon dioxide concentration due to biomass energy. The EPA framework is significant in that some version of the document is likely to be adopted by federal regulators to assess compliance with GHG emissions limits for power plants under the CPP. As such, the final Framework would directly relate to development of state or regional compliance plans. It would provide guidance to policymakers on how to calculate GHG emissions related to biomass energy.

Fundamentally, biomass carbon cycling, or the process of carbon uptake and release by plant systems, is the crux of biogenic emissions calculation methods. The EPA framework addresses the issue of biomass carbon cycling using the Biomass Accounting Factor (BAF). The BAF adjusts stack emissions from a stationary source to account for impacts of biomass use on above and below-ground carbon stocks, avoided emissions (e.g., changes in methane emissions from decomposition of biomass), leakage (indirect impacts of biomass use such as land use change resulting from biomass use) and several other factors. Notably, the EPA framework does not provide a specific calculation method for the leakage factor, which is very difficult to quantify. A BAF of zero equates to zero net CO_2 emissions. A negative BAF value corresponds to sequestration of more carbon than emissions resulting from biomass fuel production and use.

The land use and biogenic carbon implications of wood fuel use depend on a variety of factors including forest type and associated soils, forest management practices, and extent and type of existing wood product industry accessible to the end user. The policy/decision-making timeframe is also important in terms of the interpretation of the results. Additional research is needed to develop data and methods to estimate BAF factors tailored to forests and existing forest management practices in NYS. The draft EPA

Framework treats the use of fuel quality mill residues (e.g., sawdust and bark) as carbon neutral, however, this could change in the final version. Additionally, illustrative analysis provided with the EPA framework (U.S. Environmental Protection Agency 2014) in other regions of the U.S. suggest that use of harvest residues in accordance with best management practices for logging residue utilization in many cases could be carbon neutral under this approach.

The timeframe for finalizing the biogenic carbon accounting framework and the pathway for doing so is currently uncertain. The EPA established a Science Advisory Board (SAB) in 2011 to review and make recommendations to the EPA administrator. The SAB Ad-Hoc Panel (Panel) was charged with reviewing the draft framework and developing a peer review report on the draft framework (Gunning 2015). The Panel provided its latest review effort in February 2016. In March 2016, the full SAB provided the Panel with its comments on the latest review report. The SAB did not approve the submission of the latest Panel review to the EPA administrator (Environmental and Energy Study Institute 2016). On October 12, 2016 the SAB held a conference call to assess the path forward to resolving remaining issues with the Panel review.[8] Finalization of the review along with conclusions and recommendations for addressing remaining technical and scientific questions regarding the framework would facilitate finalization of the accounting framework.

Comments from the SAB published on March 28, 2016 (Science Advisory Board 2016) listed a number of issues with the Panel report. Some of the issues dealt with the overall clarity of the report, but many indicated divisions as to whether the Panel stayed within its defined review role. The volume and complexity of the comments suggested there was a lack of a clear path forward to finalizing the framework. One criticism was that the Panel review made assumptions regarding policy goals and timeframes beyond the scope of the Panel's charge. However, another SAB reviewer noted that constraining the Panel's ability to evaluate policy context limited the ability to assess the report. Another noted that the BAF framework could inform temporal scales for policy development. During the conference call held on October 12, 2016, the SAB made substantial progress on how to separate the science of biogenic carbon emissions from policy or judgement calls that many considered beyond the Panel's charge. This bodes well for a successful resolution of many of the technical issues with the Panel report, although the timing for the finalization of the Panel report is unclear.

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[8]   Meeting notice and documents available online, https://yosemite.epa.gov/sab/sabproduct.nsf/Meeting CalBOARD/BD5980491F4F4FBB85257FEF0048CBC4?OpenDocument

Under the current plan, the Framework will allow State or regional policymakers significant leeway to specify key factors in the analysis methodology, such as timeframe for analysis, spatial scale, and baseline approach. The SAB's rationale for doing this is that their purpose is to provide a scientific basis, and they do not know what all of the policy goals will be. Different approaches may be applied to address different objectives.

Considerations of timeframes for analysis contributed to a significant portion of the review comments and associated discussion during the teleconference. The SAB clearly indicates that it cannot make a specific recommendation regarding a timeframe for considering the biomass carbon emissions. The relevant timeframe differs between feedstocks and geographic regions, and the selected timeframe will have a significant impact on results. Instead of a specific recommendation, the SAB intends to illustrate how the BAF changes over time for different scenarios, as a way to provide guidance for policy makers to establish appropriate guidelines to help meet different policy objectives.

Another consideration is whether existing econometric and other models are capable of adequately providing information on economic and biophysical parameters needed to assess biomass GHG impacts. The SAB recognizes that the existing models used to develop the Framework may need some revision. At the same time, the SAB recognizes that care must be taken to correctly specify the model to balance accuracy and precision. A complex model with many inputs, many of which can be highly uncertain, runs the risk of poor precision, while a model that ignores significant variables may be more precise, but is also more likely to provide inaccurate results. Several SAB members noted that accuracy is more important than precision in this context. At a minimum, a process is needed to validate existing models and update/calibrate them using physically observed data.

SAB members support the Framework having options for selection of baseline, as these can have a significant impact on the analysis results and different baselines may be appropriate for different objectives. This includes the reference point baseline as conceived in the original draft, and the anticipated future baseline approach. A reference point baseline considers the carbon stocks and emissions at a specific point in time as a benchmark for comparison. In an anticipated future baseline (also called a "dynamic" baseline), projected emissions are estimated based on the expected activities that would occur in a business as usual scenario without use of new biomass feedstocks for energy.

Treatment of non-CO_2 GHGs needs to be clarified in terms of their role in the framework. There is disagreement in terms of the boundaries of the BAF analysis; some members suggest that the BAF is about GHG emissions only, while others believe it must incorporate mechanisms by which atmospheric carbon dioxide influences climate and climate feedback loops (e.g., consideration of radiative forcing and maximum temperature).

Most reviewers note that the need to consider variety and quality of forests managed to produce biomass is not fully addressed. Ultimately, the Framework needs to be robust enough to be able to handle all different types of forests and management regimes in the U.S.

One issue that is not addressed in comments regarding the modeling approaches is the issue of responsibility for developing, maintaining, and operating the suite of models and populating databases to support modeling efforts. The framework is likely to be implemented on multiple scales, incorporating project-specific inputs and State and regional regulatory agencies. Access to and support for complex modeling tools and data appears to represent a gap in current planning efforts.

4 Overview of Bioenergy LCA Methods and Inputs

This chapter provides a discussion of the various considerations and inputs for bioenergy LCA studies. This includes a summary of different methodologies and analysis choices for the major components of LCAs. Note that many of these items are interrelated, so one decision or approach impacts other choices.

In general, the approach and inputs selected for an LCA study will depend on the goal and scope of the study, and each choice will have an impact on the results of the assessment. The inputs for an LCA will vary not just by location and specific scenarios considered, but also based on the reference or baseline system that will be used for comparison. As a result, it is expected that different studies will have various results and outcomes. In addition to site-specific factors and different project types, analysis timeframe, spatial scale, and reference or baseline scenario have a tremendous impact on LCA results for biomass energy. If the goal of the study is to compare systems, then this needs to be determined at the start so all the systems use the same system boundaries and methodologies and deliver equivalent service.

As stated by Matthews et al. (2014), "a superficial consideration of the scientific literature on GHG emissions associated with forest bioenergy would most likely arrive at the impression that the outcomes and conclusions of different publications are highly variable and that the overall picture of forest bioenergy is confused and sometimes contradictory. However, on closer examination, it becomes evident that there is a certain level of fundamental agreement or at least consensus on some basic phenomena." Ultimately, the results from LCA studies vary because different system boundaries and methodologies are applied, which relates to the different goals and objectives of the assessments. There is no one right way to perform an LCA, or one right answer, it all depends on what the analysis is trying to achieve and the question being asked.

4.1 Modeling Approach/Purpose—A Critical Differentiator

Life Cycle Assessments are used to evaluate the environmental impacts associated with a product or service throughout its life cycle (i.e., "cradle to grave"), including acquisition and processing of input materials, production processes, product use, and disposal.

As stated in the International Organization for Standardization (ISO) 14040, which provides a general framework for life cycle assessment (2006), "LCA can assist in:

- Identifying opportunities to improve the environmental performance of products at various points in their life cycle.
- Informing decision-makers in industry, government, or non-government organizations (e.g., For the purpose of strategic planning, priority setting, product or process design or redesign).
- The selection of relevant indicators of environmental performance, including measurement techniques.
- Marketing (e.g., Implementing an ecolabelling scheme, making an environmental claim, or producing an environmental product declaration)."

The first two items are of particular relevance for this effort, as the political and public interest in understanding the potential benefits for bioenergy and its potential to help reduce anthropogenic GHG emissions has led to numerous reports and publications on biomass and bioenergy LCAs in recent years. However, it is important to realize that there are various purposes for completing an LCA and the specific goal of the assessment will ultimately determine the specific boundaries, methods and data used, and therefore the results of the study. In addition, we note that while LCA is designed to assess environmental impacts across a range of impact categories, the majority of LCA studies for bioenergy consider only the climate change category, and this is the focus of this review.

ISO delineates four phases of an LCA study (International Standard Organization 2006):

- Goal scope and definition – Identify the purpose of the study, as well as the intended audience. The ultimate goal impacts the level of detail and modeling approach. The scope considers the system boundary, functional unit, allocation procedures, data requirements, analysis limitations, and other methodological choices.
- Life cycle inventory analysis – Identify and collect data on all relevant inputs and outputs of the product system necessary to perform the assessment. This can include data on energy use, material inputs, products and by-products of processes, waste materials, and emissions. Calculations are performed to compile inputs and outputs, convert data to applicable functional unit, and allocate flows as applicable.
- Life cycle impact assessment – Evaluate inputs and outputs to determine the net environmental impacts of the product or process by impact category.
- Interpretation of results – Summarize results and provide conclusions and recommendations for decision making activities.

Figure 6. Stages of an LCA

Image reproduced from (International Standard Organization 2006)
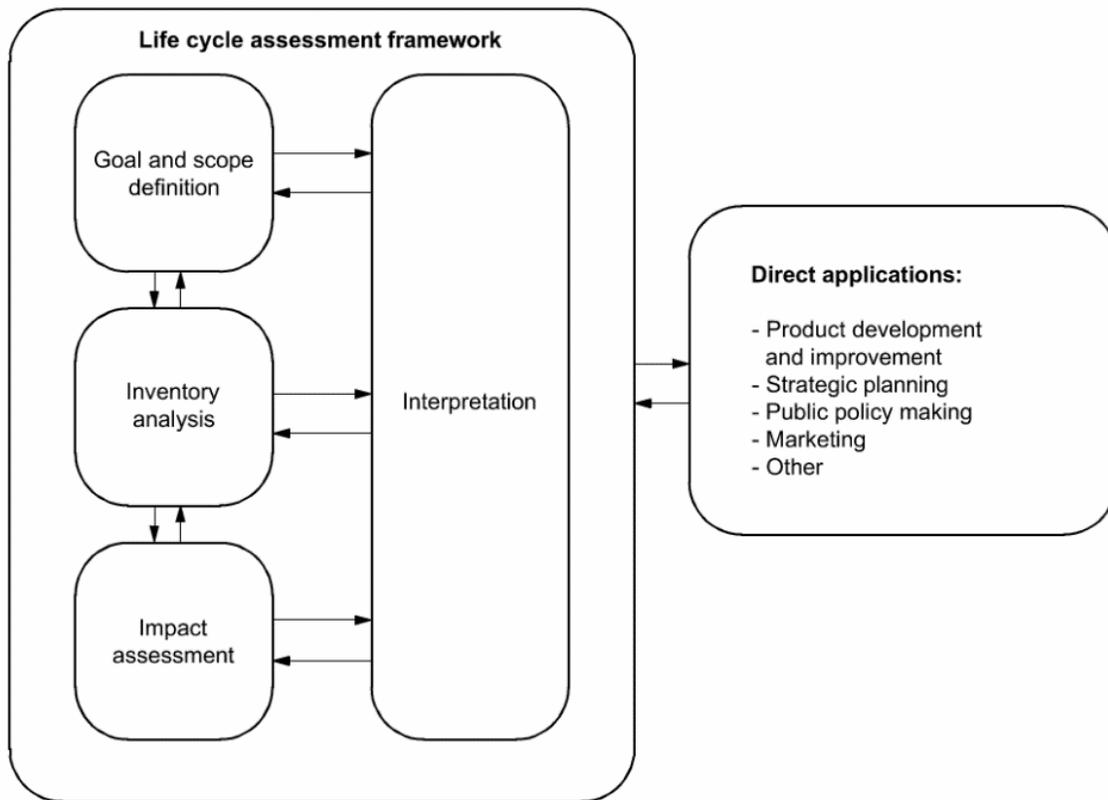
LCAs have generally evolved and become more complex over time, spurred in part by the political and public interest in energy, particularly bioenergy. LCAs were originally conceived as an evaluation tool for resource management for a specific company or product, but usage has expanded to development of standards and policies (McManus and Taylor 2015). Figure 7 shows the rise in the number of LCA related papers published annually since the late 1970s, which covers various products and systems, not just bioenergy. It is important to note that the earliest LCAs were company-specific and were not published as they contained proprietary information. McManus and Taylor stated that the published LCAs were divided between regulatory topics and policy, with a significant increase in the proportion of policy studies at the turn of the century. This increase in policy related studies was largely driven by energy considerations, including GHG accounting. They further indicate that bioenergy made up about half of the policy related studies; for example, in 2013 there were more than 350 publications addressing bioenergy related topics, and an even greater amount dealing with biofuels.

Figure 7. Increase in LCA Publications Over Time

Image reproduced from (McManus and Taylor 2015).
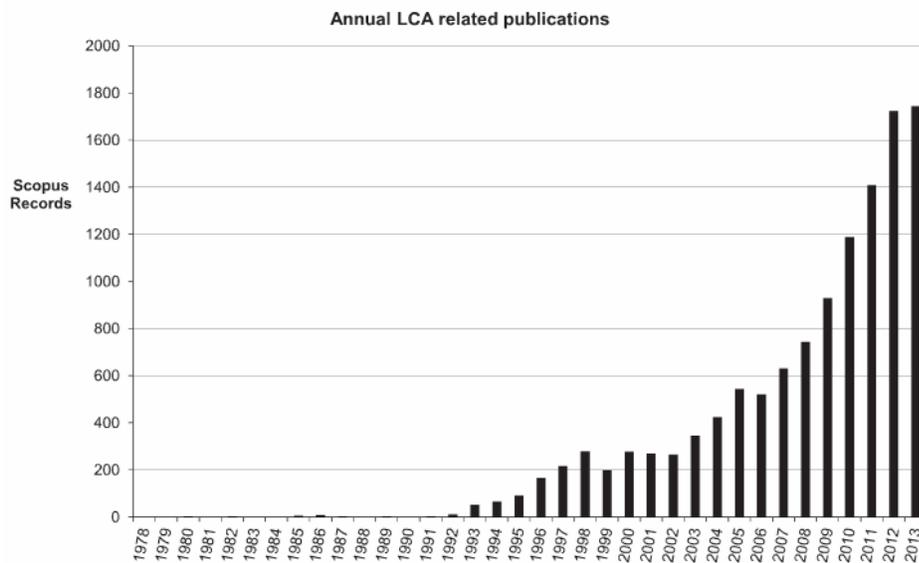
There are two distinct categories for LCAs, according to the purpose of the assessment.

- • An assessment that is used to quantify the direct impact, across its life cycle, of a particular product or service is called an attributional LCA (aLCA). An aLCA is used to evaluate direct impacts associated with the processes related to a product, and does not include indirect effects related to changes in the amount of production or use. It is useful for "consumption-based carbon accounting," allowing for comparison of environmental impacts from similar products (Brander et al., 2009). Specifically, an aLCA is used to answer the question, "What are the total emissions (and resulting impacts on the environment) from the processes and material flows identified as associated with the life cycle of a product?" (Matthews et al., 2014, modified from Brander et al., 2009).

- • An LCA used to evaluate the impact of a particular decision can be categorized as a consequential LCA (cLCA). This type of LCA models the implications of producing more or less of a specific product or service, including the causal impacts on other products or markets (indirect effects). A cLCA is used to answer the question, "What is the change in total emissions (and resulting impacts on climate) as a result of a marginal change in the production (and consumption and disposal) of a product?" (Matthews et al., 2014, modified from Brander et al., 2009).

