Literature Review and Sensitivity Analysis of Biopower Life-Cycle Assessments and Greenhouse Gas Emission

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ABSTRACT

Biomass power offers utilities a potential pathway to increase their renewable generation portfolios for compliance with renewable energy standards and to reduce greenhouse gas (GHG) emissions relative to current fossil-based technologies. To date, a large body of life-cycle assessment (LCA) literature assessing biopower's life-cycle GHG emissions has been published.

Phase A of this project performed an exhaustive search of the biopower LCA literature yielding 117 references that passed quality and relevance screening criteria. Fifty-seven papers reported 280 life-cycle GHG emission estimates. Literature indicates that, excluding land use change (LUC), well-managed and well-designed biopower systems can deliver electricity with low life cycle GHG emissions compared to fossil fuels. The use of residues and organic wastes for biopower could result in significantly lower life-cycle GHG emissions if biomass is diverted from landfill or open-air burning. Using carbon mitigation technologies such as carbon capture and storage, rarely studied for biopower systems, could yield even deeper emission reductions.

Phase B of this project constructed a spreadsheet model of the biopower life cycle to conduct a sensitivity analysis using biomass supply chain parameters that were taken from applicable literature in the LCA literature review. The spreadsheet model, created from NREL's Systems Advisor Model (SAM) structure, was expanded to evaluate GHG emissions from dedicated biomass crops. These capabilities were integrated into SAM.

Keywords
Biomass
Biopower
Carbon capture and storage
Carbon mitigation techniques
Greenhouse gas
Life-cycle assessment

EXECUTIVE SUMMARY

Biomass power offers utilities a potential pathway to increase their renewable generation portfolios for compliance with renewable energy standards and to reduce greenhouse gas (GHG) emissions relative to current fossil-based technologies. To date, a large body of life-cycle assessment (LCA) literature assessing biopower's life cycle GHG emissions has been published.

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In Phase A**,** the term *harmonization* aligned several common facility performance parameters and generalized system boundaries to facilitate cross-study comparison. The objective was to better evaluate central tendency and assess the variability in existing life-cycle GHG emission estimates. Harmonization of global warming potentials and coal contributions to co-firing estimates reduced the variability by 67% for biopower—to 20–69 g CO_2eq/kWh. The variability in co-firing related life-cycle GHG emission estimates was greatly reduced, and the median and central tendency was comparable to other technologies. Harmonization of thermal efficiency, lower heating value, system boundaries, and GHGs reduced the variability 20% for biopower to 18–59 g CO_2e/kWh. Variability reduction is mostly attributable to the harmonization of thermal efficiency.

Remaining life-cycle GHG emission variability is mostly related to factors upstream from the biopower facility. Important remaining sources of life-cycle GHG emission variability were identified as including factors such as biomass yield, field inputs, transportation assumptions, biomass preprocessing, and biomass drying. Variability in these conditions may obscure potential significant biopower system differences, such as the major GHG emission differences of biomass feedstocks. Literature limitations necessitated an alternative approach that controlled for major assumptions across multiple biopower systems; this method better addressed questions about remaining life-cycle GHG emission variability.

Phase B of this project constructed a spreadsheet model of the biopower life cycle to conduct a sensitivity analysis using biomass supply chain parameters that were taken from applicable literature in the LCA literature review. The spreadsheet model, created from NREL's Systems Advisor Model (SAM) structure, was expanded to evaluate GHG emissions from dedicated biomass crops. These capabilities were integrated into SAM.

Base case scenario runs constructed from recent literature are generally optimistic. These positive assumptions are usually technological efficiencies, as other assumptions—such as fertilizer application—are similar to median values found in the literature. Wood wastes and forest residues have the lowest GHG emission rates (11 and 34 g CO_2eq/kWh), while herbaceous crops have the highest (75 g CO_2eq/kWh). Agricultural residue and short-rotation woody crop (SRWC) combustion lead to 60 and 45 g CO_2eq/kWh, respectively. Since base cases assume no extensive intermediate steps (for example, preprocessing), major feedstock differences mostly depend on fertilizer application practices and yields. Collection/harvest practices and the assumed agricultural residue heating values also play a role. A sensitivity analysis found that the major contributors (>50% change in GHG emissions from the base case) to variability are related to net output of the biopower facility (for example, thermal efficiency), biomass production (that is, crops) or collection (that is, residues) yields, fertilizer inputs, and the inclusion of high-energy-use practices (for example, natural gas drying of biomass or pelletization). Improvements in facility or field output efficiency are potentially the best approaches to GHG emission reduction because they modulate GHG emissions over the life cycle. However, intermediate steps can become very important contributors to life-cycle GHG emission variability when longer and more complex supply chains (for example, pelletization and natural gas mechanical drying) are considered.

Among other analysis limits, life-cycle GHG emission calculations are simplistic compared to a full LCA. Our results should be regarded as indicators of relationships and relative impacts rather than as precise estimates.

ACRONYMS

ABDE	avoided biomass decomposition emissions
CCS	carbon capture and storage
CH_4	methane
CHP	combined heat and power
CO_2	carbon dioxide
CO_2eq	carbon dioxide equivalents
CPO	crude palm oil
GHG	greenhouse gas
GWP	global warming potential
IPCC SRREN	Intergovernmental Panel on Climate Change Special Report on Renewable Energy Sources and Climate Change Mitigation
kWh	kilowatt-hour
LCA	life cycle assessment
LCOE	levelized cost of energy
LHV	lower heating value
LUC	land use change
N_2O	dinitrous oxide
PFAD	palm fatty acid distillate
RRFC	relative radiative forcing commitment
SAM	System Advisory Model
SRWC	short rotation woody crops

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Phase A

1

STATE OF THE SCIENCE OF BIOPOWER LIFE CYCLE GHG EMISSIONS

State of Life Cycle Assessment of Greenhouse Gas Emissions for Biopower

A substantial body of life cycle assessment (LCA) literature has been published on a variety of biopower topics, covering a breadth of technologies and feedstocks under various current and future scenarios. While only a portion (~10 papers) are directly relevant to US conditions, a substantial collection of existing studies on GHG emissions for a range of technologies and situations could be applicable to US situations. However, the literature can vary highly in relevance, detail and transparency. Collected LCAs indicate that in the long-term on a life cycle basis (excluding LUC) biopower can reduce greenhouse gas (GHG) emissions by replacing fossil energy sources. Variability is largely caused by differences in study methods (e.g., avoided emissions), agricultural practices (e.g., fertilizer application), technology performance (e.g., conversion efficiency), feedstock selected (e.g., some wastes and residues), and system design/integration (e.g., biomass preprocessing methods). The impacts of biopower are often site and case specific and arise from a diverse set of factors and it is therefore difficult to supply exact values (Malkki and Virtanen 2003; Cowie 2004; Cherubini et al. 2009; Hacatoglu et al. 2011; Heller et al. 2004).

Recent LCA literature, reflected in the 2011 latest Intergovernmental Panel on Climate Change Special Report on Renewable Energy Sources and Climate Change Mitigation Summary for Policy Makers (IPCC SRREN Summary for Policymakers[1],SPM), indicates that well-managed and designed biopower production and utilization chains can potentially deliver high GHG mitigation amounts (> 90%, excluding LUC) compared to fossil-based reference systems (IPCC, 2011). In comparison to other renewable technologies, biopower generally has higher GHG emissions than wind, and hydro, but lower GHG emissions then solar and geothermal (IPCC, 2011). Utilizing best field management practices (e.g., fertilizer application), efficient design, and process (i.e., multiproduct systems.) integration that optimizes energy use across the life cycle can reduce GHG emissions of power generated from biomass feedstocks. For example, a higher efficiency drying process can be attained by recycling steam or by locating facilities near existing industries (or vice versa) so excess heat could be used for drying (Sikkema et al. 2010; Bergsma et al. 2003).The use of some residues and organic wastes for biopower could result in greater life cycle GHG emission reduction, especially if diverted from the landfill or open-air burning. The use of wastes and residues could also avoid LUC impacts. The uses of carbon sequestration technologies, such as carbon capture and storage (CCS), are another way to achieve greater GHG emissions reductions studied, although this configuration has not been extensively studied.

[1] Intergovernmental Panel on Climate Change (IPCC) Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN) Summary for Policy Makers (SPM).

Summary of Major Biopower Topics Covered in the Literature

A variety of technologies, biomass feedstocks, and life cycle environmental indicators have been collected. Within established screening criteria, existing LCAs focused on biomass co-firing with fossil energy sources, direct biomass combustion, and biomass gasification – combined cycle. The primary biomass feedstock systems studied involve wood. "Wood" includes a range of feedstocks from short rotation woody crops (SRWC) to forest residues from the logging industry. Other frequently-studied biomass categories included dedicated herbaceous crops (e.g., switchgrass) and agricultural wastes (e.g., corn stover). The majority of the LCA literature is focused on the evaluation of GHG emissions per kWh of electricity produced and energy consumption use (e.g., net energy ratio and cumulative energy demand), but also includes analyses of alternative GHG metrics (e.g., emissions per hectare of land), material consumption (e.g., steel and concrete, criteria air pollutants (e.g., nitrous oxides and sulfur oxides) and other air and/or water emissions (e.g., heavy metals). See Appendix I for further details.

