Arnold Schwarzenegger
Governor

BIOMASS TO ENERGY:

FOREST MANAGEMENT FOR WILDFIRE REDUCTION, ENERGY PRODUCTION, AND OTHER BENEFITS

APPENDIX 4

PIER FINAL PROJECT REPORT

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Appendix 4

Life Cycle Assessment of Producing Electricity from California Forest Wildfire Fuels Treatments

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Notice of Change in Scenario Naming Conventions

Key assumptions, modeling structures and terminology were altered and refined to accommodate new thinking during the course of this study. The reader will observe in the appendices that the scenarios are referred to as "Scenarios 1, 2 and 3" or "S1, S2 and S3."

In both the main text of the Final Report and in the Life Cycle Assessment appendix (Appendix 4), the former Scenario 1 (S1) was renamed to the "Reference Case." Scenario 3 (S3) has been renamed the "Test Scenario." Scenario 2 (S2), focused on the relative contributions and impact of Industrial Private Forestry (IPF) has been eliminated from most of the analyses that make up the entire study. These changes better reflect the focus of the study, which is fundamentally about the landscape level changes in wildfire, habitat, and other dynamics. The modification of terminology do not substantively affect the findings or recommendations of the study.

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Executive Summary

Under a contract with California Energy Commission's Public Interest Energy Research Program, the US Department of Agriculture Forest Service's Pacific Southwest Research Station worked with the University of California at Davis; the University of Washington; several State and Federal agencies; and energy, forestry, and environmental consultants to identify and analyze social, economic, and environmental costs and benefits of using biomass removed during forest wildfire treatment to generate electrical power for specific sites throughout California. To this end, the Biomass-to-Electricity project (referred to as the "B2E" project) connected a set of very complex and detailed forest management and response, transport, and industrial process models.

This document describes the environmental Life Cycle Assessment (LCA). The LCA quantified life cycle energy use, emissions of carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4) nitrous oxide (N_2O), nitrogen oxides (NOx), non-methane volatile organic compounds (NMVOCs), particulate matter less than 10 microns in diameter (PM10), and sulfur oxides (SOx)), and the associated contribution to climate change from emissions of CO_2, N_2O, and CH_4. The life cycle was assumed to include the wildfires, acquisition and processing of residual biomass (harvest, chipping operations, and underburning) for a 2.7 million-acre landscape encompassing both private and public lands (portions of the Plumas, Lassen, and Tahoe National Forests and Lassen National Park) followed by the transport of chips to the Mt. Lassen biomass power plant, and the conversion of the chips into electricity. Results are compared for a REFERENCE CASE, in which no forest management treatments were modeled, and a Test Scenario, in which forest management treatments were assumed to be carried out during a 40-year period at 10-year cycles.

The TEST SCENARIO was to be executed based on combinations of 13 prescriptions which represented on various applications of clear cutting, pre-commercial thinning, commercial thinning, salvage, select harvest, and restrictive thinning for 3 slope ranges throughout the landscape. Forest treatment included off-road equipment use (biomass harvest such as the use of feller bunchers, skidders, and chippers), on-road equipment use (harvest equipment mobilization, the use of a water truck for forest road dust control, and crew transport), and underburning during treatment operations. It was assumed both sawlogs and chips would be removed from the forest, with chips transported an average distance of 30 miles from the treatment site (followed by a return to the forest) and used to generate electricity using the Mt. Lassen biomass power plant as a representation of current generation technology.

For the LCA, life cycle energy use and emissions estimation primarily relied on data from other B2E project models, the USEPA's NONROAD and MOBILE models, and the USDOE Argonne National Lab's Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model. In this report, impacts are presented as life cycle energy consumption (total, fossil, and petroleum consumption), life cycle air emissions both within and outside the vicinity of the study landscape, and the contribution to climate change, normalized using estimates of current California use and impacts. Climate change impacts are also presented within the context of the Intergovernmental Panel on Climate Change (IPCC) model for forest carbon flows.

The LCA proceeded through four phases defined by the International Standards Organization's 14040 series on LCA. The first phase, *goal and scope definition*, described the reasons for carrying out the study, the intended audience, and the methods used. Next, the *inventory assessment* quantified life cycle energy use (total, fossil, and petroleum) and 8 air emissions for the REFERENCE CASE and TEST SCENARIO. Third, the *impact assessment* estimated contribution to global climate change (from CO_2, N_2O, and CH_4). Finally, the *interpretation* step formulated the LCA inventory and impact results to facilitate system comparisons.

The goal of the LCA was to interconnect computational models for forest management and response, transportation, and industrial processes to represent the environmental impacts and benefits of using biomass removed during forest wildfire treatment to generate electrical power for specific sites throughout California. The *intended audience* of the LCA was the Energy Commission as well as private, academic, and government organizations such as the US Forest Service interested in setting priorities for forest and bioenergy research, development, and technology dissemination based on LCA. The function of the assessed systems is the management of multiple natural resources on the 2.7 million acres of forest land over a 40 year period while producing sawlogs and electricity from chipped forest biomass.

The impacts to be considered in the LCA were based on select among the categories of decisions defined by the B2E project's Technical Advisory Committee (TAC) in April 2005. The TAC suggested a focus on infrastructure and human use impacts, public safety and human welfare impacts, and air resources impacts, and suggested impact categories within each focus area. Given the overall project goal to test model interconnection, the LCA offered only a portion of the full assessment suggested by the TAC. Specifically, the impacts on infrastructure and human use have been limited to the estimation of life cycle energy consumption, only emissions of NMVOCs as a smog precursor have been considered in the health impacts category, and only emissions of CO_2, N_2O, & CH_4 have been included in the assessment of greenhouse gases. These limitations were deliberate, resulting from constraints in resources. Because further model development would address or add additional information to the full set of decision categories, although some being highly complex and to-date including data and model limitations, their omissions here do not constitute a major deficiency of the LCA.

Herein, the LCA results are presented first in **gross** in which life cycle energy use and emissions are estimated as they would be performed and producing different amounts of sawlogs and biomass electricity. Next, the gross assessment results are interpreted through the preparation of **net** assessments for the comparison of forest management and electricity generation systems, the consideration of landscape carbon flows, and the possibility for utilizing alternative biomass to electricity power plant technologies.

In the **gross assessment** inventory analysis, the TEST SCENARIO is found to provide total energy and climate change benefits, given the consumption of fossil and petroleum energy during harvest and in small part by supporting power plant operations. For emissions, the gross assessment shows that in all cases, emissions within the vicinity of the B2E landscape dominate those outside the vicinity of the landscape. For emissions overall, although little difference was seen between emissions of NMVOCs, CO, PM10, SOx, and CH_4 between the scenarios due to the domination of wildfires, differences in NOx, N_2O, and CO_2 emissions for the TEST SCENARIO are attributed to power plant operations.

The gross assessment described in presents LCA results for systems producing different products. Thus, and according to the ISO LCA standards, the REFERENCE CASE and the TEST SCENARIO in the gross assessment are not technically comparable to each other or to alternative electricity generation systems for three reasons: (1) each result in a 2.7 million-acre landscape of differing management outcomes, as measured by extent and severity of wildfire, (2) each produces different amounts of sawlogs, and (3) each produces different amounts of electricity. In LCA terminology, the systems in the gross assessment are called multifunctional (they produce more than one valuable product). A 2.7 million-acre managed landscape and electricity are the main products of the respective life cycle systems, depending upon the perspective of those interpreting the results. For example, those interested in electricity generation such as the Energy Commission might be interested in comparing the TEST SCENARIO to other electricity generation methods such that the each system being compared only produces electricity. Similarly, those interested in forest management such as the Forest Service might be interested in comparing the REFERENCE CASE and the TEST SCENARIO to other forest management options.

Net assessments are thus presented in an attempt to facilitate comparisons. First, a forest management LCA is prepared by removing energy use and emissions for sawlog production and subtracting from the results the life cycle energy use and emissions for conventional electricity generation in an amount equal to the biomass electricity generated. Similarly, an electricity generation LCA is prepared, again by removing energy use and emissions for sawlog production and this time subtracting from the results the wildfire emissions from the REFERENCE CASE and adding credit for improvements in forest growth.

Due to these computational remedies for LCA system multi-functionality, **the net assessment provides different results than the gross assessment**. Specifically, whereas the net results still favor the TEST SCENARIO for total energy consumption (but to a greater extent), the net results show treatment to be an improvement over no-treatment for fossil and petroleum energy consumption, a result that is contrary to that seen in the gross assessment. Also contrary to the gross assessment, a reduction in SOx emissions is dominated by the credit given for avoided electricity generation and NOx emissions are found to be about the same for the REFERENCE CASE and TEST SCENARIO. Finally, although the net results show a contribution to climate change that is less for the TEST SCENARIO than for the REFERENCE CASE, the benefit is estimated to be slight and less than that estimated in the gross assessment because of the removal of the credit for the carbon embodied in the sawlogs.

The net assessment interpretation phase also evaluated landscape-level changes in carbon flows and alternative power plant technologies. For the assessment of carbon flows, the adding consideration of IPCC data on carbon flows for temperate forests revealed that both the REFERENCE CASE and the TEST SCENARIO provide a net carbon benefit. However, although the carbon balance presented can be considered life cycle-based approximation of long term carbon storage, it is lacking consideration of the carbon fluxes for disturbances. The assessment of alternative power plant technologies was included because the life cycle energy and contribution to climate change were found to be dominated by the biomass electricity generated and ultimately reflecting the power plant efficiency. Given this, LCAs of a current generation integrated gasification/ combustion power plant and a next generation thermo-chemical conversion power plant were performed. The results reveal improvements on total energy and all emissions.

Essentially, moving from the gross to net assessments defined the contribution of sawlogs vs. chips and introduced considerations of conventional electricity generation into comparisons. Since both are relevant to decision making related to B2E systems, both are relevant to the LCA. Given this, important among the results are how they might be used to inform continuing research in forest biomass to energy systems. The following observations result from the experience of connecting models in support of LCA and are intended to provide a starting place for continuing and related research:

1. **Net assessment orders-of-magnitude observations provide insights for decision making and a starting place for future assessments.** For example, how the TEST SCENARIO compared to the REFERENCE CASE or to conventional electricity generation systems can be understood through the evaluation of order of magnitude observations. Based on order-of-magnitude observations, the conclusions of the net assessments are:
    - The TEST SCENARIO provides a net benefit for total energy consumption and reduces fossil and petroleum consumption and the when compared to the REFERENCE CASE. Also, whereas the B2E power plant efficiency is critical to the overall energy balance, the consumption of fossil and petroleum fuels during harvest, chip transport, or power plant operation play a less important role.
    - The TEST SCENARIO results show an improvement for NMVOCs, CO, and SOx when compared to the REFERENCE CASE. Alternatively, little difference is seen in NOx and PM10 emissions.

- The climate change benefits (based on life cycle CO_2, CH_4, and N_2O emissions) of the TEST SCENARIO exist, but are slight when compared to the REFERENCE CASE and alternative generation methods. Alternative biomass energy generation methods and other uses for the biomass removed should be investigated.

2. **Data and models are available to represent the life cycle of a range of technologies for developing U.S. forest bioproduct systems.** Herein, reliance on the discipline-specific B2E project models combined with the U.S. EPA NONROAD and MOBILE models and the U.S. DOE's GREET model provided a wealth of data for systems assessments. Similar data availability is expected for technology alternatives. However, shortcomings herein included the limited scope (e.g., the small number of impacts assessed, the omission of infrastructure construction models, and the limited number of possible treatment scenarios investigated), lack of uncertainty data for all assessments, and the need to project estimates for all models into the future. These shortcomings do not appear to be insurmountable in the short term, and are recommended for future research. In addition to addressing scope and modeling shortcomings, there are a number of remaining forest bioproduct questions that can be explored with currently available data. For example, investigations of power plant and transfer station citing and optimization of regional utilization of forest residuals, agricultural residuals, and bio-based municipal solid waste could be built around the data presented here.

3. **Although data and models are available to assess additional impact categories such as those suggested by the TAC, lack of consensus on or lack of documentation for LCA impact characterization methods impedes their use.** Although many impact characterization methods/ equivalency factor data sets are in use in LCA, none can currently be considered the method of choice by LCA practitioners. Within this context, during the course of the B2E project, quantification of the contribution to acidification and smog formation based on equivalency factors in the U.S. Environmental Protection Agency's Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) was considered. Like the IPCC global warming potentials, TRACI equivalency factors provide a link between an emission and an impact and are measured relative to one of the emissions contributing to the impact. Herein, emissions of NOx and SOx could have been used to provide a rough estimate of the contribution to acidification and emissions of NMVOCs, CO, NOx, and CH_4 could have been used to provide a rough estimate of the contribution to photochemical smog formation based on TRACI equivalency factors. An example set of rough estimates is provided in the discussion, but are not included in the main LCA results because TRACI remains to date publicly undocumented.

4. **There are, and will most likely remain, issues with the preparation of models of truly equivalent comparative systems.** In preparation of the net assessments and specifically related to identifying the system products/ functional unit, the identification of truly equivalent comparative systems was deemed either unrepresentative or beyond the scope of the research at hand. First, developing a treatment scenario to result in equivalent end landscape quality based on Fire Regime Condition Classes was deemed unrepresentative of the decision making processes in the study region. Instead, a landscape characterized by a range of wildfire behavior conditions was assumed more likely to represent scenarios to be considered on the case study landscape. Second, even though the chips were assumed to be removed from the case study landscape during only the summer months, the life cycle of other feedstocks needed to ensure continuous power plant operation were not included in the assessment. Inclusion of data and

models representing the life cycles of other biomass energy feedstocks was deemed beyond the B2E project scope, which emphasized an understanding of in-forest feedstocks.

Finally, based on the project experience, **the conclusions of this work are:**

- Despite great complexity, it is possible to construct a set of interconnected forest operations and equipment characterization, fire behavior assessment, and the power plant analysis models in support of LCA. The flow of information between models presented here can provide a roadmap for future research.
- Data and models are available to represent the life cycle of a range of technologies for developing U.S. forest bioproduct systems, and there is great potential to extend the overall B2E project and the LCA approach to a wide variety of treatment and bioproduct scenarios.
- Presentation of results in gross and followed by a variety of computational interpretations provide insights for decision making and a starting place for future assessments.
- The LCA presented here should ultimately be extended to include consideration of the emissions beyond the 8 considered.

A detailed review of this document occurred on August 13, 2008. The review panel convened in Davis, California, with participants joining in-person, by video, or by phone. The committee members were Robert Anex (Iowa State University); Richard Bain (US Department of Energy National Renewable Energy Laboratory); Margret Mann (US Department of Energy National Renewable Energy Laboratory); Marla Mueller (California Energy Commission); Mark Nechodom (US Forest Service); Laurie Perrot (US Forest Service); Dennis Schuetzle (REI); and Linda Spiegel (California Energy Commission). Review committee changes and comments have been incorporated into this document.

1. Introduction

During the past several decades in the U.S., a generally warmer climate, combined with public-policy and land-management practices designed to protect forests (e.g., fire suppression and policies restricting thinning or excessive harvesting), has led to increasingly dense vegetation. These conditions have resulted in increased incidence and intensity of wildfires beyond what is considered healthy for fire-adapted wildlands. At the same time, actions aimed at bringing landscapes back to healthy burn patterns can have a significant impacts, including for example the costs and potential economic benefits of forest treatment (e.g., the sale of sawlogs and chips), the costs of infrastructure replacement following wildfires, environmental impacts (e.g., contributions to climate change) related to the use and emission of fossil fuels by harvest equipment, and wildlife impacts resulting from changes in habitats.

Under a contract with California Energy Commission's (Energy Commission's) Public Interest Energy Research Program, the USDA Forest Service's Pacific Southwest Research Station worked with the University of California at Davis; energy, forestry, and environmental consultants; the University of Washington; and several State and Federal agencies to construct a set of interconnected forest management and response and industrial process models. The Biomass-to-Electricity (referred to as the "B2E") models sought to identify and analyze social, economic, and environmental costs and benefits of using biomass removed during forest wildfire treatment to generate electrical power for specific sites throughout California. Specifically and as depicted in Figure 1, select economic, environmental, and landscape habitat impacts were assessed through the combination of five B2E project sub-models: (1) a landscape characterization and scenario design model, (2) a characterization of forest operations and equipment configurations, (3) a vegetation dynamics assessment, (4) an assessment of fire behavior, and (5) a power plant analysis. These five sub-models fed into three B2E project main models: a characterization of landscape and habitat response, an analysis of treatment costs and benefits, and an environmental Life Cycle Assessment (LCA). As part of the overall project, the LCA described here estimated the life cycle impacts of harvest, chip transport, and power generation given changes in wildfire emissions and changes in aboveground forest carbon sequestration. Here, the life cycle starts at resource acquisition (i.e., at the well for mobile fuels and grid electricity generation and in the forest for biomass electricity generation) through fuel combustion. The LCA included four phases based on the protocol standardized by the ISO [1-2[1]] and based on the computational structure described in Heijungs and Suh [3]. The first phase, *goal and scope definition*, described the reasons for carrying out the study, the intended audience, geographic and temporal considerations, system functions and boundaries, impact assessment and interpretation methods[2]. Next, the *inventory assessment* quantified life cycle energy use (total, fossil, and petroleum) and 8 air emissions (carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4) nitrous oxide (N_2O), nitrogen oxides (NOx), non-methane volatile organic compounds (NMVOCs), particulate matter less than 10 microns in diameter (PM10), and sulfur oxides (SOx)) for the acquisition and processing of residual biomass (harvest and chipping operations within the forest including underburning), transport of chips to a biomass power plant, the conversion of the chips into electricity, wildfire emissions, and aboveground forest carbon sequestration. Third, the *impact assessment* estimated air emissions contributing to global climate change (from CO_2, N_2O, and CH_4).

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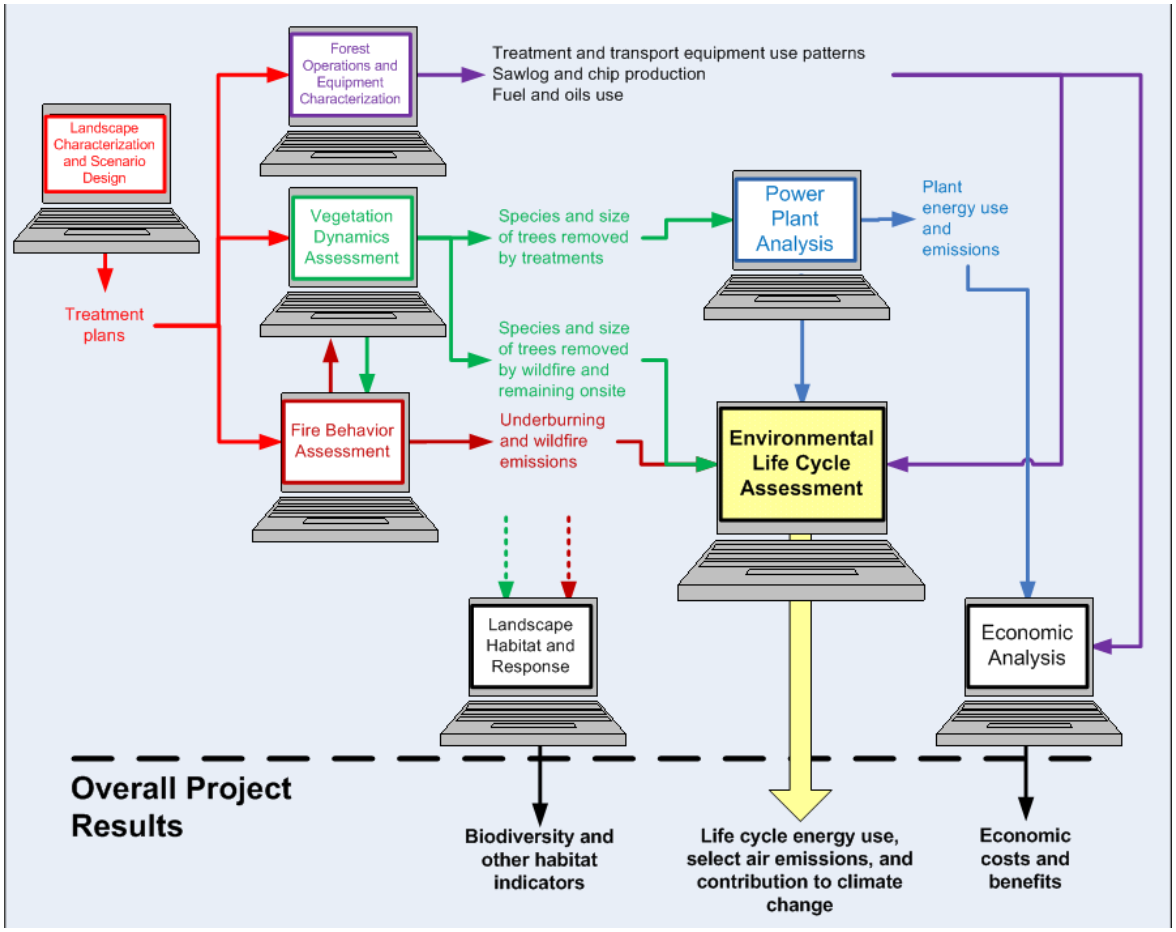
[1] ISO 14040:2006 and ISO 14044:2006 replace the previous standards (ISO 14040:1997, ISO 14041:1999, ISO 14042:2000 and ISO 14043:2000). The new editions have been updated since the development of the goal and scope [3] to improve the readability, while leaving the requirements and technical content unaffected, except for errors and inconsistencies (from http://elsmar.com/Forums/showthread.php?t=17459)

[2] An extensive literature review of forest product LCAs formed the basis for the development of the project's goal and scope definition document [4].

Finally, the *interpretation* step formulated the results in different ways, including comparison of forest management and electricity generation life cycles and an evaluation of alternative biomass electricity generation technologies.

Figure 1. B2E Information and Modeling Process Flow Diagram



Described as follows, model interconnection was tested through the development of a LCA based on situations progressing from no-treatment (resulting in fire-prone stands) to treatment on private and public forests to modify the wildfire behavior of a 2.7 million-acre landscape in northern California. The LCA results are first presented **in gross,** representing life cycle energy and environmental impacts for no treatment and as the treatments would be performed, and next **in net,** representing comparative systems in which differences in sawlog production, electricity generation, wildfires, and forest growth are accounted for.

A detailed review of this document occurred on August 13, 2008. The review panel convened in Davis, California, with participants joining in-person, by video, or by phone. The committee members were Robert Anex (Iowa State University); Richard Bain (US Department of Energy National Renewable Energy Laboratory); Margret Mann (US Department of Energy National Renewable Energy Laboratory); Marla Mueller (California Energy Commission); Mark Nechodom (US Forest Service); Laurie Perrot (US Forest Service); Dennis Schuetzle (REI); and Linda Spiegel (California Energy Commission). Review committee changes and comments have been incorporated into this document.

2. Goal and Scope

The goal of the LCA was to interconnect computational models representing forest management and response, transportation, and industrial processes to represent the environmental impacts and benefits of using biomass removed during forest wildfire treatment to generate electrical power for specific sites throughout California [4]. Towards this goal, select life cycle energy use, emissions, and impacts were estimated for the treatment of an example California landscape, the removal of sawlogs and chips, and the use of chipped biomass removed to generate electricity. Estimates were based on data from four of the five B2E project sub-models: the forest operations and equipment characterization, the vegetative dynamics assessment, the fire behavior assessment (for underburning and wildfire emissions), and the power plant analysis (see Figure 1). The *intended audience* of the LCA was the Energy Commission as well as private, academic, and government organizations such as the US Forest Service interested in setting priorities for forest and bioenergy research, development, and technology dissemination based on LCA.

The scope of the LCA was based on select among the categories of decisions defined by the B2E project's Technical Advisory Committee (TAC) in April 2005[3]. The decision categories suggested by the TAC and the associated impact categories investigated here are presented in Table 1. Given the overall project intent to test model interconnection, Table 1 reveals that the LCA offered only a portion of the full assessment suggested by the TAC. Specifically, the TAC decision categories not addressed in the LCA are impacts on infrastructure, impacts of forest management, impacts related to non-energy forest products, impacts due to emissions of toxic air pollutants, ozone formation, and acid deposition. Further, the impact categories included here and the methods used to estimate impact are also limited. For example, the impacts of energy from forest biomass systems has been limited to the estimation of life cycle energy consumption, only emissions of NMVOCs as a smog precursor have been considered in the health impacts category, and only emissions of CO2, N_2O, & CH_4 have been included in the assessment of greenhouse gases. These limitations were deliberate, resulting from constraints in resources. Because further model development would address or add additional information to the full set of decision categories, although some being highly complex and to-date including data and model limitations, their omissions here do not constitute a major deficiency of the LCA.

Given the decision and impact categories to be included here, the LCA evaluated treatment of a 2.7 million-acre landscape encompassing both public lands (portions of the Plumas, Lassen, and Tahoe National Forests and Lassen National Park) and private lands surrounding the Mt. Lassen power plant in Westwood, California. Land ownerships within the landscape were grouped into five categories by land management capabilities: public multiple use (50% of land area), public conservation and recreation (15%), industrial private forests (17%), non-industrial private forests (NIPF) (14%), and urban core (4%). Forest treatment was focused on removing small trees, branches, brush, and litter, with different prescriptions for public multiple use (PMU) and industrial private forest (IPF) lands. A no-treatment scenario was accompanied by a treatment scenario as described in Table 2. Treatments were assumed to occur during 120 days each year (during the summer months) on both private and public lands. Biomass removed from the landscape in each scenario not destined for use as sawlogs was assumed to be chipped in the forest and used in the generation of electricity.

Table 1. Decision and impact categories

TAC Decision Category	TAC Impact Categories	Impact categories included here	Impact category description

[3] "Decision Categories" were from the B2E Model: Impact Categories Document (Draft # 1, April 29, 2005)

Infrastructure and Human Use Impacts	Impacts on infrastructure (homes, businesses, facilities, roads, etc.)		
	Impacts of forest management		
	Impacts of energy from forest biomass systems	Total energy consumption*	Sum of the total energy consumption for the life cycle (as mmBTU**)
		Fossil energy consumption*	Sum of the fossil energy consumption for the life cycle (as mmBTU)
		Petroleum energy consumption*	Sum of the petroleum energy consumption for the life cycle (as mmBTU)
	Impacts related to non-energy forest products (e.g., mulch, compost)		
Public Safety and Human Welfare Impacts	Health impacts (public)	Emissions of NMVOCs (as a smog precursor)	Sum of the life cycle NMVOC emissions (as tons emitted)
Air Resources Impacts	Impacts due to emissions of criteria air pollutants[4]	Emissions of PM10, CO, NOx, and SOx	Sum of the life cycle pollutant emissions (as tons emitted, by type)
	Impacts due to emissions of toxic air pollutants		
	Ozone formation		
	Particulate emissions	Emissions of PM10	Sum of the life cycle PM10 emissions (as tons emitted)
	Acid deposition		
	Greenhouse gases	Contribution to climate change***	Total carbon dioxide equivalents from life cycle air emissions of CO_2, N_2O, & CH_4 (as tons CO_2 equiv)

* The contribution of the inventory flows was measured by the amount of the inventory flows
** mmBTU refers to 1 million BTU
*** The contribution of the inventory flows was measured using IPCC 100-year global warming potentials

Table 2. Landscape scenarios

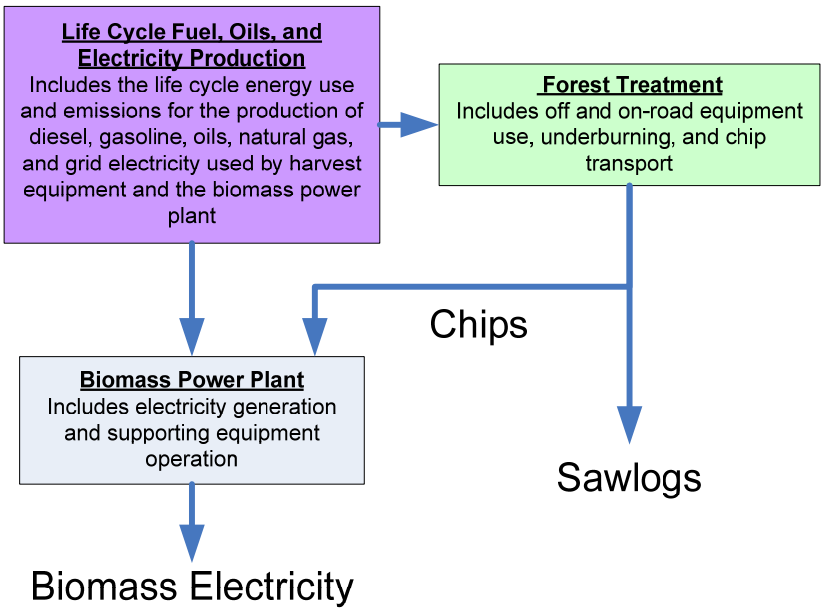
REFERENCE CASE- No Treatment	No treatment is performed on public or private lands.
TEST SCENARIO- Treatment of Industrial Private and Public Multiple Use Forests (IPF + PMU)	Treatments on Industrial Private Forests (IPFs) included pre-commercial thinning, underburning, commercial thinning, clearcutting, and selective harvest. The treatments were assumed to be carried out during a 40-year period at 10-year cycles with an average of 17 BDT/acre of biomass removed. Treatments on public multiple use (PMU) lands included thinning to create defensible fuels profile zones and strategically placed area treatments. An average of 20 BDT/acre of forest biomass was assumed to be removed after saw timber was harvested.