The type of LCA impacts many facets of the model and results. Some of the relevant key differences are summarized in Table 8, and include application and scope of the effort, system boundary, time scale, allocation procedures, data type, and market effects. Many of these items are discussed further in subsequent sections of the report.

Table 8. Comparison of aLCA and cLCA methods and inputs

Adapted from: (Brander et al., 2009; Brandão et al., 2014; Matthews et al., 2014)

	aLCA	cLCA
Application	Understanding emissions and environmental impacts associated with life cycle of a product. Can be used for comparison and improvement of product systems	Understanding the total environmental impacts of an increase or decrease in production of a product. Supports decision and policy making
Scope	Steady State/static analysis, product specific accounting	Dynamic analysis. Considers direct and indirect effects associated with changing the output of a product system
System Boundary	Include all activities (processes and materials) directly related to product production, consumption, and disposal	All activities directly or indirectly affected by a change in the output of a product system, both within the system and impacts associated with other outside systems
Time scale	Quantify impacts/emissions at a given level of production at a specific time	Quantify change in impacts/emissions associated with a change in production.
Allocation Approaches	Emissions allocated to coproducts based on common characteristics (e.g., mass, energy, economic value)	System expansion to include alternate methods of producing coproducts in reference case
Data Type*	Average data	Marginal data
Market Effects** (for production and consumption of product)	Not included	Included, as related to decision under consideration
Model Scale	Project specific; microscale	Regional to global models; macroscale

*   As an example for marginal data, if a process results in increase in electric consumption, the electric usage would be evaluated based on the electricity mix used to meet the increased demand, not grid average (Brander et al., 2009).

**   Market effects consider the pricing impacts associated with changes in production of a product. This can include impacts on demand for the product itself, coproducts, or substitute goods.

Although not everyone in the LCA community agrees, it is generally suggested that cLCA is the most appropriate type of analysis to support policy decisions, particularly for evaluating climate change mitigation potential as it is based on change relative to a baseline scenario and includes the total impacts (Plevin, Delucchi, and Creutzig 2014a). By allowing comparison of different options and scenarios, cLCA can evaluate the impact of a particular decision on a broad scale and guide policy. By including indirect effects in cLCA, the shifting of environmental impacts to different geographical areas or processes is evaluated, which is a significant concern and consideration in any energy system including bioenergy.

aLCA can compare the direct impacts of different energy producing systems. One of the arguments against using it for estimating climate mitigation impacts is that is does not include indirect effects. However, Dale and Kim (2014) point out that while cLCA studies consider indirect effects for biofuels, indirect effects are often not considered for the fossil fuel system they replace, thereby creating an imbalance and bias against the biomass system. This is one reason they support the use of aLCA. If included, indirect effects must be assessed for all considered systems in an LCA study, regardless of the type of analysis. It is important to provide equivalent analysis and boundaries for the bioenergy system as well as the comparison or baseline system to ensure a fair comparison.

Others note that while "ALCA is not an appropriate basis for *development* of policy… it may be applicable in the *implementation* of policy" (Brandão et al., 2014). This is an important point. cLCA is geared towards comparison to inform decision making, while aLCA is more typically used for project-specific accounting and can track and compare environmental impacts attributed to specific products as long as they are conducted using similar boundaries and methodologies. The inclusion of both direct and indirect effects in consequential approaches is important for policy considerations, but once a specific bioenergy system has been identified as beneficial and a policy is developed, it may be adequate to use an attributional approach to assess compliance. One reason for this is that in policy implementation, the economic operator should report on the processes over which they have control and have the data to support. This would not generally be the case for indirect effects that the operator cannot directly influence. The complexities of cLCA modeling could create a burden for individual entities, and they cannot reasonably be expected to predict future markets to determine displaced products (for example). The high uncertainty of cLCA results creates a further challenge to its application in meeting regulatory compliance requirements. aLCA methods are likely to be more practical and straightforward for implementing policies.

As other literature reviews have pointed out, many bioenergy LCA studies are not clear which type of assessment is used, causing confusion and making comparisons difficult.[9] Some researchers argue that many actual LCAs combine components of each (Suh and Yang 2014), which may reflect the gradation of approaches to cLCA ranging from relatively simple substitution assumptions to complex economic modeling. The typical analysis approach likely contributes to this as cLCA studies model a few processes

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[9] Furthermore, Brander (2009) noted that some European policies are inconsistent in type of approach applied, and use hybrid methodologies. For example, the UK's Renewable Transport Fuel Obligation would be characterized as a partial cLCA, while the EU's Renewable Energy Directive is mostly aLCA, except for excess electricity generated from CHP. The inclusion of indirect effects in these policies is also somewhat inconsistent in these examples.

consequentially, while the rest of the analysis is based on aLCA tools and databases for other processes making up the rest of the system (Dale and Kim 2014). However, others warn that the combination of the two approaches can lead to misinterpretation or unfair comparison of results (Brander et al., 2009), or even an incoherent analysis that therefore doesn't clearly meet the needs of either approach (Plevin, Delucchi, and Creutzig 2014b). "The problem with combining ALCA and CLCA methods is that the output is not suitable for either the normal purposes of ALCA (product comparison, supply chain improvements, and consumption-based carbon accounting) or for accurate policy impact analysis" (Brander et al., 2009).

Ultimately, it is useful to keep perspective on the fact that aLCA and cLCA are concepts and ways to categorize LCAs, and not basic principles on how to conduct LCA. The guiding principles of LCA from ISO or other guidelines still apply regardless of what type of LCA is being done. Furthermore, many of the actual methods used in these two types are similar when bioenergy is the determining product. The main differences are related to the scope and boundaries that are set for the study, the input data used for analysis, and the allocation approach.

Subjective choices and simplifying assumptions must be made regardless of the type of model, due to data gaps and practical limitations. Overall, aLCA is relatively simple since it only considers direct impacts of a particular product or process, it mainly requires an accounting of activities and material flows and emissions factors. In theory, the main uncertainties for an aLCA are due to the fact that these are all imperfectly known (Plevin, Delucchi, and Creutzig 2014). By comparison, cLCA includes systems outside of the one being studied. This makes it seem more uncertain since the same uncertainties in an aLCA apply as well as the additional uncertainty of analyzing systems outside the control of the economic operator, and impacts on future events and markets. However, several researchers have argued that aLCA may be more precise (less statistical uncertainty), but cLCA may be more accurate (in terms of assessing climate change impacts) due to the inclusion of indirect effects (Plevin, Delucchi, and Creutzig 2014b; Brandão et al., 2014). Furthermore, cLCA can include multiple scenarios, which can identify components that have either large or small impact on the end results (Brandão et al., 2014). This helps to provide insight into a complex system.

4.2 Analysis Boundaries

The analysis boundary for an LCA is used to delineate all of the activities included in the assessment; anything outside of the boundary is ignored. The boundary must be clearly defined, and boundary selection depends on the study goals. As stated by Matthews et al. (2014), "the system boundary in an LCA study needs to be drawn as wide as necessary (and no wider), in order to encompass all of the activities and processes relevant to addressing the research question that has been posed." *The different boundary selections contribute to the wide variations from one LCA to the next, and leads to significant differences in results.*

An LCA considers all flows within a system boundary, including input and output flows that pass the (imaginary) boundary line. These flows should include all items related to the impact categories considered in the particular analysis, such as raw materials, energy use, and emissions. Figure 8 shows a general example of flows within a system boundary for a product system.

It is important to recognize that the analysis boundary has both a physical and temporal scale. The physical scale defines the geographic area considered, which may be a particular forest management area, region, country, or even groups of countries. The temporal scale defines the time frame for the analysis, which could range from one year to 100 years or more. As with the physical scale, the analysis timeframe should reflect the study goals. Ultimately, "the temporal scale needs to capture the variable effects of forest bioenergy on GHG emissions over time" (Robert Matthews et al., 2014).

Figure 8. Generalized LCA System Boundary for Product System

Image Source: (International Standard Organization 2006)
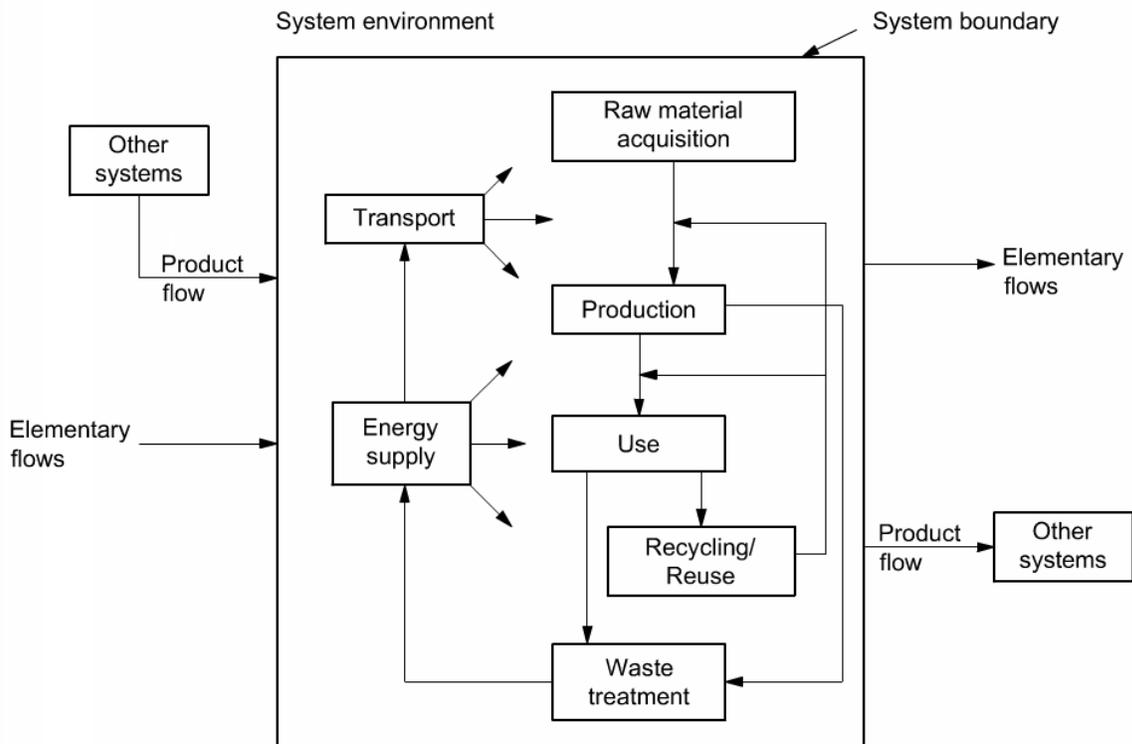
Figure 9 shows a relatively simple example of boundary selection and the impacts it has on the net emissions for a forest related system from Matthews et al. (2014). This example for illustrative purposes only, and is not representative of a full LCA study. Also, only CO_2 emissions are included in this example for the sake of simplicity. For each system considered, the CO_2 emissions are calculated by identifying and quantifying all CO_2 flows that cross the system boundary and adding them together, considering whether each flow is positive (flow into the system) or negative (flow out of the system).

This example shows how the boundary definition can impact the LCA results. None of these examples are necessarily right or wrong, it all depends on the specific purpose and scope of the LCA. Matthews et al. (2014) provide specific examples for when boundary conditions may apply. For example, the first case (example A) could be useful for monitoring management of a forest stand. The second example (B) applies for calculating GHG emissions from forest and harvested wood products, as in national reporting schemes. Meanwhile, the last example (C) could be used to calculate the GHG emissions for the production of raw harvested wood. Note that the appropriate time scale for each of these applications may differ from the 10-year period used in the example.

Figure 9. Example System Boundaries and Emissions Impact for Forest Cases

Image Source: (Robert Matthews et al. 2014)

A. Net CO_2 absorption through forest growth (sequestration) **36.7** tCO_2 Decay of harvesting residues (emission) **4.8** tCO_2 Removal of harvested wood from forest (effective emission) **12.8** tCO_2 Overall CO_2 emissions = -36.7 + 4.8 + 12.8 = **-19.1** tCO_2	Boundary: one-hectare forest stand over a 10-year period. There is an accumulation of carbon in the forest stand as trees grow. Some trees are removed through thinning, which moves stored carbon in the wood across the system boundary. There are carbon emissions from decomposing residues and soil organic matter. The net result is carbon sequestration (negative emissions) in the system over the timeframe.
B. Net CO_2 absorption through forest growth (sequestration) **36.7** tCO_2 Decay of harvesting residues (emission) **4.8** tCO_2 Loss/decay of harvested wood (emission) 0.9 tCO_2 Overall CO_2 emissions = -36.7 + 4.8 + 0.9 = **-31.0** tCO_2	Boundary: one-hectare forest stand and harvested wood over 10 years. Similar to case A, except the harvested wood is included in the boundary. This wood is converted to products, which still exist at the end of the 10-year period, retaining the stored carbon. A portion of the harvested wood decays or is destroyed during processing, resulting in some carbon emissions. The net result is additional carbon sequestration over the timeframe.
C. Fossil fuel consumed in forest operations (emission) **0.2** tCO_2 Net CO_2 absorption through forest growth (sequestration) **36.7** tCO_2 Decay of harvesting residues (emission) **4.8** tCO_2 Loss/decay of harvested wood (emission) **0.9** tCO_2 Manufacture and maintenance of forest machinery and equipment (emission) **0.001** tCO_2 Overall CO_2 emissions = -36.7 + 4.8 + 0.9 + 0.2 + 0.001 = **-30.799** tCO_2	Boundary: one-hectare forest stand, harvested wood, and machines used for forest management over 10 years. In addition to case B, this case includes fossil fuel energy sources used for forest management operations, as well as emissions associated with the production and maintenance of the equipment. This reduces the net carbon sequestration somewhat relative to the previous example.

Although not required for aLCA studies, most LCAs related to bioenergy production and use compare two or more activities or products. For cLCA studies in particular, the analysis boundary needs to include the bioenergy activities to be studied, as well as activities for a reference case providing equivalent services (Bird et al., 2011). In order to evaluate the full life cycle environmental impact, an LCA should consider the following main components for each system: land use, alternative fate of the fuel or feedstock (i.e., the alternative fate of the biomass feedstock or fossil fuel resource if not used to provide the energy service), and all activities associated with the production and use of the energy service (Figure 10). The disposal of any waste products generated, as well as emissions related to the construction, operation, and maintenance, and dismantling of facilities and equipment used for each component should also be included. The system components will be described in more detail in the following subsection.

Figure 10. Basic Components in cLCA Boundary for Bioenergy
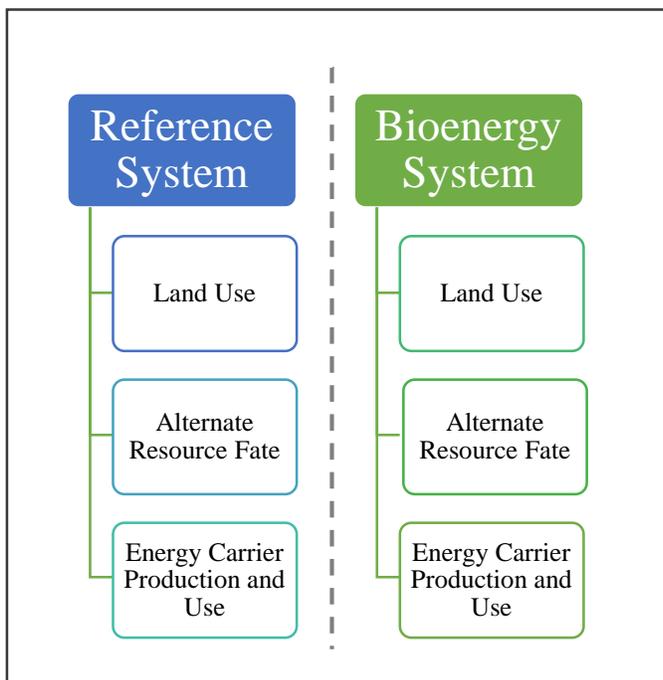
4.3   Reference System

As described previously, cLCA studies are used to evaluate the change in GHG emissions associated with a particular action or decision associated with each scenario. For example, a bioenergy scenario may evaluate the impact of a particular policy on bioenergy production and use, in comparison with an alternative in which the policy does not exist. The reference scenario (or baseline) could be based on existing conditions, or business as usual (BAU), essentially a "no change" scenario from current or

planned activities. As stated by Matthews et al. (2014), "for each scenario, it is necessary to describe 'what the world looks like' if the scenario were to be [realized]. This description takes the form of an appropriate definition of a system and its associated system boundary." It should be noted that although it is not necessary to include a reference system in an aLCA study, this type of LCA can also be used to compare two or more different systems. In this case, each system would essentially be evaluated in a separate LCA analysis; when the analyses use the same (or equivalent) boundary, methods, and data, the systems could be compared side by side.