The Biopower Life Cycle

Figure 1-1 illustrates the biopower life cycle scope covering existing literature and this analysis. The dotted box indicates the system boundary achieved through harmonization. We grouped LC phases into three aggregate categories:

- Upstream Processes: Upstream processes occur once prior to operational processes and include facility construction and supply of materials.
- Operational Processes: Operational processes result in GHGs emitted on a continual basis per unit of electricity generated. They include biomass production, prior use, harvest, collection, preprocessing, drying, storage, and combustion; facility operation and maintenance; and waste management and treatment.
- Downstream Processes: Downstream processes occur once after a facility's operational processes cease and include facility decommissioning and any disposal or recycling of material.

Operational processes could have been further subdivided into processes related directly to facility operations and biomass production. However, facility operations were typically negligible or not reported separately from other operational processes. LUC was excluded as beyond the scope of this study, largely because a significant portion of important bioenergy related LUC literature does not overlap with LCA literature. Co-products were excluded through the allocation of impacts to electricity or system expansion to account for the impacts of the product(s) displaced by co-product(s). Dashed routes and boxes indicate optional processes or system routes that are not necessarily present in all biopower systems. Biomass can come from crops or a prior use such as wastes that are sent to the landfill. Drying, preprocessing, and storage are not necessary life cycle phases depending on the feedstock. There are several opportunities for recycling of materials such as facility materials (e.g., steel) from decommissioning and ash recycling. Biopower system can be very complex and diverse and therefore difficult to cross-compare.

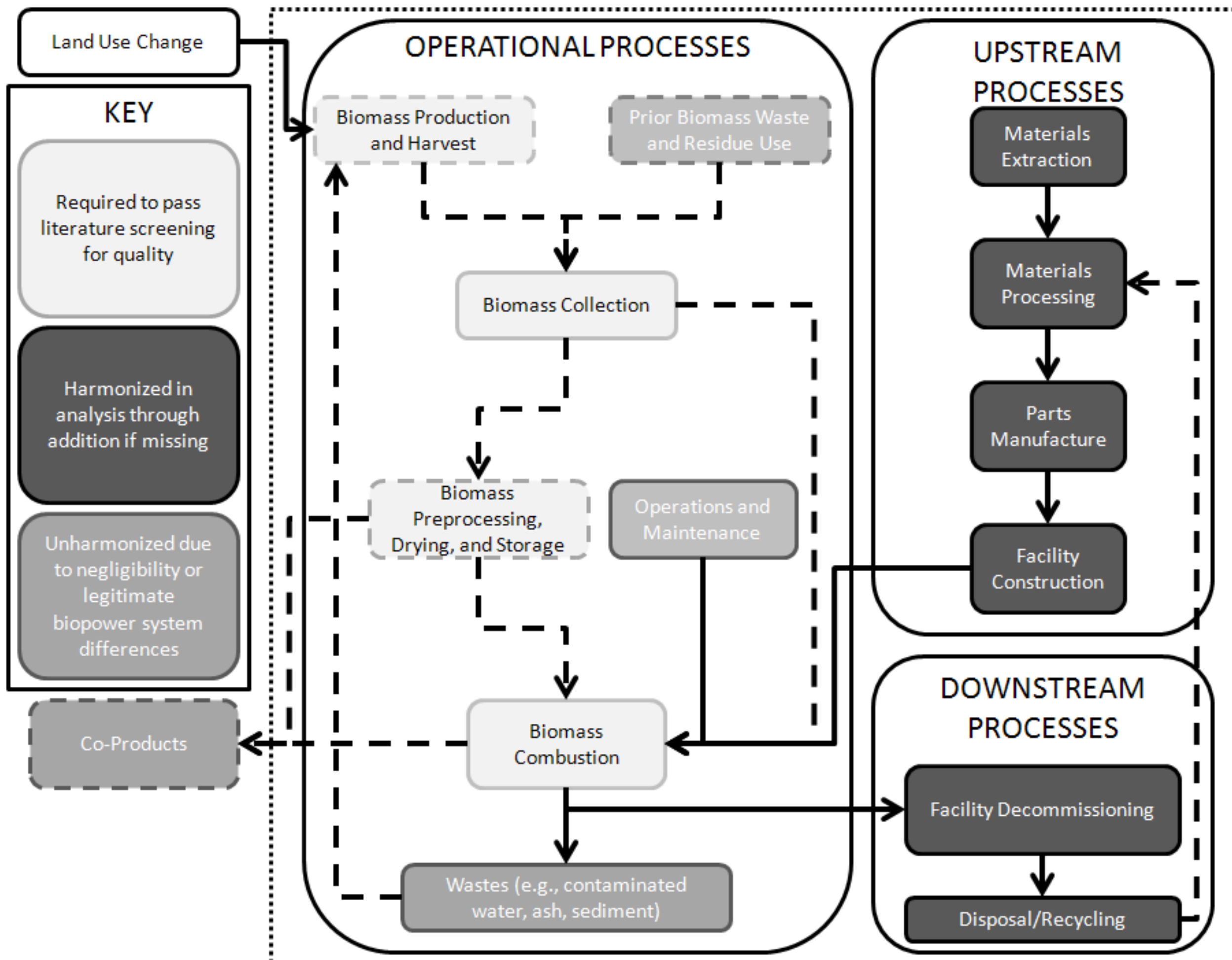


Figure 1-1
LCA literature and harmonization system boundaries (dotted line box) for biopower electricity generation

Elements outside the system boundary are harmonized by subtraction or allocation (i.e., LUC and co-products respectively). Arrows typically indicate transportation which is included in most LCAs. Dashed arrows and boxes represent optional routes and processes. Solid arrows represent routes and processes that would generally be a present in all biopower systems if not evaluated in all studies.

Literature Collection, Screening, and Figure Construction Methods

A comprehensive review of published biopower LCAs through June 2011 yielded 387 references of which 117 passed quality and relevance screens, described below, and were entered into a database. With the exception of unit conversions, the analysis of the literature did not alter or audit for calculation accuracy. Additionally, no attempt was made to identify or screen for outliers or pass judgment on the validity of input parameter assumptions. Plotting as-published results led to visible inconsistency between studies, even within technology and feedstock categories.

Literature Collection and Screening

Potentially relevant literature was identified through multiple mechanisms, including:

- Major bibliographic databases (e.g., Web of Science) using a variety of search algorithms and combinations of key words
- Collection of citation lists from relevant literature
- LCA literature databases.

Collected references were subjected to two rounds of screening by multiple experts to select references that met criteria for quality and relevance. References often reported multiple GHG emission estimates based on alternative scenarios. Where relevant, the screening criteria were applied at the level of the scenario estimate, occasionally resulting in only a subset of scenarios analyzed in a given reference passing the screens.

Sources that passed the first screen included peer-reviewed journal articles, scientifically detailed conference proceedings, PhD theses, and reports (authored by government agencies, academic institutions, non-governmental organizations, international institutions, or corporations) published after 1980 and in English. The first screen also ensured that the accepted references were true LCAs, defined as having analyzed two or more life cycle phases. Combined heat and power (CHP) papers only passed if life cycle impacts were allocated (or it was possible to easily allocate) among heat and electricity. One hundred and eighty four references passed the first screen.

All references passing the first screen were then directly judged based on more stringent quality and relevance criteria:

- Employed a currently accepted LCA and GHG accounting method, for example:
  - Not purely an economic input/output LCA assessment
  - Included critical life cycle stages including feedstock acquisition and power generation
- Reported inputs, scenario/technology characteristics, important assumptions, and results were presented in enough detail as to trace and trust the results
- Evaluated a technology of modern or future relevance (e.g., studies older than 1990 were excluded).

One hundred seventeen references passed both the quality and relevance screens and are used as the basis for the analysis reported in this paper. Figure 1-2 illustrates how the LCA literature collection, shown by publication year, changes as the first and second screens are applied. The number of collected papers and papers passing the first screen increased by publication year from 1990–2010. 2011 was excluded as our literature collection for the year is incomplete. Since 200 papers passing the second screen remained fairly constant (approximately five to 10 papers per year), with the exception of a high point in 2010. The number of collected biopower papers has been increasing overtime indicating, at the very least, a rising research interest in biopower technologies. The chart should not be construed as indicating that many more low-quality papers have been published recently, as many of them focus on heat production from CHP systems, and are thus less relevant to the present analysis.