The LCA results are presented here first as a **gross LCA** (see Section 3) representing wildfire emissions for the REFERENCE CASE and treatment as they would be performed for the TEST SCENARIO**.** The TEST SCENARIO was based on a current generation biomass combustion power plant with the main LCA process flows presented in Figure 2**.** In short, in the gross assessment the REFERENCE CASE and the TEST SCENARIO were assumed to produce a variation on three things:

1. a 2.7 million-acre managed landscape with varying extent and intensity of wildfire;
2. whereas the TEST SCENARIO produces sawlogs, the REFERENCE CASE does not; and
3. whereas the TEST SCENARIO produces chips used to generate electricity, the REFERENCE CASE does not.

[4] The EPA criteria pollutants are ozone (O_3), particulate matter (PM), carbon monoxide (CO), nitrogen oxides (NOx), sulfur dioxide (SO_2), and lead (Pb).

Figure 2. Main process flows for the TEST SCENARIO LCA



Thus, the function of the gross LCA system described in Section 3 is to manage the 2.7 million acres of forest land over a 40 year period while producing sawlogs and electricity from chipped forest biomass. Section 4 next interprets the gross LCA results: first by preparing net results that give credit for sawlog production, electricity generation, reductions in wildfires, and changes in forest growth and next by considering variations in the technology used to generate electricity from biomass. Note that omissions from all assessments included the construction, maintenance, and decommissioning of facilities and capital equipment (i.e., harvest equipment, distribution/ transport equipment, power plant buildings and equipment) and the life cycle of other feedstocks needed to ensure continuous power plant operation.

As described in Table 1, in all assessments environmental impact was measured in 2 ways:

- **By the amount of inventory flows** (e.g., the amount of energy or the mass of emissions)
- **Using impact equivalency factors** (scoring factors based on fate, transport, and effects models) from the Intergovernmental Panel on Climate Change values (see [5,6]). Specifically, one hundred year Global Warming Potentials (GWPs) of 1, 25, and 298 tons CO_2 equivalents/ ton-emitted were assumed for CO_2, methane, and nitrous oxide respectively as defined by the IPCC [6] in the characterization of the contribution to climate change.

Finally, energy consumption, emissions, and the contribution to climate change were **normalized** by estimated commensurate California estimates for the 40-year period, presented in Table 3. Energy use projections represented the 40-year sum of annual values forecasted based on linear regressions of 1996-2006 data from the U.S. Department of Energy' Annual Energy Review [7] and multiplied by the ratio of the population of California to that of the U.S. from the U.S. Census Bureau [8]. Next, and again multiplied by the same population ratio, California emissions were estimated from the 40-year sum of 2005 emission estimates from the U.S. Environmental Protection Agency [9] [5]. Finally, contribution to climate change was

[5] Although the 40-year data could be forecasted from the U.S. Environmental Protection Agency data (see [7 and 8]) this method results in negative U.S. emission values as early as 2023. Thus, using the 2005 per capita value was chosen for emissions normalization. Note also that the non-GHG U.S. emissions data does not include fire and dust.

estimated as a 40-year sum of the 2004 level for California [10]. When combined, the normalization factors are intended to allow the life cycle environmental impacts to be placed within the context of their contribution to the overall California condition.

Table 3. Normalization factors (estimated 40-year California values)

Total energy consumption	260,000	tera BTU
Fossil fuel consumption	190,000	tera BTU
Petroleum consumption	190,000	tera BTU
NMVOC emissions to air	72	million tons
CO emissions to air	400	million tons
NOx emissions to air	85	million tons
PM10 emissions to air	8.9	million tons
SOx emissions to air (as SO2)	67	million tons
Climate change	21,000	million tons CO2 equivalents

3. Gross Assessment

1. 3.1 Forest Treatment and Chip Transport Models and Data

Forest treatment and chip transport included off-road equipment use (biomass harvest such as the use of feller bunchers, skidders, and chippers), on-road equipment use (harvest equipment mobilization, the use of a water truck for forest road dust control, crew transport, and chip transport at an average distance of 30 miles from the treatment site), and underburning during treatment operations. The TEST SCENARIO uses treatments selected from a menu of prescriptions as provided by the "Forest Operations and Equipment Characterization" [11]) listed in Table 4.

Forest treatment and chip transport produces treated landscape, transported chips, and sawlogs. For each prescription, biomass managed (as sawlogs and chips) were determined for the specific spatial characteristics of the landscape on the basis of the "Forest Operations and Equipment Characterization" [11], a model depicted in Figure 1. Acres treated and chips and sawlog production for each decade are provided in Table 5 and depicted in Figure 3.

Equipment specifications for the TEST SCENARIO are provided in Table 6 with Table 7 providing the link between equipment configurations and prescriptions (also from the "Forest Operations and Equipment Characterization" [11]). Specifically, whereas Table 6 provides data on equipment power, life, and fuel and oil use, Table 7 lists the productive machine hours per dry tons of biomass managed assumed for each prescription for the biomass leaving the forest as chips or sawlogs. Based on the productive machine hours and the equipment specifications, the fuel and oil use were estimated and are provided in Table 8 and Table 9. Given the fuel and oil use on a dry tons basis, estimation of the total fuel and oil use for the TEST SCENARIO was based on the chips generated per decade (Table 5).

Table 4. Treatments applied

Treatment	Description	Slope %	Equipment Configuration	Chips (dry tons/ acre)	Sawlogs (dry tons/ acre)
Clear cut	Even-aged management. Only occurs on Industrial Forest Lands.	<35%	CC <35	30	47
		35 to 50%	CC 35-50	33	48
Pre-Commercial Thinning	No sawlogs removed. Only biomass fuel removed. Typically in plantations.	<35%	PCT <35	5.0	0
		35 to 50%	PCT 35-50	8.3	0
Commercial Thinning	Sawlogs and biomass fuel removed. Typically in plantations.	<35%	CT <35	14	7.5
		35 to 50%	CT 35-50	21	6.7
Salvage	Assumes that no biomass fuel (3"-9.9" diameter at breast height or limbs/tops) was recovered (burned up in wildfire).	<35%	SAL <35	0	11
		35 to 50%	SAL 35-50	0	13
Select Harvest	Uneven-aged management harvest removing high risk trees in mature stands.	<35%	SH <35	12	16
		35 to 50%	SH 35-50	13	16
		>50%	SH 50+ (only on Industrial Forest Lands)	14	17
Restrictive Thinning	A "light" Thin, but retain 40% canopy.	<35%	RT <35	6.6	12
		35 to 50%	RT 35-50	6.8	17

Table 5. Scenario data: treatment of industrial private and public multiple use forests (TEST SCENARIO: IPF + PMU)

	Acres Treated Per Decade				Chips Generated Per Decade (dry tons)				Sawlogs Per Decade (dry tons)			
	2006	2016	2026	2036	2006	2016	2026	2036	2006	2016	2026	2036
CC <35	24,000	24,000	24,000	24,000	680,000	800,000	650,000	700,000	970,000	1,300,000	1,000,000	1,200,000
CC 35-50	3,000	3,400	3,100	3,100	97,000	120,000	92,000	100,000	130,000	180,000	140,000	160,000
PCT <35	4,300	26,000	25,000	25,000	5,000	85,000	100,000	190,000	0	0	0	0
PCT 35-50	230	3,200	3,400	3,100	550	17,000	23,000	40,000	0	0	0	0
CT <35	0	0	7,200	25,000	0	0	110,000	350,000	0	0	160,000	71,000
CT 35-50	0	0	460	3,200	0	0	9,500	66,000	0	0	15,000	8,700
SAL <35	470	1,100	220	1,200	0	0	0	0	5,600	8,000	2,700	11,000
SAL <35 Public	4,300	470	2,900	11,000	0	0	0	0	32,000	5,700	43,000	140,000
SAL 35-50	20	150	47	260	0	0	0	0	590	1,300	530	2,500
SAL 35-50 Public	600	100	470	990	0	0	0	0	8,600	850	7,300	12,000
SH <35	250,000	200,000	220,000	180,000	2,900,000	2,700,000	2,400,000	2,100,000	3,700,000	3,800,000	3,400,000	3,200,000
SH 35-50	35,000	29,000	32,000	26,000	440,000	410,000	360,000	320,000	520,000	530,000	470,000	450,000
SH 50+	11,000	9,700	11,000	9,700	150,000	150,000	130,000	130,000	170,000	180,000	170,000	180,000
RT <35 Public	170,000	120,000	180,000	120,000	1,300,000	1,200,000	800,000	550,000	2,400,000	2,300,000	1,500,000	1,000,000
RT 35-50 Public	20,000	28,000	20,000	28,000	160,000	270,000	86,000	120,000	390,000	670,000	220,000	290,000
Total	**530,000**	**450,000**	**540,000**	**460,000**	**5,700,000**	**5,700,000**	**4,700,000**	**4,600,000**	**8,300,000**	**8,900,000**	**7,200,000**	**6,800,000**

Table 6. Forest treatment equipment specifications

	Fuel	Horsepower	Life (productive machine hours)	Productive Time (productive machine hours/ day)	Fuel use (gal/ productive machine hour)	Fuel mileage (miles per gallon)	Lubricating oil use (gal oil/ gal fuel)
Tracked Feller/Buncher - John Deere 759 G	diesel	241	8,000	8	8.5		0.12
Tracked Feller/Buncher - Timbco Model 425EXL	diesel	300	8,000	8	7.9		0.12
Tracked Feller/Buncher - Timbco Model 445EXL	diesel	300	8,000	8	7.9		0.12
Rubber Tired Feller/Buncher - Hydro-Ax 321	diesel	116	8,000	8	3		0.12
Timber Cutter with Husqvarna 575XP	gasoline	5.4	1,000	6	0.2		0.05

TowerYarder - Koller K501	diesel	152	15,000	9	2.5		0.06
Swing Yarder - Diamond 2000	diesel	230	15,000	9	3.5		0.06
Acme Model 22 Carriage (paired with Diamond 2000)	diesel	22	8,000	9	0.15		0.12
Rubber Tired Skidder - Caterpillar 525C	diesel	182	8,000	8	5.5		0.09
Rubber Tired Skidder - Caterpillar 535C	diesel	204	8,000	8	6		0.09
Tracked Skidder - Caterpillar 517	diesel	120	8,000	8	5		0.09
Tracked Skidder - Caterpillar 527	diesel	150	8,000	8	6.25		0.09
Delimber - Caterpillar 322C with Pierce Delimbinator	diesel	168	8,000	8	7.5		0.12
Processor - Link-Belt 290LX w/Logmax 7000 head	diesel	177	8,000	8	5		0.12
Landing Person with Husqvarna 575XP	gasoline	5.4	1,000	6	0.2		0.05
Chipper - Morbark Model 30/36	diesel	440	8,000	8	20		0.06
Chipper - Morbark Model 50/48	diesel	860	8,000	8	27		0.06
Loader - Link-Belt 210LX to feed chipper	diesel	138	8,000	8	4		0.12
Water Truck - Kenworth (3,600 gal capacity)	diesel	400	8,000	5-8*		6	0.04
Motorgrader - Caterpillar 140 H	diesel	185	2,667	9	5		0.06
Chip Truck Freightliner Model Columbia with Peerless 45' Trailer	diesel	450	15,000	9		7.4	0.04
Lowbed Equipment Transport - Freightliner with Peerless 60 ton Lowbed Trailer	diesel	450	15,000	10		7.4	0.04
Pickup Truck/Crew Transport -Ford F350 Crew Cab 4x4 diesel	diesel	200	2,000	2		15	0.04
Mechanics truck - Ford F550 4x4 diesel	diesel	200	8,000	4		10	0.04

* Fuel use was estimated for each prescription as CC: 8, PCT: 5, CT: 8, SAL: 8, SH<50: 8, SH50+: 5, and RT: 8.

Table 7. Productive machine hours/dry tons

For chips	CC <35	CC 35-50	PCT <35	PCT 35-50	CT <35	CT 35-50	SH <35	SH 35-50	SH 50+	RT <35 Public	RT 35-50 Public
Tracked Feller/Buncher - Timbco Model 425EXL			0.077	0.088	0.040	0.041				0.032	0.031
Tracked Feller/Buncher - Timbco Model 445EXL	0.026	0.025					0.024	0.028			
Rubber Tired Feller/Buncher - Hydro-Ax 321			0.077								
Timber Cutter with Husqvarna 575XP	0.020	0.019			0.030	0.031	0.018	0.021	0.14	0.024	0.023
TowerYarder - Koller K501									0.21		
Rubber Tired Skidder - Caterpillar 525C	0.026		0.077		0.040	0.041	0.024	0.028		0.032	0.031

Rubber Tired Skidder - Caterpillar 535C		0.025									
Tracked Skidder - Caterpillar 517				0.088							
Tracked Skidder - Caterpillar 527	0.026	0.025			0.040	0.041	0.024	0.028		0.032	0.031
Processor - Link-Belt 290LX w/Logmax 7000 head	0.026	0.025			0.040	0.041	0.024	0.028		0.032	0.031
Landing Person with Husqvarna 575XP	0.020	0.019			0.030	0.031	0.018	0.021		0.024	0.023
Chipper - Morbark Model 30/36	0.068	0.061	0.077	0.088	0.061	0.053	0.058	0.064		0.094	0.11
Chipper - Morbark Model 50/48									0.42		
Loader - Link-Belt 210LX to feed chipper									0.42		
Water Truck - Kenworth (3,600 gal capacity)	0.026	0.025	0.048	0.055	0.040	0.041	0.024	0.028	0.12	0.032	0.031
Motorgrader - Caterpillar 140 H	0.0035	0.0033	0.027	0.019	0.0079	0.0070	0.0056	0.0058	0.019	0.0079	0.0069
Chip Truck Freightliner Model Columbia with Peerless 45' Trailer	0.127	0.115	0.14	0.16	0.11	0.10	0.11	0.12	0.79	0.18	0.20
Lowbed Equipment Transport - Freightliner with Peerless 60 ton Lowbed Trailer	0.050	0.046	0.13	0.15	0.070	0.070	0.044	0.051	0.31	0.062	0.062
Pickup Truck/Crew Transport -Ford F350 Crew Cab 4x4 diesel	0.0076	0.0069	0.019	0.022	0.011	0.010	0.0066	0.0077	0.047	0.0092	0.0091
Mechanics truck - Ford F550 4x4 diesel	0.015	0.014	0.038	0.044	0.021	0.021	0.013	0.015		0.018	0.018

* Max PMH was estimated for each prescription as CC: 960, PCT: 600, CT: 960, SAL: 960, SH<50: 960, SH50+: 600, and RT: 960.

Table 9 continued. Productive machine hours/dry tons

For sawlogs	CC <35	CC 35-50	CT <35	CT 35-50	SAL <35	SAL <35 Public	SAL 35-50	SAL 35-50 Public	SH <35	SH 35-50	SH 50+	RT <35 Public	RT 35-50 Public
Tracked Feller/Buncher - Timbco Model 425EXL			0.040	0.041								0.032	0.031
Tracked Feller/Buncher - Timbco Model 445EXL	0.026	0.025							0.024	0.028			
Timber Cutter with Husqvarna 575XP	0.020	0.019	0.030	0.031	0.023	0.023	0.026	0.026	0.018	0.021	0.14	0.024	0.023
TowerYarder - Koller K501											0.21		
Rubber Tired Skidder - Caterpillar 525C	0.026		0.040	0.041	0.031	0.031	0.035	0.035	0.024	0.028		0.032	0.031
Rubber Tired Skidder - Caterpillar 535C		0.025											
Tracked Skidder - Caterpillar 527	0.026	0.025	0.040	0.041	0.031	0.031	0.035	0.035	0.024	0.028		0.032	0.031
Processor - Link-Belt 290LX w/Logmax 7000 head	0.026	0.025	0.040	0.041	0.031	0.031	0.035	0.035	0.024	0.028		0.032	0.031
Landing Person with Husqvarna 575XP	0.020	0.019	0.030	0.031	0.023	0.023	0.026	0.026	0.018	0.021		0.024	0.023
Lowbed Equipment Transport - Freightliner with Peerless 60 ton Lowbed Trailer	0.040	0.038	0.061	0.062	0.052	0.052	0.058	0.058	0.037	0.043	0.31	0.050	0.048
Pickup Truck/Crew Transport -Ford F350 Crew Cab 4x4 diesel	0.0059	0.0057	0.0091	0.0092	0.0077	0.0077	0.0087	0.0087	0.0055	0.0064	0.047	0.0075	0.0072

Mechanics truck - Ford F550 4x4 diesel	0.012	0.011	0.019	0.019	0.015	0.015	0.017	0.017	0.011	0.013		0.015	0.015

* Max PMH was estimated for each prescription as CC: 960, PCT: 600, CT: 960, SAL: 960, SH<50: 960, SH50+: 600, and RT: 960.

Table 8. Forest treatment equipment fuel use (gal/dry tons)

For chips	CC <35	CC 35-50	PCT <35	PCT 35-50	CT <35	CT 35-50	SH <35	SH 35-50	SH 50+	RT <35 Public	RT 35-50 Public
Tracked Feller/Buncher - Timbco Model 425EXL			0.61	1.4	0.64	0.96				0.26	0.25
Tracked Feller/Buncher - Timbco Model 445EXL	0.21	0.39					0.28	0.33			
Rubber Tired Feller/Buncher - Hydro-Ax 321			0.23								
Timber Cutter with Husqvarna 575XP	0.0079	0.0074			0.0061	0.0061	0.0071	0.0083	0.056	0.012	0.014
TowerYarder - Koller K501									0.53		
Rubber Tired Skidder - Caterpillar 525C	0.29		1.3		0.44	0.22	0.39	0.15		0.53	0.17
Rubber Tired Skidder - Caterpillar 535C		0.15									
Tracked Skidder - Caterpillar 517				1.3							
Tracked Skidder - Caterpillar 527	0.16	0.31			0.25	0.51	0.15	0.52		0.20	0.58
Processor - Link-Belt 290LX w/Logmax 7000 head	0.13	0.12			0.20	0.20	0.12	0.14		0.16	0.16
Landing Person with Husqvarna 575XP	0.0039	0.0037			0.0061	0.0061	0.0036	0.0042		0.0048	0.0047
Chipper - Morbark Model 30/36	1.4	1.2	1.5	1.8	1.2	1.1	1.2	1.3		1.9	2.1
Chipper - Morbark Model 50/48									1.1		
Loader - Link-Belt 210LX to feed chipper									0.17		
Water Truck - Kenworth (3,600 gal capacity)	0.044	0.041	0.13	0.15	0.067	0.068	0.040	0.046	0.31	0.054	0.052
Motorgrader - Caterpillar 140 H	0.017	0.016	0.13	0.097	0.040	0.035	0.028	0.029	0.094	0.040	0.034
Chip Truck Freightliner Model Columbia with Peerless 45' Trailer	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65
Lowbed Equipment Transport - Freightliner with Peerless 60 ton Lowbed Trailer	0.0061	0.0065	0.053	0.037	0.018	0.016	0.015	0.015	0.0072	0.021	0.018
Pickup Truck/Crew Transport -Ford F350 Crew Cab 4x4 diesel	0.061	0.056	0.10	0.12	0.085	0.084	0.071	0.082	0.37	0.098	0.097
Mechanics truck - Ford F550 4x4 diesel	0.018	0.016	0.046	0.053	0.025	0.025	0.016	0.018		0.022	0.022

Table 10 continued. Forest treatment equipment fuel use (gal/dry tons)

For sawlogs	CC <35	CC 35-50	CT <35	CT 35-50	SAL <35	SAL <35 Public	SAL 35-50	SAL 35-50 Public	SH <35	SH 35-50	SH 50+	RT <35 Public	RT 35-50 Public

Tracked Feller/Buncher - Timbco Model 425EXL			0.64	0.96								0.26	0.25
Tracked Feller/Buncher - Timbco Model 445EXL	0.21	0.39							0.28	0.33			
Timber Cutter with Husqvarna 575XP	0.0079	0.0074	0.0061	0.0061	0.023	0.023	0.026	0.026	0.0071	0.0083	0.056	0.012	0.014
TowerYarder - Koller K501											0.53		
Rubber Tired Skidder - Caterpillar 525C	0.29		0.44	0.22	0.51	0.51	0.19	0.19	0.39	0.15		0.53	0.17
Rubber Tired Skidder - Caterpillar 535C		0.15											
Tracked Skidder - Caterpillar 527	0.16	0.31	0.25	0.51	0.19	0.19	0.66	0.66	0.15	0.52		0.20	0.58
Processor - Link-Belt 290LX w/Logmax 7000 head	0.13	0.12	0.20	0.20	0.15	0.15	0.17	0.17	0.12	0.14		0.16	0.16
Landing Person with Husqvarna 575XP	0.0039	0.0037	0.0061	0.0061	0.014	0.014	0.0052	0.0052	0.0036	0.0042		0.0048	0.0047
Lowbed Equipment Transport - Freightliner with Peerless 60 ton Lowbed Trailer	0.0049	0.0053	0.015	0.014	0.021	0.021	0.019	0.019	0.012	0.012	0.0072	0.017	0.014
Pickup Truck/Crew Transport -Ford F350 Crew Cab 4x4 diesel	0.047	0.045	0.073	0.074	0.083	0.10	0.093	0.093	0.058	0.068	0.37	0.080	0.077
Mechanics truck - Ford F550 4x4 diesel	0.014	0.014	0.022	0.023	0.019	0.019	0.021	0.021	0.013	0.015		0.018	0.017

Table 9. Forest treatment equipment lubricating oil use (gal/dry tons)

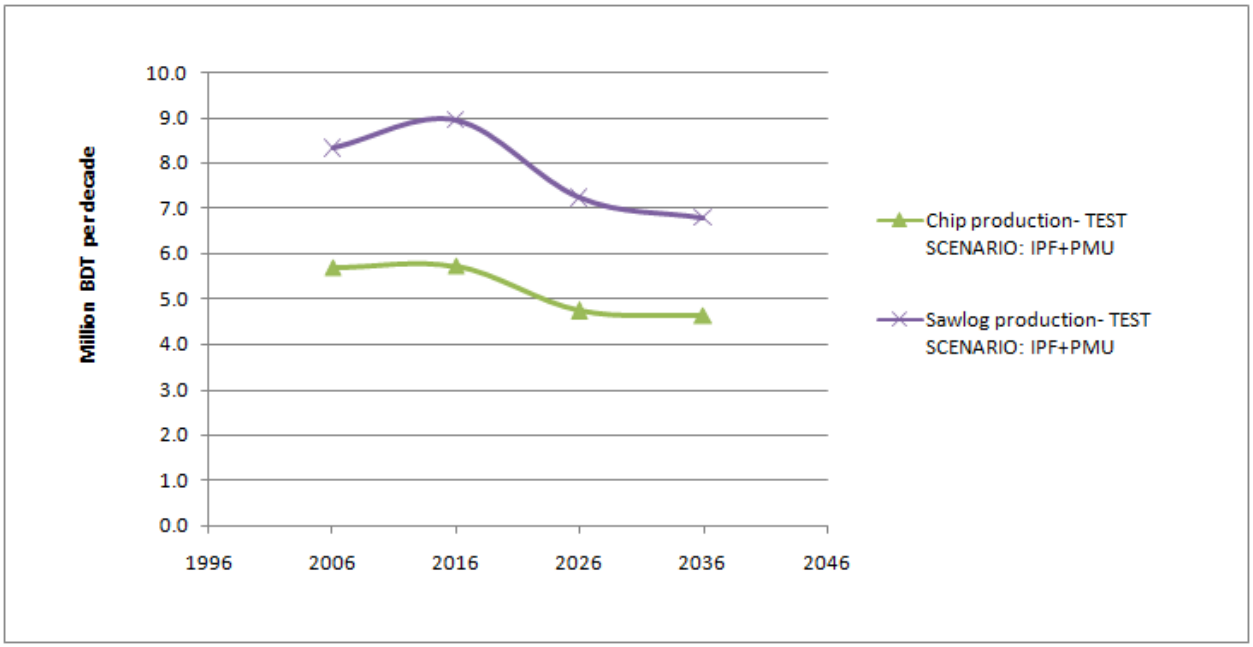
For Chips	CC <35	CC 35-50	PCT <35	PCT 35-50	CT <35	CT 35-50	SH <35	SH 35-50	SH 50+	RT <35 Public	RT 35-50 Public
Tracked Feller/Buncher - Timbco Model 425EXL			0.073	0.17	0.077	0.12				0.031	0.030
Tracked Feller/Buncher - Timbco Model 445EXL	0.025	0.047					0.034	0.040			
Rubber Tired Feller/Buncher - Hydro-Ax 321			0.028								
Timber Cutter with Husqvarna 575XP	0.00039	0.00037			0.00030	0.00031	0.00036	0.00042	0.0028	0.00061	0.00070
TowerYarder - Koller K501									0.032		
Rubber Tired Skidder - Caterpillar 525C	0.026		0.11		0.040	0.020	0.035	0.014		0.048	0.015
Rubber Tired Skidder - Caterpillar 535C		0.013									
Tracked Skidder - Caterpillar 517				0.12							
Tracked Skidder - Caterpillar 527	0.015	0.028			0.023	0.046	0.013	0.047		0.018	0.053
Delimber - Caterpillar 322C with Pierce Delimbinator											
Processor - Link-Belt 290LX w/Logmax 7000 head	0.016	0.015			0.024	0.024	0.014	0.017		0.019	0.019
Landing Person with Husqvarna 575XP	0.00020	0.00019			0.00030	0.00031	0.00018	0.00021		0.00024	0.00023
Chipper - Morbark Model 30/36	0.081	0.073	0.092	0.11	0.074	0.064	0.069	0.077		0.11	0.13
Chipper - Morbark Model 50/48									0.068		
Loader - Link-Belt 210LX to feed chipper									0.020		
Water Truck - Kenworth (3,600 gal capacity)	0.0017	0.0016	0.0051	0.0058	0.0027	0.0027	0.0016	0.0019	0.012	0.0022	0.0021
Motorgrader - Caterpillar 140 H	0.0010	0.0010	0.0080	0.0058	0.0024	0.0021	0.0017	0.0017	0.0057	0.0024	0.0021
Chip Truck Freightliner Model Columbia with Peerless 45' Trailer	0.026	0.026	0.026	0.026	0.026	0.026	0.026	0.026	0.026	0.026	0.026
Lowbed Equipment Transport - Freightliner with Peerless 60 ton Lowbed	0.00025	0.00026	0.0021	0.0015	0.00070	0.00064	0.00059	0.00059	0.00029	0.00083	0.00072
Pickup Truck/Crew Transport -Ford F350 Crew Cab 4x4 diesel	0.0024	0.0022	0.0041	0.0047	0.0034	0.0033	0.0028	0.0033	0.015	0.0039	0.0039
Mechanics truck - Ford F550 4x4 diesel	0.0007	0.00066	0.0018	0.0021	0.0010	0.0010	0.00063	0.00073		0.00087	0.00087

Table 11 continued. Forest treatment equipment lubricating oil use (gal/dry tons)

For sawlogs	CC <35	CC 35-50	CT <35	CT 35-50	SAL <35	SAL <35 Public	SAL 35-50	SAL 35-50 Public	SH <35	SH 35-50	SH 50+	RT <35 Public	RT 35-50 Public
Tracked Feller/Buncher - Timbco Model			0.077	0.12								0.031	0.030

425EXL													
Tracked Feller/Buncher - Timbco Model 445EXL	0.025	0.047							0.034	0.040			
Timber Cutter with Husqvarna 575XP	0.00039	0.00037	0.00030	0.00031	0.0012	0.0012	0.0013	0.0013	0.00036	0.00042	0.0028	0.00061	0.00070
TowerYarder - Koller K501											0.032		
Rubber Tired Skidder - Caterpillar 525C	0.026		0.040	0.020	0.046	0.046	0.017	0.017	0.035	0.014		0.048	0.015
Rubber Tired Skidder - Caterpillar 535C		0.013											
Tracked Skidder - Caterpillar 527	0.015	0.028	0.023	0.046	0.017	0.017	0.059	0.059	0.013	0.047		0.018	0.053
Processor - Link-Belt 290LX w/Logmax 7000 head	0.016	0.015	0.024	0.024	0.019	0.019	0.021	0.021	0.014	0.017		0.019	0.019
Landing Person with Husqvarna 575XP	0.00020	0.00019	0.00030	0.00031	0.00070	0.00070	0.00026	0.00026	0.00018	0.00021		0.00024	0.00023
Lowbed Equipment Transport - Freightliner with Peerless 60 ton Lowbed Trailer	0.00020	0.00021	0.00061	0.00057	0.00085	0.00085	0.00078	0.00078	0.00049	0.00049	0.00029	0.00066	0.00056
Pickup Truck/Crew Transport -Ford F350 Crew Cab 4x4 diesel	0.0019	0.0018	0.0029	0.0030	0.0033	0.0041	0.0037	0.0037	0.002	0.0027	0.015	0.0032	0.0031
Mechanics truck - Ford F550 4x4 diesel	0.00058	0.00055	0.00089	0.00090	0.00074	0.00074	0.00084	0.00084	0.001	0.00062		0.00072	0.00070

Figure 3. TEST SCENARIO chip and sawlog production



Equipment emissions were estimated based on the U.S. Environmental Protection Agency's NONROAD2004 and MOBILE6 emission inventory models (Table 10). Estimation began with zero-hour or zero-mile emissions and break-specific fuel consumption (BSFC) and was followed by adjustments (where applicable) to account for transient operation, changes in emission factors over time, and technology distributions (for tiered regulatory compliance). For example, emission factors consider that beginning June 1, 2007, non-road diesel was required to have maximum of 500 ppm sulfur; and beginning June 1, 2012, the sulfur content must be reduced to 15 ppm[6].