The reference system selection has a tremendous impact on how the LCA results portray the net benefits of bioenergy. The reference system should be *equivalent* to a bioenergy system, and evaluated in a similar way (Bird et al., 2011). Equivalent systems would include relevant activities needed to provide the same amount of the end product being evaluated. However, there is no set requirement for what is included in any given study; the specific inputs depend on the goal and scope of the study. For a bioenergy LCA used for policy decisions, the reference system boundaries may include other factors besides the production and use of an alternate energy source such as impacts related to land use, and the alternate fates for the biomass feedstock (i.e., what would have happened if the biomass was not used for energy production). This is critical. For example, if land is included in the bioenergy system (i.e., if the boundary includes growing the biomass) then the same land must be included in the reference (whatever its alternative use); if the study is focused on a specific biomass resource, then the alternative fate of that biomass must be included in the reference. This is necessary to ensure fair comparison of the different scenarios. It is also worth noting that since cLCA typically uses system expansion[10] (instead of the allocation methods used in aLCA), each scenario may need to capture multiple products and services. As such, the reference scenario may need to include the production of an alternative product that would be used instead of a product generated from the bioenergy production process. All of these considerations require making choices regarding reasonable counterfactual options for the baseline scenario. It is important to recognize that these choices and assumptions about various planned or hypothetical activities and their impacts may be difficult and uncertain.

The diagram in Figure 11 provides an illustration of the major components in a bioenergy LCA that compares a bioenergy system with a reference system. These are described below.

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[10] In the system expansion method, the system boundary is extended in order to compare two systems that are equal in scope including all products generated. This is described further in Section 4.9.

Energy Carrier Production and Use: The lower portion of the figure breaks out the components associated with the production and use of the energy service—since this section is likely familiar to anyone who has experience with energy-related LCA studies it will be discussed first. The energy carrier production and use for a bioenergy system may include biomass harvesting and collection, transportation to a conversion facility, resource conversion to an energy carrier (e.g., electricity, heat, and/or liquid fuels), energy distribution, and use of the energy. Components that occur prior to the conversion to energy are called upstream processes, while components occurring after the conversion are referred to as downstream processes. The associated emissions at each stage should be included in the LCA, and should consider the use of energy and raw materials as well as any direct emissions from the processes or activities themselves. The construction, maintenance, and dismantling of facilities and equipment should also be considered, as well as the disposal of any waste products generated.

The reference case should consider equivalent steps for the energy service. As discussed above, the reference energy source and conversion technology selected for comparison will depend on the goals of the study. For fossil fuel, this may include: resource extraction, transportation to a conversion facility, resource conversion to an energy carrier, energy distribution, and use of the energy. Facility and equipment-related emissions and disposal of wastes must be included in the reference system as well.

In order to be equivalent, the scenarios should typically be designed to provide the same quantity of end product (e.g., useful energy). For each subcomponent, only the emissions attributed to the production and use of the specific fuel/feedstock (or mix) being compared should be counted. For some studies, this requires allocation of emissions to the various coproducts generated during a process or activity.[11] A preferred approach for cLCA studies is to expand the boundary so that equivalent products are included in both systems. System expansion and allocation are discussed further in Section 4.9.

It is important to note that even for the same energy service, the distribution and use of the energy may be different between the bioenergy and reference case due to facility locations and scale, which impacts the end results. Distributed energy projects will have different loss factors than large-scale utility projects that are typical for fossil fuel conversion. Efficiencies for both conversion and use of different energy types can also vary significantly and have a large impact on the GHG emissions profiles.

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[11] For example, coproducts generated during forest harvest activities including sawlogs, roundwood, and harvest residues all have different end-uses and values.

Figure 11. Example Life Cycle Components for Bioenergy and Fossil Fuel Reference Systems

(Diagram developed by ANTARES for this report)
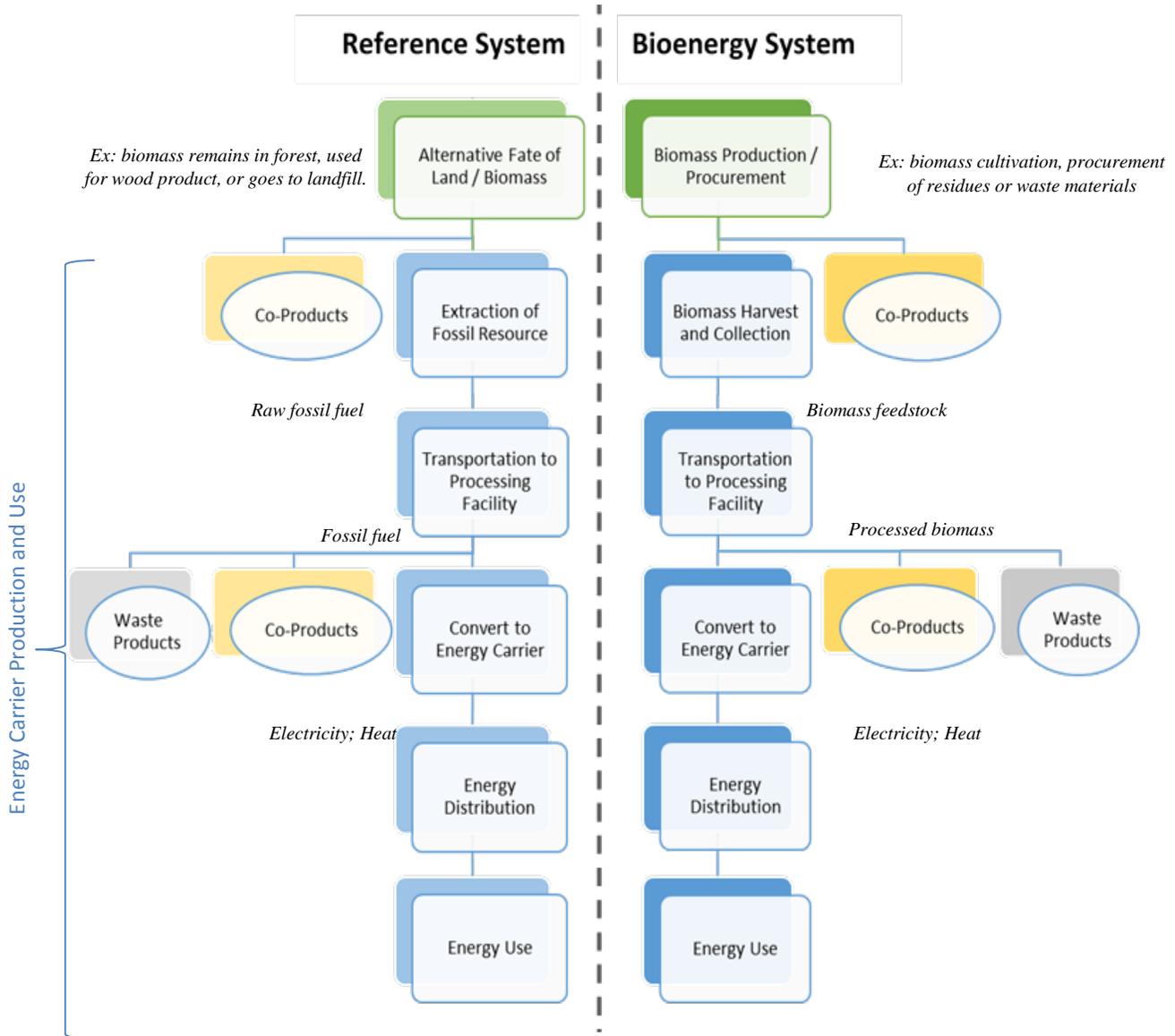
Note that many of the subcomponents shown in the diagram appear to be the same for the reference and bioenergy systems. However, it is critical to realize that while the *steps* may be the same, the actual *processes* will be different for each system, and are likely to contain different activities occurring at different scales. Showing the same components on each side of the diagram also illustrates equivalency.

If the considered bioenergy system uses biomass as a direct replacement for another fuel, such as with co-firing; in this case the reference energy system is generally clear. However, in many other cases it is not so straightforward to select an appropriate reference system, as the energy production could come from a particular fossil fuel (e.g., coal, oil, or natural gas) or a mix, and could even be compared to other renewable energy sources. In a review of nearly a hundred bioenergy LCAs, Cherubini et al. (2011) noted that about three quarters of them used a fossil fuel reference system, while a much smaller percentage (12%) used another biomass resource or bioenergy conversion technology as a reference (e.g., comparison of new pellet stoves with older pellet stoves). The rest were categorized as aLCA studies and did not use a reference system.

Schlamadinger et al. (1997) suggested that when the choice of reference system for energy is not clear, the best choice is "the least cost fossil energy system with the lowest GHG emissions and minimized environmental impact, fulfilling the same goals as the bioenergy system." This guidance is based on the logic that a new plant would be needed either way, so that if bioenergy was not developed to meet demand, a fossil fuel plant would be built instead. However, in practice, it is unlikely that biomass energy will replace the least cost fossil energy system, at least based on the current conditions in the U.S. It is more typical that bioenergy would replace marginal, higher cost sources of energy. For example, biomass may be used to replace oil or propane for heating in areas that do not have access to natural gas.

Bird et al. (2011) state that "ideally, in the most realistic evaluation, the bioenergy system should be evaluated against the energy system most likely to be displaced. However, in many real-life systems it is difficult to know which energy source will be replaced." Potential options include using the emissions impact based on the average energy source mix or, for new capacity, using emissions attributes for the most likely technology to be implemented if bioenergy is not used. Using the best performing fossil fuel technology (from a GHG emissions basis) would provide a conservative estimate of the GHG impact. This is consistent with the recommendation from Schlamadinger et al. (1997) referenced above. *In general, it is clear that comparisons of the considered systems are complicated by the fact that that it is difficult to even know what the baseline scenario should be.* This is why it is useful to consider a few different scenarios, and why many LCAs do a comparison both with coal and with natural gas.

The bioenergy scenario and reference scenario should generally use the same level of technology (such as best available) in order to avoid bias, unless there is a specific reason to consider a future technology that is not yet commercially available such as IGCC (Schlamadinger et al., 1997).

For a fossil fuel reference case, the study must also consider the technology and processes used to extract and process the fuel. For example, will it be based on the average of all the resource extracted such as conventional oil or natural gas, or a marginal resource such as shale oil or natural gas generated from fracking.

Alternate Fate of Resource: The first component shown in Figure 11 considers the alternate fate of the resource, which is not used to provide the energy service being evaluated. This considers what would have happened to the resource if it was not used to provide that service. For example, if the biomass was not used as a feedstock for bioenergy generation, it may be landfilled or used in manufacturing a wood product. Typically, the alternative fate of the fossil fuel is that it would be left in place, unextracted from underground reserves, therefore having no emissions impact (R. Matthews et al., 2014).

For forest biomass, the alternative fate of the material will depend on the specifics of the resource. For example, trees may be left to stand in the forest; harvest residues may be left in the forest to decompose; clean wood chips may be used to produce paper products; milling residues may be used for animal bedding or mulch; and wood waste products may end up in the landfill. Each of these alternative fates would have a different impact on the life cycle GHG emissions associated with the system. These are discussed further in Section 4.6.

Biomass Production/Procurement: The bioenergy system should include impacts associated with production and procurement of the biomass feedstocks used to provide the energy service. This may include biomass cultivation activities and can include planting and management for energy crops or managed forests, which is directly related to the land use impacts described further below.

Land Use: Changes in land use and land management is an important consideration in bioenergy LCA studies. For biomass resources generated from the land such as forest and agricultural biomass (in contrast to recovered materials from secondary processes, such as sawmill residues or urban wood waste), the land use activities will be considered in the bioenergy system. The reference system would consider what would have happened to that same land if it was not used to grow biomass for bioenergy. In a fossil fuel reference system, there will also be some land impacts associated with the fossil fuel extraction. The alternative use of this land should also be considered in the bioenergy system scenario, although this is not explicitly shown in the figure for simplicity. For both the bioenergy and fossil fuel scenarios, the land use impacted can include roads or other transportation networks to move the material, if those roads and networks can be attributed to the system under consideration. The LCA considers the

environmental impact of any changes made to the land, including changes in the carbon sequestration in vegetation or soil. For example, beginning to extract wood from a forest that was not previously managed or harvested would reduce the carbon stocks, while planting trees on marginal lands that were not previously forested could lead to an increase in carbon stocks.

Indirect land use change can also be an important factor. Although particularly relevant for bioenergy systems using agricultural feedstocks, it can also be a consideration for forest biomass. This type of land use change refers to activities that occur outside of the system boundary, as an indirect result of biomass cultivation or use. For example, if bioenergy development or activity supplants cultivation or development of another product (e.g., a food crop) as part of direct land use change, this may result in a subsequent land use change elsewhere in order to produce the product that was offset by bioenergy. Further discussion of land use change (both direct and indirect) is included in Section 4.11.

There has been controversy in the LCA community regarding appropriate baseline scenarios for aLCA studies, particularly with respect to Land Use. On one side of the debate, it is argued that aLCA should be solely based on the impact of the system under consideration, essentially an accounting of the absolute emissions associated with the product or activity (Soimakallio et al., 2015). This has been described as a no-baseline scenario, or a zero emission baseline scenario. The other side considers the fact that bioenergy can have a significant impact on land use and associated carbon stocks, and argues that without any human intervention the land would revert back to its original state (i.e., 'natural relaxation') (Milà i Canals et al., 2007; Helin et al.). For forestland, this would imply a baseline scenario in which all forest management and harvest activities are stopped, so that forests would continue to develop naturally and sequester carbon (potentially indefinitely, considering long-term forest cycles and barring natural disturbances such as diseases or wildfires). This situation has been described as a "no use" baseline scenario.

Matthews et al. (2014) note studies that argue this second point appear to assume that if all forest management activities were stopped, the land would be left to develop naturally. This is not necessarily intended as a realistic option, but is proposed to provide a clear separation between the effects of "human-induced land-use" in a study system as compared to natural processes (Soimakallio et al., 2015). This type of baseline essentially assumes that there is no other use for the wood in this forest and that bioenergy is the only end use. However, forest management and harvesting typically result in a variety of output wood products; biomass fuels are often a byproduct of other higher-value products from the forest. Forests are rarely managed for just biomass alone.

That said, "It may be possible to justify the application of a 'no use' baseline in attributional LCA in contexts where the objective is to quantify the effects on the environment of an existing system, representing an existing activity, in comparison to the situation where the activity does not take place. It is certainly possible to understand the thinking of the proponents of such an approach by drawing an analogy with the calculation of GHG emissions associated with the use of fossil fuels" (R. Matthews et al., 2014). The point regarding fossil fuels refers to the fact that in many biomass LCAs, the alternative fate for fossil fuels is that they are not used (see discussion for the "Resource Use" category above). However, this type of argument is not analogous on both sides when the comparison is applied only to bioenergy, since a 'no use' baseline for fossil fuels assumes they are left in the ground undisturbed, but a 'no use' baseline for wood from a forest assumes there is no other managed use for the land and that natural relaxation would continue unhindered.

4.4   Temporal Considerations and Impacts

As mentioned in Section 4.2, it is important to consider the analysis timeframe in the system boundary, because there are a number of components and factors influenced by the selected period. Both aLCA and cLCA can have time dependent components. This includes potential changes in technology development over the considered period (such as improvements in process or conversion efficiency, or commercialization of advanced technologies), changes in biomass yield factors, market variations influencing demand for products included in the study, as well as the time difference between carbon uptake in the biomass and release during the energy conversion process or decomposition in the case of reference scenario (McManus and Taylor 2015). *The latter point (and related considerations) regarding the time delay between emissions and removals is possibly the most important, particularly for forest biomass, which has long growing cycles. It is also an area that has inspired a lot of debate.*

While LCA studies associated with policy decisions may use relatively short timeframes associated with the policy horizon (20 years, for example), the climate impacts of bioenergy can extend much further. Furthermore, there is general agreement that while net emissions from bioenergy systems may initially be greater than the reference case, the cumulative emissions are often lower over an extended period. As such, some researchers stress the importance of considering longer timeframes to evaluate long-term impacts as well (e.g., Berndes et al., 2013; Miner and Gaudreault 2013). It is important to recognize that conventional LCA studies typically do not consider when emissions and removals occur; all emissions

and removals are assumed to occur at the same time. Since there is no set standard or requirements for such considerations, temporal issues are considered on an "ad hoc basis" for bioenergy systems (McManus and Taylor 2015). This means assumptions in the model and what is included can vary from one LCA to the next. The time frame for analysis will also vary based on the period of interest for the analysis goal and the associated system boundary.