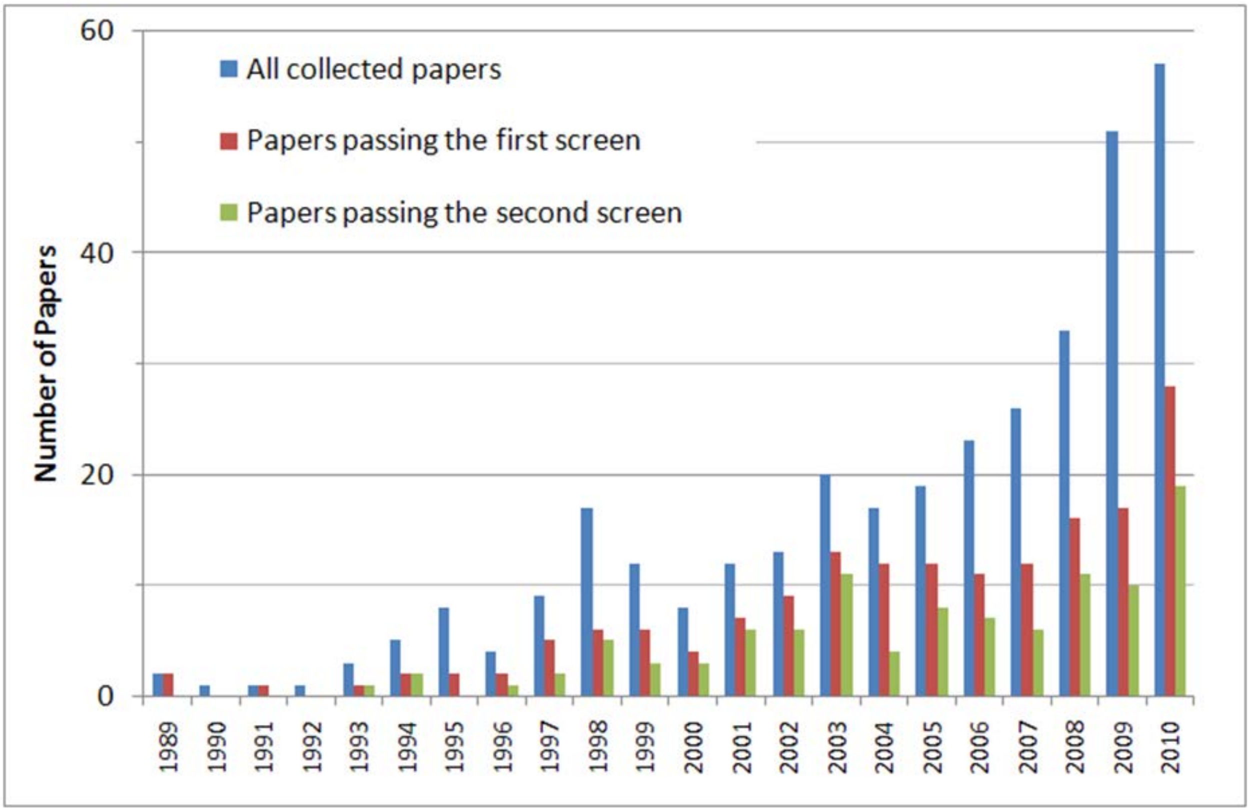


Figure 1-2
Biopower literature by year of publication prior to and after the application of the two sets of screening criteria

Harmonization Methods

Farrell et al. (2006) was the first notable study to attempt to harmonize previously published energy technology LCAs of GHG emissions. The method employed by Farrell et al. (2006) thus serves as a model from which our harmonization is based. In that study, the researchers began with a subset of the available literature of ethanol LCAs, carefully disaggregated the estimates of life cycle GHG emissions, and then constructed a meta-model to recalculate the estimates. The meta-model adjusted parameters to consistent values, realigned system boundaries within each life cycle phase, and reviewed the appropriateness and accuracy of all data sources. From Farrell et al.'s example we identified two avenues for harmonization: a more resource-intensive process similar to Farrell et al. and a second, less-intensive process where estimates are not disaggregated but rather are adjusted proportionally to consistent values for select influential parameters such as power plant thermal efficiency. In this study we implemented the second approach, enabling analysis of a larger group of studies to develop a more accurate range of life cycle GHG emission and gain insight into the drivers of existing literature variability.

Life cycle assumptions associated with biopower facility performance parameters and generalize system boundaries were selected for proportional adjustment. See Appendix II for a detailed explanation of proportional adjustment methods. The facility operating parameters of biomass conversion efficiencies, facility lifetime, facility capacity factor, and biomass lower heating value were harmonized to a consistent suite of assumptions. Functional units and system boundaries (i.e., upstream and downstream life cycle phases) were harmonized to a consistent set of GWP weighting factors and life cycle phases, respectively. Missing non-CO_2 GHG emissions and life cycle phases were added along with removal of coal related co-firing GHG emissions in order to improve cross-study consistency. These parameters were selected for harmonization because they were reported in the majority of papers and recalculation of new estimates based on new parameters was possible.

GWPs were modified, where possible, to reflect current IPCC standards as some GHGs have much longer atmospheric persistence then others. In order to compare carbon dioxide over various time horizons the calculation of different relative GHG impacts are necessary. GWPs were harmonized to the IPCC 2007 100-year time horizon values, where possible, for methane and nitrous oxide, i.e., 25 g CO_2/g CH_4 and 298 g CO_2/g N_2O (IPCC 2007). Literature published prior to 2007 used older GWPs, but harmonization was prevented in some instances as studies did not always report individual GHGs.

Life cycle GHG emissions from the co-firing of biomass with coal often included coal combustion and upstream life cycle phases (e.g., coal mining and transport). To allow for more consistent comparison across biomass technologies, GHG emission from coal systems were removed based on directly reported coal contributions or by approximation. Approximation was based on 100% coal reference systems data and other co-firing system specification such as the co-firing rate and assumed efficiency losses for co-firing systems

Non-CO_2 GHG emissions can be important contributors to life cycle GHG emissions. Significant N_2O emissions (~10-20 g CO_2eq/kWh) are commonly the result of fertilizer application to dedicated energy crops. Methane is not typically a major source of GHG emissions, but some studies include biomass decomposition along the supply chain during transportation, storage, and drying. Biomass decomposition produces CH_4 emissions that can be significant (~5-15 g CO_2eq/kWh). Median CH_4 and N_2O estimates by feedstock category (post-GWP harmonization), from collected literature were added to life cycle GHG emission estimates where they were absent. Only a relatively small number of studies excluded CH_4 and N_2O.

The efficiency of a plant measures the production of electricity in comparison to the energy input. Thermal efficiency was selected as a commonly reported efficiency parameter for harmonization. Thermal efficiency is defined as:

$$\text{Thermal Efficiency (\%)} = \frac{\mathit{Electrical\ Output}\ (\text{kWh}) * 3{,}413\left(\frac{\text{Btu}}{\text{kWh}}\right)}{\mathit{Heat\ Input\ from\ Fuel}\ (\text{Btu})} \quad \textbf{(1)}$$

Higher efficiencies result in fewer GHG emissions per unit electricity output since less biomass is combusted per unit electricity produced. Thermal efficiencies reported in the literature ranged from 12% to 50% and, where possible, were harmonized to 33%. 33% was selected as the median thermal efficiency reported in the literature. Heating value represents the energy content of the fuel or the amount of energy released when a fuel is combusted. Heating values are indirectly related to emissions per unit electricity. Lower heating values reported in the literature ranged from 4300 to 8800 Btu/lb of dry biomass. The heating value of all biomass feedstocks were harmonized to the literature's median estimate, 7700 Btu/lb of dry biomass.

The remaining parameters harmonized were lifetime, capacity factor, and, where missing, upstream and downstream life cycle GHG emissions. Lifetime and capacity factor influence the distribution of one-time upstream and downstream GHG emissions over the life of a biopower facility. Lifetime represents the number of years the power plant is in operation and was harmonized to 25 years as representative of the median literature value. The capacity factor represents the percentage of nameplate capacity at which the power plant operates, averaged over the course of a year. The capacity factor was harmonized to 76% as representative of the median value in the literature. Upstream and downstream life cycle phases were added where missing based on median estimates from studies that reported on those life cycle stages. GHG emissions from upstream and downstream life cycle phases are generally considered minor (Styles and Jones 2007; Sebastian et al. 2011; Hartmann and Kaltschmitt 1999; Gartner et al. 2008; Corti and Lambordi 2004). Therefore, the impact of harmonizing the interrelated factors of lifetime, capacity factor, and missing life cycle phase harmonization steps were expected to be minimal. Harmonization of these parameters was completed to reduce variability from outliers that did report significant life cycle GHG emissions from construction and decommissioning.