Table 10. Harvest and chip transport emissions models

Off-road equipment except chainsaws	NONROAD2004 emission inventory model (technology distributions, zero hour emissions, deterioration factors, transient adjustment factors) [12]; California Statewide Off-Road Fuel Correction Factors [13]
Chainsaws	NONROAD2004 emission inventory model (zero hour emissions, deterioration factors, transient adjustment factors) [14]; Deterioration rates [15]
On-road equipment	MOBILE6 emission inventory model (zero hour emissions, correction factors) [16, 17]; Native road PM emissions [18]

Specifically, equipment were assumed to be dedicated to the project, to be new in the first year of the project, and subsequently replaced at the end of their operating life (thus returning to zero-hour or zero-mile performance and as for example depicted in Figure 4 for a Morbark Model 30/36 chipper used for 8,000 hours and then replaced). Specifically, the required machine hours were estimated per decade for each treatment scenario as presented in Table 11 (from the productive machine hours (Table 7) and the chips generated per decade in Table 5) and the average cumulative operating hours per decade were estimated for each piece of equipment (Table 12). Also, although emissions were adjusted for transient operation and degraded until the equipment was replaced, fuel and oils use was assumed to be constant over the life of the equipment (to match assumptions made in the project's economic analysis).

[6] See Final regulatory analysis: control of emissions from non-road diesel engines, EPA420-R-04-007, 2004.

Finally, PM emissions for on-road equipment traveling on native roads have been considered and regulated adjustments in fuel sulfur levels have been considered in appropriate years as described in [18]. The resulting "effective" emission factors are presented in Appendix A.

Figure 4. Example new equipment purchase dates for emissions degradation estimation

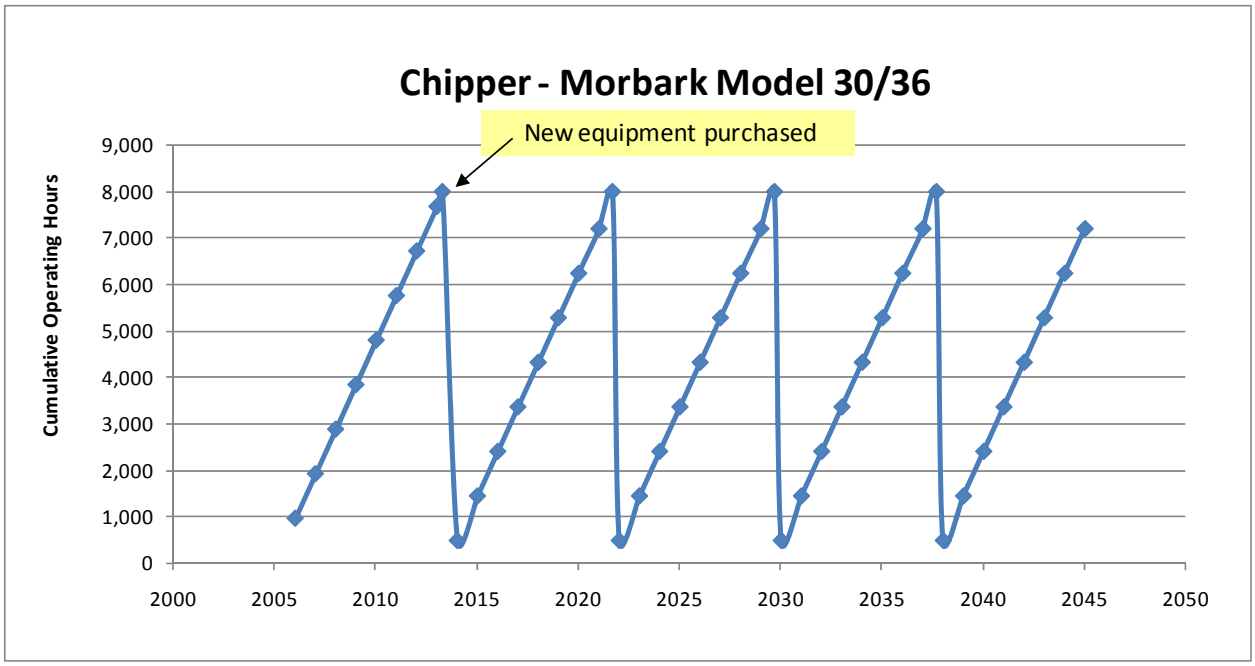


Table 11. Required machine hours per decade

	TEST SCENARIO: IPF + PMU			
Equipment	2006	2016	2026	2036
Tracked Feller/Buncher - Timbco Model 425EXL	48,000	55,000	43,000	57,000
Tracked Feller/Buncher - Timbco Model 445EXL	100,000	99,000	86,000	79,000
Rubber Tired Feller/Buncher - Hydro-Ax 321	390	6,600	7,900	15,000
Timber Cutter with Husqvarna 575XP	130,000	130,000	110,000	110,000
TowerYarder - Koller K501	31,000	31,000	28,000	27,000
Rubber Tired Skidder - Caterpillar 525C	150,000	150,000	120,000	130,000
Rubber Tired Skidder - Caterpillar 535C	2,400	3,100	2,300	2,500
Tracked Skidder - Caterpillar 517	48	1,500	2,100	3,500
Tracked Skidder - Caterpillar 527	150,000	150,000	120,000	120,000
Processor - Link-Belt 290LX w/Logmax 7000 head	150,000	150,000	120,000	120,000
Landing Person with Husqvarna 575XP	110,000	110,000	89,000	88,000
Chipper - Morbark Model 30/36	390,000	390,000	310,000	300,000
Chipper - Morbark Model 50/48	61,000	63,000	56,000	54,000
Loader - Link-Belt 210LX to feed chipper	61,000	63,000	56,000	54,000
Water Truck - Kenworth (3,600 gal capacity)	see below*			
Motorgrader - Caterpillar 140 H	36,000	37,000	31,000	33,000
Chip Truck Freightliner Model Columbia with Peerless 45' Trailer	840,000	850,000	690,000	670,000
Lowbed Equipment Transport - Freightliner with Peerless 60 ton Lowbed Trailer	330,000	340,000	280,000	290,000
Pickup Truck/Crew Transport -Ford F350 Crew Cab 4x4 diesel	49,000	50,000	42,000	43,000
Mechanics truck - Ford F550 4x4 diesel	83,000	86,000	71,000	74,000

* Machine hours were estimated for each equipment configuration for the water truck as:

		CC <35	CC 35-50	PCT <35	PCT 35-50	CT <35	CT 35-50	SH <35	SH 35-50	SH 50+	RT <35 Public	RT 35-50 Public
TEST SCENARIO: IPF + PMU	2006	18,000	2,400	240	30			68,000	12,000	17,000	43,000	5,000
	2016	21,000	3,100	4,100	910			64,000	11,000	17,000	39,000	8,500
	2026	17,000	2,300	4,900	1,300	4,500	390	56,000	10,000	16,000	26,000	2,700
	2036	18,000	2,500	9,100	2,200	14,000	2,700	49,000	8,800	15,000	18,000	3,900

Table 12. Average cumulative operating hours per decade

	TEST SCENARIO: IPF + PMU			
Equipment	2006	2016	2026	2036
Tracked Feller/Buncher - Timbco Model 425EXL	3,600	3,600	4,000	4,400
Tracked Feller/Buncher - Timbco Model 445EXL	3,600	3,600	4,000	4,400
Rubber Tired Feller/Buncher - Hydro-Ax 321	190	3,300	3,900	4,400
Timber Cutter with Husqvarna 575XP	400	360	360	360
TowerYarder - Koller K501	5,900	6,500	8,400	8,600
Rubber Tired Skidder - Caterpillar 525C	3,600	3,600	4,000	4,400
Rubber Tired Skidder - Caterpillar 535C	1,200	1,500	1,100	1,300
Tracked Skidder - Caterpillar 517	24	730	1,000	1,700
Tracked Skidder - Caterpillar 527	3,600	3,600	4,000	4,400
Processor - Link-Belt 290LX w/Logmax 7000 head	3,600	3,600	4,000	4,400
Landing Person with Husqvarna 575XP	400	360	360	360
Chipper - Morbark Model 30/36	3,600	3,600	4,000	4,400
Chipper - Morbark Model 50/48	3,600	3,600	4,000	4,400
Loader - Link-Belt 210LX to feed chipper	3,600	3,600	4,000	4,400
Water Truck - Kenworth (3,600 gal capacity)	1,843	1,843	1,997	2,150
Motorgrader - Caterpillar 140 H	1,200	1,100	1,100	1,100
Chip Truck Freightliner Model Columbia with Peerless 45' Trailer	5,900	6,500	8,400	8,600
Lowbed Equipment Transport - Freightliner with Peerless 60 ton Lowbed Trailer	6,600	6,600	7,800	8,900
Pickup Truck/Crew Transport -Ford F350 Crew Cab 4x4 diesel	910	910	1,000	1,100
Mechanics truck - Ford F550 4x4 diesel	2,600	4,300	4,300	3,400

Forest treatment also included underburning emissions. Data were provided by the "Fire Behavior Assessment" [19], again a model depicted in Figure 1. These data are presented in Table 13. N_2O emissions were added based on data from Vose [20], included based on the mass percent of conifers and hardwoods (provided in Table 14 from the "Vegetation Dynamics Assessment" [21] and representing percent of each species burned) provided by the "Fire Behavior Assessment" [19] and resulting in a ratio of N_2O to NOx emissions of 0.13 in all decades.

Table 13. Underburning emissions for the TEST SCENARIO (tons)

	TEST SCENARIO: IPF + PMU			
	2006	2016	2026	2036
PM 10	3,200	3,800	2,500	2,100
SOx (as SO2)	210	250	150	130
NOx	330	400	210	180
NM VOC	7,600	9,100	6,000	5,100
CO	33,000	39,000	26,000	22,000
CO2	450,000	530,000	320,000	270,000
CH4	1,600	1,900	1,200	1,000
N2O	45	53	29	23

Table 14. Percent of each tree species modeled

	TEST SCENARIO: IPF + PMU			
	2006	**2016**	**2026**	**2036**
Hardwoods	30%	30%	29%	35%
Douglas-Fir	7.4%	7.9%	8.3%	8.1%
Firs	19%	20%	20%	18%
Incense Cedar	3.2%	3.1%	3.0%	2.6%
Pine	14%	14%	16%	14%
Western Juniper	0.37%	0.38%	0.54%	0.44%
Conifers, other	26%	25%	23%	21%

2. 3.2 Fuel, Oils, and Electricity Production Models and Data

The USDOE Argonne National Lab's Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model (Version 1.7) [22] was used to estimate the life cycle of diesel and oils production, grid electricity, and natural gas power plants in California. Since the Version 1.7 estimates emissions only to the year 2020, energy use and emissions beyond 2020 have been assumed to be at 2020 levels. The data used are presented in Appendix B, essentially representing well-to-point of use values for all fuels, oils, and electricity production processes.

3. 3.3 Biomass Power Plant Operation Models and Data

For the gross LCA, data for a current generation combustion plant were provided by the "Power Plant Analysis" [23] a model depicted in Figure 1 and based on operations at the Mt. Lassen biomass power plant. Plant capacity, efficiency, and stack emissions are presented in Table 15 as described in Nechodom, et al. [24] and supplemented to include CH_4 and N_2O emissions as

described by the USEPA [25] and CO_2 emissions based on the carbon contents of the chips (by combining the species mix in Table 14 and the percent carbon dry mass[7] in Table 16) less the carbon in the NMVOC, CO, and CH_4 (at carbon ratios of 0.85, 0.43, and 0.75 respectively and from [22]). The use of supporting equipment (a dozer, 2 loaders, a bobcat, a tub grinder, and a natural gas emergency generator) and ancillary grid electricity use were also included. Although the fuel use and emissions of the supporting equipment have been deteriorated over time based on the USEPA's NONROAD2004 Model [12], the stack emissions and efficiency were as presented in Table 15.

Appendix C presents the inventory data used for the biomass power plant, also considering the species make-up (Table 14) and the heating values (Table 16) based on data provided by the "Fire Behavior Assessment" [19]. This allowed the estimation of the electricity generated, assuming an 8% transmission loss and given the power plant efficiency.

Table 15. Gross power plant characterization

	Current Generation Biomass Combustion Power Plant
Electricity (kWh/dry ton)	1,000
Plant Energy Efficiency	20%
Plant Emissions (lbs/mmBTU output)	
NO_x	0.33
SO_x	0.13
PM	0.27
CO	0.90
NMVOC	0.085
CO_2	970
CH_4	19
N_2O	0.065

Table 16. Heating values and carbon content by species

	mmBTU/BDT	**% carbon dry mass**
Hardwoods	16.7	50%
Douglas-Fir	18.1	52%
Firs	17.2	51%
Incense Cedar	17.8	49%
Pine	17.2	51%
Western Juniper	18.7	51%
Conifers, other	17.2	51%

[7] Based on data from the World Bank at http://www.worldbank.org/html/fpd/em/power/sources/easrbiom.stm

4. 3.4 Wildfire Emissions

Data for the emissions from wildfires that occur despite treatment were provided by the "Fire Behavior Assessment" [19], again a model depicted in Figure 1. These data are presented in Table 17 and , as in the estimation of underburning emissions, N_2O emissions were added based on data from Vose [20], included based on the mass percent of conifers and hardwoods (provided in Table 14).

Table 17. Wildfire emissions for the TEST SCENARIO (tons)

	REFERENCE CASE: no treatment				TEST SCENARIO: IPF + PMU			
	2006	2016	2026	2036	2006	2016	2026	2036
PM 10	16,000	20,000	36,000	51,000	15,000	14,000	25,000	48,000
SOx (as SO_2)	1,100	1,400	2,500	3,400	970	960	1,700	3,100
NOx	1,700	2,300	4,200	5,700	1,600	1,600	2,700	4,700
NM VOC	39,000	47,000	84,000	120,000	35,000	34,000	59,000	110,000
CO	170,000	210,000	370,000	520,000	150,000	150,000	260,000	500,000
CO2	2,000,000	2,600,000	4,600,000	6,500,000	1,800,000	1,800,000	3,100,000	5,700,000
CH4	8,000	9,900	18,000	25,000	7,300	7,000	12,000	23,000
N2O	220	300	550	720	210	210	370	600

5. 3.5 Accounting for the Carbon in Chips and Sawlogs

For the gross assessment, credit was given for the carbon embodied in the biomass removed from the forest as sawlogs and chips. Specifically, the carbon and CO_2 equivalents in the biomass removed as sawlogs and chips are presented in Table 18. The carbon was estimated based on the BDT of carbon to chips and sawlogs (presented in Table 5) and assuming the carbon contents estimated by combining data in Table 14 and Table 16. Next and in support of the impact assessment, the tons CO_2 equivalents in the sawlogs and chips were estimated by multiplying the tons of carbon by 44/12, the ratio of the molecular weight of CO_2 to that of carbon.

Table 18. Carbon and carbon dioxide equivalents sequestered as sawlogs and chips for the TEST SCENARIO

2006	2016	2026	2036	2006	2016	2026	2036
BDT of trees removed as chips				**BDT of trees removed as sawlogs**			
5,700,000	5,700,000	4,700,000	4,600,000	8,300,000	8,900,000	7,200,000	6,800,000
tons carbon removed as chips				**tons carbon removed as sawlogs**			
2,900,000	2,900,000	2,400,000	2,400,000	4,200,000	4,500,000	3,700,000	3,500,000
tons CO2 equivalents for chips removed				**tons CO2 equivalents for sawlogs removed**			
11,000,000	11,000,000	8,800,000	8,600,000	16,000,000	17,000,000	13,000,000	13,000,000

6. 3.6 Gross Inventory Results

The gross inventory assessment estimated the life cycle energy use and emissions assuming use of the current generation biomass combustion power plant and as the treatments would be performed (as in Figure 2). Again each scenario in the gross assessment was assumed to produce a 2.7 million-acre landscape of differing management outcomes as measured by extent

and intensity of wildfire and different amounts of sawlogs and biomass electricity over the 40 study years and over the 2.7 million-acre landscape (as in Table 19). Also, for the TEST SCENARIO, the area actually treated was assumed to be ~2,000,000 acres.

Table 19. Gross assessment system products

	REFERENCE CASE: No treatment	TEST SCENARIO: IPF + PMU
Landscape managed (acres)	2,700,000	2,700,000
Area treated (acres)	0	2,000,000
Sawlogs produced (dry tons)	0	31,000,000
Biomass electricity generation: current generation biomass combustion power plant (MWh)	0	19,000,000
Installed biomass electricity generation capacity (MW)	0	61

Figure 5 and Figure 6 and Appendix D present the gross inventory analysis results including the life cycle energy use and emissions for harvest equipment operation (including forest treatment and chip transport), underburning, power plant operations, and wildfires. As shown, differences are found between the REFERENCE CASE and the TEST SCENARIO. Starting with energy consumption, because REFERENCE CASE did not include any treatment, chip transport, or power plant operations, the total, fossil, and petroleum energy consumption are zero. For the TEST SCENARIO, total life cycle energy included the life cycle for fuels used by harvest equipment and during chip transport and for energy use by the power plant (i.e., for the use of diesel in forklifts, the use of propane for building heat and plant start up, etc.), and less that generated by the power plant. As shown, the TEST SCENARIO is found to provide a total energy benefit, but given greater consumption of fossil and petroleum energy when compared to the REFERENCE CASE. As expected, life cycle fossil and petroleum consumption for the gross assessment of the TEST SCENARIO was dominated by fuel use for harvest and chip transport.

For emissions, Figure 6 shows that in all cases, emissions within the vicinity of the B2E landscape, including wildfires, harvest operations and underburning, chip transport, and power plant operations, dominate those outside the vicinity of the landscape (essentially representing the life cycles of fuel and electricity production). The small fraction of emissions outside the landscape reflects their sources. Specifically, because harvest operations are a small portion of the overall life cycle, so is the life cycle of fuel used harvest operations. Similarly, because the fuel and electricity use by the power plant are a very small part of power plant operation, the life cycle emissions are commensurately small. For emissions overall, although little difference is seen between emissions of NMVOCs, CO, PM10, SOx, and CH_4 as dominated by wildfires in both scenarios, differences in NOx, N_2O, and CO_2 emissions for the TEST SCENARIO are attributed to power plant operations.

7. 3.7 Gross Impact Characterization

Next, Figure 8 presents the estimated life cycle contribution to climate change for the gross assessment. These results were based on the inventory results presented in Figure 6 and Appendix D, the IPCC GWPs for CO_2, CH_4, and N_2O [6], and accounting for the carbon in chips and sawlogs as described in Section 3.5. As shown in Figure 8, the contribution to climate change is found to be less for the TEST SCENARIO and dominated by the credit given for the carbon in the chips and sawlogs and to a lesser extent by the power plant emissions.

Figure 5. Gross Life Cycle Inventory Results: Energy

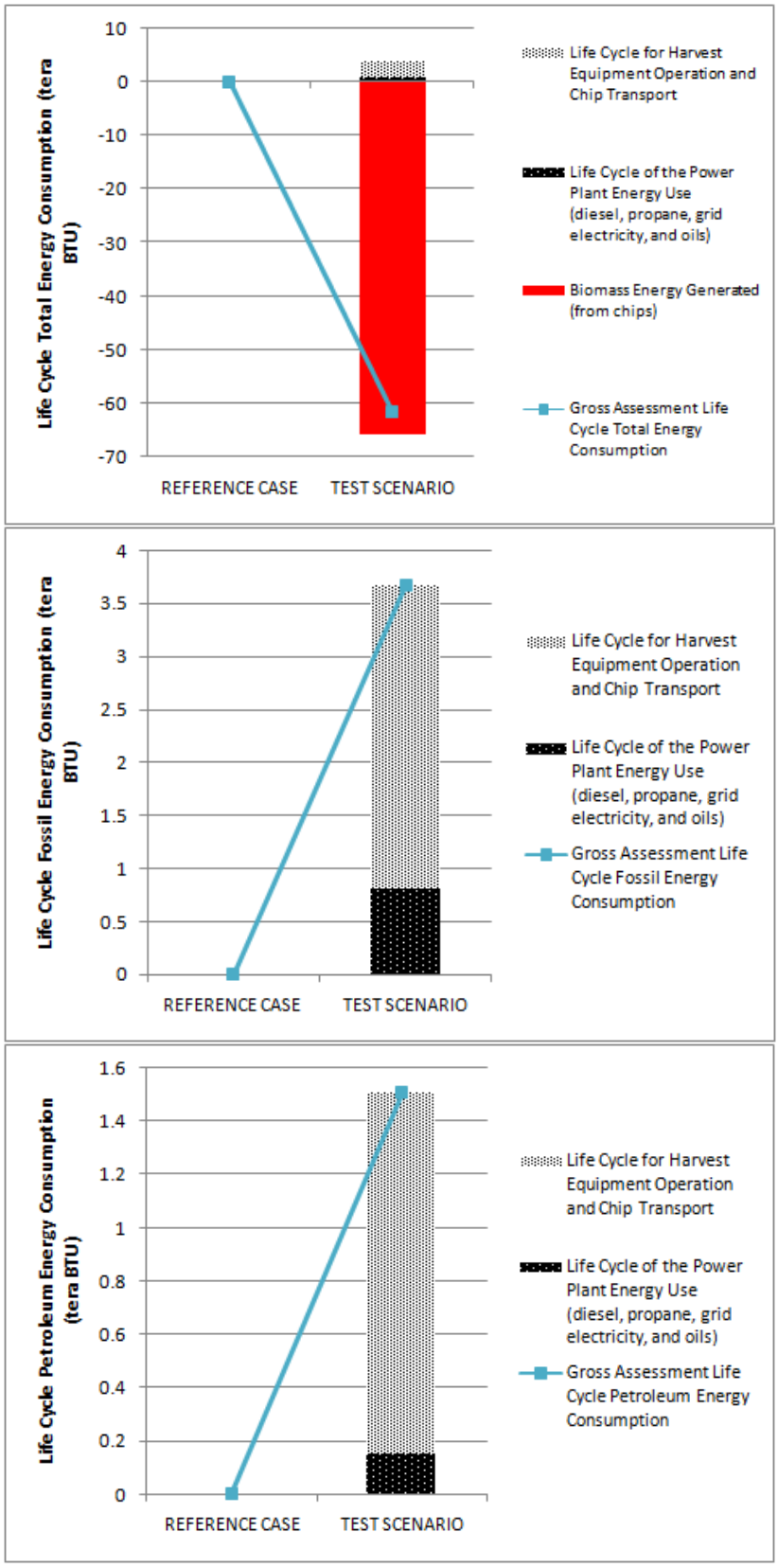
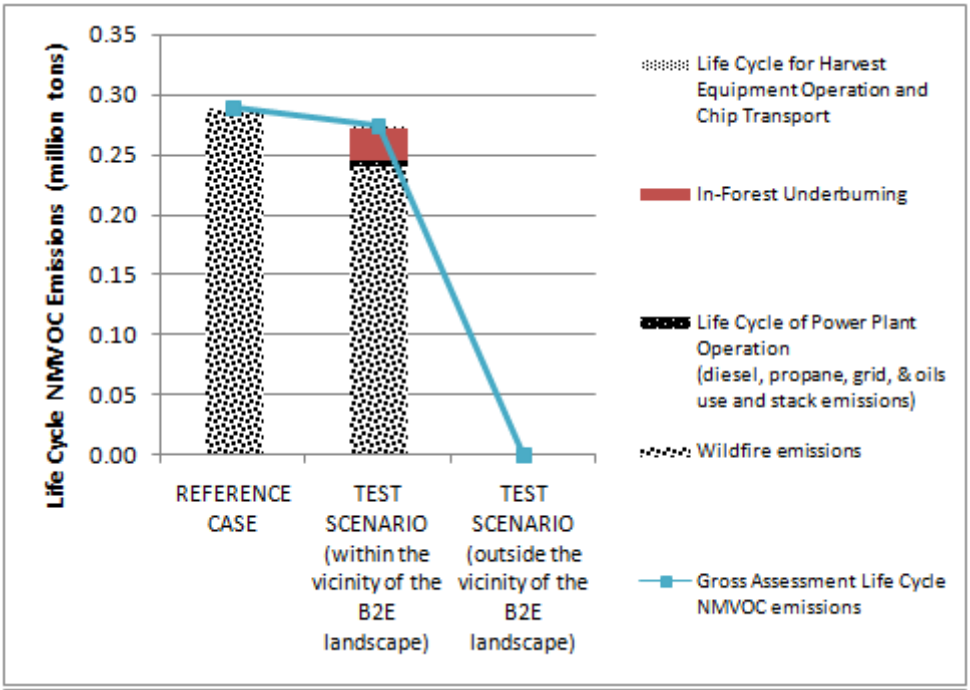


Figure 6. Gross Life Cycle Inventory Results: Emissions



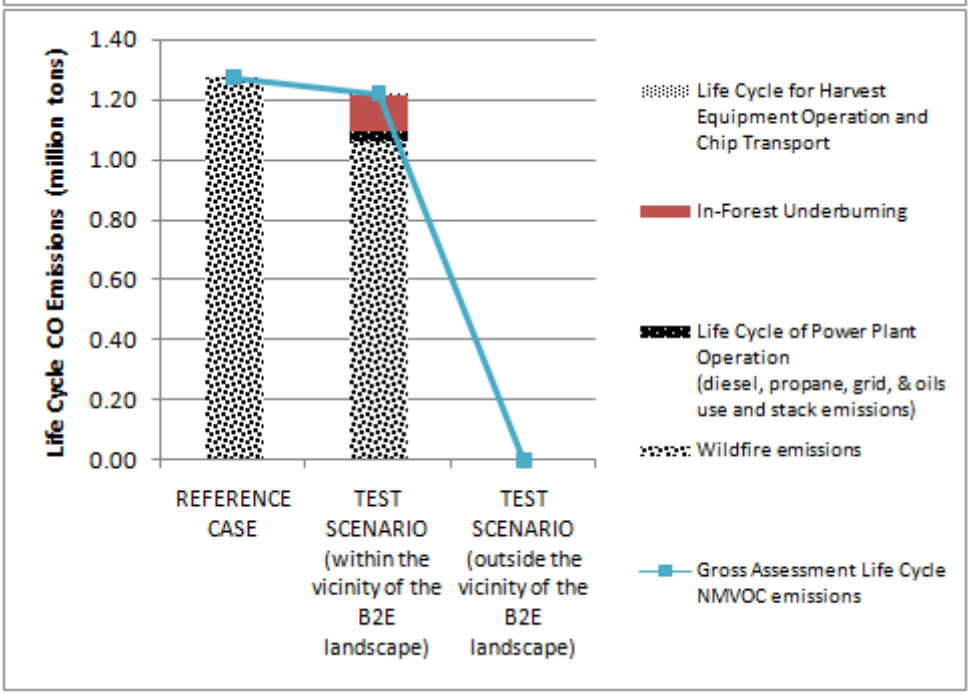
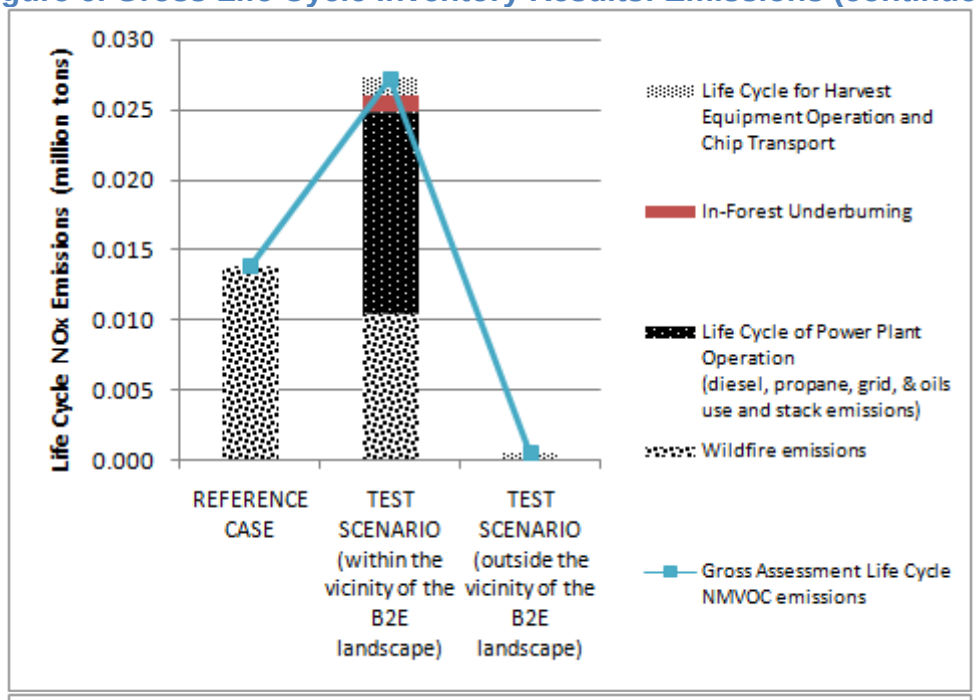