Forest systems have both short- and long-term carbon cycles. Carbon is sequestered as the trees grow; the rate of uptake varies based on tree age, forest type, and growth rate. However, since it can take decades for trees to reach maturity, this is a long-term sequestration process. Emissions or removals occur as a result of decomposition, harvest, and disruptions such as wildfires, diseases, or pests. In contrast to the sequestration activities, these releases can occur in very short timescales. Decomposition is a possible exception; depending on the environmental factors the process can occur relatively quickly or take a very long time for the material decompose fully. "Different components of forestry systems (e.g., vegetation, litter, soil and harvested wood) can also respond to management with different reaction times" (Robert Matthews et al., 2014).

There is general consensus that the carbon sequestration and emission cycles have an impact on the timing of the net GHG benefit of bioenergy systems. "For a number of possible sources of additional forest bioenergy, there must be an initial period during which associated GHG emissions are increased, followed by a 'switch-over' to net decreases in GHG emissions. A number of research studies have reported such a pattern in GHG emissions of forest bioenergy sources, with estimates of the period to the point of switch-over ranging from one year to 100 years or more" (Robert Matthews et al., 2014). As a result, for some biomass sources the time period considered in the LCA study is critical, and can impact whether bioenergy has a net carbon benefit or liability.

These types of temporal considerations vary among biomass feedstocks. For example, agricultural resources and short rotation energy crops have much shorter growth cycles, so the timescale is less important. For wood waste materials, the reference scenario has the most impact on time considerations, since the alternative fate of these resources is likely to be disposal in a landfill. Since the decomposition process can take a very long time in landfills, the carbon in the wood is also being stored for some time (Bird et al., 2011).

As noted above, the analysis period also impacts assumptions in the reference case. For example, for short time frames current or near-term technologies will be adequate, while for long time frames it would be appropriate to consider changes in technology and fuel type (Agostini, Giuntoli, and Boulamanti 2014).

4.5 Spatial Scale

The spatial boundary is used to define the area that will be included in the analysis. For forest biomass, the spatial scale or geographical extent of the analysis impacts the LCA in terms of forest dynamics and carbon stock changes. This is related to the temporal impacts described in the Section 4.4, as the carbon stock can vary significantly for an individual stand of trees associated with forest management, but may average out over an entire forest area depending on the level and type of harvest activities. As described by Miner and Gaudreault (2013), "the importance of spatial boundaries depends on how temporal boundaries are established and on whether it is important to understand the timing of transfers of carbon to and from the atmosphere." The latter point is based on when the analysis timeframe begins, as some analyses start the assessment at the time of harvest, resulting in a significant 'carbon debt' due to the removal of standing carbon in the forest.

Thus, particularly for forest biomass there is an important link between the area included in the assessment and the timeframe considered. As an example, the well-known and much debated Manomet study considered only the stand of trees harvested in a given year, defending the position by stating that "when a complete representation of the baseline is taken into account, the landscape-scale and the stand-level frameworks may yield the same result" (Walker et al., 2010). This decision led to a number of critiques from bioenergy defenders, such as Strauss (2011) who noted that the selected scale "ignore(s) the fact that the forest is a system." The study's stand level analysis contributes to its conclusions that a relatively long period (referred to as 'carbon debt payoff' period) occurs during which bioenergy has greater GHG emissions than a fossil fuel reference case for many of the considered scenarios in the study (Walker et al., 2010).

Other researchers have suggested that the spatial scale for forest bioenergy systems should at least be the entire supply area (Miner and Gaudreault 2013). Furthermore, on a large scale, changes in forest management resulting from bioenergy demand can lead to net additional carbon sequestration overall, even if some of the stand level impacts lead to a reduction in carbon sequestration relative to the reference scenario (Cowie, Berndes, and Smith 2013).

Considering the impact that scale can have on analysis results, Cowie, Berndes, and Smith (2013) suggest that for policy decisions, GHG impacts should be evaluated on landscape scale, referring to the overall area that is important to the policy and climate change mitigation (e.g., national or regional area). Miner and Gaudreault (2013) note that spatial boundaries for policy studies are often based on the area where the policy will be implemented (e.g., state of interest for state-level policies). However, larger spatial boundaries can help to reduce sources of leakage and other indirect effects, such as by including areas where forest activity may be shifted as a result of bioenergy system activities (Miner and Gaudreault 2013). This could include nearby states or counties at a minimum. However, larger spatial boundaries do add additional complexity to the analysis.

4.6   Biomass Resource Type and Alternate Fates

The biomass resource type used for bioenergy, and its alternate fate in a reference scenario, both have a significant impact on the results of the LCA. In a prospective analysis, the LCA will need to consider the likely source of material and evaluate accordingly. For biomass systems using forest resources, changes in forest management associated with obtaining new resources must be considered since they can have a significant impact on the GHG impacts.

Bioenergy feedstocks used to generate heat and power typically comprise:

- Wood from commercial harvests
- Silvicultural waste wood (e.g., harvesting residues, small and unmerchantable trees from thinning operations)
- Mill residues (e.g., by-products of sawmills)
- Site conversion waste wood (wood from clearing forestland for development)
- Recovered wood waste from products at end of life (e.g., recovered C&D wood or source-separated wood from municipal solid waste)

The carbon cycles in forest systems are complex. Figure 12 illustrates how carbon is naturally sequestered, released, and exchanged amongst the five carbon pools in forests: aboveground biomass, belowground biomass, litter, coarse woody debris, and soil. Another related carbon pool is harvested wood products, which may be considered when human interaction and forest management is included.

Figure 12. Forest Carbon Pools and Naturally Occurring GHG Dynamics

Image Source: (Robert Matthews et al., 2014).
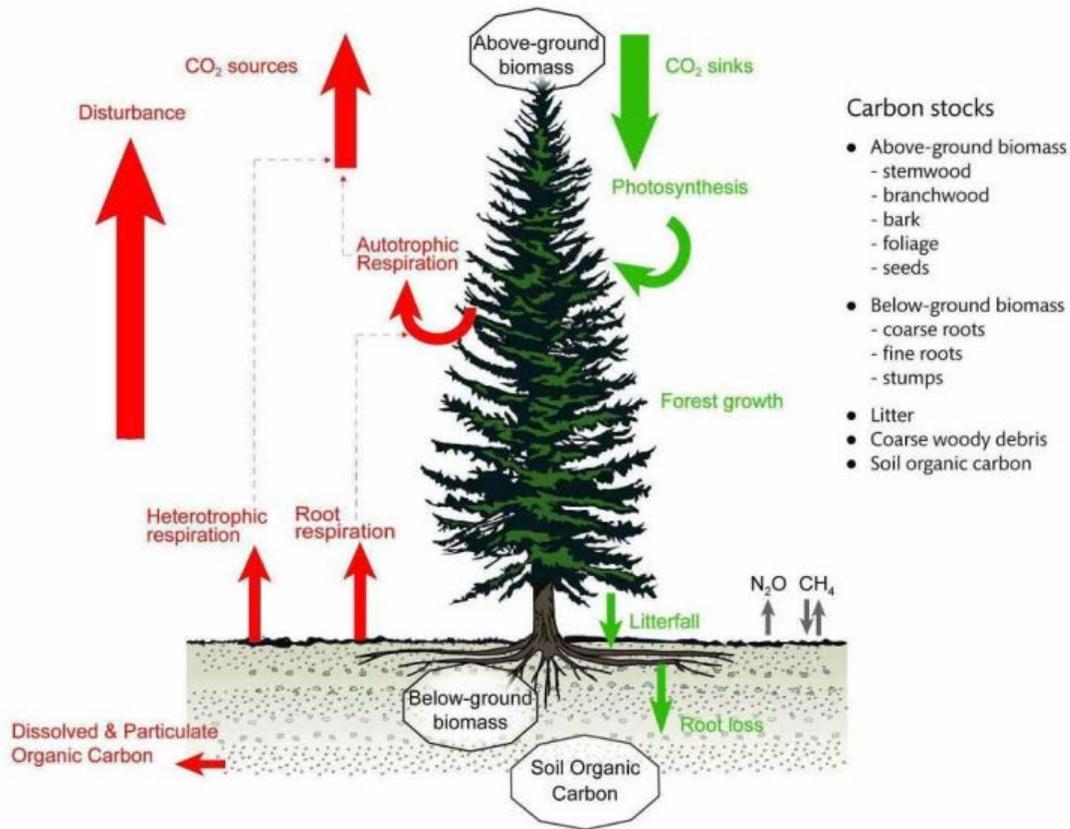
Forest management activities can impact all of these carbon pools. Various methods could be used to intensify harvesting or removals in order to obtain additional woody biomass resources from forests. Some activities can increase forest carbon stocks, while others are more likely to reduce long-term carbon stocks. Table 9 lists a number of potential activities that could be implemented in order to obtain additional forest biomass materials for bioenergy production, and describes examples of what may be expected to happen without that change. The alternative fate of the resource is relevant for the reference scenario in a cLCA study, for example. Some of these potential management activities are very unlikely to occur in any near-term practice, unless there are drastic changes in incentives or value for bioenergy or other drivers, and are noted as such. The right-most column of the table indicates the activities that are most relevant to the State, based on ANTARES internal knowledge of forestry in the area.

Table 9. Examples of Potential Changes in Forest Management to Meet Increases in Bioenergy Demand

Table adapted and modified from (Matthews et al., 2014, pp.47-50), except last column "Relevance to NY" added based on ANTARES experience.

Activity to obtain additional biomass resources	Examples of what would happen otherwise	Relevance to NY
Extraction of harvest residues that were previously not harvested.	The harvest residues would be left on site to decompose, or burnt on site as part of site management for new tree establishment.	Likely, except burning of residues not common
Introduction of thinning of small-diameter trees that were previously uneconomic to harvest.	The thinning operations would not be carried out. By not thinning, it is likely the forest stand may not develop as well (e.g., higher tree density, less vigorous stand, lower-value trees in the stand, smaller tree sizes, suppressed understory vegetation).	Possible, not likely
Introduction of harvesting for co-production of materials and bioenergy in forest areas previously not managed for production (e.g., because this was uneconomic). (Note 1)	The harvest would not be carried out at all. Consequences would be site-specific (e.g., depending on the details of harvesting, tree species involved, whether stands are plantations or semi-natural). In some situations, a private landowner may decide to convert the land to another productive use (potentially involving deforestation).	Possible, not likely
Diversion of harvest residues or sawmill coproducts from use in alternate products (such as paper products or engineered wood products) for use as bioenergy instead.	Depends on future demand and prices for alternate products compared to bioenergy.	Possible, not likely
Enrichment of areas of degraded forest to create more productive forest that is managed for co-production of materials and bioenergy feedstocks. (Note 1)	Most likely the land areas would remain as degraded forest. In some situations, a private landowner may decide to convert the land to another productive use (potentially involving deforestation).	Not likely
Shortening of rotations in forest areas that are already harvested to optimize for total biomass production.	Rotations would remain longer, to optimize for other products.	Not likely
Conversion of cropland or grassland areas to 'short rotation biomass forests' for bioenergy as a sole product. (Note 2)	Land would remain as cropland or grassland.	Not likely in the near term
Conversion of cropland or grassland areas to forest stands managed for production. Silvicultural wood waste used for bioenergy. (Note 2)	Land would remain as cropland or grassland.	Possible, not likely

Note 1 - Biomass demand for energy results in added value that helps to make activity economic.
Note 2 - Extreme scenario, unlikely without external driving force (policy or incentives).

Forest systems and wood markets are complex, and there are a variety of pathways to obtaining potential bioenergy feedstocks. Since wood can be used to make a lot of different products, many of the components of trees have a variety of potential uses. It is important to consider this in LCA studies, as the alternative fate of the material impacts the carbon emissions for biomass.

Although it is very unlikely that bioenergy demand would divert wood from high-value sawtimber products, there is a possibility that woody residues and coproducts used for lower value products like paper and engineered wood products could be diverted to bioenergy if prices for this material at different end users are similar. This can have a subsequent impact on the bioenergy GHG emissions (relative to the reference scenario) if alternate materials or products are needed to meet market demands. Using urban waste wood (such as recovered C&D debris) for bioenergy is generally preferable from a GHG emissions perspective to disposal in a landfill.[12] However, this is not necessarily the case if the wood waste that was diverted for bioenergy would otherwise be recycled for manufacture of a wood product (like engineered wood) (R. Matthews et al., 2014).

Another likely target for additional biomass supply is extraction of harvest residues in areas where it is not already done. This can lead to an overall decrease in carbon stock of the forest (such as in the coarse woody debris carbon pool), when accounting for the cycles of accumulation and decomposition over time (Cowie, Berndes, and Smith 2013). An example of this is illustrated in the simplified graph in Figure 13, which shows a total reduction of about 2% of total forest carbon over a 50-year period. The harvesting cycle occurs throughout the entire period shown, but only on a small portion of the forest area considered. The extraction of harvest residues starts at year 10 in the graph, and assumes removal of half of the branches and deadwood. Note that the *y*-axis does not go to zero; the small scale emphasizes the relatively small reduction in carbon stocks.

The main point here is that if forest management practices change to start removing harvest residues in areas where residues were not previously collected, this can have a long-term impact on forest carbon stocks, all else being equal (Holtsmark 2013). Specifically, when considered on its own and without additional forest management changes, additional removal of harvest residues will decrease forest carbon

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[12] However, wood typically takes a very long time to decompose in landfill, so the carbon in the wood is essentially "stored" in the landfill. The relative merit of storing wood in a landfill vs. using it for bioenergy will depend on the reference energy product displaced and the efficiency of the bioenergy system.

stocks, reaching a new equilibrium once all stands are brought into the new management regime, after a period equal to the rotation length of the forest management system. This means that harvest residues cannot be assumed to be a carbon neutral feedstock, even if they would otherwise decompose in the forest over time.[13] This should be a factor in LCA studies for bioenergy.

Figure 13. Example Impact of Additional Residue Extraction on Forest Carbon Stock

Image Source (R. Matthews et al., 2014). Note that soil carbon impacts are not included. The wavy lines indicate natural changes in carbon stocks due to decay and growth.
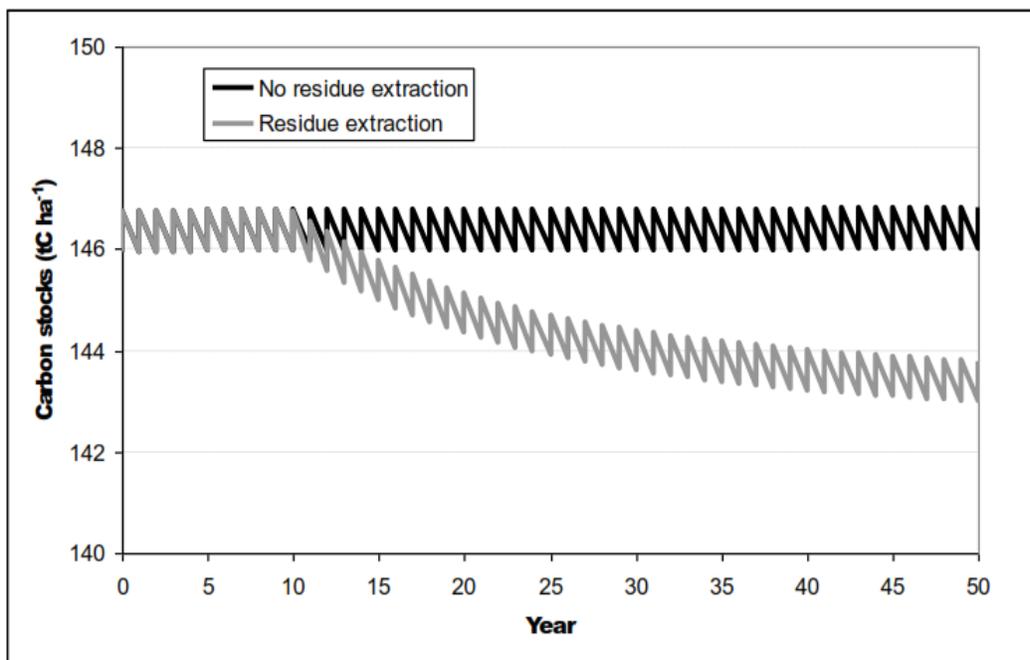
Furthermore, LCA studies should consider the level of additional biomass demand for bioenergy relative to the available resource. "The contribution of biogenic carbon to GHG emissions of forest bioenergy is sensitive to the scale of consumption" (R. Matthews et al., 2014). This is because the level of consumption can impact the type of resources used, and can also influence the types of forest management activities that are used to supply the resource. In the long run, this may or may not have significant impact on forest carbon stocks depending on activities used and site- and region-specific factors.