Figure and Table Construction

Estimates of life cycle GHG emissions from studies passing both screens were analyzed and plotted. First, estimates were categorized by technology and feedstock within the broad classes considered. Second, for the published results to be analyzed, estimates had to pass a final set of criteria:

- To ensure accuracy in transcription, only GHG emission estimates that were reported numerically (i.e., not only graphically) were included.
- Estimates duplicating prior published work were not included.
- Results had to have been convertible to the functional unit chosen for this study: grams of life cycle CO_2eq per kilowatt-hour generated.
- Studies that did not use technologies or feedstocks considered definitively applicable to utility scale U.S. conditions (i.e., bagasse as feedstock and direct biomass combustion in an engine) or were requested in the statement of work (i.e., food crops, bio-oils, and lumber) were excluded.

Most life cycle GHG emission estimates from the 57 remaining papers were plotted with minimum, 25th percentile, median, 75th percentile, and maximum for each technology or feedstock category. Distributions only relate to estimates currently available in LCA literature, not necessarily to underlying theoretical or practical extremes or the true central tendency when considering all deployment conditions weighted by generation.

Life cycle GHG emission estimates representing avoided GHG emissions from the use of non-harvest wastes and residues or biopower systems using carbon sequestration are represented as single data points These life cycle GHG emission estimates are reported in this manner because of their large and distinct impact of underlying biopower system assumptions on results. Figure 1-3 displays life cycle GHG emission data as published compared to data post-harmonization of GWPs and coal in cofiring cases. Once the impact of this harmonization step is examined in the subsequent technology and feedstock figures, i.e., Figure 1-4 and Figure 1-5, respectively, only examine life cycle GHG emission data after harmonization of coal and GWPs relative to data after all selected factors were harmonized.

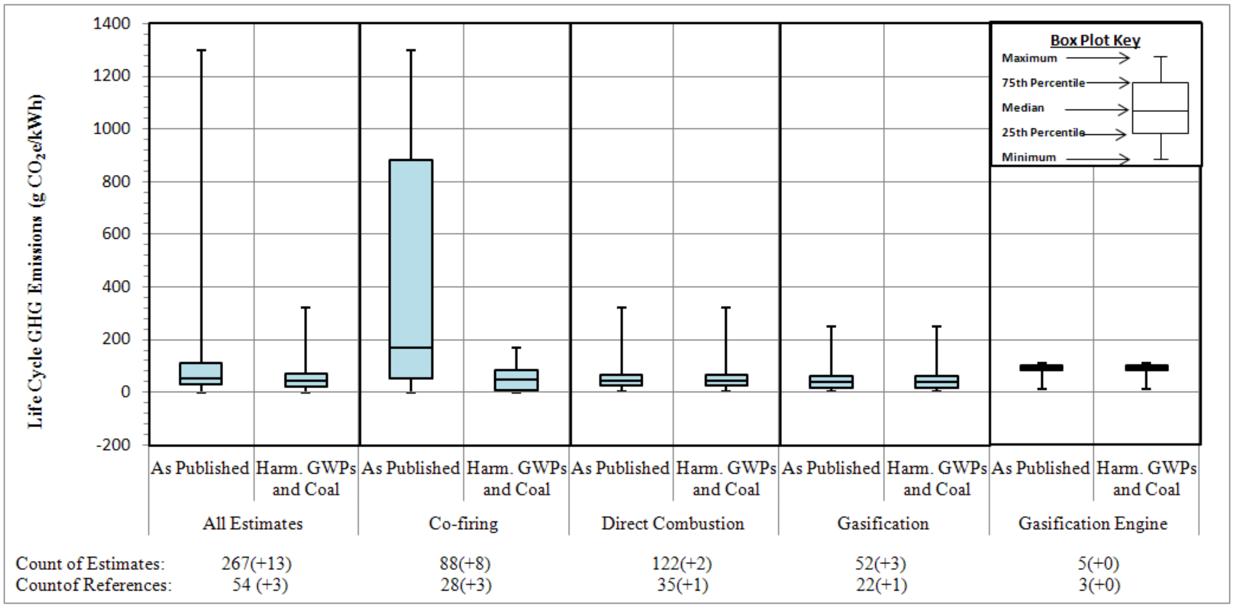
Summary Life Cycle Greenhouse Gas Emissions: Figures, Statistics, and Literature Counts

As-Published Life Cycle Greenhouse Gas Emissions by Biopower Technology Category

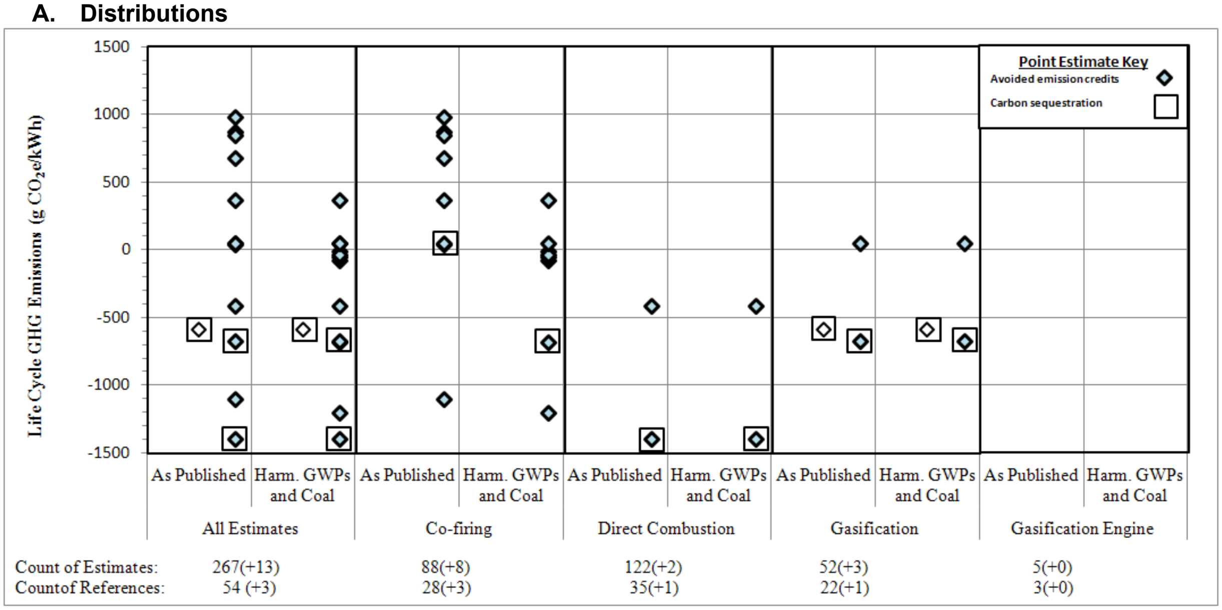
Distributions of as-published life cycle GHG emissions from literature that passed the study's screens and categorized by biopower technology are illustrated in Figure 1-3A and listed in Table 1-1. Figure 1-3B shows, in a similar format, point estimates for carbon sequestration and avoided GHG emissions from the use of non-harvest wastes and residues. All three primary biopower technologies (co-firing, direct combustion, and gasification) have been well studied, as reflected by the publication of at least 20 papers each. The variability in co-firing estimates is significant due to the inclusion of studies that report life cycle GHG emissions from only biomass as well as biomass with coal. Co-firing estimate variability is also compounded by combining the inherent variability within coal and biomass systems.

Harmonized GWPs and Coal Life Cycle Greenhouse Gas Emissions by Biopower Technology Category

Figure 1-3A and 1-3B also illustrates life cycle GHG emissions once GWPs are harmonized and co-firing related coal GHG emissions are removed. More detailed results and statistics are also listed in Table 1-1. In Figure 1-3A the majority of the estimates cluster between about 20 and 69 g CO_2eq/kWh, which represent the 25^{th} and 75^{th} percentiles, respectively. The maximum estimate is 320 g CO_2eq/kWh. Once co-firing related coal GHG emissions were removed the range and central tendency of each evaluated biopower technology are generally comparable. The gasifier engine systems had higher life cycle GHG emissions then other technologies. Harmonizing GWP had little impact on life cycle GHG emissions as indicated by the at most 3% change in IQR from Table 1-1. Most biopower papers have been published after 2001 and GWPs have not changed significantly. Depending on business-as-usual assumptions, avoided GHG emissions (usually methane from landfills) from non-harvest wastes and residues can more than outweigh GHG emissions associated with the biomass delivery and power portions of the life cycle. Carbon mitigation technologies were reported in very few references, but did lead to large life cycle GHG emissions reductions.



A. Distributions



B. Point Estimates

Figure 1-3
Life cycle GHG emissions from biopower technologies per kilowatt-hour generated (excluding LUC)

Estimates reported as published and post-harmonization of GWPs and removal of co-firing related coal GHG emissions. Included in the avoided GHG emissions[2] category are estimates in which the use of the feedstock itself leads to avoided emissions, usually in the form of avoided methane from landfills. Estimates that include avoided emissions from the production of co-products are not included in the avoided GHG emissions categories. Transparent boxes indicate that a carbon sequestration technology (e.g., CCS) was considered. Along the bottom of the

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[2] Unlike the case of bioenergy combined with CCS, avoided emissions do not remove GHG emissions from the atmosphere.

figure and aligned with each column are the number of estimates and the number of references producing the distributions Figure 1-3A. In parenthesis are the number of additional estimates and references used to construct the point estimate Figure 1-3B.