Figure 6. Gross Life Cycle Inventory Results: Emissions (continued)



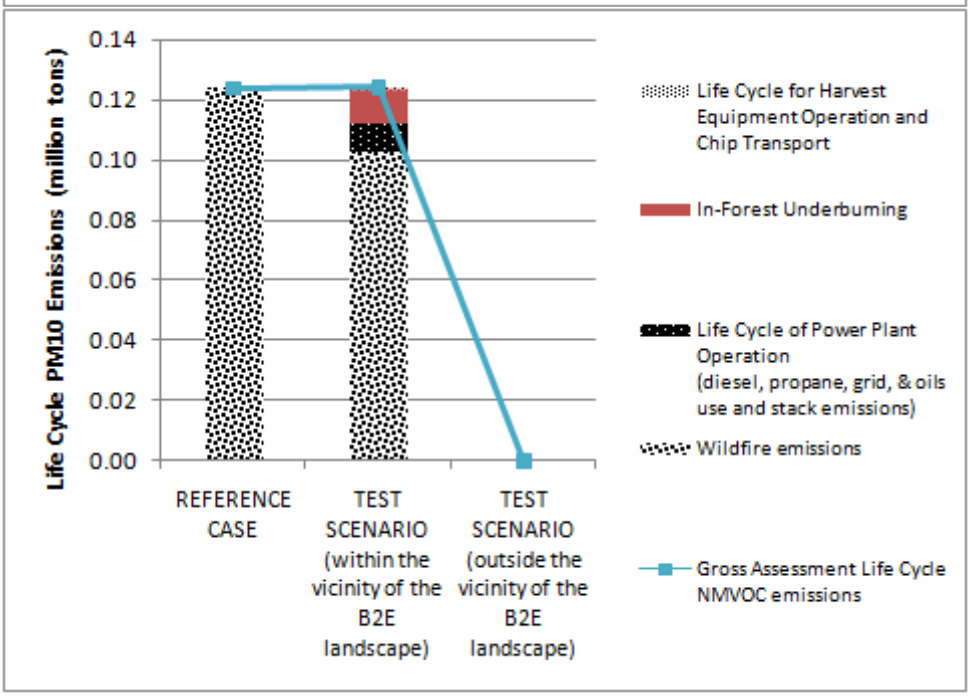
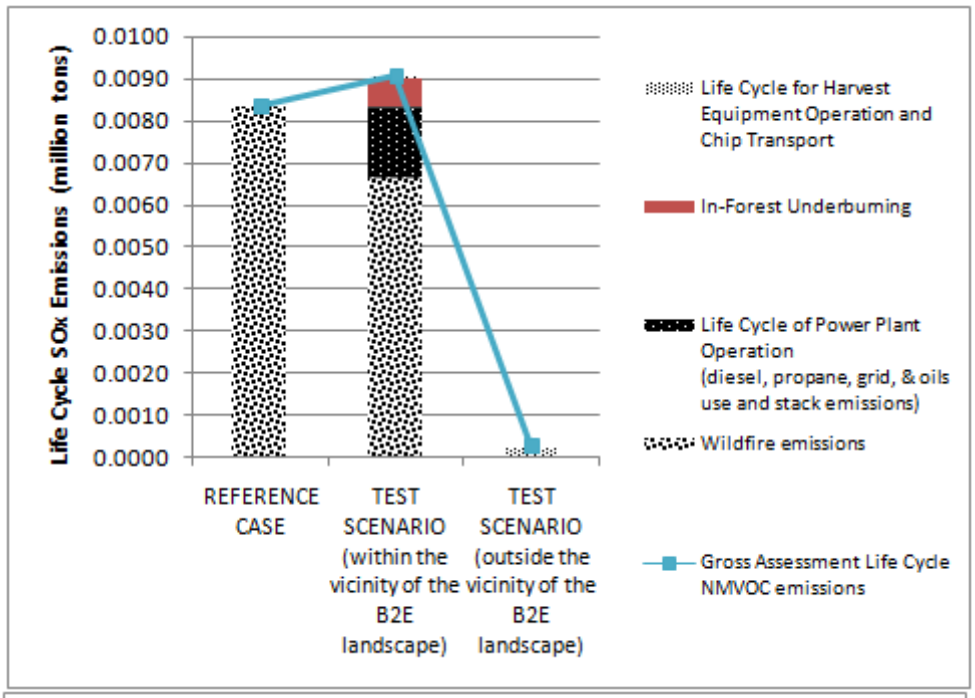


Figure 6. Gross Life Cycle Inventory Results: Emissions (continued)



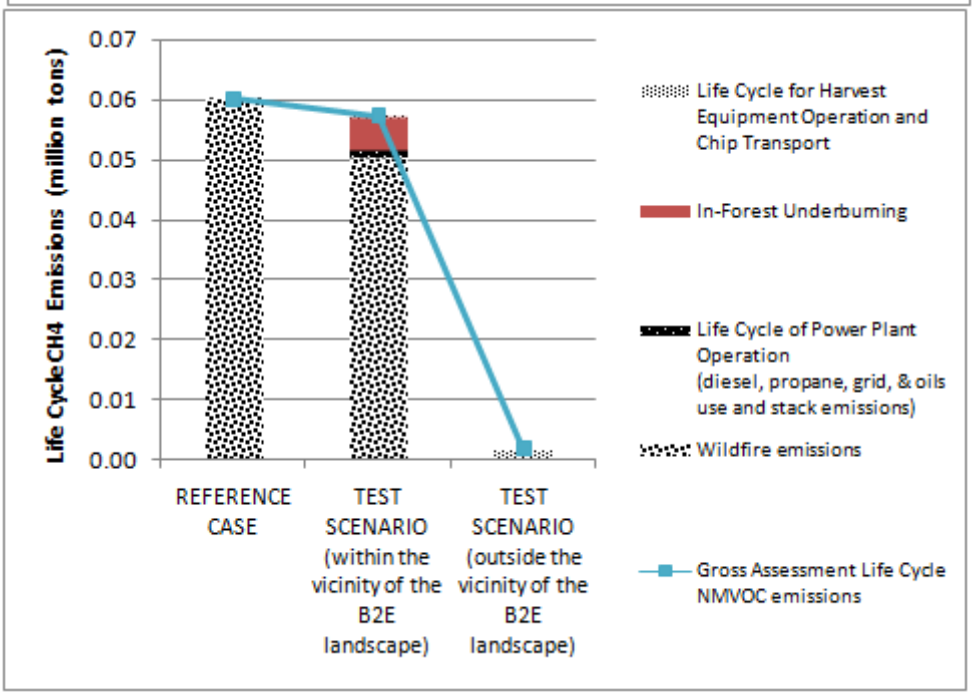


Figure 6. Gross Life Cycle Inventory Results: Emissions (continued)

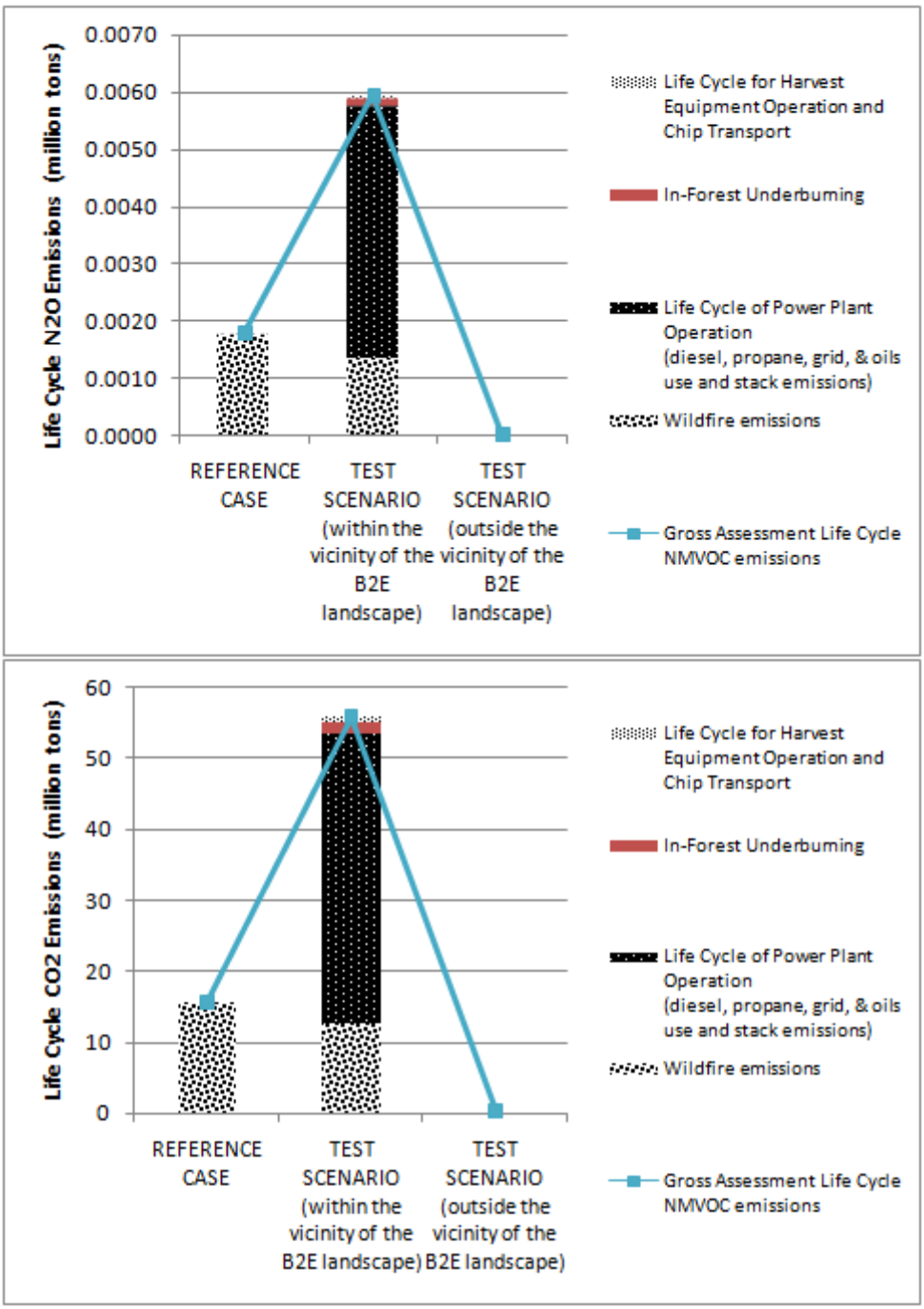


Figure 7. Gross assessment comparison of scenario emissions

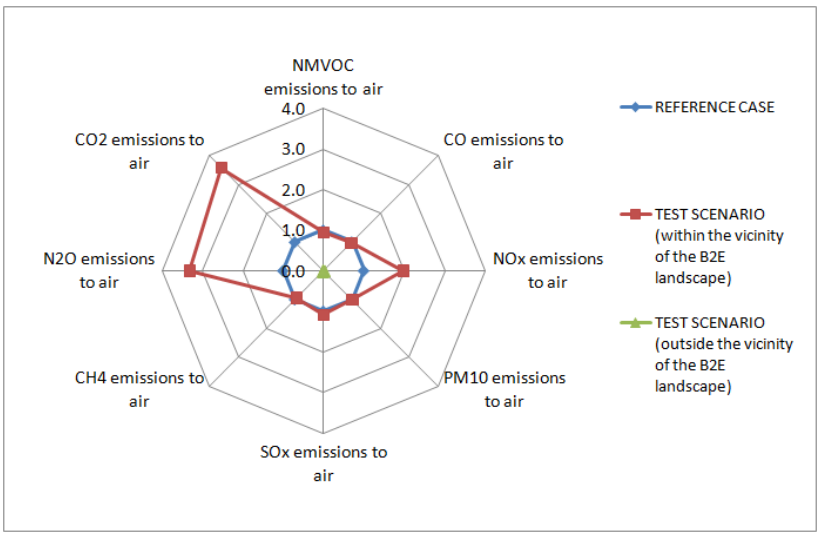
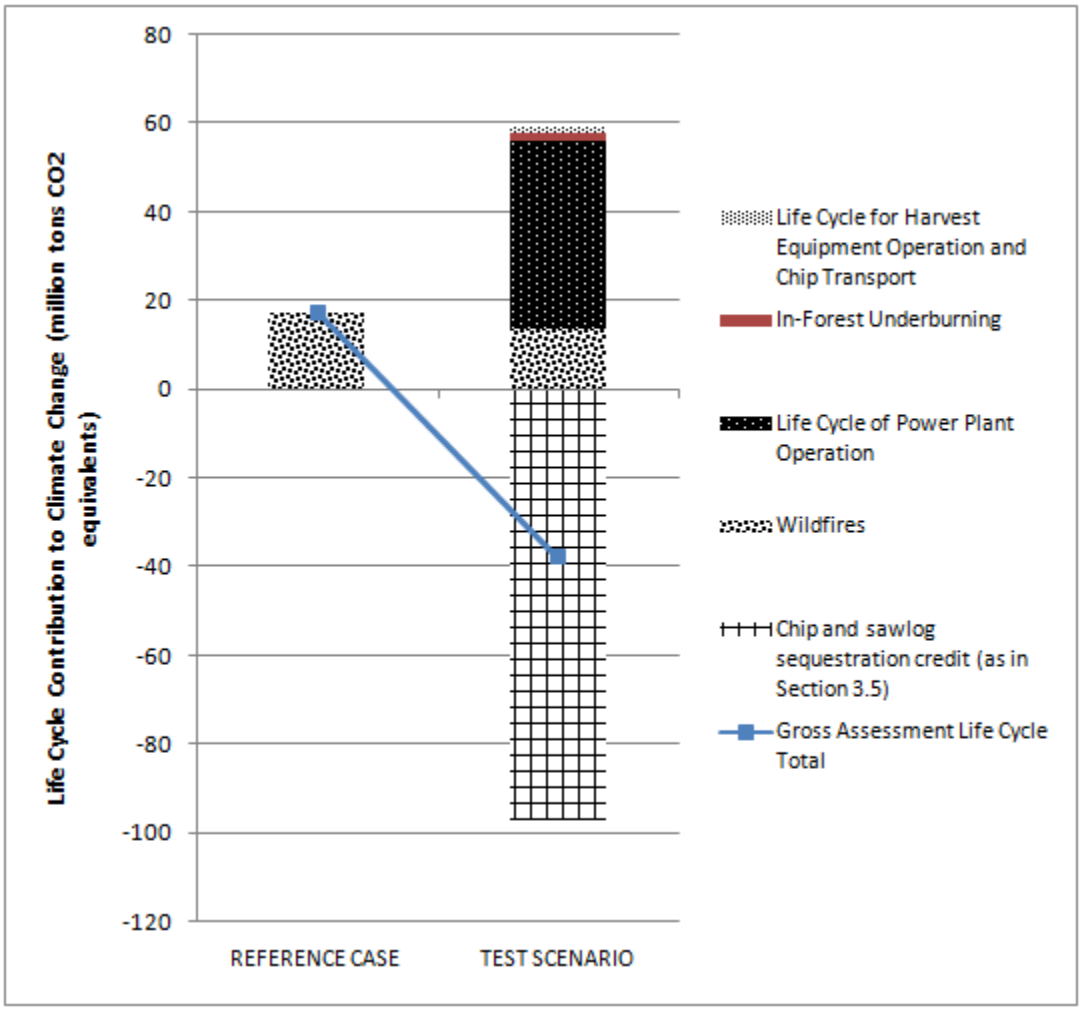


Figure 8. Gross assessment of the contribution to climate change



8. 3.8 Normalization

Finally, Table 20 presents the gross assessment energy consumption and the contribution to climate change normalized by the 40-year California contribution using the data presented in Table 3. As shown, all estimated changes are small. Specifically, the life cycle total energy is estimated to decrease the California total by 0.024% for the TEST SCENARIO and lessen the contribution to climate change by 0.26%. Otherwise, changes in values are less than ~0.02% of the California totals.

Table 20. Gross assessment normalization (as percent of California impact)

	Total energy	Fossil energy	Petroleum energy	NMVOC emissions to air	CO emissions to air	NOx emissions to air	PM10 emissions to air	SOx emissions to air (as SO2)	Climate change
REFERENCE CASE	0	0	0	0.40%	0.32%	0.016%	1.4%	0.012%	0.082 %
TEST SCENARIO	-0.024 %	0.0019 %	0.00080 %	0.38%	0.31%	0.033%	1.4%	0.014%	-0.18%

4. Interpretation

9. 4.1 Net Assessment

Again as detailed in Table 19, the gross assessment described in Section 3 presents LCA results for systems producing different products. Thus, and according to the ISO LCA standards, the REFERENCE CASE and the TEST SCENARIO in the gross assessment are not technically comparable to each other or to alternative electricity generation systems for three reasons: (1) each produces a 2.7 million-acre landscape of differing management outcomes as measured by extent and intensity of wildfire, (2) each produces different amounts of sawlogs, and (3) each produces different amounts of electricity.

In LCA terminology, the systems represented by each scenario in the gross assessment are multifunctional. A 2.7 million-acre landscape of differing management outcomes and electricity are the main products of the respective life cycle systems, depending upon the perspective of those interpreting the results. For example, those interested in electricity generation such as the Energy Commission might be interested in comparing the TEST SCENARIO to other electricity generation methods (e.g., the California grid or a natural gas power plant (NGPP)) such that the each system being compared only produces electricity. Similarly, those interested in forest management such as the U.S. Forest Service might be interested in comparing the REFERENCE CASE and the TEST SCENARIO to other forest management options in terms of extent and intensity of wildfire.

The LCA standards provide computational remedies for managing multifunctional systems. Specifically and in an LCA terminology, co-products are products produced but not used within the system boundaries. Options for the computational management of co-products in LCA [1-3] are **system expansion** (subtracting from the inventory analysis the life cycle energy use and emissions for an alternative means to produce the co-product), **allocation** (dividing the energy use and emissions among process products and co-products on the basis of the equipment applied, stoichiometry, or co-product mass, energy, or economic value), or **ignoring the co-products** (which is essentially what has been done in the gross assessment described in Section 3). System expansion is the preferred method when an alternative means to produce the co-product exists (such as another way to produce electricity or sawlogs), with most LCA practitioners using allocation when system expansion is not feasible.

The spirit of these computational remedies is to facilitate a **net or comparative assessment** (e.g., the comparison of ways to produce electricity or ways to manage the forest) by giving credit for system co-products as needed to create systems that produce only one product. For example, consider the 2 net assessments defined in Table 21[8]. While the forest management system produces a 2.7 million-acre landscape of differing management outcomes as measured by extent and intensity of wildfire, the electricity generation system produces electricity.

Table 21. Net assessment system characteristics

	Forest management systems	**Electricity generation systems**
Final product	Managed landscape	Electricity
Magnitude of service	per acre managed	per MWh
Duration of service	40 years	40 years
Expected level of performance	landscape scale fire behavior modification (for TEST SCENARIO)	continuous electricity generation
For comparison to	larger, more severe wildfires (as in the REFERENCE CASE)	electricity generation by conventional means such as using the California grid or a natural gas power plant
What needs to be done computationally	• **Remove energy use, emissions, sequestration, and impacts for sawlog production** • **Give credit for electricity generation**- e.g., by subtracting from the assessment results the life cycle energy use, emissions, sequestration, and impacts for a conventional means of electricity generation	• **Remove energy use, emissions, sequestration, and impacts for sawlog production** • **Give credit for forest management**- e.g., by subtracting from the assessment results the life cycle energy use, emissions, sequestration, and impacts for a no treatment management scenario

The assessment of each of the systems defined in Table 21 follows in Sections 4.1.1 and 4.1.2 for the comparison of forest management and electricity generation systems respectively. In both net assessments, energy use, emissions, credit given for the carbon embodied in sawlogs, and impacts for sawlog production were removed from the gross assessment results using allocation, because system expansion was deemed unfeasible in the absence of a viable process to only generate sawlogs ("sawlog only harvesting" is rarely applied today [26]). To remove sawlogs from the assessment, the harvest and chip transport equipment were first grouped as dedicated to chip production, dedicated to sawlog production, or dedicated to both. Next, fuel and oil use and emissions for chips were estimated to include that for equipment dedicated to chips and that for equipment dedicated to both chips and sawlogs, with the latter mass allocated to the amount of sawlogs produced. Thus, a combination of process-based and mass allocation was used in each net assessment. In addition to the removal of sawlog related flows and impacts, the comparison of forest management systems presented in Section 4.1.1 includes credit for biomass electricity generation and the comparison of electricity generation systems presented in 4.1.2 includes credit for wildfire reductions and increased growth resulting from treatment.

4.1.1 Comparing forest management systems

Based on the gross assessment results less the benefits and impacts of sawlog production, a comparison of forest management systems as defined in Table 21 was performed with one additional computational consideration. Specifically, the life cycle flows and impacts for electricity generated by conventional means (using a NGPP or the California grid), equal in amount to that generated in the TEST SCENARIO, was subtracted from the sawlog adjusted gross assessment results (i.e., **electricity generation is being avoided**).
Figure 9 and Figure 10 present both the gross and net results, with the net results subtracting the life cycle energy use and emissions of a 2006 NGPP (as presented in Appendix B) from the

[8] Table 21 essentially presents a comparative LCA's functional units.

gross results. As shown, some of the trends seen in the gross assessment have changed in the net assessment. Specifically, whereas the net results still favor the TEST SCENARIO for total energy consumption (to a greater extent), the net results show treatment to be an improvement over no-treatment for fossil and petroleum energy consumption, a result that is contrary to that seen in the gross assessment. As in the gross assessment, the TEST SCENARIO results show an improvement for NMVOCs and CO, which are both dominated by the wildfire emissions, and similar results for both scenarios for PM10. Contrary to the gross assessment, an improvement for SOx which is dominated by the wildfire emissions and the credit given for avoided electricity generation and NOx emissions are found to be about the same for the REFERENCE CASE and TEST SCENARIO. Finally, although the net results show a contribution to climate change that is less for the TEST SCENARIO than for the REFERENCE CASE, the benefit is estimated to be slight and less than that estimated in the gross assessment because of the removal of the credit for the carbon embodied in the sawlogs.

Figure 9. Forest Management System Net assessment: Energy

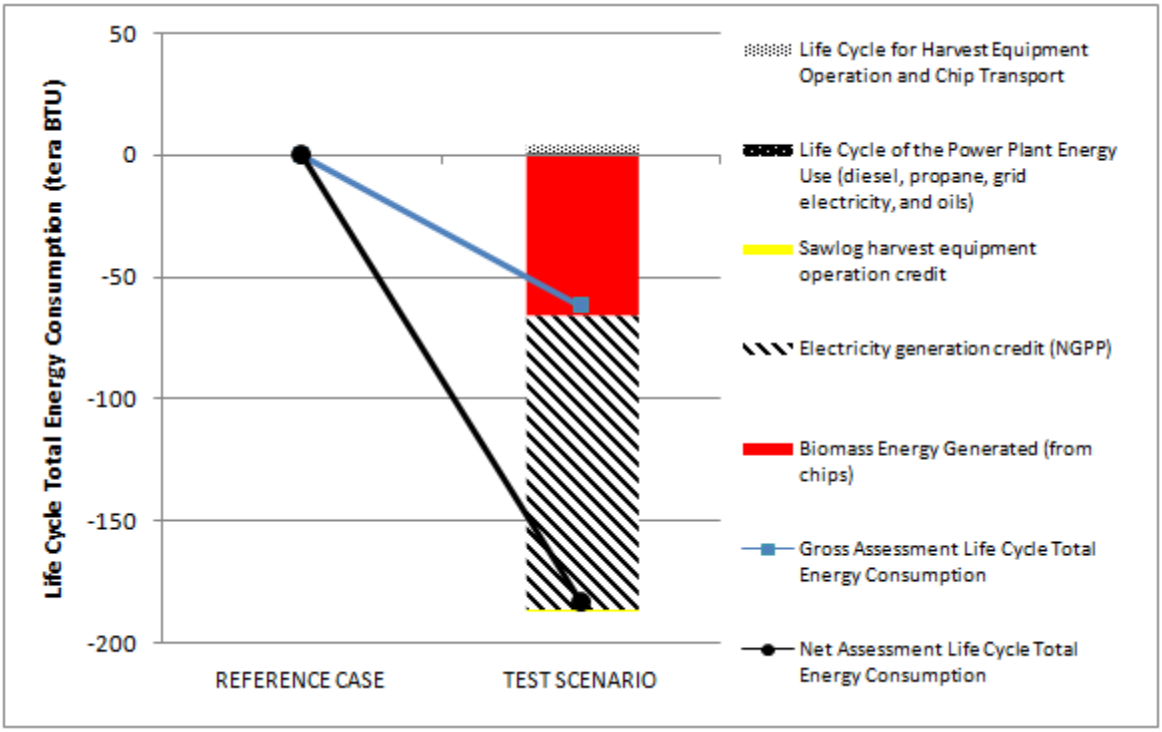
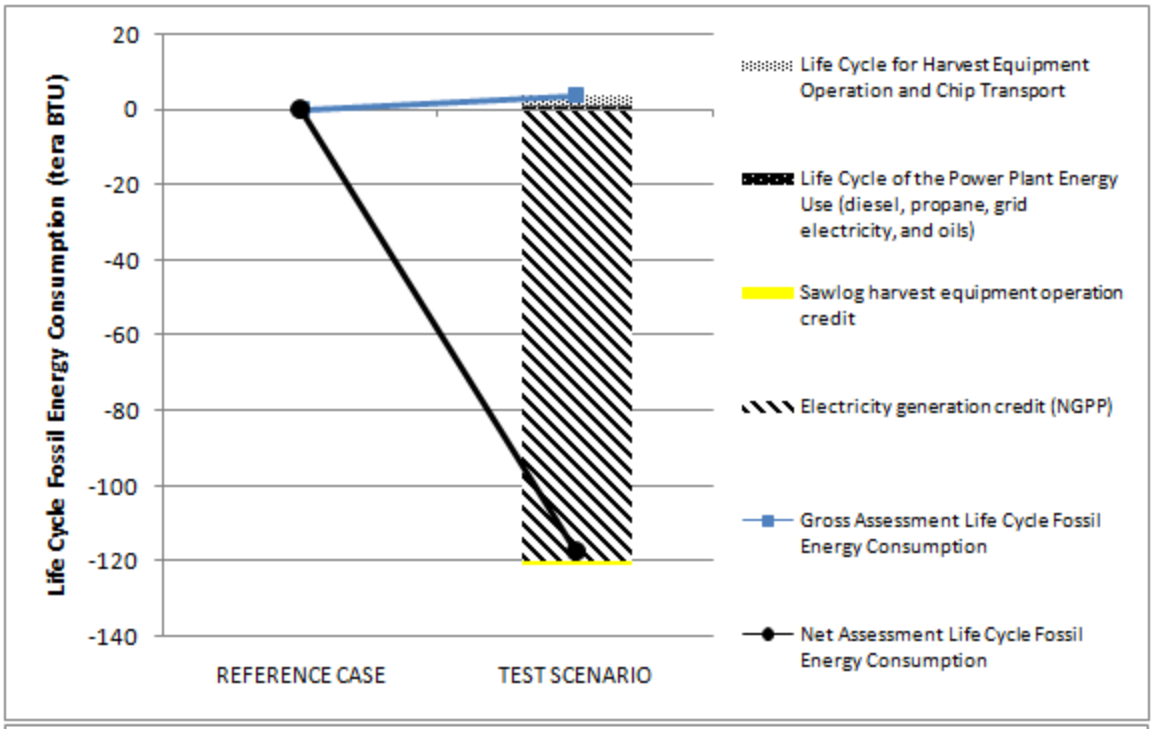


Figure 9. Forest Management System Net assessment: Energy (continued)