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[13]   There are some areas, particularly hot and wet climates where the decomposition process produces methane. In these cases, removal of harvest residues may provide a net benefit. However, such conditions do not apply in New York State.

4.7   Impact Categories Included in Analysis

While all LCAs consider the environmental impacts of a product or system, there can be significant variation in terms of the specific impact included. The ultimate goal of the study should inform selection of what impacts to consider, although in some cases data availability may limit the selection. As stated in Chapter 1, GHG emissions is the main factor of interest in this report. However, this section also describes some of the other factors that may be included in LCAs for informational purposes.

Most, but not all, bioenergy LCAs consider GHG emissions. Carbon dioxide is one of the main GHG emissions associated with forests and energy production. Bioenergy LCAs also typically account for CH_4, and N_2O emissions. Methane (CH_4) is generated during anaerobic decomposition of organic materials such as biomass. It is also a product of incomplete combustion and can be emitted in mining and extraction of fossil fuel resources (Bird et al., 2011). Nitrous Oxide (N_2O) can be generated during combustion, as well as through the microbial processes of nitrification and denitrification, which are related to synthetic fertilizers, manure, and nitrogen-fixing plants (Anderson, et al. 2010). Other direct GHGs such as SF_6, HFCs, PFCs, and Halocarbons are rarely considered in bioenergy LCAs, as they do not contribute significant emissions in most energy systems.[14]

All considered GHGs are typically converted to CO_2-equivalent ($CO_{2\text{-eq}}$) emissions using 100-year global warming potential (GWP) values from Intergovernmental Panel on Climate Change (IPCC), so that the various emissions can be combined and compared. It is important to note that there are alternative methods that could be used to evaluate climate impacts, and Plevin et al. (2014) point out that there is ongoing debate regarding the use of GWPs to estimate climate impacts rather than one of the other metrics, although the IPCC method is still the standard method applied by the LCA community. Part of the issue is that GWP values are only applicable for well-mixed greenhouse gases, which have a long lifetime. GWP does not include other anthropogenic factors that impact climate such as near-term climate forcers (e.g., ozone and aerosols, and their precursors), which have very short lifetimes, but still cause a near-term impact on climate warming over a period of several decades (Levasseur et al., 2016). Although reduction of such emissions could reduce peak warming temperatures, they are not captured in the GWP metric. In order to capture such effects, the most recent IPCC guidance (IPCC AR5)

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[14]   Note that generally only anthropogenic GHG emissions as delineated by the Intergovernmental Panel on Climate Change (IPCC) are included in LCA studies. This is why water vapor is not included, for example.

recommends using both GWP and another metric, the Global Temperature change Potential (GTP)[15] (Levasseur et al., 2016). The GTP estimates the change in global mean surface temperature at a selected year in the future following an emission of a given substance (relative to CO_2 reference), and considers the overall potential climate response based on the amount of time the substance remains in the atmosphere and the effectiveness in causing radiative forcing (IPCC 2014). In contrast, GWP only measures the radiative forcing of an emission over an accumulated time period, relative to CO2 reference.

In addition to GHG emissions, some LCAs also include environmental factors such as emissions of other air pollutants (e.g., NO_x besides N_2O, SO_x, particulates), and water resource impacts such as acidification and eutrophication, which can be significant particularly for agricultural biomass feedstocks (Cherubini and Strømman 2011). Bioenergy LCAs often also include an evaluation of the energy balance of the system, although that tends to be primarily included in LCAs for agricultural resources and energy crops, and for biofuel conversion processes. In some cases, an evaluation of social impacts is also considered in LCA studies.

It should be noted that bioenergy impacts climate change through other climate forcers beyond the direct GHGs described above. However, as indicated by Plevin et al., "because there are no widely accepted GWPs for several pollutants that are known to significantly affect climate, the climate forcing resulting from these pollutants is generally not included in LCAs" (Plevin, Delucchi, and Creutzig 2014b). One of these pollutants is black carbon, an aerosol produced from combusting biomass and coal, which "causes a positive radiative forcing through direct absorption of solar radiation, … indirectly induces changes in cloud properties, and also changes snow albedo once it deposits on the surface" (Agostini, Giuntoli, and Boulamanti 2014). Other pollutants with climate changing impacts include sulfates, and indirect GHGs or GHG precursors such as CO, VOCs, and NO_x. Different types of land cover also impact climate change due to albedo, which is a measure of reflectivity of the Earth's surface. Lighter colors reflect solar radiation, while darker colors absorb solar radiation. As a result, darker colored trees, for example, tend to absorb more energy than areas with snow and thereby cause additional warming (climate forcing). The impacts of albedo are typically most important in boreal and snow-covered regions, and less important in areas with deciduous forests (Matthews et al., 2014).

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[15] More specifically, as defined in Levasseur et al. (2016), the Global Temperature change Potential is "the change in global mean surface temperature at a chosen point in time *TH* [yr] after a pulse-emission, relative to the temperature change following a pulse emission of a unit quantity of CO_2."

4.8   Functional Unit

In an LCA, the environmental performance of a system or process is presented in terms of a single *functional unit* in order to facilitate comparison between systems as well as components of the systems. However, there is no single functional unit consistently applied for bioenergy LCA studies, and the goal and scope of the LCA study typically influences selection of the functional unit. The unit selection can impact the results and make comparison between studies difficult. Several typical functional units that apply to bioenergy LCAs are described below, with examples specifically based on the GHG emissions impact since that is the focus of this report.

One option for functional unit selection is to express LCA results on the basis of biomass feedstock input, either on a mass or energy basis (e.g., kg $CO_{2\text{-eq}}$ / kg biomass, or kg $CO_{2\text{-eq}}$ / MJ biomass). This option is independent of both the conversion process and the type of output, and can therefore be useful to compare alternative uses for a given feedstock (Cherubini et al., 2009).

Another input-based functional unit is based on the land area (e.g., kg $CO_{2\text{-eq}}$ / hectare). This is particularly useful in the context of agricultural land use, when the availability of land is a constraining factor and is therefore recommended predominately for studies evaluating dedicated biomass crop feedstocks (Cherubini et al., 2009; Bird et al., 2011).

Output-based functional units are expressed in terms of useful energy output (e.g., kg $CO_{2\text{-eq}}$ / kWh for heat and power generation, where the kWh can be expressed in terms of electricity or heat output, or both. For heat generation a functional unit of kg $CO_{2\text{-eq}}$ / MMBtu may be used instead). Presenting results in this way includes the conversion efficiency and is useful to compare the impacts of providing the same service from different fuels (Cherubini & Strømman 2011; Bird et al., 2011). This is particularly useful for energy produced from biomass residue feedstocks (Cherubini et al., 2009), since a unit based on land area would not apply.

As part of a literature review of biomass energy LCA studies, Cherubini & Strømman (2011) also identified another type of functional unit based on year (e.g., kg $CO_{2\text{-eq}}$/yr). This was noted as useful when it is desired to avoid allocation of emissions for conversion processes that result in several products as it would provide total annual emissions for the process itself instead of for a particular product. However, it is worth noting that this functional unit was the least utilized, making up only 5% of the 104 different studies reviewed. The majority of these studies (70%) used output-related functional units, while 15% used land area as the basis for results, and 10% were based on input-related units.

For bioenergy, the functional unit should be the energy service delivered. However, some studies also use a delivered feedstock unit (e.g., per MJ feedstock prior to conversion to energy product) in order to facilitate comparisons of intermediate products such as wood pellets.

It is important to note that overall LCA results may be presented in a different way, especially for forest biomass resources. This is a different consideration than the functional unit, and will be discussed in Section 4.12.

4.9 Allocation Methods

Various methods are applied in order to attribute life-cycle emissions and other environmental impacts to the various outputs of a product system (coproducts). Despite much discussion in this area, there is no consensus on a single method to use, and often the applied method depends on the goals and type of assessment. The selected method is particularly important because it can significantly impact the end result (Curran 2007). As noted in Section 4.1, cLCA uses system expansion, while aLCA uses other allocation methods.

For bioenergy systems evaluated via aLCA, the most typical allocation methods are based on the following qualities of the products: mass, energy content, or economic value. For these types of allocations, the emissions or other environmental impacts are attributed to each product based on their contribution to the total outputs. For example, if an energy-based allocation was applied to the outputs in a CHP process in which 40% of the total useful energy output was electricity (and the other 60% was steam), then 40% of the emissions would be attributed to the generated electricity.

Another option is to essentially avoid allocation by using system expansion, which is the method used for cLCA studies. With this method, the system boundary is extended in order to compare two systems that are equal in scope including all products generated. For example, if the process of interest generates two distinct products that would otherwise be produced via two separate processes, both of these separate process would be included in the reference system for comparison. Another way this can be applied is by subtraction, or the "avoided burden approach" (Curran 2007). This process has also been called substitution (Wardenaar et al., 2012). In this case, the environmental impacts associated with production of the secondary product via an alternate method is subtracted from the environmental impacts associated with the production of the primary product being considered. It is considered "conceptually equivalent" to system expansion, but that does not mean it will have the same results when applied (Wardenaar et al., 2012).

Allocation may be needed at several stages within the system being considered, whenever multiple products are generated from the processes within the product system. For example, woody biomass feedstocks are often generated as a by-product or coproduct, particularly for forest biomass. If a harvesting operation generates sawtimber, pulpwood, and bioenergy residues from the same operation, it will be necessary to decide how to allocate GHG emissions and energy inputs among these three products in an LCA study. Allocation could also be needed if multiple end products are generated, although this is more common for biofuel production than other energy carriers.[16] For bioenergy conversion processes that only result in a single main product such as heat or power, no allocation is necessary for the end product (although allocation may still be needed for the feedstock coproducts). However, some procedure would be needed for combined heat and power projects. In this case, system expansion would be a reasonable option to avoid allocation, although allocation by energy content or economic value could also be applied for an aLCA.

Similar allocation methods can be applied for feedstocks and end products; mass and market value are likely to be most applicable. For example, these methods were both applied for a life cycle inventory assessment for wood fuel pellets produced from hardwood flooring residues (Reed et al., 2012). The allocation method had a significant impact on the GHG assessment for the pellets, since the residue made up approximately 50% of the mass of the input material, but contributed only around 1% of the total value of the end products (pellets and hardwood flooring).

Each allocation method has advantages and disadvantages, and selection of which method to use often depends on the goals of the study. Mass and energy allocation are relatively straightforward, but may not accurately describe resultant emissions or environmental impacts. Economic or market value allocation is complicated by the fact that values change over time, and can also vary by location.[17]

Both ISO and the International Energy Agency Bioenergy Task 38 consider "best practice to expand the system boundary of both the study and reference systems to include all significant sources of GHG emissions and energy uses, and assure equivalent services and coproducts" (Bird et al., 2011). System expansion can avoid the sometimes arbitrary allocation process, but also adds to the modeling complexity and requires additional data. Data accessibility and time limitations can impact the practicality of utilizing

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[16] Biofuel production processes typically result in multiple coproducts that are generated concurrently with the main biofuel product, such as dried distillers grain solids, which is an animal feed generated as a coproduct of corn ethanol.

[17] As such, a standardized value is usually applied within a given study.

this method, although life cycle inventory databases such as the one developed by National Renewable Energy Laboratory or Ecoinvent can help to provide generic information for background processes (National Renewable Energy Laboratory 2013). It is important to consider the accuracy of additional data and assumptions made when utilizing this method. In some cases, it may be impossible to apply system expansion, such as when there is no substitute for another product, or it involves processes that have other coproducts, extending the expansion in an unending cycle (Curran 2007).

Note that allocation is typically only applied to the main products generated from the process, not to waste products. Ultimately each analysis will require decisions on what approach to take with allocation, and which products are included. Allocation decisions are needed at many points in the analysis, including feedstock, conversion, and end products with value. Because of the inevitable variation from one assessment to the next, it is important to be clear in the presentation of results where allocation was applied and how it was done.

4.10 Data Inputs and Selection

A lot of data are required in an LCA study and will vary based on system boundary, location, time frame, and other choices. Examples of some of the basic information needed for a bioenergy system and a fossil fuel reference system are shown in Table 10 and Table 11, respectively. These tables are only examples intended to provide a high-level indication of the complexity and depth of data that may be needed for an LCA study, considering that each listed data point will vary based on specific choices in the analysis, and will be impacted by site specific factors, and spatial and temporal boundaries. In practice, each study will have specific data requirements to meet the goal and scope of the analysis.

Table 10. Example Data Requirements for GHG and Energy Balance for Bioenergy System

Adapted from (Bird et al., 2011)

Process step	Parameters to be collected or estimated	Variable calculated
Land management change	Change in carbon stocks in soil and vegetation as a result of the bioenergy system Biomass yield/growth rates Residue amount and use	Carbon stock change due to change in land use or land management activities
Cultivation and harvest of biomass	Co-products amount and type Fertilizer amount and type, and herbicides and pesticides use Fuel use by machines e.g. tractor, feller, skidder GHG emissions for fertilizer, herbicide and pesticide production	GHG emissions and energy input from cultivation, management, and collection and upstream emissions associated with agrochemical inputs.
Transportation of feedstock	Transport distance and mode Fuel use per unit distance transported	GHG emissions and energy input from transportation
Conversion to energy carrier	Auxiliary materials input Co-products amount and type Energy and material efficiency of conversion process Energy demand of conversion facility GHG emissions and energy balance for auxiliary materials production	GHG emissions and energy input from conversion
Distribution of energy carrier	Distribution distance and mode Distribution losses (e.g. electricity grid) Energy demand of distribution system (e.g. district heating system) Fugitive GHG emissions for the distribution system (e.g. natural gas grid)	GHG emissions and energy input from distribution
Energy Use	Energy efficiency Auxiliary energy demand Auxiliary materials input	GHG emissions and energy input from use
Disposal of Wastes	Quantity and type of waste generated throughout various processes	GHG emissions from waste products and end-of-life phase

Table 11. Example Data Requirements for GHG and Energy Balance for Fossil Reference System

Adapted from (Bird et al., 2011)

Process step	Parameters to be collected or estimated	Variable calculated
Biomass usage change	Carbon stocks in wood products, forest residues, and landfill (for waste wood materials), as applicable	Carbon stock change due to change in biomass use
Land management change	Carbon stocks in soil and vegetation affected by the reference system	Carbon stock change due to change in land use or land management activities
Extraction of fossil fuel	Energy requirement in fossil fuel extraction (e.g. equipment, pumps) Co-products amount and type Auxiliary materials input GHG emissions for auxiliary materials production	GHG emissions and energy input from extraction
Transportation of fossil fuel	Transportation distance and mode Energy requirements by transportation	GHG emissions and energy input from transportation
Conversion to energy carrier	Energy and material efficiency of conversion process Energy demand of conversion facility GHG emissions and energy balance for auxiliary materials production	GHG emissions and energy input from conversion
Distribution	Distribution distance and mode Distribution losses (e.g. electricity grid) Energy demand of distribution system (e.g. district heating system) Fugitive GHG emissions from the distribution system (e.g. natural gas grid)	GHG emissions and energy input from distribution
Energy Use	Energy efficiency Auxiliary energy demand Auxiliary materials input	GHG emissions and energy input from use
Disposal of Wastes	Quantity and type of waste generated throughout various processes	GHG emissions from waste products and end-of-life phase

4.11 Land Use Change

As described previously, land use is an important component in bioenergy LCA studies, and can result in negative or positive impacts on the GHG balance for bioenergy systems. As with other factors, there should be an intentional choice to include or exclude this in an LCA study, and a clear explanation of this decision in results. Furthermore, if considered in the bioenergy system analysis, equivalent land use change components should be considered for the baseline scenario.