Table 1-1
Life Cycle GHG Emission Variability and Central Tendency Statistics for Biopower Technologies

All Values	As Published Life Cycle GHG (g CO_2eq/kWh)	Harmonized GWPs (g CO_2eq/kWh)	Harmonized GWPs and Coal (g CO_2eq/kWh)	Harmonized by GHGs (g CO_2eq/kWh)	Harmonized by System Boundaries (g CO_2eq/kWh)	Harmonized by Thermal Efficiency (g CO_2eq/kWh)	Harmonized by Heating Value (g CO_2eq/kWh)	Harmonized by All (g CO_2eq/kWh)
Mean	190	190	52	53	52	50	50	49
Std Dev	320	320	44	43	44	43	42	43
Minimum	-3	-3	-3	0.012	-3	-3	-3	-3
25th Quartile	28	28	20	23	20	18	18	18
Median	52	52	43	44	43	40	40	40
75th Quartile	110	110	69	71	69	61	66	59
Maximum	1300	1300	320	320	320	280	270	300
IQR (75th - 25th Quartile)	82	82	49	48	49	43	48	41
Range (max - min)	1300	1300	320	320	320	280	270	300
Change in Mean (%)	-	0%	-270%	2%	0%	-4%	-4%	-6%
Change in SD (%)	-	0%	-630%	-2%	0%	-2%	-5%	-2%
Change in Median (%)	-	0%	-21%	2%	0%	-8%	-8%	-8%
Change in Interquartile Range (%)	-	0%	-67%	-2%	0%	-14%	-2%	-20%
Change in Range (%)	-	0%	-310%	0%	0%	-14%	-19%	-7%
Count of Estimates	-	17	43	46	25	176	106	206
Count of References	-	7	14	10	9	43	27	48
Co-firing								
Mean	470	470	56	57	56	56	55	56
Std Dev	430	430	49	48	49	50	50	51
Minimum	-3	-3	-3	0.012	-3	-3	-3	-3
25th Quartile	53	55	9	11	9	9.6	8.8	9.2
Median	170	170	48	48	49	49	49	48
75th Quartile	880	880	84	84	84	80	83	80
Maximum	1300	1300	170	170	170	170	170	170
Interquartile Range (75th - 25th)	830	830	75	73	75	70	74	71
Range (max - min)	1300	1300	170	170	170	170	170	170
Change in Mean (%)	-	0%	-740%	2%	0%	0%	-2%	0%
Change in SD (%)	-	0%	-780%	-2%	0%	2%	2%	4%
Change in Median (%)	-	0%	-250%	0%	2%	2%	2%	0%
Change in Interquartile Range (%)	-	0%	-1000%	-3%	0%	-7%	-1%	-6%
Change in Range (%)	-	0%	-660%	0%	0%	0%	0%	0%
Count of Estimates*	-	8	43	14	4	52	29	69
Count of References*	-	3	14	2	3	19	11	24
Direct Combustion								
Mean	49	49	49	51	49	43	46	41
Std Dev	38	38	38	37	38	34	32	31
Minimum	3	3	3	7	3	3	3	3.5
25th Quartile	25	25	25	30	25	23	23	18
Median	42	42	42	42	42	37	39	35
75th Quartile	64	65	65	66	64	53	59	48
Maximum	320	320	320	320	320	190	220	150
Interquartile Range (75th - 25th)	39	40	40	36	39	30	36	30
Range (max - min)	320	320	320	310	320	190	220	150
Change in Mean (%)	-	0%	0%	4%	0%	-14%	-7%	-20%
Change in SD (%)	-	0%	0%	-3%	0%	-12%	-19%	-23%
Change in Median (%)	-	0%	0%	0%	0%	-14%	-8%	-20%
Change in Interquartile Range (%)	-	3%	3%	-11%	-3%	-33%	-11%	-33%
Change in Range (%)	-	0%	0%	-3%	0%	-68%	-45%	-110%
Count of Estimates*	-	8	0	20	18	85	55	91
Count of References*	-	6	0	7	5	27	21	29

Table 1-1 (continued)
Life Cycle GHG Emission Variability and Central Tendency Statistics for Biopower Technologies

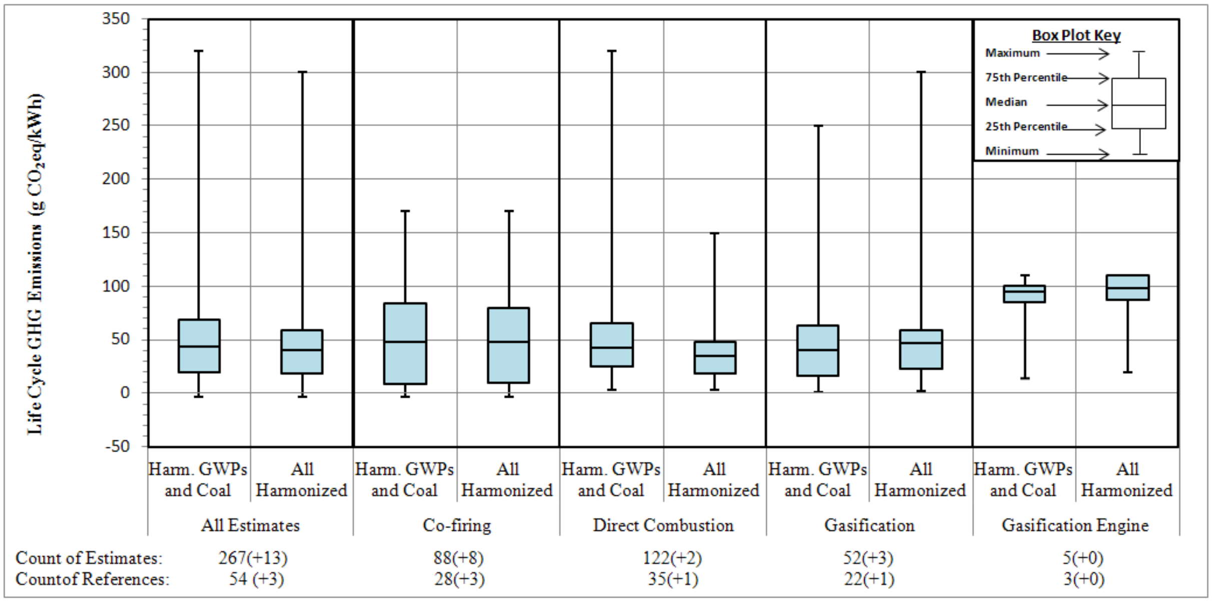
Gasification	As Published Life Cycle GHG (g CO_2eq/kWh)	Harmonized GWPs (g CO_2eq/kWh)	Harmonized GWPs and Coal (g CO_2eq/kWh)	Harmonized by GHGs (g CO_2eq/kWh)	Harmonized by System Boundaries (g CO_2eq/kWh)	Harmonized by Thermal Efficiency (g CO_2eq/kWh)	Harmonized by Heating Value (g CO_2eq/kWh)	Harmonized by All (g CO_2eq/kWh)
Mean	49	49	49	52	50	53	47	53
Std Dev	48	48	48	47	48	49	47	48
Minimum	1.2	1.2	1.2	2.3	1.2	1.3	1.2	2.1
25th Quartile	16	16	16	22	16	17	14	23
Median	40	40	40	43	40	44	40	47
75th Quartile	63	63	63	63	63	63	52	59
Maximum	250	250	250	250	250	280	270	300
Interquartile Range (75th - 25th)	47	47	47	41	47	46	38	36
Range (max - min)	250	250	250	250	250	280	270	300
Change in Mean (%)	-	0%	0%	6%	2%	8%	-4%	8%
Change in SD (%)	-	0%	0%	-2%	0%	2%	-2%	0%
Change in Median (%)	-	0%	0%	7%	0%	9%	0%	15%
Change in Interquartile Range (%)	-	0%	0%	-15%	0%	-2%	-24%	-31%
Change in Range (%)	-	0%	0%	0%	0%	11%	7%	17%
Count of Estimates*	-	1	0	11	2	38	19	42
Count of References*	-	1	0	6	2	18	13	21
Gasification Engine								
Mean	81	81	81	82	81	81	84	85
Std Dev	34	34	34	32	34	35	36	34
Minimum	14	14	14	19	16	13	14	20
25th Quartile	85	85	85	85	85	85	87	87
Median	95	95	95	95	95	95	98	98
75th Quartile	100	100	100	100	100	100	110	110
Maximum	110	110	110	110	110	110	110	110
Interquartile Range (75th - 25th)	15	15	15	15	15	15	23	23
Range (max - min)	96	96	96	91	94	97	96	90
Change in Mean (%)	-	0%	0%	1%	0%	0%	4%	5%
Change in SD (%)	-	0%	0%	-6%	0%	3%	6%	0%
Change in Median (%)	-	0%	0%	0%	0%	0%	3%	3%
Change in Interquartile Range (%)	-	0%	0%	0%	0%	0%	35%	35%
Change in Range (%)	-	0%	0%	-6%	-2%	1%	0%	-7%
Count of Estimates*	-	0	0	1	1	1	3	4
Count of References*	-	0	0	1	1	1	1	2

Per kilowatt-hour generated, excluding LUC. The harmonization of GWPs and co-firing related coal GHG emissions are reported as cumulatively harmonization steps. Therefore, the percent changes in both cases are compared to published estimates. GHGs, system boundaries, thermal efficiency, heating value, and the harmonization of all these factors are reported as harmonization steps applied data that has harmonized GWPs and co-firing related GHG emissions. In these cases, the percent changes are compared to data with GWPs and co-firing related coal GHG emissions harmonized.