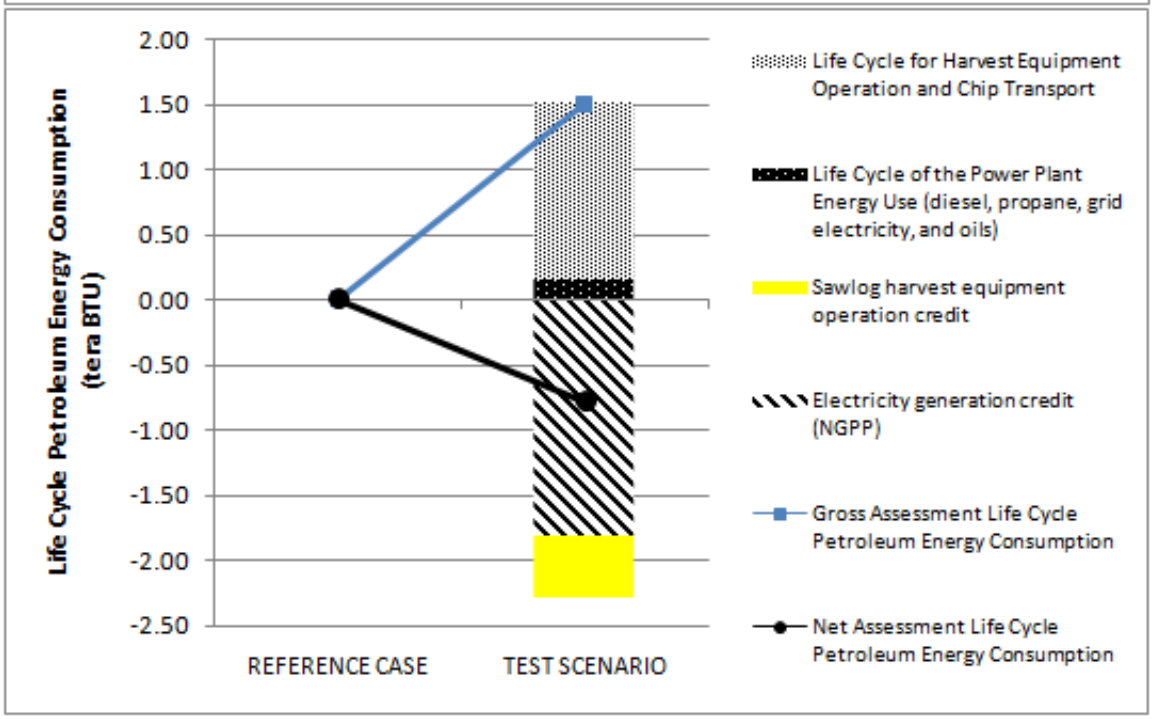


Figure 10. Forest Management System Net assessment: Emissions

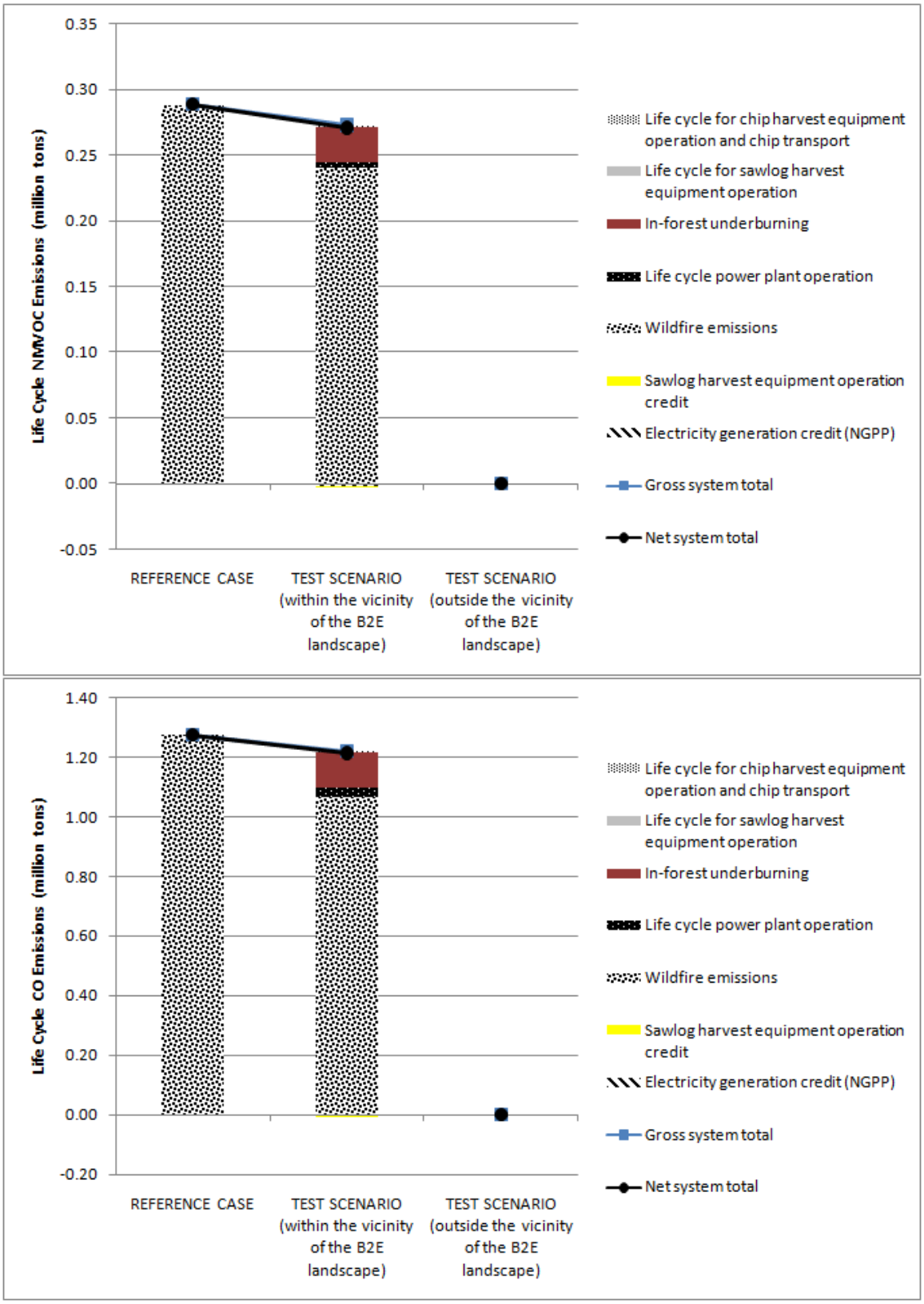
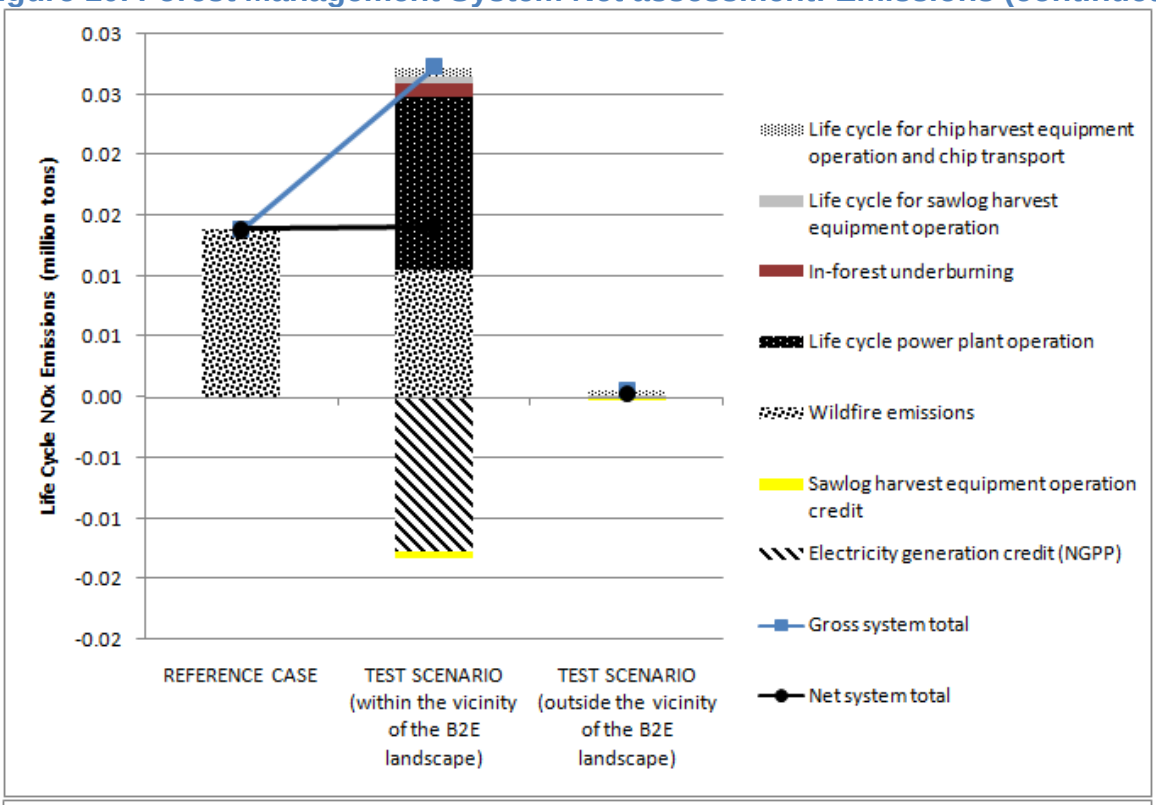


Figure 10. Forest Management System Net assessment: Emissions (continued)



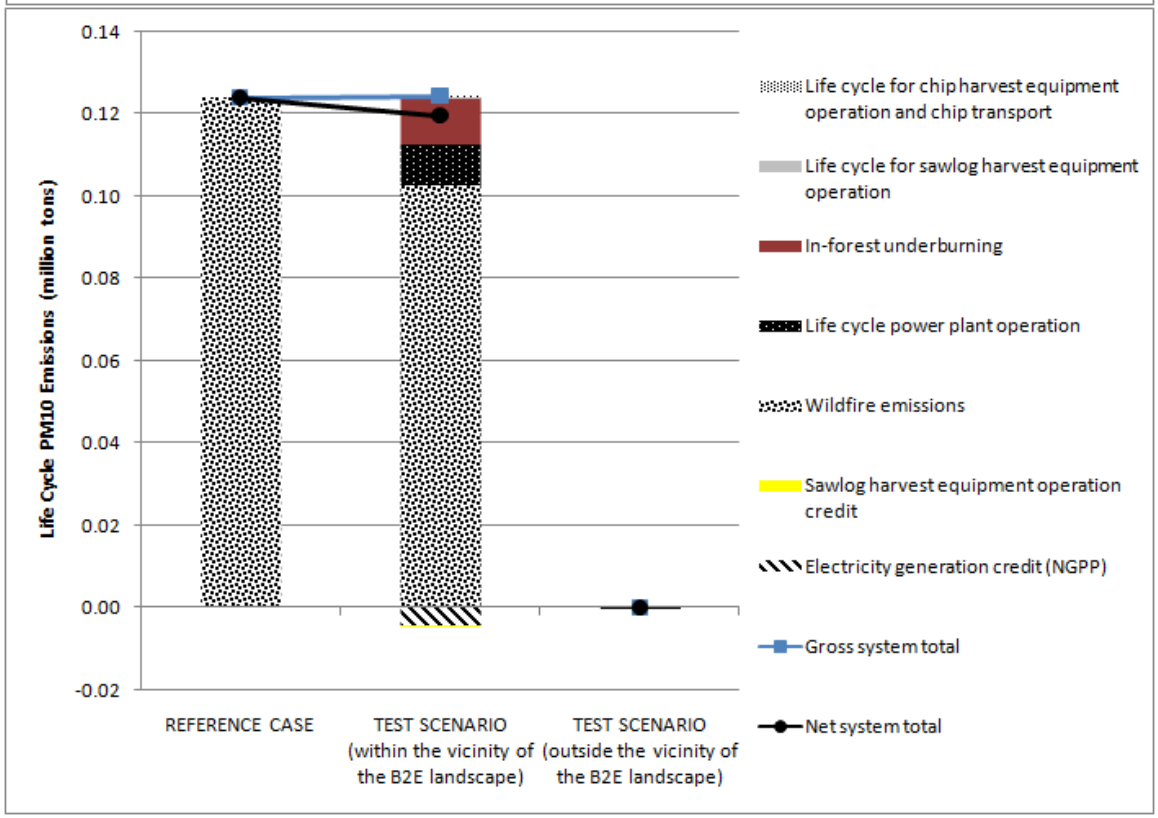


Figure 10. Forest Management System Net assessment: Emissions (continued)

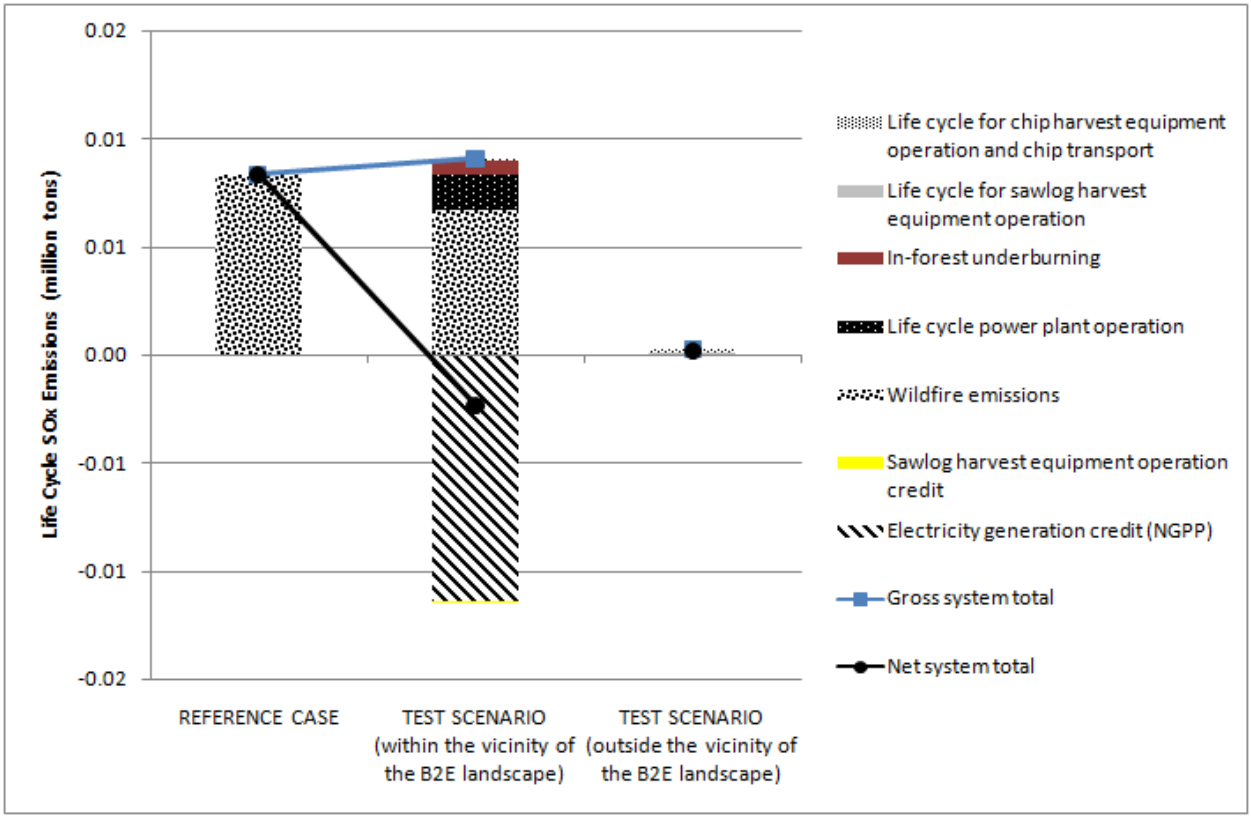
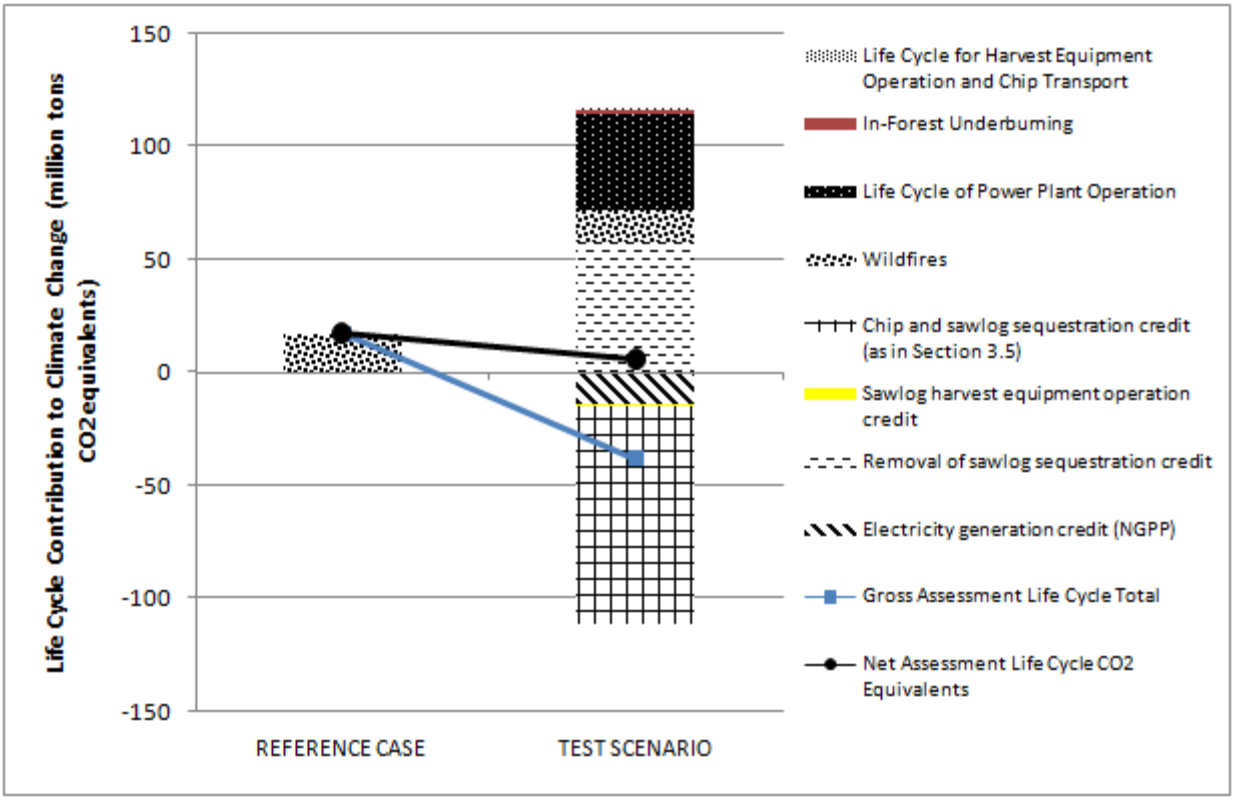


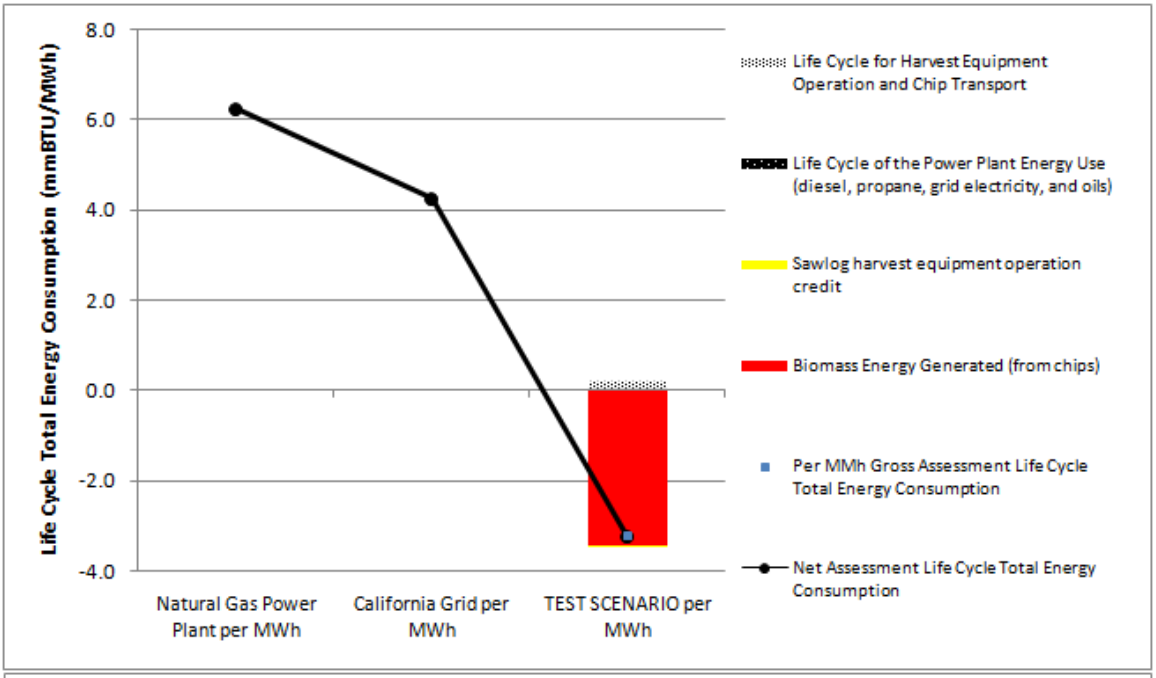
Figure 11. Forest Management System Net assessment: Contribution to Climate Change



4.1.2 Comparing electricity generation systems

Again based on the gross assessment results less the benefits and impacts of sawlog production, a comparison of electricity generation systems as defined in Table 21 was performed, again with one additional computational consideration. Specifically, the life cycle wildfire emissions from the REFERENCE CASE were subtracted from the sawlog adjusted gross assessment results, this time to represent the net benefit of treatment (i.e., **wildfires are being avoided**). Figure 12 and Figure 14 present both the gross and net results, in comparison to the life cycle energy use, emissions, and the contribution to climate change for the life cycle of a NGPP and the California grid. The results are very similar to those for the net forest management system.

Figure 12. Electricity Generation System Net assessment: Energy



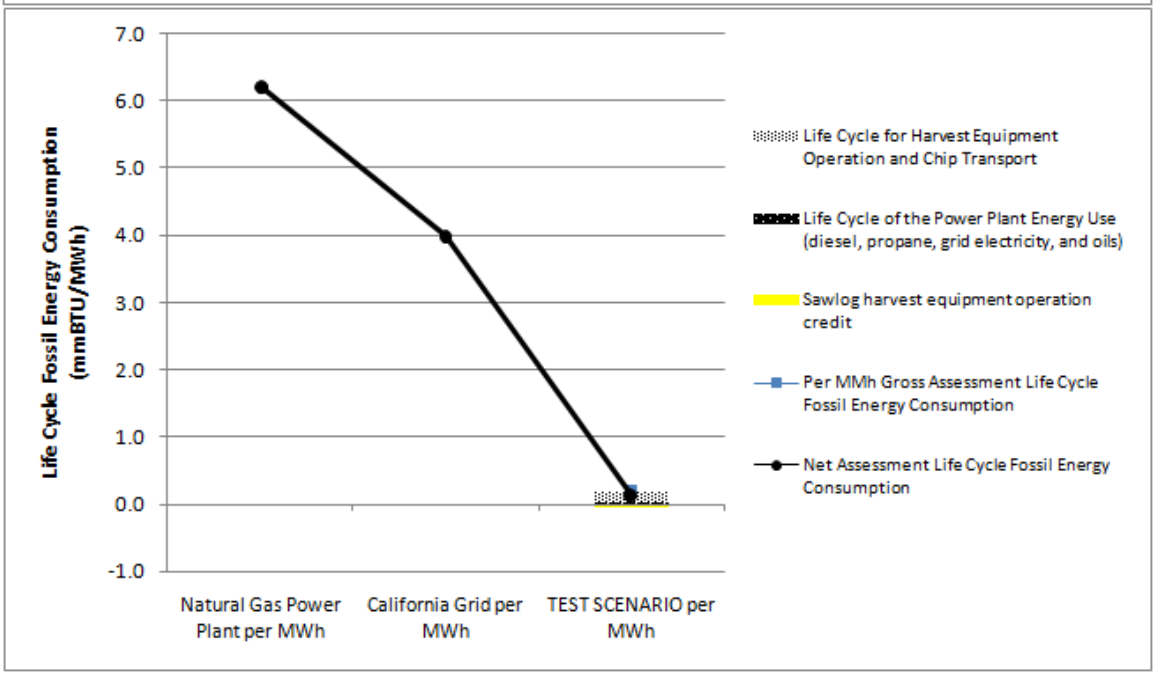


Figure 12. Electricity Generation System Net assessment: Energy (continued)

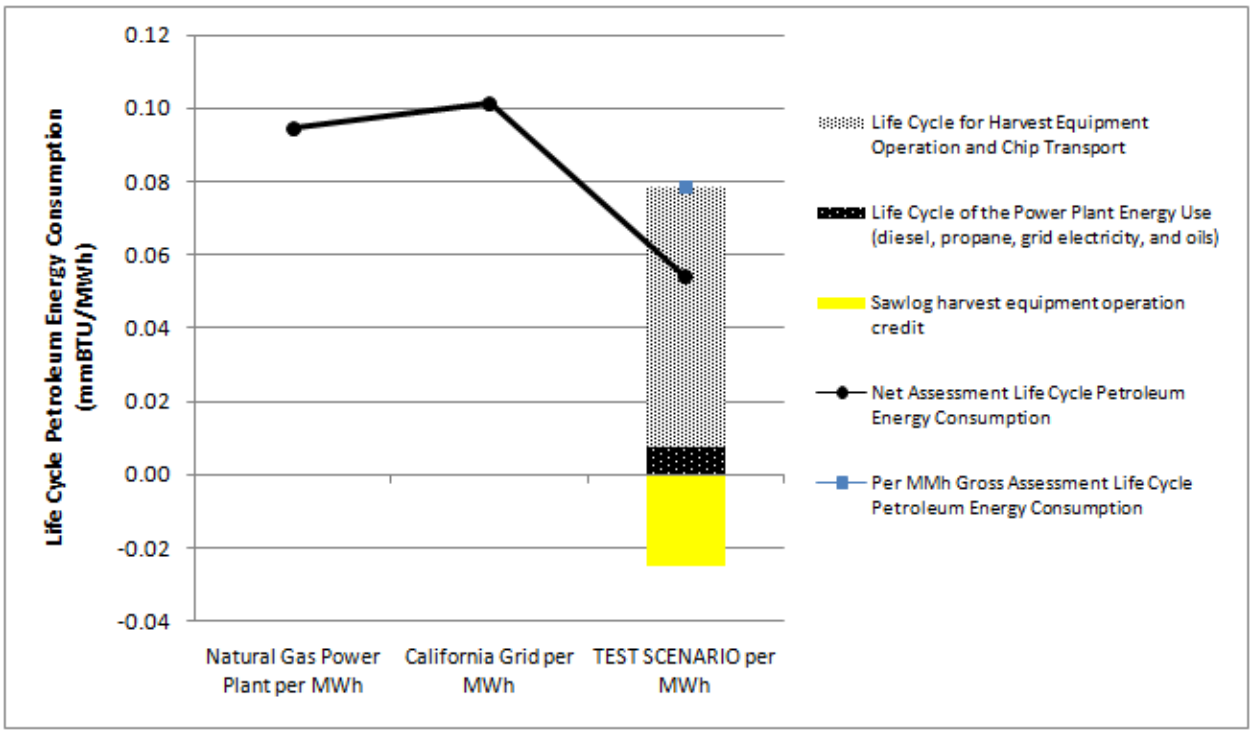


Figure 13. Electricity Generation System Net assessment: Emissions

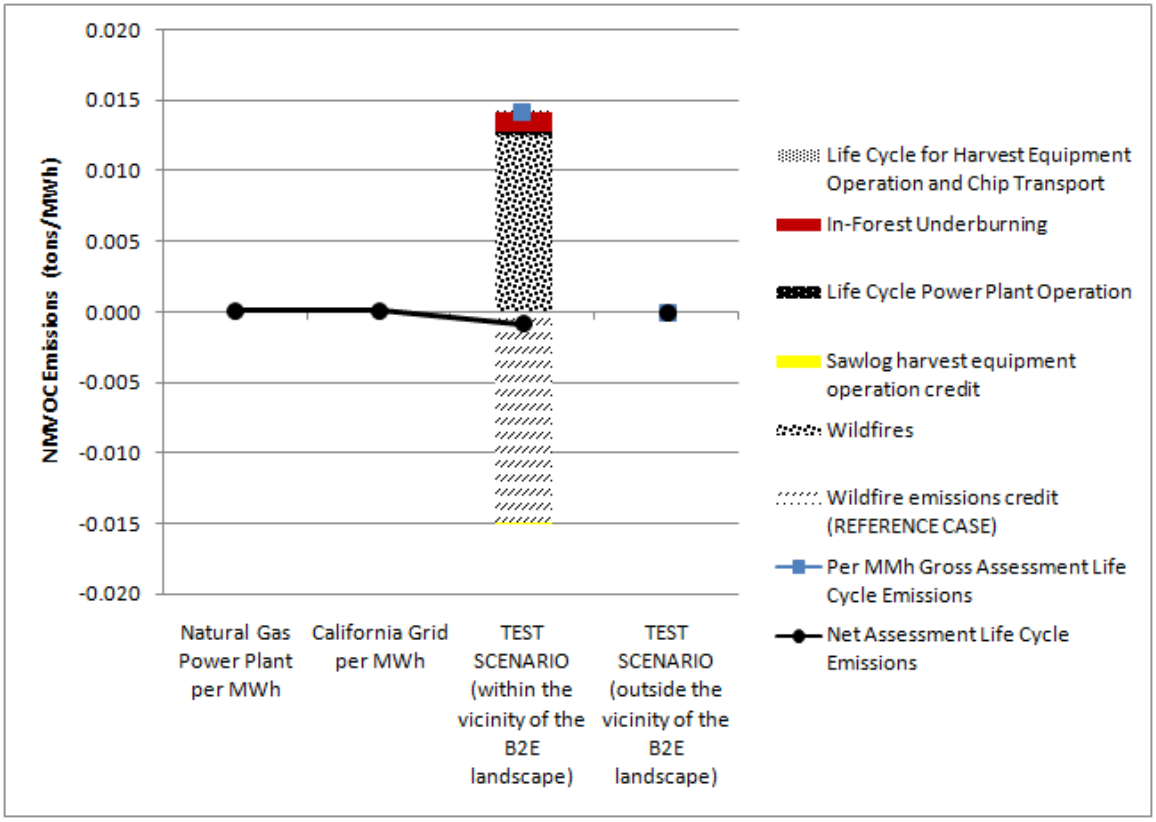


Figure 13. Electricity Generation System Net assessment: Emissions (continued)