At a high level, Land Use Change (LUC) can include "either the conversion of natural ecosystems into managed lands, or changes in the management of already appropriated land" (Berndes et al., 2013). Forest clearing so land can be used for something other than forest growth, or afforestation where open land is converted to forest land are clear examples of land conversion. For forest lands, LUC can also include management activities such as changes in tree species or stand density, harvest cycles, harvest residue management, and other forest management practices.

It is important to realize that not all researchers mean the same thing by Land Use Change. For example, some researchers do not include land management change as part of LUC, although such activities may still be considered elsewhere in the study. This is one reason why it is important to clearly state what is included in an analysis. For the purposes of this report, we are using the broader definition including land use changes and land management changes, to facilitate discussion of these related components together.

As stated by Berndes et al., (2013), "LUC can affect GHG balances in a number of ways, including: (1) when biomass is burned in the field during land clearing; (2) when the land management practice changes so that the C stocks in soils and vegetation change, and/or non-CO_2 emissions (N_2O, CH_4) change; and (3) when LUC results in changes in rates of C sequestration, i.e., the CO_2 assimilation of the land may increase or decrease relative to the case in which LUC is absent."

Forest management changes can result in an increase or decrease in carbon stocks, depending on specific activities implemented. An example of an activity that would have a carbon sequestration benefit is reforestation of degraded land, which can result in higher carbon stocks and improvement of soil quality over time. Meanwhile, "shortening forest rotation length in order to obtain increased output of timber and biomass fuels leads to decreased C stock in living biomass (other things being equal)" (Berndes, Bird, and Cowie 2011). An example of this is shown in Figure 14, in which the quantity of carbon stored in the forest (black line) decreases as the length of rotation period decreases.

This is not to say that a bioenergy market will lead to a decrease in rotation length. In practice, rotation periods are generally determined based on economic value, such that growth and associated harvest volumes are optimized for the desired end product mix, based on various factors including markets for different products and forest response to thinning or other management activities. Cintas et al. (2016) provides an example in which the bioenergy market led to increased rotation length.

Further, while decreasing rotation periods can diminish the living biomass in the forest, a significant portion of this material may be used in long-lived harvested wood products, thereby limiting the GHG emissions impact. It is also important to point out that other management changes can increase carbon stocks on forest land when rotation length is decreased, such as by increasing stocking density, using improved trees that grow faster (and therefore sequester carbon at a faster rate), adding fertilizer to increase growth, or managing weeds in a plantation to increase growth rates.

Figure 14. Example Relationship Between Forest Carbon Stocks and Rotation Period

Image reproduced from (R. Matthews et al., 2014).
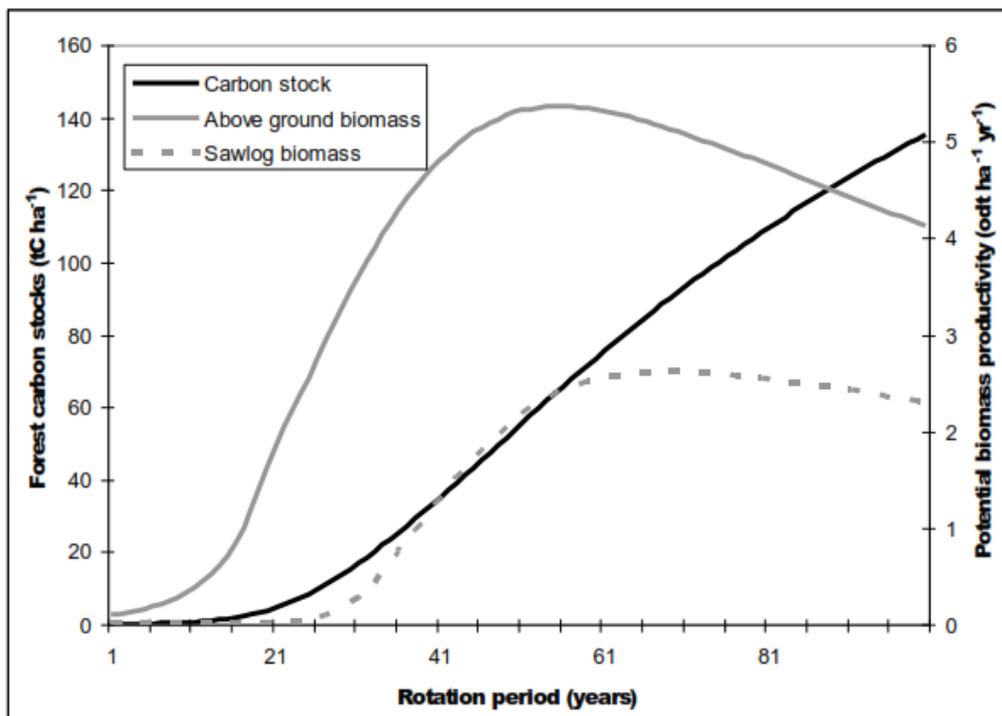
Increasing harvest removals from forests can also lead to a decrease in carbon stocks, unless accompanied by forest management activities to increase growth. As stated by Berndes, Bird, and Cowie (2011), "to the extent that increased demand for forest bioenergy makes such measures feasible (i.e., they would not have taken place in a scenario without bioenergy demand) the effects of changed forest management should be considered when evaluating the climate change mitigation benefit of forest bioenergy."

Direct land use change refers to changes occurring in the area where biomass feedstocks are cultivated or harvested within the boundary of the LCA study. When such activities lead to changes in other areas outside of the product system, this is called indirect land use change (iLUC). In addition to displacement of activities previously realized on the land where biomass is generated (e.g., crop production), iLUC can also include changes in land management such as intensification of activities elsewhere (Berndes, Bird, and Cowie 2011). Note that these connections are very difficult to measure in the real world, because there are lots of factors influencing decisions on land use outside the LCA system boundary.

Additional use of biomass for energy can also potentially lead to other indirect effects (leakage), which can impact life cycle GHG emissions. One example is the rebound effect: a large increase in bioenergy production would result in lower fossil fuel demand, which could then lead to decreased prices for fossil fuels and thereby cause demand to grow again. Another example is if the increase in bioenergy leads to a perceived greener energy source, such that end users reduce conservation efforts and use more energy overall. Ideally, cLCA studies should consider such indirect effects. So far, such effects are mostly all hypothetical, and the amount of bioenergy that would be needed to make such an impact, and the significance of such effects, are not well understood.

LUC impacts are typically very difficult to quantify, as there are a lot of uncertainties. Although generally easier to evaluate than iLUC, estimating emissions from direct land use change can still be challenged by data limitations and understanding of how land management practices impact carbon dynamics (Berndes et al., 2013). Meanwhile, iLUC and leakage require large scale or global modeling of complex markets dynamics. However, there is growing acknowledgement in the bioenergy LCA community that it is important to consider these effects.[18]

Concerns and issues for iLUC are generally focused on the agricultural sector, particularly with regards to converting crop land used for food to biomass crops for energy. Although indirect effects can be a factor in the forestry sector, it is typically most critical for deforestation/afforestation or development of energy crops. Matthews et al. (2014) stated that a typical approach for cLCA studies is to "constrain the relevant activities so as to avoid significant risks of iLUC."

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[18]   Of course if LUC impacts are included in a bioenergy LCA, they should also be considered for the comparison or reference case scenarios as well, regardless of the energy source used.

Avoiding or reducing negative LUC effects can be accomplished by setting up land use restrictions, and targeting unused marginal or degraded lands for conversions (e.g., energy crop cultivation); in some cases, this can even increase carbon stocks in the soil (Berndes, Bird, and Cowie 2011). It is also worth noting that productivity improvements reduce land requirements and LUC pressure.

Some examples of biomass that could be used for bioenergy with limited LUC impacts include:

- Biomass obtained from forest clearing as a result of activities unrelated to biomass production, such as to clear land for development – no LUC impact (assuming all of the burden of the activity is allocated to the primary land clearing purpose) (Berndes et al., 2013).
- Biomass that would otherwise be landfilled or would decompose in wet conditions – no iLUC impact, and possibly some additional benefits from avoided methane emissions (Berndes et al., 2013; Haberl et al., 2012).
- Removal of harvest residues that would otherwise remain on-site and decompose – no LUC impact, but can affect forest carbon stocks (Berndes et al., 2013; Haberl et al., 2012).
- Planting high-yielding energy crops on unused grasslands (particularly those with non-native, invasive species) – unlikely to have adverse carbon sequestration effects from LUC (Haberl et al., 2012).

The use of wood waste materials and by-products for bioenergy can have LUC effects if they were previously used for other purposes, as it would require the users to find alternate resources or different materials (e.g., Cowie and Gardner 2007).

It is important to consider the fate of biomass feedstocks that are not used for bioenergy. For example, natural disturbances in forests such as wildfires, diseases, and pests can result in a release of carbon stocks, and such considerations are often underrepresented in LCA models and studies (Matthews et al., 2014). Furthermore, "in forested lands susceptible to periodic fires, good silvicultural practices can lead to less frequent, lower intensity fires and can improve site conditions for replanting leading to higher growth and productivity (i.e., accelerated forest growth rates and soil carbon storage). Using biomass removed in such practices for bioenergy can provide GHG and particulate emission reductions by [utilizing] biomass that might otherwise burn in open-air forest fires," or decompose over time (Berndes, Bird, and Cowie 2011, p. 21).

As described in Section 4.3, there are also LUC emissions associated with fossil fuel use, which should be considered in the reference scenario analysis. This can include coal mining, extraction of oil and gas, and deforestation or land conversion for access roads, structures, and pipelines (Berndes, Bird, and Cowie 2011). Although the GHG emissions associated with such activities can be similar in magnitude to emissions from biomass production on a per-unit area basis of land affected, the impact is lower for fossil fuels when considered on an energy output basis, due to the higher yield and energy content relative to biomass. However, it has also been suggested that at least a portion of the GHG emissions from military activities undertaken to secure fuel supplies should be applied to fossil fuels (Berndes, Bird, and Cowie 2011). This has been shown to have a relatively small impact on the overall GHG emissions impact in some cases (Wang et al., 2012), although the impact on other environmental factors may be larger.

4.12 Metrics for Assessing the Climate Change Effects of Bioenergy Systems

LCA results are expressed per functional unit. However, there are a variety of ways that results from such studies are presented in the literature in terms of assessing climate change impacts. Some of the metrics that have been used with some regularity are listed below, based on the summary provided by Matthews et al. (2014) and other sources. These metrics can vary widely in terms of what is included (e.g., comparison with land or energy production reference case), time considerations (annual, cumulative), and clarity of presentation.

- The emissions intensity of a product (aLCA), or the emissions saved per unit biomass resource or per unit land area (cLCA) are relevant metrics for assessing climate impacts of bioenergy.
- Annual CO_2 or GHG emissions for the system – net impact considering emissions and sequestration at a given point in time. GHG emissions presented on $CO_{2\text{-eq}}$ basis.

  - Results presented on an absolute basis indicate only emissions directly related to the system were considered (aLCA type analysis).
  - Results presented on a relative basis indicate change in emissions were relative t o a reference scenario (cLCA type analysis). This metric may include emissions associated with land use change.

- Cumulative or average CO_2 or GHG emissions for a system – similar to above, but considers emissions impact over entire study period instead of just one year. Average emissions are annualized values calculated from the cumulative total.
- Carbon Neutrality factor, payback time, and parity point (defined below) are applied to a scenario in which bioenergy is produced each year, and displaces a specific reference energy product. These are useful for analyzing the effect of a policy or project.

- o Carbon Neutrality factor – The Carbon Neutrality factor is defined as "the ratio between the net reduction/increase of carbon emissions in the bioenergy system and the carbon emissions from the substituted reference energy system, over a certain period of time" (Zanchi, Pena, and Bird 2010). The comparison with the reference system considers energy generation from other sources as well as land use impacts.
- o Carbon payback period, or GHG emissions payback time – This metric indicates the amount of time until the initial increase in GHG emissions due to harvest or removals is offset by GHG reductions from displaced fossil fuel use or other factors. Particularly relevant for forest bioenergy studies. The payback time represents the number of years until the cumulative emissions associated with the bioenergy system are equivalent to the emissions associated with the reference scenario. According to (Buchholz et al., 2016), use of this metric is becoming fairly typical in LCA studies.
- o Carbon parity point – applicable for forest bioenergy. Somewhat based on the carbon payback time, but also includes the time needed to make up for missed growth in forest that would have occurred in an unmanaged forest scenario (Agostini, Giuntoli, and Boulamanti 2014). It is typically longer than the carbon payback period.
- Other metrics can be used to quantify the climate impacts based on the life cycle inventory of emissions over time, such as cumulative radiative forcing and GWP_{bio}.
- GWP_{bio} factor – a global warming potential for bioenergy that is analogous to GWPs for non-CO_2 GHGs, which was introduced in (Cherubini et al., 2011). These factors are "derived by approximating the atmospheric decay of carbon from long-rotation biomass with a simplified forest growth equation. [They] are calculated for situations in which carbon in stemwood (with a rotation period of 1–100 year) is released into the atmosphere within a year after harvest" (Helin et al., 2013) (pp. 480-481). This can be useful for comparison to fossil fuel emissions, but is focused on energy use and may not consider the full host of system components of interest for all studies. Other variations of this idea have also been used for relative comparisons including consideration of temporary carbon sequestration in wood products, as well as consideration of cumulative displaced GHG emissions from fossil fuel sources.
- Cumulative radiative forcing – used to present results in terms of climate impact. Accounts for the timing and dynamics of emissions and removals.

On another note, there is wide agreement that LCA results need to be presented clearly, in order to avoid misunderstandings, or a false impression that a specific technology causes (or does not cause) climate mitigation. All LCAs have innate uncertainty due to assumptions, data limitations, and level of complexity. Some researchers have expressed concern that LCA results often do not acknowledge the limitations and can therefore be misleading (Plevin, Delucchi, and Creutzig 2014b). This goes beyond the complications of presenting the results in a useful way. It is especially important to understand the limitations of a study and the conditions for which the results apply when it used to make policy decisions.

5   Analysis and Comparison

This section of the report provides a summary of the key areas where there is general agreement
on analytical methods for woody biomass LCA studies, as well as areas where there are divergent
methods or inputs. The areas that continue to spark significant ongoing debate are also discussed.

5.1   Areas with Fundamental Agreement

There is significant agreement that bioenergy derived from forest-based feedstocks should not
automatically be designated as carbon neutral in policy considerations without further evaluation,
even when the material is produced and harvested sustainably. As stated by Agostini et al. (2014),
"in order to assess the climate change mitigation potential of forest bioenergy pathways, the assumption
of biogenic carbon neutrality is not valid under policy relevant time horizons (in particular for dedicated
harvest of stemwood for bioenergy only) if carbon stock changes in the forest are not accounted for."
To be clear, biomass used for bioenergy can have beneficial carbon impacts, but additional evaluation
is needed to determine if this is the case for a given scenario. "The potential carbon neutrality of forest
biomass is a source of considerable scientific debate because of the complexity of dynamic forest
ecosystems, varied feedstock types, and multiple energy production pathways" (Buchholz et al., 2015).

There is general agreement that LCA is an appropriate method to evaluate GHG impacts of bioenergy and
other systems (Matthews et al., 2014). More specifically, although there is not complete consensus on the
matter, it is generally agreed that cLCA is appropriate for policy and decision making, particularly for
evaluating climate change mitigation potential, as such analyses are based on change relative to a baseline
scenario and include consideration of indirect effects. There is also some agreement that aLCA methods
may be reasonable for implementation of policy, and to meet regulatory requirements, as it is used for
project-specific accounting.

The LCA community also understands that the complexity of the analyses can lead to significantly
different results based on methods, assumptions, approach, and data used. As such, many have noted
that it is crucial to clearly define the purpose and scope of the LCA, and to make analysis choices
consistent with these considerations. While unfortunate from the perspective of gaining widespread
understanding, and potentially contributing to the large amount of confusion that already exists regarding
LCAs, there is no one right way to do an assessment—the methods and inputs depend greatly on the
purpose of the study. Furthermore, while there is general agreement that system boundary and reference
case are important in LCA studies and depend on study goals, there is no consensus on the specific

geographic or physical boundaries and parameters that should be applied. Additionally, because LCA results vary based on site-specific factors and project specific inputs, as well choices for analysis methods and approach, it is difficult to generalize results or apply results from one study broadly. This is especially true for forest bioenergy where there are important differences in forest types, growth rates, management practices, and rotation lengths among the studies in the literature. As a result of these factors, it is important for any study to clearly present the results, including context and limitations of the analysis. Likewise, caution needs to be applied when transferring results from a study in one region to a different region or management system.