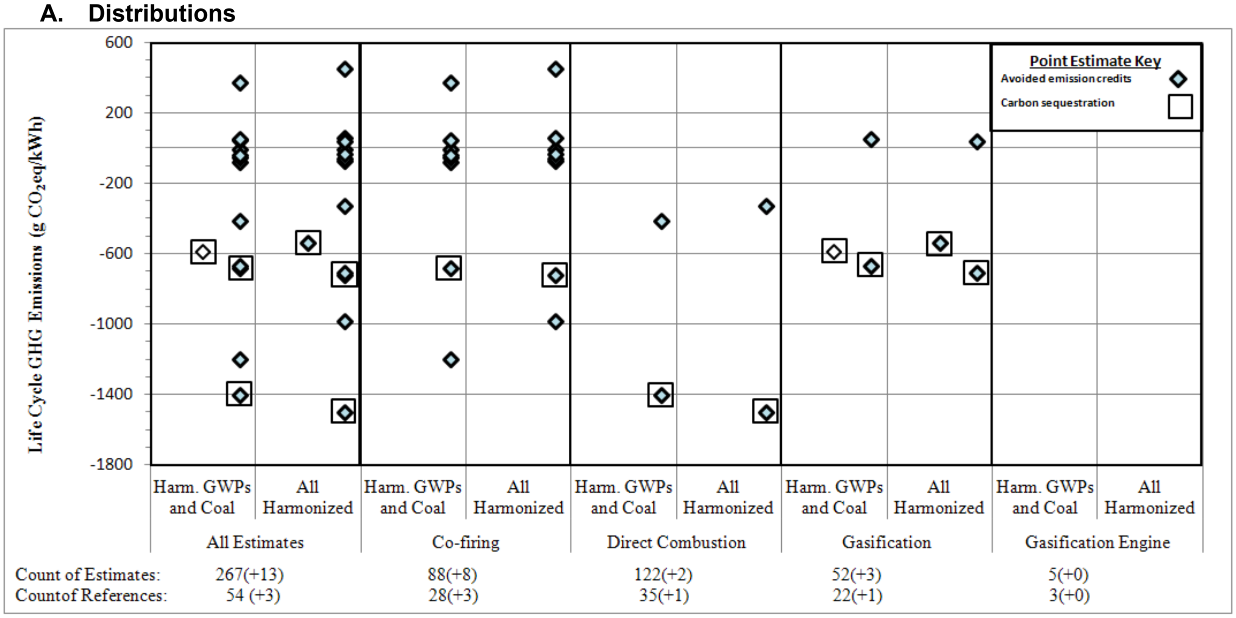
*on which a given harmonization step was applied.

Harmonized Life Cycle Greenhouse Gas Emissions by Biopower Technology Category

Figure 1-4 illustrates life cycle GHG emissions once all other selected factors are harmonized compared to data distribution where only coal GHG emissions are removed and GWPs are harmonized. More detailed results and statistics are also listed in Table 1-1. Figure 1-4A shows the majority of estimates cluster between about 18 and 59 g CO_2eq/kWh, which represent the 25^{th} and 75^{th} percentiles, respectively. The maximum estimate has decreased to 300 g CO_2eq/kWh. The most significant change was for direct combustion systems in which IQR and range were decreased by 33% and 110%, respectively. Gasification estimates' range increased slightly by 17%, but the more robust measure of variability, IQR, decreased by 31%. Co-firing estimates largely did not change and gasification engine IQR increased by 35%. However, in the latter case this was due to a shift of only one estimate among a very small pool of estimates. The thermal efficiency of the plant has the greatest influence on LCA results at the plant which reflects its importance as documented in much of the literature (Yoshioka et al. 2005; Sebastian et al., 2011; Lu et al. 2010; Gartner et al. 2008; Cherubini et al. 2009).



A. Distributions



B. Point Estimates

Figure 1-4
Life cycle GHG emissions from biopower technologies per kilowatt-hour generated (excluding LUC)

Estimates reported post-harmonization of GWPs and removal of co-firing related coal GHG emissions as compared to the harmonization other selected factors. Included in the avoided GHG emissions[3] category are estimates in which the use of the feedstock itself leads to avoided

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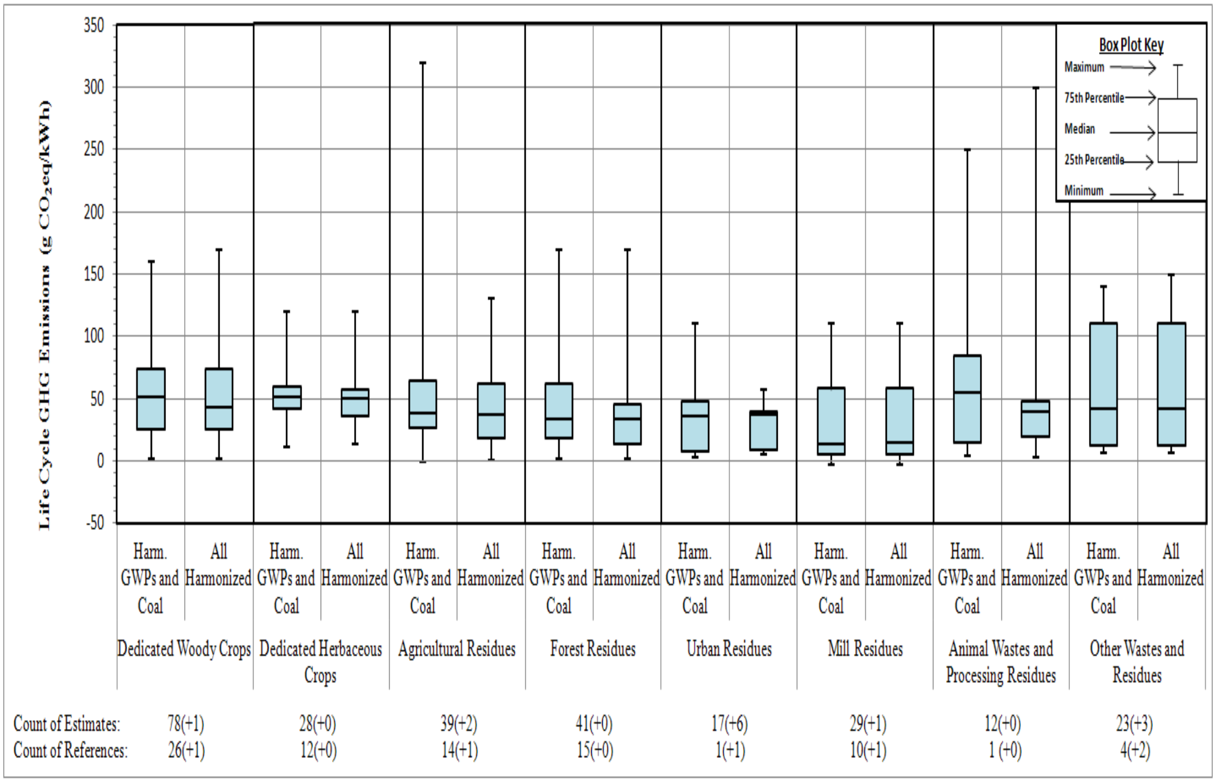
[3] Unlike the case of bioenergy combined with CCS, avoided emissions do not remove GHG emissions from the atmosphere.

emissions, usually in the form of avoided methane from landfills. Estimates that include avoided emissions from the production of co-products are not included in the avoided GHG emissions categories. Transparent boxes indicate that a carbon sequestration technology (e.g., CCS) was considered. Along the bottom of the figure and aligned with each column are the number of estimates and the number of references producing the distributions Figure 1-4A. In parentheses are the number of additional estimates and references used to construct the point estimate Figure 1-4B.