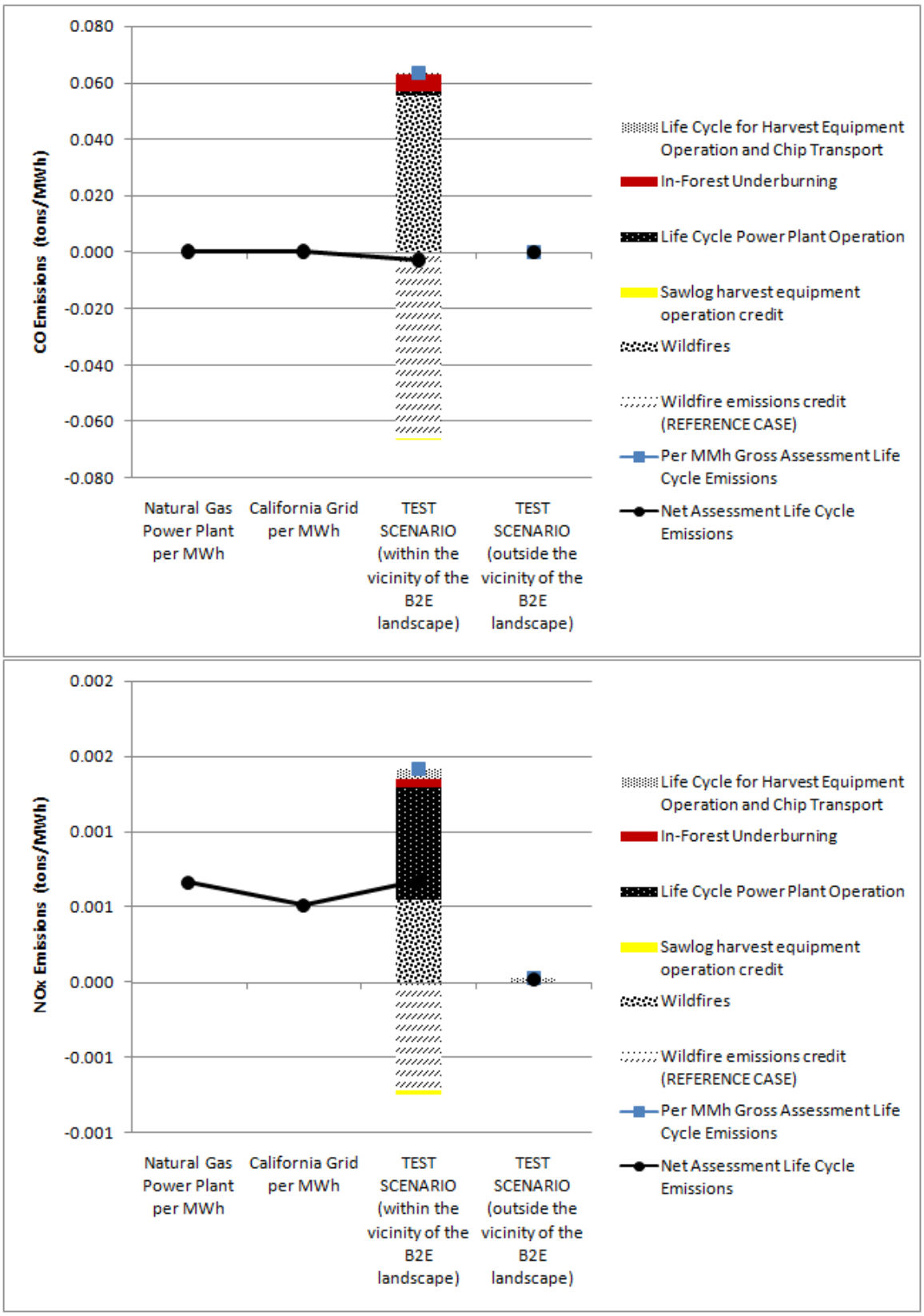


Figure 13. Electricity Generation System Net assessment: Emissions (continued)

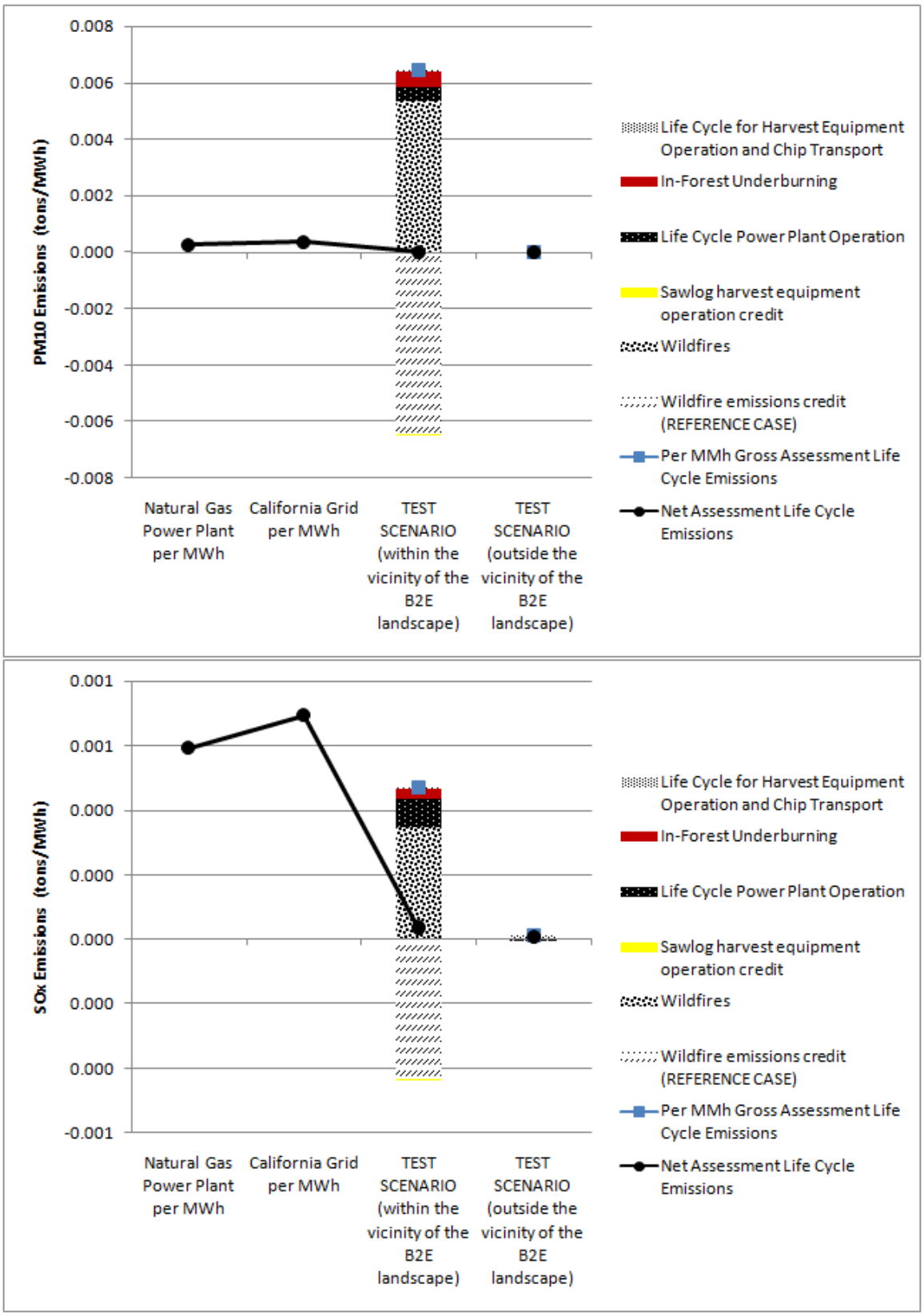
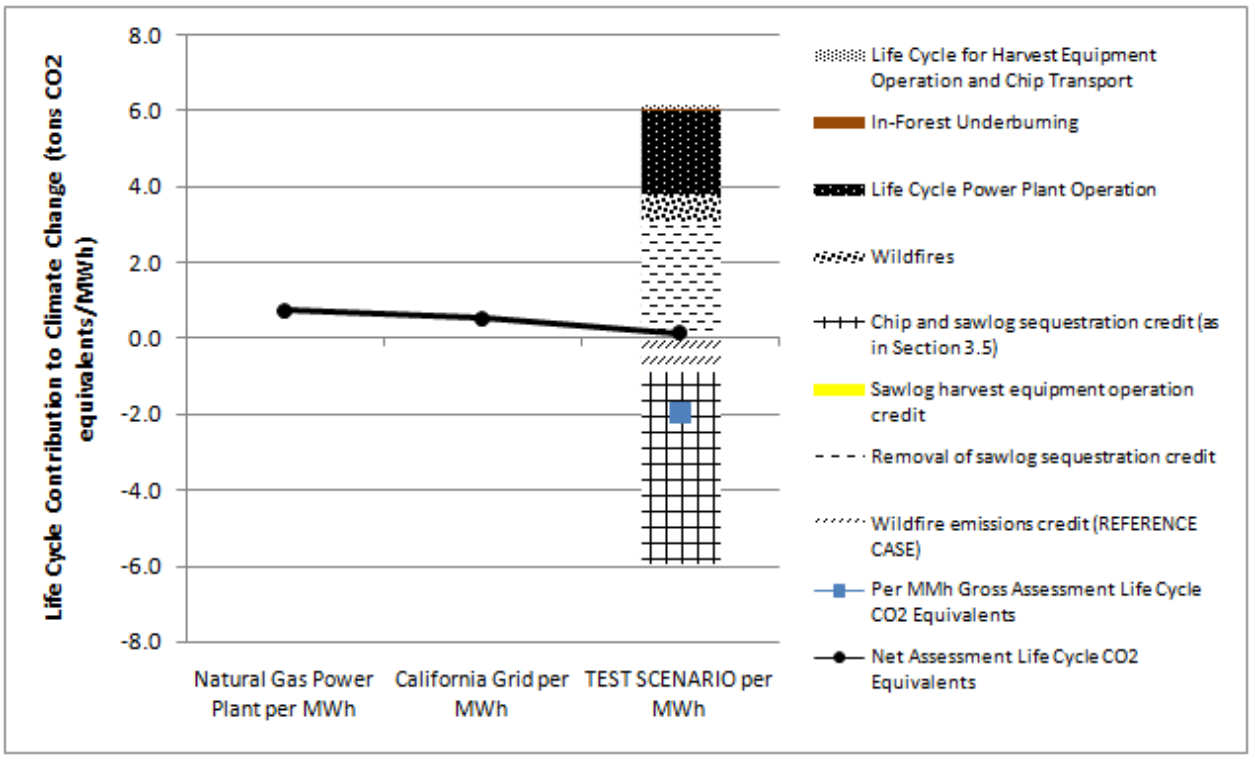


Figure 14. Electricity Generation System Net assessment: Contribution to Climate Change



10. 4.2 Assessment of Carbon Flows

Although the gross and net assessments described above gave credit for carbon embodied in the biomass removed from the forest as sawlogs and chips, forest growth, litter decomposition, and soil processes were not considered. The Intergovernmental Panel on Climate Change (IPCC) [27] provides guidance on terminology and what should be included when modeling carbon cycling on land. Specifically, carbon fixed by photosynthesis is called gross primary production (GPP). Plant respiration releases CO_2 to the atmosphere, reducing GPP to net primary production (NPP) and resulting in short-term carbon uptake. Decomposition of litter and soils in excess of that resulting from disturbance, further releases CO_2 to the atmosphere, reducing NPP to net ecosystem production (NEP) and resulting in medium-term carbon uptake. NEP less the impact of disturbances from harvest, forest clearance, and fire, etc. is called Net Biome Production (NBP), intended to represent the net production of organic matter in a region containing a range of ecosystems (a biome) over the long-term. Thus,

$GPP - R_{plant} = NPP$ for short-term carbon uptake

$NPP - d_{l\text{-}s} = NEP$ for medium-term carbon uptake

$NEP – D_{h\text{-}f} = NBP$ for long-term carbon uptake

where:

GPP = gross primary production (mass carbon/year)

R_{plant} = plant respiration (mass carbon/year)

NPP = net primary production (mass carbon/year)

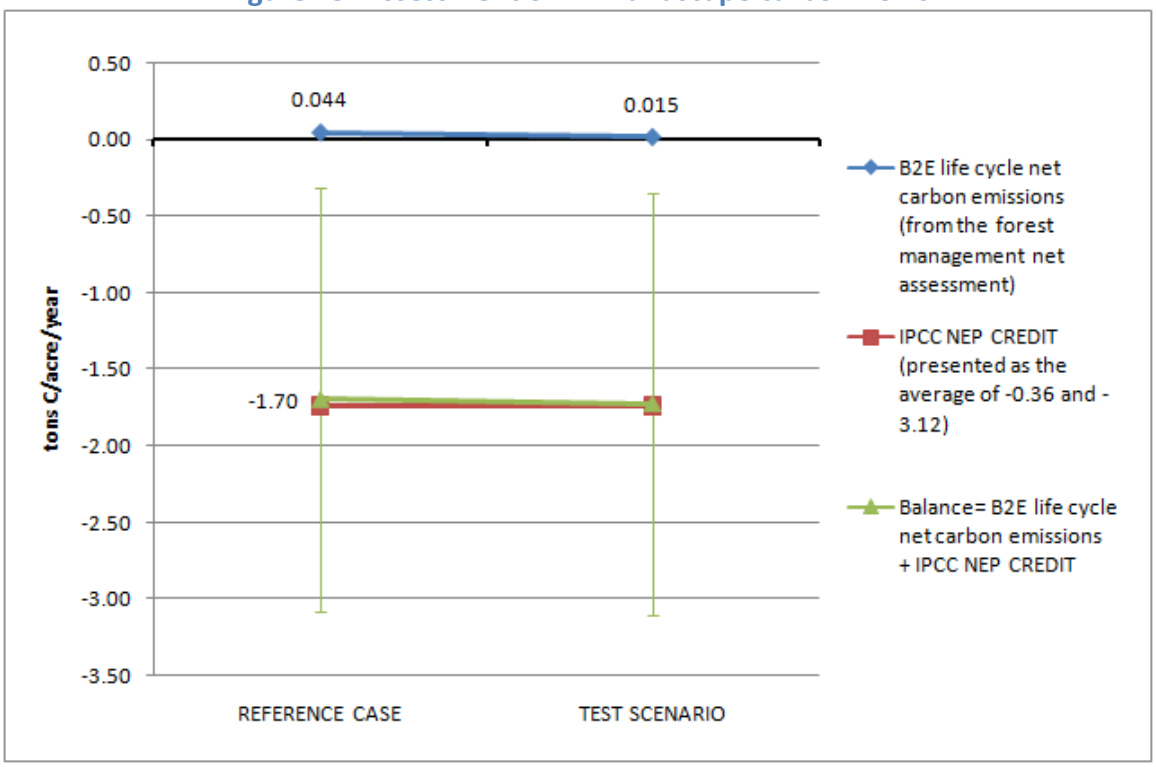
$d_{l\text{-}s}$ = decomposition of litter and soils (mass carbon/year)

$D_{h\text{-}f}$ =disturbance (in the B2E project, as in that from harvest, underburning, and wildfires)

NBP = net biome production

For temperate forests, the IPCC estimates that annual NEP flow measurements are in the range of 0.36 to 3.12 tons C/acre/year (or 0.8 to 7.0 MgC/ha/year). Figure 15 considers this within the context of the net forest management system, with the net climate change emissions from Figure 11 converted to tons C/acre/year for the 2.7 million acre landscape on average for each of the 40 years. When the B2E system emissions were combined with the IPCC NEP and even when the range of IPCC temperate forest NEP values were considered, the REFERENCE CASE and the TEST SCENARIO provided a net carbon benefit. Further, although the "balance" presented in Figure 15 can be considered life cycle-based approximation of NBP (again, the Net Biome Production representing long term carbon storage), it is lacking consideration of the carbon fluxes for disturbances.

Figure 15. Assessment of B2E landscape carbon flows



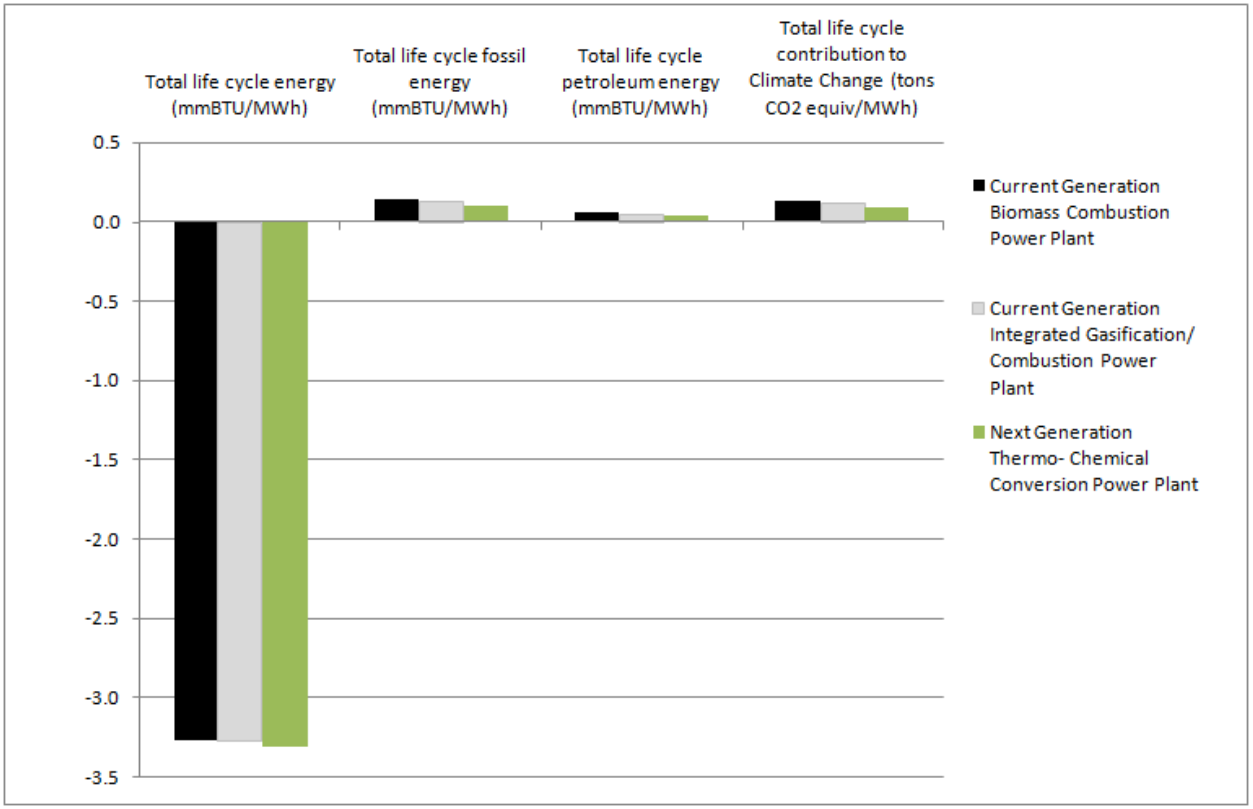
11. 4.3 Assessment of Alternative Power Plant Technologies

In Figure 9 and Figure 12, life cycle energy is dominated by the biomass electricity generated, again ultimately reflecting the power plant efficiency. Given this, Table 22 provides alternative power plant characterizations for a current generation integrated gasification/ combustion power plant and a next generation thermo- chemical conversion power plant as described in Nechodom, et al. [24]. In all cases, the supporting equipment energy use and emissions were assumed to be consistent with that of the current generation combustion plant characterized in Table 15, with the exception of the use of gate grease, which was assumed only to be applicable in operations at the combustion plant. Again Appendix C presents the inventory data used for the biomass power plant, also considering the species make-up (Table 14) and the heating values (Table 16) based on data provided by the "Fire Behavior Assessment" [19] and assuming an 8% transmission loss. The results are presented in Figure 16, showing improvements on all points.

Table 22. Alternative power plant characterizations

	Current Generation Integrated Gasification/ Combustion Power Plant	Next Generation Thermo- Chemical Conversion Power Plant
Electricity (kWh/dry ton)	1,200	1,400
Plant Energy Efficiency	22%	28%
Plant Emissions (lbs/mmBTU output)		
NO_x	0.067	0.0084
SO_x	0.010	0.0016
PM	0.030	0.032
CO	0.070	0.042
NMVOC	0.018	0.0031
CO_2	890	690
CH_4	19	19
N_2O	0.065	0.065

Figure 16. Assessment of power plant alternatives for the TEST SCENARIO



12. 4.4 Data quality analysis

An analysis of data quality is presented in Appendix F, as required by the ISO LCA standards. Both the scoring method used and the results are included. As shown in Appendix F, all LCA data sources were of **high data quality with respect to geographical coverage (indicator 2), technology coverage (indicator 3), and reproducibility of the methods used throughout the LCA (indicator 6).** Alternatively, all LCA data sources were of **low data quality** for

- Time-related coverage (indicator 1): based on uncertainty from the projection of impacts over the 40-year study period;
- Precision and uncertainty of the data, and completeness and representativeness of the data (indicator 4): based on the omission of uncertainty analysis as part of the LCA; and

- Completeness and representativeness of the data (indicator 5): again reflecting the low data quality for time-related coverage.

Just below high and mixed data quality were found for the remaining indicators (sources of the data and their representativeness, and consistency of the analysis- indicators 7-8).

5. Discussion

A summary of the gross and net assessments is presented in Table 23. Essentially, moving from the gross to net assessments defined the contribution of sawlogs vs. chips and introduced considerations of conventional electricity generation into comparisons. Since both are relevant to decision making related to B2E systems, both are relevant to the assessment. Given this, important among the results are how they might be used to inform continuing research in forest biomass to energy systems. The following observations result from the experience of connecting models in support of LCA and are intended to provide a starting place for continuing and related research.

1. **Net assessment orders-of-magnitude observations provide insights for decision making and a starting place for future assessments.** Order-of-magnitude estimates, gained for example by inspection of Figure 9 through Figure 16. Specifically, how the TEST SCENARIO compared to the REFERENCE CASE or to conventional electricity generation systems is noted where there were visible differences in the results, as follows:
    - The TEST SCENARIO provides a net benefit for total energy consumption and reduces fossil and petroleum consumption when compared to the REFERENCE CASE. Also, whereas the B2E power plant efficiency is critical to the overall energy balance, the consumption of fossil and petroleum fuels during harvest, chip transport, or power plant operation play a less important role.
    - The TEST SCENARIO results show an improvement for NMVOCs, CO, and SOx when compared to the REFERENCE CASE. Alternatively, little difference is seen in NOx and PM10 emissions.
    - Forest processes related to photosynthesis, plant respiration, decomposition of litter and soils, despite the uncertainty in estimates, are the most important to understanding NBP. If trying to optimize the B2E system, the carbon embodied in what is removed from the forest and the power plant efficiency is important. Further and within the context of optimizing forest bioproduct systems development, herein sawlog carbon dominated the net results. If the chips had been used, for example, to make composite wood products instead of released in the short-term by the power plant, further benefit is expected, as presented in Figure 17.

Table 23. Gross and net results summary

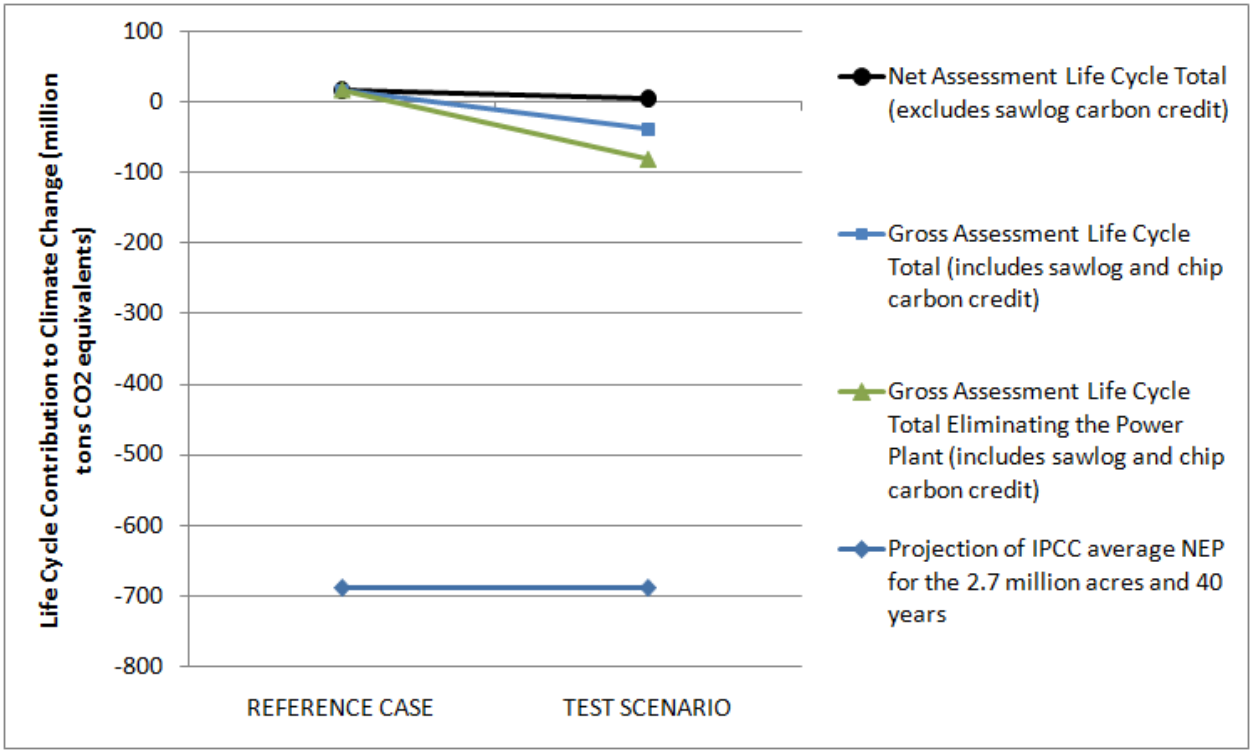
		Gross assessment (a)		Forest Management Comparative LCA (b)		Electricity Generation Comparative LCA (c)		
		REFERENCE CASE	TEST SCENARIO	REFERENCE CASE	TEST SCENARIO	NGPP	Cal grid	TEST SCENARIO
Sawlog production (million tons)	total life cycle	0	3.1E+01	0	0	0	0	0
Electricity generation (MWh)		0	1.9E+07	0	0	1	1	1
Total energy (tera BTU)		0	-6.2E+01	0	-1.8E+02	6.3E-06	4.2E-06	-3.3E-06
Fossil energy (tera BTU)		0	3.7E+00	0	-1.2E+02	6.2E-06	4.0E-06	1.4E-07
Petroleum energy (tera BTU)		0	1.5E+00	0	-7.8E-01	9.4E-08	1.0E-07	5.4E-08
Climate change (million tons)		1.7E+01	-3.8E+01	1.7E+01	5.9E+00	7.3E-07	5.2E-07	1.3E-07
NMVOC emissions to air (million tons)	within the vicinity of the B2E landscape	2.9E-01	2.7E-01	2.9E-01	2.7E-01	0	0	-8.3E-10
	outside the vicinity of the B2E landscape	0	1.5E-04	0	9.5E-05	8.6E-11	5.6E-11	4.9E-12
	total life cycle	2.9E-01	2.7E-01	2.9E-01	2.7E-01	8.6E-17	5.6E-17	-8.3E-10
CO emissions to air (million tons)	within the vicinity of the B2E landscape	1.3E+00	1.2E+00	1.3E+00	1.2E+00	0	0	-2.9E-09
	outside the vicinity of the B2E landscape	0	2.0E-04	0	1.3E-04	3.0E-10	2.0E-10	6.9E-12
	total life cycle	1.3E+00	1.2E+00	1.3E+00	1.2E+00	3.0E-16	2.0E-16	-2.9E-09
NOx emissions to air (million tons)	within the vicinity of the B2E landscape	1.4E-02	2.7E-02	1.4E-02	1.4E-02	0	0	6.7E-10
	outside the vicinity of the B2E landscape	0	5.4E-04	0	3.6E-04	6.6E-10	5.2E-10	1.9E-11
	total life cycle	1.4E-02	2.8E-02	1.4E-02	1.4E-02	6.6E-16	5.2E-16	6.9E-10
PM10 emissions to air (million tons)	within the vicinity of the B2E landscape	1.2E-01	1.2E-01	1.2E-01	1.2E-01	0	0	1.6E-11
	outside the vicinity of the B2E landscape	0	1.1E-04	0	6.9E-05	2.4E-10	3.7E-10	3.6E-12
	total life cycle	1.2E-01	1.2E-01	1.2E-01	6.9E-05	2.4E-10	3.7E-10	2.0E-11
SOx emissions to air (as SO2) (million tons)	within the vicinity of the B2E landscape	8.3E-03	9.1E-03	8.3E-03	-2.3E-03	0	0	3.7E-11
	outside the vicinity of the B2E landscape	0	2.5E-04	0	1.7E-04	5.9E-10	6.9E-10	8.7E-12
	total life cycle	8.3E-03	9.3E-03	8.3E-03	-2.2E-03	5.9E-16	6.9E-16	4.6E-11

(a) In the gross assessment, the REFERENCE CASE and TEST SCENARIO were evaluated as performed such that each scenario produced a different amount of sawlogs and biomass-electricity and a different landscape condition as measured by extent and severity of wildfire. Key figures for the gross assessment are Figure 5 through Figure 8.