5.2   Potential Areas of Analytical Divergence

There are many areas in which methodologies for LCA studies can diverge, and selection of approach has a tremendous impact on end results. As stated by Miner and Gaudreault (2013), "there is no single correct way to calculate biogenic CO_2 emissions. Different methods are appropriate for different objectives. Even for a given objective, however, there can still be controversy regarding these calculations." Arguments tend to arise about the most appropriate choices for analysis inputs, especially selection of baseline and system boundary, including temporal and spatial scales. These and other methodological selections with divergent methods for LCA studies are summarized below.

5.2.1 Analysis Scope

LCA studies vary widely in terms of what carbon pools and activities are included in the analysis. A recent meta-analysis of forest bioenergy GHG accounting studies performed by Buchholz et al. (2015) provides a useful example. This evaluation included a literature review of 66 studies, covering 149 different cases, which were published between 1991 and 2014. The analysis showed that there was a large variation in what forest and non-forest carbon pools and activities were included in the studies. Buchholz et al., identified 16 different potential carbon pools and fluxes that could impact characterization of a resource:[19]

- Forest ecosystem – aboveground live biomass, aboveground standing dead biomass, belowground live biomass, belowground dead biomass, soil, forest floor, merchantable timber, harvest residue.
- Material processing – forest treatment operations, recovery of biomass in the forest, transport, mill residue.

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[19]   It is important to note that in this evaluation, the analysis of included carbon pools and activities was only one of the twenty attributes considered by Buchholz et al. (2015).

- Product fate – wood products in use, wood products in landfill.
- Indirect effects – leakage, product substitution.

The study found that on average, the cases considered only included nine of these 16 carbon pools and fluxes, with various choices of components included. Indirect effects in particular were only considered in a small number of cases.

LCA studies are also inconsistent in terms of what indirect effects are included, and how they are evaluated. This includes changes in land use or forest management activities outside of the system boundary, how fossil fuel use and prices are impacted by increased bioenergy use, as well as leakage effects such as how the flow of wood products and biomass are changed when forest biomass use increases. Although there is a growing acknowledgement in the bioenergy LCA community that it is important to consider such effects, they are typically very difficult to quantify and require large-scale or global modeling of complex market dynamics. Furthermore, the selection of what is included in any LCA depends on the goal of the study, as well as the study boundaries. For example, indirect effects would not be included in an aLCA study used to evaluate direct GHG impacts of a specific project or process.

5.2.2 Temporal Boundary Selection

LCA studies differ in terms of the timeframe for the analysis and the temporal boundaries. This is particularly important for forest biomass, due to the differences in the time scale between emissions from harvested bioenergy and forest growth rates across the landscape. In a meta-analysis of forest bioenergy carbon accounting studies, Buchholz et al. (2015) noted that the temporal scale of the analysis ranged from 20 to 10,000 years, which has a median of 240 years. Some LCA studies associated with policy decisions use relatively short timeframes associated with the policy horizon (20 years, for example), although the climate impacts can extend much further. It is also important to recognize that the use of short timeframes is inconsistent with use of 100-year GWPs (Miner et al., 2014; Ter-Mikaelian, Colombo, and Chen 2015).

The temporal boundaries also impact the processes included in an LCA study, and the selection of the starting point of forest bioenergy LCAs is important. This is a significant source of ongoing debate. For example, some studies extend the boundary back in time to include the growth of the trees prior to harvest (creating a carbon dividend at harvest), while other studies only consider activities starting at or just

before harvest (creating a carbon debt at harvest). Results are also connected to the spatial boundary, where some studies start at the time of harvest of each forest stand ("stand level"), while other studies begin at a single point across the landscape or region so that both harvested and unharvested plots are included at the start of the study ("landscape level"). Currently there is no consensus on where to place these temporal and spatial boundaries, so it is important they are clearly defined in studies of these systems.

There is general consensus that carbon sequestration and emission cycles have an impact on the timing of the net GHG benefit of bioenergy systems. However, there is no agreement on the appropriate timeframe to use for GHG emissions analyses, even among studies focused on evaluating climate change mitigation opportunities. Some of this disagreement is connected to the complexity of climate dynamics and carbon cycles. Miner et al. (2014) point out that some of the interest in the timing of emissions is related to concerns about short-term spikes in emissions leading to a "tipping point" in which a critical threshold is crossed that results in a large-scale change in the climate system. However, Miner et al. (2014) also provides the following useful summary regarding the alternative view on the importance of cumulative emissions: "whereas the science on tipping points and abrupt changes continues to advance, a consensus has developed on the importance of cumulative CO_2 emissions as a predictor of peak global temperatures." This is of significant importance for forest bioenergy LCA studies in particular, since net emissions from some bioenergy systems may initially be greater than a fossil fuel reference case. However, the cumulative emissions are usually lower over an extended period (depending on the specifics of the system being studied).

5.2.3 Spatial Boundary Selection

For forest biomass, the spatial scale or geographical extent of the analysis impacts the LCA in terms of forest dynamics and carbon stock exchanges. It is related to the temporal impacts as the carbon cycles associated with forest management can vary significantly for a single tree or individual stand of trees, but may average out over an entire forest supply shed, depending on the level, frequency and type of harvest activities.

The spatial scale used in an LCA study can have a significant impact on analysis results, particularly for forest bioenergy. The carbon stock in a single stand will vary tremendously during growth and harvest cycles over time. Such fluctuations are tempered when considered on a larger forest area. Harvesting activities are typically only performed on a small portion of the forest each year, so the removals make up a relatively small portion of the total forest carbon stock. A larger-scale perspective accounts for various

stand ages and real-world commercial management activities throughout the forests. The spacing of harvests of biomass for bioenergy across the landscape also raises issues for the temporal analysis of the system because decisions will need to be made on how to account for forest growth that occurs on stands prior to being harvested. The importance of the interaction between these spatial and temporal boundaries in forest bioenergy assessments requires the decisions about these issues are clearly defined for each study.

5.2.4 Baseline/Reference Scenario Selection

There are several different methods for baseline or reference scenario type; some of the typical methods used for bioenergy systems are summarized below.

- No baseline: GHG impacts for system of interest are not compared with a reference case. The assumption that all biomass is carbon neutral would fall into this category (Johnson and Tschudi 2012).
- Reference point baseline: considers the carbon stocks and emissions at a specific point in time as a benchmark for comparison.

  o This type of baseline is used to calculate actual emissions over a period of time, by comparing emissions at the reference point with the emissions at another point in time (Miner and Gaudreault 2013). It is typically associated with aLCA studies.
  o Some of the benefits of a reference point baseline are that it is used to calculate actual GHG transfers during a select timeframe, and that it has fewer assumptions than an anticipated future baseline. However, since a reference point baseline is defined by characteristics at a specific point in time (generally in the past or present), it cannot be used to consider a baseline in which an alternate course of action was pursued (Miner and Gaudreault 2013). For example, a reference point baseline would not typically be used to compare the impacts of a specific policy under consideration with another alternate policy that is being evaluated.

- Anticipated future baseline (also called a dynamic baseline): projected emissions are estimated based on the expected activities that would occur in a BAU scenario without use of additional biomass feedstocks for energy.

  o This type of baseline is typically used for cLCA studies, as it can be used to evaluate the impacts of implementing a new policy or replacing a product relative to BAU (Miner and Gaudreault 2013).
  o The main benefit of this type of baseline is that it can be used to inform decision-making efforts to achieve reduced GHG emissions within set constraints. The disadvantages of the anticipated future baseline are that it does not calculate actual GHG emissions associated with a system or policy, but rather projected GHG emissions based on set conditions. As a result, it is more complex, requires more assumptions, and has more uncertainty than a reference point baseline.

GHG emissions analyses are very sensitive to a number of factors in the reference scenario, including the counterfactuals for energy production systems and land use, as well as the alternative fate of the biomass feedstock. Especially when using an anticipated future baseline, various assumptions must be made to select applicable counterfactual scenarios.

- Energy counterfactual: the alternative source of the end-product (e.g., electricity, heat, or transportation fuel) and coproducts must be considered in the reference case. This could be a specific fuel type or system or mix of resources. Unless a bioenergy system is directly replacing a specific fuel type, the choice of alternative fuel or system will be based on assumptions that are a mix of technical and market factors. The most conservative option would be to compare bioenergy with the best performing (fossil fuel) alternative, although this has the potential to underestimate potential benefits. Other potential options include evaluating the emissions impact based on the average current energy source mix or, for new capacity, using either the emissions attributes for the most likely technology to be implemented if bioenergy is not used, or the emissions attributes for aging infrastructure that would be replaced by bioenergy.

- Biomass resource use counterfactual: the alternate fate of the biomass material if it was not used for bioenergy. For harvest residues, sawmill residues, or recovered waste materials, the biomass could otherwise decompose in a landfill or the forest floor, be used for an alternate product (e.g., engineered wood products, or mulch), or it could be burned (either during a wildfire event or intentionally by human activities). Other forest materials used for bioenergy, such as small roundwood, may otherwise be used for another product such as paper or oriented strand board (OSB) if there are markets available in the area of study. In some cases, limited demand or low value for such alternative uses may lead to reduced harvest activities; in this case the alternate fate of a less harvested forest should be considered, as the trees may continue to grow for longer periods, or the forest could be impacted by natural disturbances (e.g., wildfire, pests, diseases) or human activities (e.g., deforestation for development).

- Land use counterfactual: this considers use of the land or forest management practices that would have occurred if the biomass feedstock considered in the study was not used for bioenergy. An area of ongoing debate is when it is appropriate to apply a "no use" baseline, in which all forest management activities are suspended and the land is allowed to return to its natural state. Although this approach could (in theory) maximize the carbon sequestration in the forest land, it is not realistic to assume that is a likely outcome for forests currently managed and harvested due to their commercial value. Using a "no use" baseline also assumes either that the area being studied will no longer use any wood products or that the supply of wood products will come from outside the region, which creates challenges to calculation of leakage effects. In addition, unmanaged forests can be more vulnerable to natural disturbances (Lippke et al., 2011); forest management activities help to protect forests. It is also important to note that forest management activities can increase carbon sequestration in the forests in some cases, due in part to the variation in growth cycles over time, since growth (and associated carbon sequestration rates) slows as forests mature.

5.2.5 Allocation

Allocation is used to attribute life cycle emissions and other environmental impacts to the various products generated from a multi-output product system (coproducts). Allocation may be needed at several stages within the system being considered, whenever multiple products are generated from the processes within the product system.

The choice of allocation approach has been shown to have a significant impact on LCA results for multifunctional processes (e.g., Wardenaar et al., 2012). Despite much discussion in this area, there is no consensus on a single method to use, and often the applied method depends on the goals and type of assessment. For forest bioenergy systems, allocation is important for feedstocks that are generated as a by-product or coproduct of harvesting or other activities.

For bioenergy systems evaluated via aLCA, the most typical allocation methods are based on the qualities of the end products, such as attributing environmental impacts to each product generated based on mass, energy content, or economic value. System expansion is typically used for cLCA studies, in which the system boundary is extended in order to compare two systems that are equal in scope including all products generated.

Different existing bioenergy policies have different requirements for allocation. For example, the California Low Carbon Fuel Standard and EPA Renewable Fuel Standard use substitution for allocation, while the European Renewable Energy Directive uses energy content as the basis for allocation (except for electricity coproduced with biofuel or biogas, which is allocated using substitution) (Wardenaar et al., 2012). It is worth noting that since the EU methodology requires industries to prepare their own GHG emission analyses, allocation needs to be relatively simple. However, in some U.S. policies, LCA is performed upfront and used to generate default values that are then used for reporting. In this case the calculations can be more complex, since they are only done once for the policy application and do not need to be completed by each entity submitting a report.

When needed, there are benefits to using allocation based on physical properties (energy content, mass), particularly because the method is relatively straightforward and simple to apply, and it does not vary based on time or location like economic properties or market value. In contrast, system expansion is not as straightforward and can result in differing results depending on choices made. However, system expansion is appropriate for cLCA studies, as it provides an assessment of how the bioenergy system will impact other systems outside the immediate bioenergy product system.

5.3   Likely Points of Debate/Analytical Divergence

As summarized above, there are several areas within bioenergy LCA studies where decisions need to be made to complete the study. The decisions impact the outcome of the study, and currently there are disagreements about which of these approaches is the most appropriate. The major areas of ongoing debate for forest-based bioenergy are related to system boundary and reference selection, including: when the analysis timeframe should begin, selection of spatial boundary, and land management/use baseline. These are described further below. Other areas of ongoing debate include selection of reference energy system (including comparison with other renewables), use of average versus marginal data, and substitution effects and inputs for LCA studies, which use system expansion allocation methods. These have been touched upon elsewhere in the report and are not discussed here in detail.

As summarized by Miner and Gaudreault (2013), the analysis timeframe consideration is based on "the question of whether the analysis should extend temporal boundaries back to include photosynthesis in the wood eventually harvested for the product or in the inventory year of interest, or only consider photosynthesis in trees that are regrown after the harvest. In other words, this controversy is over whether CO_2 removals occur before or after harvest." For LCA studies that start the assessment at the time of harvest, there is a significant upfront 'carbon debt' due to the removal of standing carbon in the forest. Such studies evaluate how long it takes for the carbon debt to be paid back by regrowth of trees, as well as other activities considered in the system boundary. Miner and Gaudreault (2013) suggest that the alternate approach is appropriate for LCA studies that focus on the "attributes of specific forest products." In this case, the temporal boundary for the analysis would extend back in time to include all processes associated with the growth of the tree, including carbon sequestration as a result of photosynthesis. Ter-Mikaelian et al. (2015) point out that this "dividend-then-debt" approach does not consider the fact that new trees typically replace trees that were previously harvested, in an ongoing cycle. As such, "moving the starting point of carbon accounting backwards in time to when carbon stocks in a given piece of land were low takes credit for the latest cycle of carbon accumulation but ignores the fact that over time, on average, forests contain substantial amounts of carbon." They argue that for this reason, the dividend-then-debt approach is not appropriate for areas that were naturally forestland.

The selection of analysis scale (spatial boundaries) is related to the analysis timeframe. On the one hand, LCA studies using stand-level accounting typically start the evaluation of carbon impacts at harvest. As described above, this results in an immediate carbon debt that is paid back over time as the forest grows. The other approach is to consider larger spatial areas for accounting, referred to as a landscape-scale analysis. Some researchers argue that this approach appropriately considers the forest as a system (Strauss 2011). In addition, the use of larger spatial boundaries for forest bioenergy are more representative of supply areas for biomass plants (Miner and Gaudreault 2013), or for areas that will be impacted by policy decisions. In a landscape-scale assessment, different plots within a forest or supply area will be at different points in the growth cycle at any given time, so although carbon is removed from one plot the other areas continue to sequester carbon as the trees grow. This essentially reduces the large fluctuations in forest carbon stock that seem apparent in the stand-level approach. Miner and Gaudrealt (2013) also argue that landscape-scale assessment better relates to how sustainable management practices are applied, as "the growth occurring on plots that will supply forest biomass in the future is a critical part of the planning required to ensure a sustainable wood supply." Miner and Gaudrealt further note that use of larger spatial scales makes it easier to account for "forces that are influential at larger scales, such as natural disturbances and market forces" in LCA studies.

In the "Manomet Study", Walker et al (2010) expressed concern regarding an assumption of carbon neutrality during a landscape-scale assessment. It is still important to consider the reference scenario in the LCA study, which may consider business as usual activities or even a no-use baseline for the forestland (depending on the study choices). When considered fully in an LCA study, "accounting at the landscape-scale integrates the effects of all changes in the forest management and harvesting regime that take place in response to bioenergy demand. Taken together, these changes may have a positive or negative influence on the development of forest carbon stocks as a whole" (Cowie, Berndes, and Smith 2013, p. 2).

The considerations for land use baseline is another big source of debate for forest biomass. One side argues that a "no-use" baseline is appropriate, in which forest management and harvest activities are completely stopped, and the land is allowed to return to its natural state. Many proponents of this approach argue this would maximize carbon sequestration in the forests, and is therefore appropriate to determine the best way to reduce overall GHG emissions to the atmosphere. Detractors of this approach raise concerns that such "natural relaxation" is not a realistic alternative in many cases. Forest harvest activities bring value to landowners, who are unlikely to stop harvesting without significant external driving factors (such as incentives or regulatory requirements). If a 'no-use'

approach was applied across a region then wood products would no longer be available for that region, in which case they may be replaced with alternative non-wood products, or would rely on wood products generated outside the system boundary and imported in to the region. Such leakage or substitution effects should be considered if a no-use approach is used. Further, if landowners are unable to obtain value from harvests, some may opt to sell their land, which could ultimately lead a reduction in forest land and carbon stocks if the land is used for development or other activities (Miner et al., 2014). The loss and fragmentation of forest land to urbanization has impacted millions of acres in the past few decades and changed the carbon dynamics of these areas.