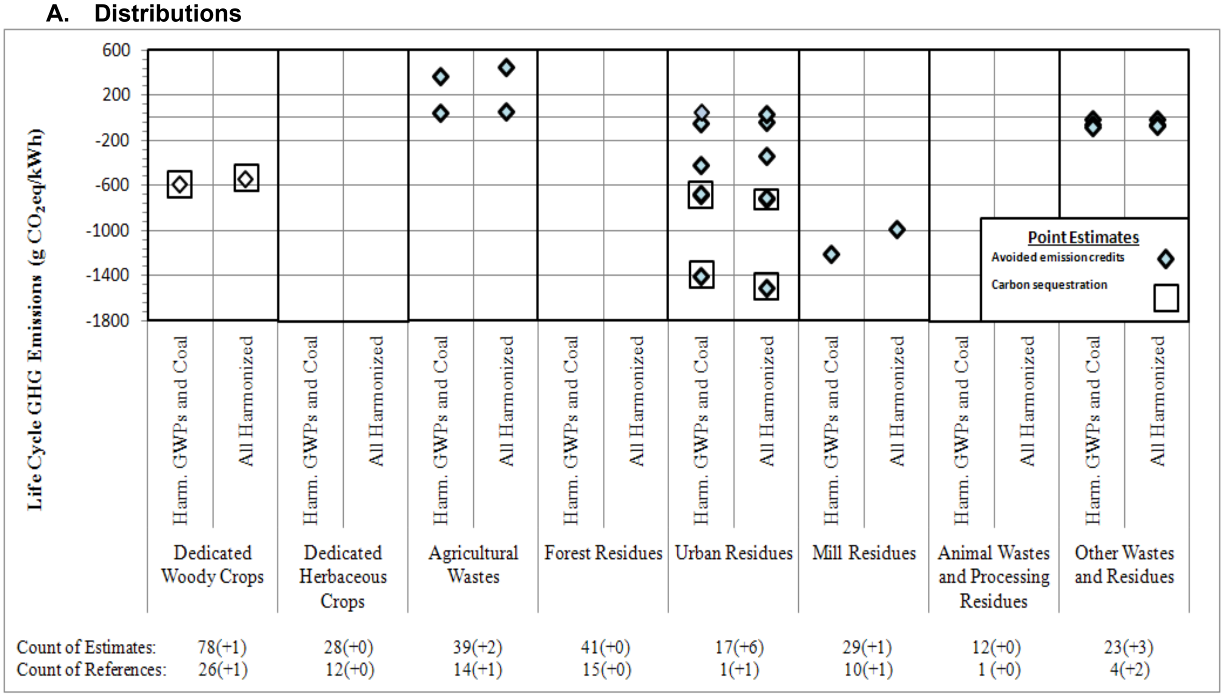
Harmonized Life Cycle Greenhouse Gas Emissions by Biopower Feedstock Category

Distributions of life cycle GHG emissions by feedstocks categories are shown in Figure 1-5A with associated point estimates in Figure 1-5B. More detailed results are listed in Table 1-2. When comparing medians with 25^{th} and 75^{th} percentiles, biomass systems that utilize some waste and residue categories (i.e., mill and forest residues) seem to be lower than at least woody crops. Most feedstock categories were largely unchanged by harmonization (i.e., dedicated woody crops, mill residues, dedicated herbaceous crops, and other wastes and residues). The IQR for urban residues, animal wastes and processing residues and forest residues decreased by 32%, 140% and 42%, respectively. The range of life cycle GHG emissions for agricultural wastes decreased by 150%, but the IQR increased by 14%.

Within most feedstock categories there is still significant life cycle GHG emission variation most likely due to system specifications unrelated to the items harmonized, typically upstream of the biopower facility. One piece of evidence for this is that the “urban residues” and the “animal wastes and processing residues” categories, even once harmonized, still show a high degree of variation just from the one study. Given the prevalence of legitimate differences in biopower system design (e.g., alternative field practices) is unsurprising that substantial variability is present. Dedicated woody crops, dedicated herbaceous crops, crop residues, and forest residues have each been well studied (i.e., > 10 papers). These feedstock categories represent a large portion of biomass resources in the United States (Milbrant).



A. Distributions



B. Point Estimates

Figure 1-5
Life cycle GHG emissions from biopower feedstock categories per kilowatt-hour generated (excluding LUC)

Estimates after the application of harmonization methods are compared to estimates post-harmonization of GWPs and co-firing related coal GHG emissions in co-firing cases. The “other” category includes undefined mixtures of other established biomass feedstock categories. Included in the avoided GHG emissions[4] category are estimates in which the use of the feedstock itself leads to avoided emissions, usually in the form of avoided methane from landfills. Estimates that include avoided emissions from the production of co-products are not included in the avoided GHG emissions categories. Transparent boxes indicate that a carbon sequestration technology (e.g., CCS) was considered. Along the bottom of the figure and aligned with each column are the number of estimates and the number of references producing the distributions Figure 1-5A. In parenthesis are the number of estimates and references use to construct the point estimate Figure 1-5B.

Table 1-2
Life Cycle GHG Emission Variability and Central Tendency Statistics for Biopower Technologies Per Kilowatt-hour Generated

Dedicated Woody Crops	As Published Life Cycle GHG (g CO_2eq/kWh)	Harmonized GWPs (g CO_2eq/kWh)	Harmonized GWPs and Coal (g CO_2eq/kWh)	Harmonized by GHGs (g CO_2eq/kWh)	Harmonized by System Boundaries (g CO_2eq/kWh)	Harmonized by Thermal Efficiency (g CO_2eq/kWh)	Harmonized by Heating Value (g CO_2eq/kWh)	Harmonized by All (g CO_2eq/kWh)
Mean	86	86	58	60	58	57	58	58
Std Dev	140	140	41	40	41	44	42	45
Minimum	1.3	1.3	1.3	2	1.3	1.6	1.3	2.2
25th Quartile	28	28	26	31	26	24	26	26
Median	52	52	51	51	51	43	48	43
75th Quartile	84	84	74	75	74	74	74	74
Maximum	880	880	160	160	160	160	170	170
Interquartile Range (75th - 25th)	56	56	48	44	48	50	48	48
Range (max - min)	880	880	160	160	160	160	170	170
Change in Mean (%)	-	0%	-48%	3%	0%	-2%	0%	0%
Change in SD (%)	-	0%	-240%	-3%	0%	7%	2%	9%
Change in Median (%)	-	0%	-2%	0%	0%	-19%	-6%	-19%
Change in Interquartile Range (%)	-	0%	-17%	-9%	0%	4%	0%	0%
Change in Range (%)	-	0%	-450%	0%	0%	0%	6%	6%
Count of Estimates*	-	1	3	15	7	52	29	62
Count of References*	-	1	3	7	3	22	11	23
Dedicated Herbaceous Crops								
Mean	280	280	52	53	52	50	50	49
Std Dev	400	400	23	22	23	21	21	21
Minimum	11	11	11	19	11	12	11	14
25th Quartile	43	43	42	42	42	42	38	36
Median	54	56	52	52	52	52	50	50
75th Quartile	300	300	60	61	60	57	58	57
Maximum	1100	1100	120	120	120	120	120	120
Interquartile Range (75th - 25th)	260	260	18	19	18	15	20	21
Range (max - min)	1100	1100	110	100	110	110	110	110
Change in Mean (%)	-	0%	-440%	2%	0%	-4%	-4%	-6%
Change in SD (%)	-	0%	-1600%	-5%	0%	-10%	-10%	-10%
Change in Median (%)	-	4%	-4%	0%	0%	0%	-4%	-4%
Change in Interquartile Range (%)	-	0%	-1300%	5%	0%	-20%	10%	14%
Change in Range (%)	-	0%	-900%	-10%	0%	0%	0%	0%
Count of Estimates*	-	4	7	2	3	13	13	19
Count of References*	-	2	5	1	2	8	5	9
Agricultural Residues								
Mean	260	260	53	56	53	48	46	45
Std Dev	400	400	56	55	56	42	42	34
Minimum	0.012	0.012	0.012	0.012	0.85	0.011	0.0084	0.85
25th Quartile	31	31	27	31	27	23	23	18
Median	56	56	39	42	39	29	32	37
75th Quartile	220	220	65	65	65	66	62	62
Maximum	1300	1300	320	320	320	190	220	130
Interquartile Range (75th - 25th)	190	190	38	34	38	43	39	44
Range (max - min)	1300	1300	320	320	320	190	220	130
Change in Mean (%)	-	0%	-390%	5%	0%	-10%	-15%	-18%
Change in SD (%)	-	0%	-610%	-2%	0%	-33%	-33%	-65%
Change in Median (%)	-	0%	-44%	7%	0%	-34%	-22%	-5%
Change in Interquartile Range (%)	-	0%	-400%	-12%	0%	12%	3%	14%
Change in Range (%)	-	0%	-310%	0%	0%	-68%	-45%	-150%
Count of Estimates*	-	1	11	4	4	33	21	33
Count of References*	-	1	6	2	3	13	6	12

[4] Unlike the case of bioenergy combined with CCS, avoided emissions do not remove GHG emissions from the atmosphere.