(b) The REFERENCE CASE and TEST SCENARIO were evaluated such that each scenario produced no sawlogs, no electricity, and a different landscape condition as measured by extent and severity of wildfire. Key figures for the Forest Management Comparative LCA are Figure 9 through Figure 11.

(c) The TEST SCENARIO and the life cycle of a NGPP and the California grid were evaluated such that all produced no sawlogs, 1MWh of electricity, and a different landscape condition as measured by extent and severity of wildfire. Key figures for the Electricity Generation Comparative LCA are Figure 12 through Figure 14.

Figure 17. Towards the optimization of forest bioproduct systems development



2. **Data and models are available to represent the life cycle of a range of technologies for developing U.S. forest bioproduct systems.** Herein, reliance on the discipline-specific B2E project models (the forest operations and equipment characterization, the vegetative dynamics assessment, the fire behavior assessment, and the power plant analysis) combined with the U.S. EPA NONROAD and MOBILE models and the U.S. DOE's GREET model provided a wealth of data for systems assessments. Similar data availability is expected for technology alternatives, as demonstrated in the assessment of power plant alternatives and as listed in Table 24. However, shortcomings herein included the limited scope (e.g., the small number of impacts assessed, the omission of infrastructure construction models, and the limited number of possible treatment scenarios investigated), lack of uncertainty data for all assessments, and the need to project estimates for all models into the future. These shortcomings do not appear to be insurmountable in the short term, and are recommended for future research.

In addition to addressing scope and modeling shortcomings, there are a number of remaining forest bioproduct questions that can be explored with currently available data. For example, investigations of power plant and transfer station citing and optimization of regional utilization of forest residuals, agricultural residuals, and bio-based municipal solid waste could be built around the data presented here.

Table 24. Technology alternatives for forest biomass to electricity systems

Process Category	Unit Process	Process Alternatives

Process Category	Unit Process	Process Alternatives
Forest remediation	Harvest - fuel delivery and on-site storage	Fuel delivery truck– conventional diesel
	Harvest - operations preparations (grading, etc.)	Motorgrader– red diesel
	Harvest - crew transport	o Pickup truck- conventional diesel o Pickup truck– conventional gas
	Harvest - dust abatement (water truck)	Water truck– conventional diesel
	Harvest - felling	o Feller Buncher– red diesel o Excavator-based machines with harvester heads– red diesel o Chainsaw felling
	Harvest - collection to a central landing area	o Skidder– red diesel o rubber tires or tracks, with the timber either picked up using a grapple or using a winch and a set of wire rope chokers o Forwarder– red diesel
	Harvest - chipping	Chipper– red diesel
	Wildfires that occur	0-100% of landscape burns
	Chemical Treatments	No treatments Treatments based on: o Nitrogen, phosphate, and potassium fertilizers by direct or indirect fertilization o Insecticides (Chloripyrifos, Esfenvalerate, Diflubenzuron – Adept) o Herbicides (Oxyfluorfen- Goal; Sulfometuron-methyl – Oust; Glyphosate -Accord, Roundup; 2,4-D; Triclopyr-Garlon) o Fungicides (Benomyl, Chlorothalonil, Mancozeb, Fenhexamid - Decree) o Fumigants (Methyl bromide, Chloropicrin)
Biomass to electricity	B2E Power Plant Operation	o Combustion (without and with combined heat and power) o Gasification (fixed or fluidized beds; without and with combined heat and power) o Pyrolysis (without and with combined heat and power) o *and possibly* the integration of microturbines, fuel cells, and hydrogen production
Distribution/ transport	Mobilization of forest remediation equipment	Lowboy Tractor and Trailer
	Chip transport from forest to power plant	Chip truck– conventional diesel
	Transport of waste to waste management	Truck– conventional diesel
Alternative residuals management schemes	Treatment/ disposal	Landfilling Composting
	Use in construction	Wood composites
	Use in the production of chemical feedstocks	Ethanol production, etc.

3. **Although data and models are available to assess additional impact categories such as those suggested by the TAC (see Table 1), lack of consensus on or lack of documentation for LCA impact characterization methods impedes their use.** Specifically, although many impact characterization methods/ equivalency factor data sets are in use in LCA[9], none can currently be considered the method of choice by LCA practitioners and arguably only the U.S. Environmental Protection Agency's

[9] For example, EcoInvent (from the Swiss Centre for Life Cycle Inventories and described at http://www.ecoinvent.ch/) implements twelve life cycle impact assessment methods: Cumulative Energy Demand (CED), Cumulative Exergy Demand (CExD), Impact-oriented characterization (CML 2001), Environmental Design of Industrial Products (EDIP 1997), Environmental Design of Industrial Products (EDIP 2003), Eco-indicator 99 (all three perspectives), Ecological Footprint, Ecological Scarcity 1997, Environmental Damage Potential (EDP), Climate change (IPCC 2001), Impact 2002+, and TRACI. Many of these methods overlap (e.g., providing different equivalency factors for the same impact) and none can currently be considered the method of choice by LCA practitioners.

Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) has been designed for use in the U.S. Within this context, during the course of the B2E project, quantification of the contribution to acidification and smog formation based on equivalency factors in TRACI was considered. Like the IPCC GWPs, TRACI equivalency factors provide a link between an emission and an impact and are measured relative to one of the emissions contributing to the impact. For example, contribution to photochemical smog formation is measured in "NOx equivalents" such that each emission is assumed to have some multiple of the impact of NOx (e.g., an emission of 1 kg of CO might contribute 0.013 times that of an emission of 1 kg of NOx). Herein, emissions of NOx and SOx could have been used to provide a rough estimate of the contribution to acidification and emissions of NMVOCs, CO, NOx, and CH_4 could have been used to provide a rough estimate of the contribution to photochemical smog formation based on TRACI equivalency factors. An example set of rough estimates is provided in Table 25.

Table 25. Example Rough Estimation of the Contribution to Acidification and Smog Formation

		Contribution to Acidification (million tons H+ equiv; based on emissions of NOx and SOx)*		Contribution to Smog Formation (million tons NOx equiv; based on emissions of NMVOCs, CO, NOx, & CH4)**	
		within the vicinity of the B2E landscape	outside the vicinity of the B2E landscape	within the vicinity of the B2E landscape	outside the vicinity of the B2E landscape
Gross assessment	REFERENCE CASE	9.8E-01	0	2.6E-01	0
	TEST SCENARIO	1.5E+00	3.4E-02	2.6E-01	6.5E-04
Forest Management Comparative LCA	REFERENCE CASE	9.8E-01	0	2.6E-01	0
	TEST SCENARIO	4.4E-01	2.3E-02	2.4E-01	4.3E-04
Electricity Generation Comparative LCA	NGPP	0	5.7E-08	0	7.3E-10
	Cal grid	0	5.6E-08	0	5.6E-10
	TEST SCENARIO	2.9E-08	1.2E-09	-1.5E-11	2.3E-11

*TRACI equivalency factors for acidification were 40 and 50.8 *H+ equivalents* for NOx and SOx respectively
** TRACI equivalency factors for smog formation were 0.78, 0.013, 1, and 0.0030 *NOx equivalents* for NMVOCs, CO, NOx, and CH_4 respectively

It is important to note that the data in Table 25 are only provided here as an example. Because TRACI equivalency factors remain undocumented to date, they would receive data quality scores (as in Appendix F) of **3** for "reproducibility of the methods used throughout the LCA" (data quality score 6), "sources of the data and their representativeness" (data quality score 7), and "consistency of the analysis" (8). Therefore, because the supporting TRACI data are of substantially lower quality that that used in the remainder of the LCA, they have not been included in the gross and net assessments presented above.

4. **There are, and will most likely remain, issues with the preparation of models of truly equivalent comparative systems.** In preparation of the net assessments and specifically related to identifying the system products/ functional unit, the identification of truly equivalent comparative systems was deemed either unrepresentative or beyond the scope of the research at hand. First, developing a treatment scenario to result in equivalent end landscape quality

based on Fire Regime Condition Classes[10] was deemed unrepresentative of the decision-making processes in the study region. Instead, a landscape characterized by a range of wildfire behavior conditions was assumed to result from likely scenarios considered on the case study landscape. Second, even though the chips were assumed to be removed from the case study landscape during only the summer months, the life cycle of *other feedstocks needed to ensure continuous power plant operation were not included in the assessment.* Inclusion of data and models representing the life cycles of other biomass energy feedstocks was deemed beyond the B2E project scope, which emphasized an understanding of in-forest feedstocks. Therefore, the suggestion in Table 21 that the net assessment of electricity generation systems provides continuous power is not well represented by what is modeled.

However, case study scope was developed by consensus of the project's Technical Advisory Committee and domain experts as the most appropriate for the case study landscape stakeholders and the project resources. Thus, whereas creating truly equivalent comparative systems might make sense from LCA practitioner and computational standpoints, it might not make sense for a given modeling activity.

6. Conclusions and Recommendations

Based on the project experience, **the conclusions of this work are:**

1. It is possible to construct a set of interconnected forest operations and equipment characterization, fire behavior assessment, and the power plant analysis models in support of LCA.
2. Data and models are available to represent the life cycle of a range of technologies for developing U.S. forest bioproduct systems.
3. Presentation of results in gross and followed by a variety of computational interpretations provide insights for decision making and a starting place for future assessments.

Based on the assessment results, **the conclusions of this work are:**

- The TEST SCENARIO provides a net benefit for total energy consumption and reduces fossil and petroleum consumption when compared to the REFERENCE CASE. Also, whereas the B2E power plant efficiency is critical to the overall energy balance, the consumption of fossil and petroleum fuels during harvest, chip transport, or power plant operation play a less important role.
- The TEST SCENARIO results show an improvement for NMVOCs, CO, and SOx when compared to the REFERENCE CASE. Alternatively, little difference is seen in NOx and PM10 emissions.
- Forest processes related to photosynthesis, plant respiration, decomposition of litter and soils, despite the uncertainty in estimates, are the most important to understanding whether or not the REFERENCE CASE and the TEST SCENARIO contribute to climate change.

Recommendations for future work include the addition of sensitivity analysis to the assessments, comparison of the results to related LCAs, consideration of additional process alternatives throughout the life cycle, and other aspects needed to complete the study as described in the goal and scope document.

[10] See http://frames.nbii.gov/portal/server.pt?open=512&objID=309&&PageID=1397&mode=2&in_hi_userid=2

The LCA results presented here do not meet the requirements established by the Goal and Scope document [4] prepared for the project. Most importantly, results should include consideration of the emissions beyond the 8 considered. Specifically, data categories and components for energy, water consumption, solid waste, and landuse were important to forest and power plant operations, the raw materials data category included materials for fuel and buildings construction, and the air emissions data category should include a broader set of emissions reflective of wildfire and electricity generation systems.

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Appendix A: Harvest and Transport Equipment Emission Factors

Table 26. Effective Emission Factors: Emissions of Particulate Matter (PM10, tons/ gallon)

	TEST SCENARIO: IPF + PMU			
Equipment	2006	2016	2026	2036
Tracked Feller/Buncher - John Deere 759 G	2.21E-06	1.73E-07	1.73E-07	1.73E-07
Tracked Feller/Buncher - Timbco Model 425EXL	2.49E-06	1.95E-07	1.97E-07	2.00E-07
Tracked Feller/Buncher - Timbco Model 445EXL	2.49E-06	1.95E-07	1.97E-07	2.00E-07
Rubber Tired Feller/Buncher - Hydro-Ax 321	3.58E-06	1.93E-07	1.97E-07	2.00E-07
Timber Cutter with Husqvarna 575XP	9.35E-05	9.29E-05	9.29E-05	9.29E-05
TowerYarder - Koller K501	2.40E-06	1.94E-07	2.00E-07	2.01E-07
Swing Yarder - Diamond 2000	2.21E-06	1.73E-07	1.73E-07	1.73E-07
Acme Model 22 Carriage (paired with Diamond 2000)	4.90E-06	4.74E-06	4.74E-06	4.74E-06
Rubber Tired Skidder - Caterpillar 525C	2.49E-06	1.95E-07	1.97E-07	2.00E-07
Rubber Tired Skidder - Caterpillar 535C	2.30E-06	1.82E-07	1.80E-07	1.80E-07
Tracked Skidder - Caterpillar 517	3.56E-06	1.77E-07	1.79E-07	1.83E-07
Tracked Skidder - Caterpillar 527	4.01E-06	1.95E-07	1.97E-07	2.00E-07
Delimber - Caterpillar 322C with Pierce Delimbinator	3.56E-06	1.73E-07	1.73E-07	1.73E-07
Processor - Link-Belt 290LX w/Logmax 7000 head	2.49E-06	1.95E-07	1.97E-07	2.00E-07
Landing Person with Husqvarna 575XP	9.35E-05	9.29E-05	9.29E-05	9.29E-05
Chipper - Morbark Model 30/36	2.36E-06	1.89E-07	1.91E-07	1.92E-07
Chipper - Morbark Model 50/48	2.41E-06	5.67E-07	5.72E-07	5.77E-07
Loader - Link-Belt 210LX to feed chipper	4.01E-06	1.95E-07	1.97E-07	2.00E-07
Water Truck - Kenworth (3,600 gal capacity)	1.63E-06	1.63E-06	1.63E-06	1.63E-06
Motorgrader - Caterpillar 140 H	2.48E-06	1.92E-07	1.92E-07	1.92E-07
Chip Truck Freightliner Model Columbia with Peerless 45' Trailer	5.34E-06	5.34E-06	5.34E-06	5.34E-06
Lowbed Equipment Transport - Freightliner with Peerless 60 ton Lowbed Trailer	6.30E-06	6.30E-06	6.30E-06	6.30E-06
Pickup Truck/Crew Transport -Ford F350 Crew Cab 4x4 diesel	8.16E-06	8.16E-06	8.16E-06	8.16E-06
Mechanics truck - Ford F550 4x4 diesel	6.02E-06	6.02E-06	6.02E-06	6.02E-06

Table 27. Effective Emission Factors: Emissions of Nitrogen Oxides (NOx, tons/ gallon)

	TEST SCENARIO: IPF + PMU			
Equipment	2006	2016	2026	2036
Tracked Feller/Buncher - John Deere 759 G	3.40E-05	5.06E-06	5.06E-06	5.06E-06
Tracked Feller/Buncher - Timbco Model 425EXL	3.41E-05	5.08E-06	5.08E-06	5.08E-06
Tracked Feller/Buncher - Timbco Model 445EXL	3.41E-05	5.08E-06	5.08E-06	5.08E-06
Rubber Tired Feller/Buncher - Hydro-Ax 321	3.84E-05	5.07E-06	5.08E-06	5.08E-06
Timber Cutter with Husqvarna 575XP	1.03E-05	1.03E-05	1.03E-05	1.03E-05
TowerYarder - Koller K501	3.31E-05	5.08E-06	5.08E-06	5.08E-06
Swing Yarder - Diamond 2000	3.40E-05	5.06E-06	5.06E-06	5.06E-06
Acme Model 22 Carriage (paired with Diamond 2000)	7.26E-05	7.33E-05	7.33E-05	7.33E-05
Rubber Tired Skidder - Caterpillar 525C	3.41E-05	5.08E-06	5.08E-06	5.08E-06
Rubber Tired Skidder - Caterpillar 535C	3.40E-05	5.07E-06	5.07E-06	5.07E-06
Tracked Skidder - Caterpillar 517	3.84E-05	5.07E-06	5.07E-06	5.07E-06
Tracked Skidder - Caterpillar 527	3.85E-05	5.08E-06	5.08E-06	5.08E-06
Delimber - Caterpillar 322C with Pierce Delimbinator	3.84E-05	5.06E-06	5.06E-06	5.06E-06
Processor - Link-Belt 290LX w/Logmax 7000 head	3.41E-05	5.08E-06	5.08E-06	5.08E-06
Landing Person with Husqvarna 575XP	1.03E-05	1.03E-05	1.03E-05	1.03E-05
Chipper - Morbark Model 30/36	3.31E-05	5.07E-06	5.07E-06	5.07E-06
Chipper - Morbark Model 50/48	6.07E-05	4.40E-05	4.40E-05	4.40E-05
Loader - Link-Belt 210LX to feed chipper	3.85E-05	5.08E-06	5.08E-06	5.08E-06
Water Truck - Kenworth (3,600 gal capacity)	1.10E-05	1.64E-06	1.64E-06	1.64E-06
Motorgrader - Caterpillar 140 H	3.41E-05	5.07E-06	5.07E-06	5.07E-06
Chip Truck Freightliner Model Columbia with Peerless 45' Trailer	1.21E-05	5.43E-06	5.43E-06	5.43E-06
Lowbed Equipment Transport - Freightliner with Peerless 60 ton Lowbed Trailer	1.21E-05	6.41E-06	6.41E-06	6.41E-06
Pickup Truck/Crew Transport -Ford F350 Crew Cab 4x4 diesel	9.56E-06	8.25E-06	8.25E-06	8.25E-06
Mechanics truck - Ford F550 4x4 diesel	1.09E-05	6.09E-06	6.09E-06	6.09E-06

Table 28. Effective Emission Factors: Emissions of Carbon Monoxide (CO, tons/ gallon)

	TEST SCENARIO: IPF + PMU			
Equipment	2006	2016	2026	2036
Tracked Feller/Buncher - John Deere 759 G	1.28E-05	1.57E-06	1.57E-06	1.57E-06
Tracked Feller/Buncher - Timbco Model 425EXL	1.33E-05	1.64E-06	1.64E-06	1.65E-06
Tracked Feller/Buncher - Timbco Model 445EXL	1.33E-05	1.64E-06	1.64E-06	1.65E-06
Rubber Tired Feller/Buncher - Hydro-Ax 321	1.75E-05	1.89E-06	1.91E-06	1.91E-06
Timber Cutter with Husqvarna 575XP	3.41E-03	3.39E-03	3.39E-03	3.39E-03
TowerYarder - Koller K501	1.50E-05	1.83E-06	1.85E-06	1.85E-06
Swing Yarder - Diamond 2000	1.28E-05	1.57E-06	1.57E-06	1.57E-06
Acme Model 22 Carriage (paired with Diamond 2000)	4.51E-05	4.08E-05	4.08E-05	4.08E-05
Rubber Tired Skidder - Caterpillar 525C	1.33E-05	1.64E-06	1.64E-06	1.65E-06
Rubber Tired Skidder - Caterpillar 535C	1.29E-05	1.60E-06	1.59E-06	1.60E-06
Tracked Skidder - Caterpillar 517	1.74E-05	1.84E-06	1.85E-06	1.86E-06
Tracked Skidder - Caterpillar 527	1.81E-05	1.90E-06	1.91E-06	1.91E-06
Delimber - Caterpillar 322C with Pierce Delimbinator	1.74E-05	1.82E-06	1.82E-06	1.82E-06
Processor - Link-Belt 290LX w/Logmax 7000 head	1.33E-05	1.64E-06	1.64E-06	1.65E-06
Landing Person with Husqvarna 575XP	3.41E-03	3.39E-03	3.39E-03	3.39E-03
Chipper - Morbark Model 30/36	1.49E-05	1.81E-06	1.82E-06	1.83E-06
Chipper - Morbark Model 50/48	1.33E-05	1.64E-06	1.65E-06	1.65E-06
Loader - Link-Belt 210LX to feed chipper	1.81E-05	1.90E-06	1.91E-06	1.91E-06
Water Truck - Kenworth (3,600 gal capacity)	2.45E-06	2.45E-06	2.45E-06	2.45E-06
Motorgrader - Caterpillar 140 H	1.33E-05	1.63E-06	1.63E-06	1.63E-06
Chip Truck Freightliner Model Columbia with Peerless 45' Trailer	2.64E-06	2.64E-06	2.64E-06	2.64E-06
Lowbed Equipment Transport - Freightliner with Peerless 60 ton Lowbed Trailer	2.64E-06	2.64E-06	2.64E-06	2.64E-06
Pickup Truck/Crew Transport -Ford F350 Crew Cab 4x4 diesel	2.02E-06	2.02E-06	2.02E-06	2.02E-06
Mechanics truck - Ford F550 4x4 diesel	1.92E-06	1.92E-06	1.92E-06	1.92E-06

Table 29. Effective Emission Factors: Emissions of Non-Methane Volatile Organic Carbon (NMVOC, tons/ gallon)

	TEST SCENARIO: IPF + PMU			
Equipment	2006	2016	2026	2036
Tracked Feller/Buncher - John Deere 759 G	3.67E-06	2.90E-06	2.90E-06	2.90E-06
Tracked Feller/Buncher - Timbco Model 425EXL	3.69E-06	2.92E-06	2.93E-06	2.93E-06
Tracked Feller/Buncher - Timbco Model 445EXL	3.69E-06	2.92E-06	2.93E-06	2.93E-06
Rubber Tired Feller/Buncher - Hydro-Ax 321	4.15E-06	2.92E-06	2.92E-06	2.93E-06
Timber Cutter with Husqvarna 575XP	6.02E-04	5.99E-04	5.99E-04	5.99E-04
TowerYarder - Koller K501	3.42E-06	2.92E-06	2.93E-06	2.93E-06
Swing Yarder - Diamond 2000	3.67E-06	2.90E-06	2.90E-06	2.90E-06
Acme Model 22 Carriage (paired with Diamond 2000)	8.79E-06	8.70E-06	8.70E-06	8.70E-06
Rubber Tired Skidder - Caterpillar 525C	3.69E-06	2.92E-06	2.93E-06	2.93E-06
Rubber Tired Skidder - Caterpillar 535C	3.68E-06	2.91E-06	2.91E-06	2.91E-06
Tracked Skidder - Caterpillar 517	4.15E-06	2.91E-06	2.91E-06	2.91E-06
Tracked Skidder - Caterpillar 527	4.18E-06	2.92E-06	2.93E-06	2.93E-06
Delimber - Caterpillar 322C with Pierce Delimbinator	4.15E-06	2.90E-06	2.90E-06	2.90E-06
Processor - Link-Belt 290LX w/Logmax 7000 head	3.69E-06	2.92E-06	2.93E-06	2.93E-06
Landing Person with Husqvarna 575XP	6.02E-04	5.99E-04	5.99E-04	5.99E-04
Chipper - Morbark Model 30/36	3.41E-06	2.92E-06	2.92E-06	2.92E-06
Chipper - Morbark Model 50/48	4.96E-06	2.92E-06	2.92E-06	2.92E-06
Loader - Link-Belt 210LX to feed chipper	4.18E-06	2.92E-06	2.93E-06	2.93E-06
Water Truck - Kenworth (3,600 gal capacity)	2.81E-06	2.81E-06	2.81E-06	2.81E-06
Motorgrader - Caterpillar 140 H	3.69E-06	2.92E-06	2.92E-06	2.92E-06
Chip Truck Freightliner Model Columbia with Peerless 45' Trailer	3.04E-06	3.04E-06	3.04E-06	3.04E-06
Lowbed Equipment Transport - Freightliner with Peerless 60 ton Lowbed Trailer	3.04E-06	3.04E-06	3.04E-06	3.04E-06
Pickup Truck/Crew Transport -Ford F350 Crew Cab 4x4 diesel	2.32E-06	2.32E-06	2.32E-06	2.32E-06
Mechanics truck - Ford F550 4x4 diesel	2.65E-06	2.65E-06	2.65E-06	2.65E-06

Table 30. Effective Emission Factors: Emissions of Methane (CH4, tons/ gallon)

	TEST SCENARIO: IPF + PMU			
Equipment	2006	2016	2026	2036
Tracked Feller/Buncher - John Deere 759 G	5.57E-08	4.41E-08	4.41E-08	4.41E-08
Tracked Feller/Buncher - Timbco Model 425EXL	5.61E-08	4.44E-08	4.45E-08	4.45E-08
Tracked Feller/Buncher - Timbco Model 445EXL	5.61E-08	4.44E-08	4.45E-08	4.45E-08
Rubber Tired Feller/Buncher - Hydro-Ax 321	6.30E-08	4.44E-08	4.44E-08	4.45E-08
Timber Cutter with Husqvarna 575XP	5.24E-06	5.21E-06	5.21E-06	5.21E-06
TowerYarder - Koller K501	5.19E-08	4.44E-08	4.45E-08	4.45E-08
Swing Yarder - Diamond 2000	5.57E-08	4.41E-08	4.41E-08	4.41E-08
Acme Model 22 Carriage (paired with Diamond 2000)	1.34E-07	1.32E-07	1.32E-07	1.32E-07
Rubber Tired Skidder - Caterpillar 525C	5.61E-08	4.44E-08	4.45E-08	4.45E-08
Rubber Tired Skidder - Caterpillar 535C	5.59E-08	4.42E-08	4.42E-08	4.42E-08
Tracked Skidder - Caterpillar 517	6.30E-08	4.42E-08	4.42E-08	4.42E-08
Tracked Skidder - Caterpillar 527	6.35E-08	4.44E-08	4.45E-08	4.45E-08
Delimber - Caterpillar 322C with Pierce Delimbinator	6.30E-08	4.41E-08	4.41E-08	4.41E-08
Processor - Link-Belt 290LX w/Logmax 7000 head	5.61E-08	4.44E-08	4.45E-08	4.45E-08
Landing Person with Husqvarna 575XP	5.24E-06	5.21E-06	5.21E-06	5.21E-06
Chipper - Morbark Model 30/36	5.19E-08	4.43E-08	4.44E-08	4.44E-08
Chipper - Morbark Model 50/48	7.54E-08	4.43E-08	4.44E-08	4.44E-08
Loader - Link-Belt 210LX to feed chipper	6.35E-08	4.44E-08	4.45E-08	4.45E-08
Water Truck - Kenworth (3,600 gal capacity)	4.28E-08	4.28E-08	4.28E-08	4.28E-08
Motorgrader - Caterpillar 140 H	5.61E-08	4.44E-08	4.44E-08	4.44E-08
Chip Truck Freightliner Model Columbia with Peerless 45' Trailer	4.62E-08	4.62E-08	4.62E-08	4.62E-08
Lowbed Equipment Transport - Freightliner with Peerless 60 ton Lowbed Trailer	4.62E-08	4.62E-08	4.62E-08	4.62E-08
Pickup Truck/Crew Transport -Ford F350 Crew Cab 4x4 diesel	3.53E-08	3.53E-08	3.53E-08	3.53E-08
Mechanics truck - Ford F550 4x4 diesel	4.02E-08	4.02E-08	4.02E-08	4.02E-08

Table 31. Effective Emission Factors: Emissions of Nitrous Oxide (N2O, tons/ gallon)