Even beyond the selection of an appropriate baseline choice, different studies have shown different and conflicting results regarding which method would result in higher carbon sequestration – sustainable forest management, or leaving the forest to be a natural carbon sink ("no use"). Part of this disagreement is because forest types, growth rates, and management practices vary between regions. Ultimately, the different inputs and choices impact the analyses, and can lead to tremendously different results. Nevertheless, the majority of studies that take a long-term view and analyze bioenergy as a coproduct of a forest management system that produces timber products plus biomass for energy, show that after a couple of rotations the production forest has climate benefits in comparison with the no use scenario (e.g., de Ximenes et al., 2012). The following statement from Berndes, Bird, and Cowie (2011) provides a good summary of the key inputs that affect these results.

"The relative merits of forest biomass extraction for bioenergy versus C sinks management are dependent on:

- The efficiency with which bioenergy can displace fossil-based energy. This efficiency is high if (i) the biomass is produced and converted efficiently; (ii) the biomass production and conversion causes few GHG emissions; (iii) a carbon intensive fossil fuel is displaced; and (iv) the replaced fossil fuel would have been used with low efficiency.
- The time period of consideration: the longer the time frame of the analysis, the more attractive bioenergy is in comparison with C sequestration, because the latter is constrained by saturation (only a limited amount of C can be stored on a hectare of land), whereas bioenergy can be produced repeatedly, from harvest cycle to harvest cycle.
- The growth rate of the site: the higher the growth rate, the sooner the saturation constraints of C sequestration will be reached."

6   Recommendations

6.1   Recommendations to Meet Policy Objectives

This literature review provided a number of insights that could be helpful to meet NYSERDA's policy objectives. These are summarized below.

Recommendations for NYSERDA Regarding a Potential LCA for NYS Woody Bioenergy GHG Impacts:

- NYSERDA will first need to develop a clear goal for the LCA (and policy objectives), which can then be used to inform decisions on how to frame the biomass LCA, including definition of the system boundary and reference case. At a high level, NYSERDA's objective is to develop policies to support GHG emissions reductions. However, additional detail will be needed to fully define the scope for an LCA, and develop the inputs for a baseline and system boundary that includes analysis timescales, geographical boundaries, and policy mechanisms. While some of these decisions may seem obvious (restricting geographical boundaries to NY borders for example), as has been pointed out in this report, choices that may seem simple can have a profound impact on LCA results and meaning.
- The choice of LCA approach will likely be different for decision-making and policy implementation. cLCA is likely to be the appropriate approach for policy decisions, while aLCA may be more helpful for policy implementation. A well done aLCA for forest bioenergy systems in NY is needed before a cLCA can be conducted. Therefore, it may be very valuable to plan the analyses for pre/post implementation holistically to ensure that future metrics are consistent with the analysis supporting policy development.
- For cLCA baseline, it is typical to use an "anticipated future baseline," which projects two scenarios into the future—one with the considered policy and one BAU scenario without the policy. NYSERDA will need to determine what the BAU scenario looks like in terms of fuel and energy technologies used to provide the services, baseline forest management activities, and alternate fates for biomass feedstock materials. In addition, "because of the inherent uncertainties involved in policy studies, especially those involving alternative future baselines, it is important to perform sensitivity analyses around policy scenarios so that the robustness of the findings to various assumptions and uncertainties can be understood" (Miner and Gaudreault 2013, p. 28).

- The choice of baseline scenario has a large impact on LCA results. For example, a recent LCA study by Mika and Keeton (2015) indicated that higher levels of biomass removals in Northeast forests for bioenergy would result in increased net GHG emissions compared to the non-bioenergy harvests, based on a landscape level analysis with staggered harvests over a 160-year timeframe.[20] Overall, the results of the study showed that "[the] *choice of baseline yields profoundly contrasting conclusions about wood bioenergy emissions*. Relative to [the] starting landscape condition, all scenarios added carbon to terrestrial sinks and/or offset fossil fuel emissions… [However], if foregone C sequestration potential (or 'opportunity cost') is the benchmark, and if harvest intensities increase, then our results show wood bioenergy to result in net increased emissions" (Mika and Keeton 2015, p. 450. *emphasis added*). As with all studies, this paper had a specific set of assumptions that influenced these results. For example, biomass heat was used to replace natural gas systems and biomass electricity replaced a regional grid average.
- The Scope includes all relevant processes that will be different, or could result in significant GHG impacts between the policy scenario and BAU, including impacts from indirect effects associated with the changes. Some of the major processes that could be directly impacted and affect GHG emissions include: alternate fate of the fuel used (e.g., decomposition of biomass, fossil fuel used for an alternate product other than heat or power); transportation of the fuel (distance and mode), processing of the fuel, energy production and distribution, land use changes, and generation and disposal of wastes. Landowner response to change in market conditions is an example of an indirect effect that can be important for forest biomass.[21] As indicated in Section 2.2, a large portion of the State forest is privately owned, and much of this is not actively managed. This indicates a large potential to increase the available supply of sustainable biomass through added landowner engagement and forest management efforts. Improving forest management also has the potential to change growth rates and forest carbon dynamics that need to be accounted for.

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[20] Some additional information about the study: Biomass for bioenergy was only one of the products from harvesting, and the increased biomass included removals of poorly formed trees, small stem trees, tops and branches, and dead wood. The LCA included the following carbon pools: aboveground forest carbon and wood products, direct and indirect emissions from wood products and bioenergy, and avoided direct and indirect emissions from fossil fuels. The study considered use of the biomass to generate electricity or heat; the electricity would offset grid electricity with the Northeast regional fuel mix, while the heat would offset natural gas generated heat. It is worth noting that both of these reference fuels have relatively low GHG intensity.

[21] An anticipated increase in demand or value can prompt landowners to increase forest productivity or acreage (Lippke et al. 2011; Miner and Gaudreault 2013).

- When LCAs are to be used for policy development, several researchers indicated the importance of considering full impacts associated with a system, including indirect effects and market dynamics as applicable. For example, Lippke et al. (2011) noted that considering only a limited set of carbon pools can lead to "unintended consequences on other impacted carbon pools." This can be especially important for forest feedstocks. Miner et al. (2014) also supports taking a broad view of forest-based activities. "Of particular importance to understanding the emissions impacts of increased use of biomass from forests are fossil fuel substitution effects, markets for wood, causes for ongoing gains and losses in forest area and forest carbon [stocks], landowners' motivations, benefits and timing of investments in forestry, and the warming impact of near-term and long-term increases in CO_2 emissions."

- Boundary considerations:

  o Spatial – The appropriate spatial scale would typically be based on the scope of the policy; in this case the minimum area would likely be New York State. However, larger spatial boundaries could be considered to help reduce potential leakage impacts, although the trade-off is a more complex model and analysis. Larger boundaries could include adjacent counties, or even the entire region. In addition, data used for smaller regional or project-level studies may help to inform a larger state or regional analysis. As summarized by Miner and Gaudreault (2013) "small-scale analysis is likely to understate the benefits of using forest biomass, suggesting that, in general, policy studies should be performed at large spatial scales (Galik and Abt 2012)." Even if NYSERDA does use plot- or project-level evaluation, a larger landscape-level analysis should also be considered. "There is a risk that designing policies and incentive structures that use project level evaluations as a basis creates a situation where the most economical way of managing a forest is very different from how we can best shape forest management in response to future demand for bioenergy and other forest products while also considering longer-term political climate targets… which ultimately require far reaching energy system transformation" (Berndes, Bird, and Cowie 2011, p. 40).

  o Temporal – For NYSERDA's current objective, the policy horizon may extend for 20 years. This should be the minimum starting place for the LCA boundary. However, to properly account for changes in forest carbon the time frame should cover at least two rotations in order to see the effect of gradual introduction of new management across sequential stands. Longer timeframes of at least 100 years should also be considered. The analysis timeframe is particularly important considering the fact that for forest biomass, some resources could have short-term increases in GHG emissions when the temporal boundary is set at the point of harvest, although this is typically reversed in intermediate or long term. For policy-related LCAs, the period for the analysis should at least include the entire period relevant to the policy, although if this is relatively short, a longer time frame should also be considered in the evaluation (if consistent with the goal of the study). As stated by Berndes et al. (2013), "project level evaluations that use a relatively short time horizon and narrow spatial perspective need to be complemented with additional analyses that balance near-term targets and the long-term objective" for climate change mitigation.

- Impact Categories – In order to calculate the climate change impact, the LCA study should at a minimum consider all GHGs expected to be impacted at a significant level due to considered activities. This would likely at least include fluxes of CO_2, CH_4, and N_2O. Other impacts that might influence human health and ecosystem quality could be included in these studies, but are beyond the scope of this report.

- Allocation – cLCA studies typically use system expansion and substitution rather than allocation based on mass, energy or market values. In aLCA, use of mass or market value is typical for assigning impacts to biomass feedstocks that are a coproduct of multi-output product systems. For CHP conversion processes that generate energy outputs in multiple forms, allocation by energy content or value would likely be reasonable.

- Land use change – Policy measures should consider LUC impacts to the extent possible (including changes in land management). In practice, this will largely depend on available data that relates to the specific areas and changes being studied. Of note, many of the unadulterated woody biomass feedstocks eligible in the current New York State policy regime are unlikely to have significant LUC impacts. The primary exceptions are harvested wood (from commercial harvesting), and energy crops.[22] However, development of energy crops could have a beneficial LUC impact in terms of carbon sequestration, depending on the existing use of the land. Several examples of biomass that could be used for bioenergy with limited or no LUC impacts were presented in Section 4.11, including: biomass obtained from forest clearing for land development (if all burden of the activity is allocated to the primary land clearing purpose); biomass that would otherwise be landfilled (such as source separated wood from municipal solid waste or C&D debris); and harvest residues that would otherwise decompose on-site.

- General recommendations for LCA studies:

  o A clear statement of the goal and scope of any LCA is needed so that decisions about the study can be made to most effectively address the stated goals.
  o Policy-related LCAs used for governmental regulation and monitoring should strive to achieve consistency and robustness, with comparable results between products (e.g., equivalency).
  o Transparency is very important for LCA studies. Methodologies, assumptions, and limitations should be clearly stated. A description of what processes and activities are included should also be provided, as well as what indirect effects are included and how they were analyzed. Following protocols such as the ISO 14040 is a good step to address this concern, but the details of any study need to be easy to locate and understand.

Additional Considerations and Recommendations Related to Policy Implementation:

- Although LCA results will vary depending on specific analysis choices and framing, nevertheless, there are some general statements that can be made regarding what types of bioenergy are most likely to have a positive GHG emissions impact. NYSERDA should certainly consider these resources and technologies in their study; and may also consider targeted incentives or support for those with the most beneficial impacts.

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22 There would also be LUC impacts associated with site conversion, but this is not generally attributed to the waste wood collected from site conversion unless the value of the recovered wood was a contributing factor for the change.

o Feedstocks that are likely to have the fastest GHG emissions benefits include biomass by-products, recovered waste materials, and harvest residues (unless they are needed for soil fertility) (Haberl et al., 2012). Agostini et al. (2014) indicate that harvest residues, thinning wood, and salvage logging wood all have potential near- to medium-term GHG benefits, depending on the specific pathways used and the alternate use of the biomass material. Berndes et al. (2011) point out that "generally, bioenergy will be most effective for GHG mitigation when it is adopted in association with other products, i.e., by [utilizing] biomass wastes of primary product chains, or biomass that has already served one or more functions." A significant portion of the potential additional woody biomass resources in New York State could come from these types of materials. As summarized in Section 2.2.3, the Renewable Fuels Roadmap effort identified a total of 4.3–8.1 million ODT per year of potentially available forest biomass, of which up to 0.9 million ODT/yr would result from harvest residues.[23] This value is dependent on future forest management and harvest activities in the state. In addition, another 0.7 million ODT per year of clean C&D wood could also be used for bioenergy. A further 0.9 million ODT/yr of adulterated C&D wood could also potentially be recovered and used in gasification technologies.

o Using biomass energy systems with the highest conversion efficiency to offset the most GHG-intensive energy sources will generally provide the largest near-term benefit, and higher overall GHG emissions benefits, all else being equal.
As an example, the Northern Forest Center recently released results of a study indicating that compared to heating with heating oil, use of regionally-produced wood pellets for heating in the Northeast with state-of-the art wood pellet boilers had immediate GHG benefits (Northern Forest Center 2016). There were also benefits relative to propane and natural gas systems. It is important to note only a summary of the results and the analysis methodology is currently publicly available, although a more detailed report is in progress.[24] The results are also very sensitive to the biomass feedstocks used for the pellets, as illustrated in a presentation from November 2016 (Buchholz and Gunn 2016).

- GHG emissions benefits can also be enhanced by connecting policy to support of sustainable harvest and forest management activities that increase forest carbon stocks. This could help to increase carbon sequestration even with increased removals in some cases. As stated by Miner et al. (2014): "Policies that provide incentives for landowners to expand forest area, make forests more productive, and store more carbon could have important carbon benefits. On the other hand, policies that increase transaction costs to landowners or devalue forest biomass could have negative carbon consequences, by reducing incentives for investments in working forests, reducing biomass supplies, limiting afforestation activities, and leading to increased conversion of forests to other land uses." There is certainly potential for forest management to

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[23] In the analysis, the potentially available harvest residues dropped to 0.5 million ODT/yr when landowner interest in forest management was considered.

[24] This study included GHG emissions from sourcing, processing, and transporting fuels. Based on the available data, this appears to be an aLCA type of analysis, with no consideration of indirect effects. The methodology document includes description of forest activities and pellet mill operations, but other processes are not described in detail (Buchholz and Gunn 2016). In addition, there is no description of how (or if) allocation was applied to the pellet feedstock materials. The fossil fuel boiler technology used for comparison is also not described.

improve value and increase the sustainable flow of timber products from forests in the State. As an example that was noted in Section 2.2, approximately half of the forest land in the state is owned by family forest owners with parcels greater than 10 acres, but only 9% of these have forest management plans in place (U.S. Department of Agriculture Forest Service 2015). This is an indication that there is a significant potential for improved forest management. Landowner preferences are an important barrier to improved forest management, although reduced upfront costs for management activities, or increased value for doing so, could make an impact.

- In order to determine which bioenergy scenarios are most likely to have beneficial climate impacts for New York State, it will be useful to consider overall trends in the analysis results and not to get hung up on relatively minor differences. LCA studies can have significant uncertainty due to the complexity of the models and the underlying ecological processes and macroeconomic effects, which can make it difficult to make very specific statements with a high level of certainty.

6.2   Priorities and Areas Requiring Additional Support

Based on the literature review, there are a few areas where additional research would be beneficial.

- Additional research and data foundational to conducting accurate LCAs for naturally regenerated hardwood dominated forests is needed for NY and the Northeast region (much of the existing data is based on models, or field data from conifer plantation forests). There also tends to be a lack of well-tested models that include responses to management activities. These models could be improved with additional data and expert knowledge.
- Creation of standardized baseline data and forecasting methods specific to NYS bioenergy system evaluation for reference scenarios. A substantial start has already been developed through various studies surrounding NYS energy and renewable energy programs, but work specific to this requirement is needed.
- Including other climate impacts in LCA methods would be beneficial to provide a more complete picture for studies intended to evaluate climate change mitigation potential. As stated by Brandão et al. (2014), "LCA methods need to be updated to include the latest scientific understanding (e.g., on impacts of short-lived climate forcers, albedo, and effect of timing of greenhouse gas emissions and removals). These elements should be addressed in standards and product category rules and reflected in all forms of LCA studies." Further research may be needed to obtain necessary data for the short-lived climate forcers or albedo. Industry participation would be beneficial for development of the rules and standards.
- Development of a resource assessment, forest products market model, and policy statement focused on mobilizing biomass fuels with greatest potential to reduced GHG emissions in accordance with NYS policy objectives. For example, NY RPS included allowance for C&D (potentially very favorable from GHG perspective), but the program had restrictions that may not result in maximum utilization of this resource.

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