	TEST SCENARIO: IPF + PMU			
Equipment	2006	2016	2026	2036
Tracked Feller/Buncher - John Deere 759 G	2.84E-07	2.79E-07	2.79E-07	2.79E-07
Tracked Feller/Buncher - Timbco Model 425EXL	2.84E-07	2.79E-07	2.79E-07	2.79E-07
Tracked Feller/Buncher - Timbco Model 445EXL	2.84E-07	2.79E-07	2.79E-07	2.79E-07
Rubber Tired Feller/Buncher - Hydro-Ax 321	2.83E-07	2.79E-07	2.79E-07	2.79E-07
Timber Cutter with Husqvarna 575XP	2.49E-07	2.49E-07	2.49E-07	2.49E-07
TowerYarder - Koller K501	2.84E-07	2.79E-07	2.79E-07	2.79E-07
Swing Yarder - Diamond 2000	2.84E-07	2.79E-07	2.79E-07	2.79E-07
Acme Model 22 Carriage (paired with Diamond 2000)	2.77E-07	2.79E-07	2.79E-07	2.79E-07
Rubber Tired Skidder - Caterpillar 525C	2.84E-07	2.79E-07	2.79E-07	2.79E-07
Rubber Tired Skidder - Caterpillar 535C	2.84E-07	2.79E-07	2.79E-07	2.79E-07
Tracked Skidder - Caterpillar 517	2.83E-07	2.79E-07	2.79E-07	2.79E-07
Tracked Skidder - Caterpillar 527	2.82E-07	2.79E-07	2.79E-07	2.79E-07
Delimber - Caterpillar 322C with Pierce Delimbinator	2.83E-07	2.79E-07	2.79E-07	2.79E-07
Processor - Link-Belt 290LX w/Logmax 7000 head	2.84E-07	2.79E-07	2.79E-07	2.79E-07
Landing Person with Husqvarna 575XP	2.49E-07	2.49E-07	2.49E-07	2.49E-07
Chipper - Morbark Model 30/36	2.84E-07	2.79E-07	2.79E-07	2.79E-07
Chipper - Morbark Model 50/48	2.72E-07	2.79E-07	2.79E-07	2.79E-07
Loader - Link-Belt 210LX to feed chipper	2.82E-07	2.79E-07	2.79E-07	2.79E-07
Water Truck - Kenworth (3,600 gal capacity)	2.46E-08	2.46E-08	2.46E-08	2.46E-08
Motorgrader - Caterpillar 140 H	2.84E-07	2.79E-07	2.79E-07	2.79E-07
Chip Truck Freightliner Model Columbia with Peerless 45' Trailer	4.72E-08	4.72E-08	4.72E-08	4.72E-08
Lowbed Equipment Transport - Freightliner with Peerless 60 ton Lowbed Trailer	5.67E-08	5.67E-08	5.67E-08	5.67E-08
Pickup Truck/Crew Transport -Ford F350 Crew Cab 4x4 diesel	1.62E-07	1.62E-07	1.62E-07	1.62E-07
Mechanics truck - Ford F550 4x4 diesel	9.26E-08	9.26E-08	9.26E-08	9.26E-08

Table 32. Effective Emission Factors: Emissions of Carbon Dioxide (CO_2, tons/ gallon)

	TEST SCENARIO: IPF + PMU			
Equipment	2006	2016	2026	2036
Tracked Feller/Buncher - John Deere 759 G	1.11E-02	1.11E-02	1.11E-02	1.11E-02
Tracked Feller/Buncher - Timbco Model 425EXL	1.11E-02	1.11E-02	1.11E-02	1.11E-02
Tracked Feller/Buncher - Timbco Model 445EXL	1.11E-02	1.11E-02	1.11E-02	1.11E-02
Rubber Tired Feller/Buncher - Hydro-Ax 321	1.11E-02	1.11E-02	1.11E-02	1.11E-02
Timber Cutter with Husqvarna 575XP	7.85E-03	7.86E-03	7.86E-03	7.86E-03
TowerYarder - Koller K501	1.11E-02	1.11E-02	1.11E-02	1.11E-02
Swing Yarder - Diamond 2000	1.11E-02	1.11E-02	1.11E-02	1.11E-02
Acme Model 22 Carriage (paired with Diamond 2000)	1.10E-02	1.10E-02	1.10E-02	1.10E-02
Rubber Tired Skidder - Caterpillar 525C	1.11E-02	1.11E-02	1.11E-02	1.11E-02
Rubber Tired Skidder - Caterpillar 535C	1.11E-02	1.11E-02	1.11E-02	1.11E-02
Tracked Skidder - Caterpillar 517	1.11E-02	1.11E-02	1.11E-02	1.11E-02
Tracked Skidder - Caterpillar 527	1.11E-02	1.11E-02	1.11E-02	1.11E-02
Delimber - Caterpillar 322C with Pierce Delimbinator	1.11E-02	1.11E-02	1.11E-02	1.11E-02
Processor - Link-Belt 290LX w/Logmax 7000 head	1.11E-02	1.11E-02	1.11E-02	1.11E-02
Landing Person with Husqvarna 575XP	7.85E-03	7.86E-03	7.86E-03	7.86E-03
Chipper - Morbark Model 30/36	1.11E-02	1.11E-02	1.11E-02	1.11E-02
Chipper - Morbark Model 50/48	1.11E-02	1.11E-02	1.11E-02	1.11E-02
Loader - Link-Belt 210LX to feed chipper	1.11E-02	1.11E-02	1.11E-02	1.11E-02
Water Truck - Kenworth (3,600 gal capacity)	8.45E-04	8.45E-04	8.45E-04	8.45E-04
Motorgrader - Caterpillar 140 H	1.11E-02	1.11E-02	1.11E-02	1.11E-02
Chip Truck Freightliner Model Columbia with Peerless 45' Trailer	1.32E-03	1.32E-03	1.32E-03	1.32E-03
Lowbed Equipment Transport - Freightliner with Peerless 60 ton Lowbed Trailer	1.58E-03	1.58E-03	1.58E-03	1.58E-03
Pickup Truck/Crew Transport -Ford F350 Crew Cab 4x4 diesel	2.24E-03	2.24E-03	2.24E-03	2.24E-03
Mechanics truck - Ford F550 4x4 diesel	1.92E-03	1.92E-03	1.92E-03	1.92E-03

Table 33. Effective Emission Factors: Emissions of Sulfur Oxides (SOx, tons/gallon)

	TEST SCENARIO: IPF + PMU			
Equipment	2006	2016	2026	2036
Tracked Feller/Buncher - John Deere 759 G	1.99E-08	5.49E-10	5.49E-10	5.49E-10
Tracked Feller/Buncher - Timbco Model 425EXL	1.99E-08	5.49E-10	5.49E-10	5.49E-10
Tracked Feller/Buncher - Timbco Model 445EXL	1.99E-08	5.49E-10	5.49E-10	5.49E-10
Rubber Tired Feller/Buncher - Hydro-Ax 321	2.06E-08	5.49E-10	5.49E-10	5.49E-10
Timber Cutter with Husqvarna 575XP	5.37E-07	5.38E-07	5.38E-07	5.38E-07
TowerYarder - Koller K501	1.99E-08	5.49E-10	5.49E-10	5.49E-10
Swing Yarder - Diamond 2000	1.99E-08	5.49E-10	5.49E-10	5.49E-10
Acme Model 22 Carriage (paired with Diamond 2000)	2.32E-08	7.66E-10	7.66E-10	7.66E-10
Rubber Tired Skidder - Caterpillar 525C	1.99E-08	5.49E-10	5.49E-10	5.49E-10
Rubber Tired Skidder - Caterpillar 535C	1.99E-08	5.49E-10	5.49E-10	5.49E-10
Tracked Skidder - Caterpillar 517	2.06E-08	5.49E-10	5.49E-10	5.49E-10
Tracked Skidder - Caterpillar 527	2.06E-08	5.49E-10	5.49E-10	5.49E-10
Delimber - Caterpillar 322C with Pierce Delimbinator	2.06E-08	5.49E-10	5.49E-10	5.49E-10
Processor - Link-Belt 290LX w/Logmax 7000 head	1.99E-08	5.49E-10	5.49E-10	5.49E-10
Landing Person with Husqvarna 575XP	5.37E-07	5.38E-07	5.38E-07	5.38E-07
Chipper - Morbark Model 30/36	1.99E-08	5.49E-10	5.49E-10	5.49E-10
Chipper - Morbark Model 50/48	1.99E-08	5.49E-10	5.49E-10	5.49E-10
Loader - Link-Belt 210LX to feed chipper	2.06E-08	5.49E-10	5.49E-10	5.49E-10
Water Truck - Kenworth (3,600 gal capacity)	6.46E-08	6.46E-08	6.46E-08	6.46E-08
Motorgrader - Caterpillar 140 H	1.99E-08	5.49E-10	5.49E-10	5.49E-10
Chip Truck Freightliner Model Columbia with Peerless 45' Trailer	1.00E-07	1.00E-07	1.00E-07	1.00E-07
Lowbed Equipment Transport - Freightliner with Peerless 60 ton Lowbed Trailer	1.21E-07	1.21E-07	1.21E-07	1.21E-07
Pickup Truck/Crew Transport -Ford F350 Crew Cab 4x4 diesel	1.70E-07	1.70E-07	1.70E-07	1.70E-07
Mechanics truck - Ford F550 4x4 diesel	1.46E-07	1.46E-07	1.46E-07	1.46E-07

Appendix B: GREET Life Cycle Inventory Data

The USDOE Argonne National Lab's Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model (Version 1.7) [22] was used to estimate the life cycle of diesel and oils production, grid electricity, and natural gas power plants. Default model values were used with the exception of input parameters representing operations for the state of California. Life cycle energy use and emissions estimates were made for each year from 2006 to 2020 with the latter being the latest date supported by GREET. Decade data were estimated as an average of the years in each decade, assuming all years after 2020 to be at 2020 levels. Inspection of the data presented in this Appendix reveals a variety of trends which are linked to time-series assumptions within GREET. For example, consider the increase in total life cycle energy consumption by the California grid, progressing from 1.25E+06 BTU/mmBTU in the 2006 decade to 1.39E+06 in the 2036 decade as shown in Table 36. This trend is the result of projected electricity mixes for California presented in Table 38. These data do not compare well to data through 2006 from the U.S. Department of Energy's Energy Information Administration dataset "1990 - 2006 Net Generation by State by Type of Producer by Energy Source (EIA-906)"[11] which estimates a higher percentage of coal and a lower percentage of natural gas use in California.

For the mixes applied, the well-to-point-of-use generation efficiencies, the resulting well-to-point-of-use generation efficiency for the California grid decreases from 44% to 42%. Overall, the change in projections leads to both increasing and decreasing trends in life cycle energy use and emissions. Further analysis is required to determine the sensitivity of these projections on the LCA results.

Table 34. Fuel Life Cycle Inventories (well-to-pump, /mmBTU)

		Diesel LC				Gas LC			
		2006	**2016**	**2026**	**2036**	**2006**	**2016**	**2026**	**2036**
Total energy	BTU	191,000	199,000	199,000	199,000	238,000	258,000	262,000	262,000
Fossil fuels	BTU	186,000	195,000	195,000	195,000	232,000	253,000	256,000	256,000
Petroleum	BTU	88,500	91,900	91,900	91,900	107,000	112,000	113,000	113,000
VOC	tons	0.000008	0.000008	0.000008	0.000008	0.000030	0.000030	0.000030	0.000030
CO	tons	0.000014	0.000013	0.000013	0.000013	0.000018	0.000018	0.000018	0.000018
NOx	tons	0.000038	0.000034	0.000034	0.000034	0.000053	0.000050	0.000050	0.000050
PM10	tons	0.000006	0.000007	0.000007	0.000007	0.000009	0.000010	0.000011	0.000011
SOx	tons	0.000017	0.000017	0.000017	0.000017	0.000021	0.000022	0.000023	0.000023
CH4	tons	0.000114	0.000115	0.000115	0.000115	0.000120	0.000123	0.000123	0.000123
N2O	tons	0.000000	0.000000	0.000000	0.000000	0.000001	0.000002	0.000002	0.000002
CO2	tons	0.016100	0.016900	0.017000	0.017000	0.018100	0.018500	0.018600	0.018600

Table 35. Lubricating Oil Life Cycle Inventory (well-to-point of use, /gallon)

		Lubricating oil LC			
		2006	**2016**	**2026**	**2036**

[11] See http://www.eia.doe.gov/cneaf/electricity/epa/epa_sprdshts.html

Total energy	BTU	4.25E+04	4.27E+04	4.28E+04	4.28E+04
Fossil fuels	BTU	4.14E+04	4.19E+04	4.20E+04	4.20E+04
Petroleum	BTU	2.03E+04	2.03E+04	2.03E+04	2.03E+04
VOC	tons	2.96E-05	2.95E-05	2.95E-05	2.95E-05
CO	tons	1.84E-05	1.71E-05	1.71E-05	1.71E-05
NOx	tons	5.07E-05	4.51E-05	4.48E-05	4.48E-05
PM10	tons	9.90E-06	1.07E-05	1.08E-05	1.08E-05
SOx	tons	2.35E-05	2.29E-05	2.32E-05	2.32E-05
CH4	tons	1.24E-04	1.24E-04	1.24E-04	1.24E-04
N2O	tons	4.16E-07	4.20E-07	4.20E-07	4.20E-07
CO2	tons	2.47E-02	2.52E-02	2.53E-02	2.53E-02

Table 36. Electricity Life Cycle Inventory (well-to-point of use, /mmBTU)

		California Grid LC				Natural Gas Power Plant LC			
		2006	**2016**	**2026**	**2036**	**2006**	**2016**	**2026**	**2036**
Total energy	BTU	1.25E+06	1.38E+06	1.39E+06	1.39E+06	1.83E+06	1.74E+06	1.72E+06	1.72E+06
Fossil fuels	BTU	1.17E+06	1.31E+06	1.33E+06	1.33E+06	1.82E+06	1.74E+06	1.72E+06	1.72E+06
Petroleum	BTU	2.98E+04	3.39E+04	3.50E+04	3.50E+04	2.77E+04	1.06E+04	1.05E+04	1.05E+04
VOC	tons	1.65E-05	1.82E-05	1.84E-05	1.84E-05	2.52E-05	2.40E-05	2.39E-05	2.39E-05
CO	tons	5.82E-05	6.20E-05	6.23E-05	6.23E-05	8.92E-05	9.37E-05	9.35E-05	9.35E-05
NOx	tons	1.51E-04	1.65E-04	1.69E-04	1.69E-04	1.95E-04	1.43E-04	1.42E-04	1.42E-04
PM10	tons	1.09E-04	1.83E-04	1.95E-04	1.95E-04	7.10E-05	6.48E-06	6.45E-06	6.45E-06
SOx	tons	2.03E-04	2.63E-04	2.79E-04	2.79E-04	1.74E-04	3.05E-05	3.03E-05	3.03E-05
CH4	tons	2.91E-04	3.14E-04	3.14E-04	3.14E-04	4.89E-04	5.06E-04	5.01E-04	5.01E-04
N2O	tons	3.21E-06	3.46E-06	3.48E-06	3.48E-06	4.22E-06	4.27E-06	4.24E-06	4.24E-06
CO2	tons	1.45E-01	1.82E-01	1.87E-01	1.87E-01	2.02E-01	1.82E-01	1.81E-01	1.81E-01

Table 37. Natural Gas Boiler Life Cycle Inventory (well-to-point of use, /mmBTU throughput)

		natural gas burned in a small industrial boiler (10-100 mmBtu/hr input)			
		2006	**2016**	**2026**	**2036**
Total energy	BTU	1.98E+05	1.91E+05	1.89E+05	1.89E+05
Fossil fuels	BTU	1.96E+05	1.89E+05	1.88E+05	1.88E+05
Petroleum	BTU	1.28E+04	1.28E+04	1.28E+04	1.28E+04
VOC	tons	7.81E-06	7.63E-06	7.62E-06	7.62E-06
CO	tons	1.51E-05	1.33E-05	1.32E-05	1.32E-05
NOx	tons	5.28E-05	4.48E-05	4.42E-05	4.42E-05
PM10	tons	1.53E-06	1.64E-06	1.66E-06	1.66E-06
SOx	tons	1.48E-05	1.49E-05	1.49E-05	1.49E-05
CH4	tons	3.13E-04	3.11E-04	3.11E-04	3.11E-04

N2O	tons	3.01E-07	2.89E-07	2.87E-07	2.87E-07
CO2	tons	1.41E-02	1.37E-02	1.37E-02	1.37E-02

Table 38. Projected Changes in the California Grid Electricity Mix

5-year period	Residual Oil	Natural Gas	Coal	Nuclear	Biomass	Others
2005	0.8%	35.2%	15.9%	21.5%	1.6%	25.0%
2010	0.7%	41.5%	14.6%	18.9%	1.7%	22.6%
2015	0.6%	42.0%	21.0%	15.6%	1.5%	19.3%
2020	0.7%	36.0%	31.4%	13.5%	1.5%	16.9%

Appendix C: Biomass Power Plant Models

Table 39. Current Generation Biomass Combustion Power Plant Data (per dry tons throughput)

		TEST SCENARIO: IPF + PMU			
		2006	**2016**	**2026**	**2036**
Biomass electricity	MWh	9.25E-01	9.25E-01	9.26E-01	9.24E-01
Diesel	BTU	6.17E+03	6.17E+03	6.17E+03	6.17E+03
Lubricating oil	gal	1.08E-02	1.08E-02	1.08E-02	1.08E-02
Cal grid elect	BTU	7.46E+03	7.46E+03	7.46E+03	7.46E+03
Natural gas	BTU	2.19E-01	2.19E-01	2.19E-01	2.19E-01
Total energy	BTU	1.40E+07	1.40E+07	1.40E+07	1.40E+07
Fossil fuels	BTU	2.46E+04	2.46E+04	2.46E+04	2.46E+04
Petroleum	BTU	6.17E+03	6.17E+03	6.17E+03	6.17E+03
VOC	tons	1.76E-04	1.71E-04	1.71E-04	1.71E-04
CO	tons	1.69E-03	1.56E-03	1.56E-03	1.55E-03
NOx	tons	8.65E-04	6.17E-04	6.18E-04	6.17E-04
PM10	tons	4.82E-04	4.63E-04	4.63E-04	4.62E-04
SOx	tons	7.77E-05	7.75E-05	7.75E-05	7.74E-05
CH4	tons	7.29E-05	7.29E-05	7.29E-05	7.27E-05
N2O	tons	2.10E-04	2.10E-04	2.11E-04	2.10E-04
CO2	tons	1.96E+00	1.96E+00	1.96E+00	1.96E+00

Table 40. Current Generation Integrated Gasification/ Combustion Power Plant Data (per dry tons throughput)

		TEST SCENARIO: IPF + PMU			
		2006	**2016**	**2026**	**2036**
Biomass electricity	MWh	1.02E+00	1.02E+00	1.02E+00	1.02E+00
Diesel	BTU	6.17E+03	6.17E+03	6.17E+03	6.17E+03
Lubricating oil	gal	9.63E-03	9.63E-03	9.63E-03	9.63E-03
Cal grid elect	BTU	7.46E+03	7.46E+03	7.46E+03	7.46E+03
Natural gas	BTU	1.63E+04	1.63E+04	1.63E+04	1.63E+04
Total energy	BTU	1.37E+07	1.37E+07	1.37E+07	1.37E+07
Fossil fuels	BTU	2.46E+04	2.46E+04	2.46E+04	2.46E+04
Petroleum	BTU	6.17E+03	6.17E+03	6.17E+03	6.17E+03
VOC	tons	6.55E-05	6.04E-05	6.05E-05	6.04E-05
CO	tons	2.81E-04	1.51E-04	1.51E-04	1.51E-04
NOx	tons	4.27E-04	1.79E-04	1.79E-04	1.79E-04
PM10	tons	7.70E-05	5.83E-05	5.84E-05	5.83E-05
SOx	tons	7.77E-05	7.75E-05	7.75E-05	7.74E-05
CH4	tons	7.29E-05	7.29E-05	7.29E-05	7.27E-05
N2O	tons	2.10E-04	2.10E-04	2.11E-04	2.10E-04
CO2	tons	1.96E+00	1.96E+00	1.96E+00	1.96E+00

Table 41. Next Generation Thermo- Chemical Conversion Power Plant Data (per dry tons throughput)

		TEST SCENARIO: IPF + PMU			
		2006	**2016**	**2026**	**2036**
Biomass electricity	MWh	1.30E+00	1.30E+00	1.30E+00	1.29E+00
Diesel	BTU	6.17E+03	6.17E+03	6.17E+03	6.17E+03
Lubricating oil	gal	9.63E-03	9.63E-03	9.63E-03	9.63E-03
Cal grid elect	BTU	7.46E+03	7.46E+03	7.46E+03	7.46E+03
Natural gas	BTU	1.63E+04	1.63E+04	1.63E+04	1.63E+04
Total energy	BTU	1.28E+07	1.28E+07	1.28E+07	1.27E+07
Fossil fuels	BTU	2.46E+04	2.46E+04	2.46E+04	2.46E+04
Petroleum	BTU	6.17E+03	6.17E+03	6.17E+03	6.17E+03
VOC	tons	3.87E-05	3.35E-05	3.36E-05	3.36E-05
CO	tons	2.49E-04	1.19E-04	1.19E-04	1.19E-04
NOx	tons	3.21E-04	7.34E-05	7.35E-05	7.34E-05
PM10	tons	9.65E-05	7.78E-05	7.79E-05	7.77E-05
SOx	tons	7.77E-05	7.75E-05	7.75E-05	7.74E-05
CH4	tons	7.29E-05	7.29E-05	7.29E-05	7.27E-05
N2O	tons	2.10E-04	2.10E-04	2.11E-04	2.10E-04
CO2	tons	1.96E+00	1.96E+00	1.96E+00	1.96E+00

Appendix D: Gross Assessment Results

In Figure 18, cell shading indicates the contribution of harvest operations and chip transport, underburning, the power plant, wildfires, and sequestration credit to the scenario life cycle totals in each row.

Figure 18. Gross Life Cycle Inventory Results[12]

	REFERENCE CASE	TEST SCENARIO								
		Life Cycle for Harvest Equipment Operation and Chip Transport		In-Forest Underburning	Life Cycle of Power Plant Operation		Wildfire emissions	Sequestration credit		Total life cycle
					Power Plant Energy Use (diesel, propane, grid electricity, and oils)	Biomass Energy Generated (from chips)				
Total energy consumed (mmBTU)			2.9E+06		9.8E+05	6.6E+07				7.0E+07
Fossil energy consumed (mmBTU)			2.9E+06		8.1E+05					3.7E+06
Petroleum energy consumed (mmBTU)			1.4E+06		1.5E+05					1.5E+06
	Wildfire emissions	within the vicinity of the B2E landscape	outside the vicinity of the B2E landscape	within the vicinity of the B2E landscape	within the vicinity of the B2E landscape	outside the vicinity of the B2E landscape	within the vicinity of the B2E landscape	chips	sawlogs	
NMVOC emissions to air (tons)	2.9E+05	7.4E+02	1.4E+02	2.8E+04	3.6E+03	4.6E+00	2.4E+05			2.7E+05
CO emissions to air (tons)	1.3E+06	2.9E+03	1.9E+02	1.2E+05	3.3E+04	6.9E+00	1.1E+06			1.2E+06
NOx emissions to air (tons)	1.4E+04	1.2E+03	5.1E+02	1.1E+03	1.4E+04	2.2E+01	1.1E+04			2.8E+04
PM10 emissions to air (tons)	1.2E+05	2.5E+02	1.0E+02	1.2E+04	9.8E+03	1.8E+00	1.0E+05			1.2E+05
SOx emissions to air (tons)	8.3E+03	3.2E+00	2.5E+02	7.4E+02	1.7E+03	7.9E+00	6.7E+03			9.3E+03
CH4 emissions to air (tons)	6.0E+04	8.5E+00	1.6E+03	5.7E+03	1.6E+03	1.2E+02	5.0E+04			5.9E+04
N2O emissions to air (tons)	1.8E+03	2.4E+01	4.3E+00	1.5E+02	4.4E+03	1.5E-01	1.4E+03			5.9E+03
CO2 emissions to air (tons)	1.6E+07	9.4E+05	2.5E+05	1.6E+06	4.1E+07	7.6E+03	1.2E+07			5.6E+07
Contribution to climate change (tons CO2 equiv)	1.7E+07	9.4E+05	2.8E+05	1.7E+06	4.2E+07	1.0E+04	1.4E+07	-3.9E+07	-5.8E+07	-3.8E+07

[12] Credit has not been given for the carbon in chips and sawlogs as described in Section 3.5.

Appendix E: Power Plant Alternatives

Table 42 presents the LCA results for alternative power plant technologies based on the electricity generation net assessment.

Table 42. Comparison of Alternative Power Plant Technologies for the TEST SCENARIO

		Current Generation Biomass Combustion Power Plant	Current Generation Integrated Gasification/ Combustion Power Plant	Next Generation Thermo-Chemical Conversion Power Plant
Total energy consumed	mmBTU/MWh	-3.3E+00	-3.3E+00	-3.3E+00
Fossil energy consumed	mmBTU/MWh	1.4E-01	1.3E-01	9.9E-02
Petroleum energy consumed	mmBTU/MWh	5.4E-02	4.9E-02	3.9E-02
Climate Change	tons CO2 equiv/MWh	1.3E-01	1.2E-01	9.3E-02

Appendix F: Data Quality Analysis

Table 43. Data Quality Analysis

Data Quality Indicator	Forest Operations and Equipment Assessment	Vegetation Dynamics Assessment	Fire Behavior Assessment	Power Plant Analysis	NONROAD	GREET	Data Quality Scores	Notes
(1) Time-related coverage	4	4	4	4	4	4	Deviation from intended period: (1) Less than 6 years difference to the year of study, (2) Less than 10 years difference, (3) Less than or equal to 15 years difference, (4) Age of data unknown or more than 15 years of difference	In all models, projections were made beyond 2006.
(2) Geographical coverage	1	1	1	1	1	1	Deviation from intended area: (1) Data from area under study, (2) Average data from larger area in which the area under study is included, (3) Data from area under similar production conditions, (4) Data from unknown area or area with different production conditions	
(3) Technology coverage	1	1	1	1	1	1	Deviation from intended technology: (1) Data from enterprises, processes, and materials under study (2) Data from processes and materials under study but different enterprises (3) Data on related process and materials but same technology (4) Data from processes and materials under study but unknown technology	
(4) Precision and uncertainty of the data	4	4	4	4	4	4	(1) Data include a mean value, standard deviation, uncertainty type, and a description of strengths and weaknesses (e.g., occurrence of data gaps). (2) The mean value, standard deviation, uncertainty type, and a description of strengths and weaknesses (e.g., occurrence of data gaps) can be approximated. (4) The mean value, standard deviation, uncertainty type, and a description of strengths and weaknesses (e.g., occurrence of data gaps) are not available or were not approximated.	Uncertainty analysis has been left for future work.
(5) Completeness and representativeness of the data	4	4	4	4	4	4	(1) Data are based on site-specific locations reporting primary data as available with the resulting percentages of locations reporting data from the potential number in existence noted. (2) Data are based on site-specific locations reporting primary data as available with no information on the resulting percentages of locations reporting data from the potential number in existence. (3) Data are estimated or calculated and have received data quality scores of 1 or 2 in the categories of Time-related coverage, Geographical coverage, and Technology coverage. (4) Data are estimated or calculated and have received data quality scores of 3 or 4 in the categories of Time-related coverage, Geographical coverage, and Technology coverage.	All data received data quality scores of 4 in the category of Time-related coverage.

Table 43. Data Quality Analysis (continued)

Data Quality Indicator	Forest Operations and Equipment Assessment	Vegetation Dynamics Assessment	Fire Behavior Assessment	Power Plant Analysis	NONROAD	GREET	Data Quality Scores	Notes
(6) Reproducibility of the methods used throughout the LCA	1	1	1	1	1	1	(1) Very high (Data are based on direct measurements using a widely accepted test methods or on sound engineering models representing current technology and have been extensively peer reviewed. Also, the source provides a transparent account of the assumptions made.) (2) High (Although the data are based on a generally sound test method or model and the source provides a transparent account of the assumptions made, the data are dated or lack enough detail for adequate validation or have not been extensively peer reviewed.) (3) Moderate (Data are based on an unproven or new methodology but include a significant amount of background information.) (4) Low (Data are based on a generally unacceptable, ill defined, or unpublished method, but the method may provide an order-of-magnitude value)	
(7) Sources of the data and their representativeness	1	1	1	2	1	1	Type of reference (1) Data from reviewed source; (2) Data from public written source (not reviewed); (3) Data from closed written source (including review information); (4) Other sources	
(8) Consistency of the analysis	2 (2.3)	2 (2.3)	2 (2.3)	2 (2.4)	2 (2.3)	2 (2.3)	(1) The data are part of a unit process model with an average data quality score less than 1.5 (2) The data are part of a unit process model with an average data quality score less than 2.5 (3) The data are part of a unit process model with an average data quality score of less than 3. (4) The data are part of a unit process model with an average data quality score of more than 3.	Average scores for items 1-7 are included parenthetically.