Table 1-2 (continued)
Life Cycle GHG Emission Variability and Central Tendency Statistics for Biopower Technologies Per Kilowatt-hour Generated

Forest Residues	As Published Life Cycle GHG (g CO_2eq/kWh)	Harmonized GWPs (g CO_2eq/kWh)	Harmonized GWPs and Coal (g CO_2eq/kWh)	Harmonized by GHGs (g CO_2eq/kWh)	Harmonized by System Boundaries (g CO_2eq/kWh)	Harmonized by Thermal Efficiency (g CO_2eq/kWh)	Harmonized by Heating Value (g CO_2eq/kWh)	Harmonized by All (g CO_2eq/kWh)
Mean	170	170	45	46	45	43	43	43
Std Dev	310	310	38	38	38	41	39	41
Minimum	7	7	2	2	2	2.2	2	2.2
25th Quartile	22	22	18	18	18	18	17	14
Median	36	36	34	34	34	34	34	34
75th Quartile	74	74	62	67	62	45	56	45
Maximum	1000	1000	170	170	170	170	170	170
Interquartile Range (75th - 25th)	52	52	44	49	44	27	39	31
Range (max - min)	990	990	170	170	170	170	170	170
Change in Mean (%)	-	0%	-280%	2%	0%	-5%	-5%	-5%
Change in SD (%)	-	0%	-720%	0%	0%	7%	3%	7%
Change in Median (%)	-	0%	-6%	0%	0%	0%	0%	0%
Change in Interquartile Range (%)	-	0%	-18%	10%	0%	-63%	-13%	-42%
Change in Range (%)	-	0%	-480%	0%	0%	0%	0%	0%
Count of Estimates*	-	2	6	11	8	31	11	31
Count of References*	-	2	4	4	2	12	5	12
Urban Residues								
Mean	410	410	41	41	41	31	39	30
Std Dev	390	390	33	33	33	17	32	17
Minimum	30	30	3.5	3.5	3.5	5	3.5	5
25th Quartile	36	36	7.5	7.5	7.5	9.1	7.1	8.7
Median	49	49	36	36	36	37	36	37
75th Quartile	790	800	48	48	48	42	46	40
Maximum	910	910	110	110	110	57	110	57
Interquartile Range (75th - 25th)	750	760	41	41	41	33	39	31
Range (max - min)	880	880	110	110	110	52	110	52
Change in Mean (%)	-	0%	-900%	0%	0%	-32%	-5%	-37%
Change in SD (%)	-	0%	-1100%	0%	0%	-94%	-3%	-94%
Change in Median (%)	-	0%	-36%	0%	0%	3%	0%	3%
Change in Interquartile Range (%)	-	1%	-1700%	0%	0%	-24%	-5%	-32%
Change in Range (%)	-	0%	-700%	0%	0%	-110%	0%	-110%
Count of Estimates*	-	3	8	0	0	17	7	17
Count of References*	-	1	1	0	0	1	1	1
Mill Residues								
Mean	92	92	32	35	32	32	32	33
Std Dev	220	220	35	34	35	36	36	36
Minimum	-3	-3	-3	2.3	-3	-3	-3	-3
25th Quartile	6	6	5.3	9.7	5.3	5.3	5.3	5.3
Median	15	15	14	19	15	13	14	15
75th Quartile	74	75	58	58	58	60	54	59
Maximum	910	910	110	110	110	110	110	110
Interquartile Range (75th - 25th)	68	69	53	48	53	55	49	54
Range (max - min)	910	910	110	110	110	110	110	110
Change in Mean (%)	-	0%	-190%	9%	0%	0%	0%	3%
Change in SD (%)	-	0%	-530%	-3%	0%	3%	3%	3%
Change in Median (%)	-	0%	-7%	26%	7%	-8%	0%	7%
Change in Interquartile Range (%)	-	1%	-28%	-10%	0%	4%	-8%	2%
Change in Range (%)	-	0%	-730%	0%	0%	0%	0%	0%
Count of Estimates*	-	2	2	14	2	11	7	13
Count of References*	-	2	2	2	1	7	5	7

Table 1-2 (continued)
Life Cycle GHG Emission Variability and Central Tendency Statistics for Biopower Technologies Per Kilowatt-hour Generated

Animal Wastes and Processing Residues	As Published Life Cycle GHG (g CO_2eq/kWh)	Harmonized GWPs (g CO_2eq/kWh)	Harmonized GWPs and Coal (g CO_2eq/kWh)	Harmonized by GHGs (g CO_2eq/kWh)	Harmonized by System Boundaries (g CO_2eq/kWh)	Harmonized by Thermal Efficiency (g CO_2eq/kWh)	Harmonized by Heating Value (g CO_2eq/kWh)	Harmonized by All (g CO_2eq/kWh)
Mean	620	420	67	67	67	62	57	53
Std Dev	390	390	42	42	42	42	42	42
Minimum	68	68	4.6	4.6	4.6	5.6	2.7	3.3
25th Quartile	74	74	33	33	33	35	20	24
Median	130	130	72	72	72	57	52	46
75th Quartile	850	850	100	100	100	85	82	68
Maximum	900	900	130	130	130	140	140	130
Interquartile Range (75th - 25th)	780	780	67	67	67	50	62	44
Range (max - min)	830	830	130	130	130	130	140	130
Change in Mean (%)	-	-48%	-830%	0%	0%	-8%	-18%	-26%
Change in SD (%)	-	0%	-830%	0%	0%	0%	0%	0%
Change in Median (%)	-	0%	-81%	0%	0%	-26%	-38%	-57%
Change in Interquartile Range (%)	-	0%	-1100%	0%	0%	-34%	-8%	-52%
Change in Range (%)	-	0%	-540%	0%	0%	0%	7%	0%
Count of Estimates*	-	4	8	0	0	12	11	12
Count of References*	-	1	1	0	0	1	1	1
Other Wastes and Residues								
Mean	60	60	60	60	60	64	58	61
Std Dev	49	49	49	49	49	56	47	51
Minimum	7	7	7	7	7	7	7	7
25th Quartile	12	12	12	12	12	12	12	12
Median	42	42	42	42	42	42	42	42
75th Quartile	110	110	110	110	110	120	100	110
Maximum	140	140	140	140	140	170	130	150
Interquartile Range (75th - 25th)	98	98	98	98	98	110	88	98
Range (max - min)	130	130	130	130	130	160	120	140
Change in Mean (%)	-	0%	0%	0%	0%	6%	-3%	2%
Change in SD (%)	-	0%	0%	0%	0%	13%	-4%	4%
Change in Median (%)	-	0%	0%	0%	0%	0%	0%	0%
Change in Interquartile Range (%)	-	0%	0%	0%	0%	11%	-11%	0%
Change in Range (%)	-	0%	0%	0%	0%	19%	-8%	7%
Count of Estimates*	-	0	0	0	1	9	7	8
Count of References*	-	0	0	0	1	4	2	4

Excluding LUC. The harmonization of GWPs and co-firing related coal GHG emissions are reported as cumulatively harmonization steps. Therefore, the percent changes in both cases are compared to published estimates. GHGs, system boundaries, thermal efficiency, heating value, and the harmonization of all these factors are reported as harmonization steps applied data that has harmonized GWPs and co-firing related GHG emissions. In these cases, the percent changes are compared to data with GWPs and co-firing related coal GHG emissions harmonized.

*on which a given harmonization step was applied.

Analysis Limitations

Literature and Method Limitations

Meta-analysis and harmonization of existing life cycle GHG emission assessments has been limited by several inherent literature and selected method barriers. Analysis scope was significantly determined by the availability of information in the literature. Some potentially useful dimensions were left unharmonized (i.e., everything upstream of the biopower facility) due to reporting or logistical barriers (i.e., dynamic relationships) to completing a more detailed analysis. Other limitations include: 1) The potential for dataset bias from estimate clustering, and 2) Possible result misinterpretation as collected studies may not be truly representative of current or future nuclear power deployment.

A potential limitation to collected data is clustering resulting from the use of similar methods along at least one of three dimensions: multiple estimates reported in the same reference, multiple estimates from the same or similar author groups publishing serially, and multiple references citing the same sources of input data. Author related data clustering is unlikely as there is little overlap between paper's authors and these papers did not contribute a significant portion of total estimates. Clustering due to input data and multiple scenarios are potentially more important given that overlap in source data has been observed (e.g., EcoInvent) and several studies carried out detailed sensitivity analyses with many alternative scenarios. For example, almost twenty papers calculated five or more scenarios of life cycle GHG emissions.

Collected life cycle GHG emissions data do not represent a statistically independent population and certainly do not represent the full range of potential impacts, how the technology has been or could be deployed. We gathered all available high quality studies for biopower, but that doesn't guarantee that they reviewed all possible cases of manufacture, deployment, or use (i.e., our range may be narrower than the true range for the technology). Collected data may not necessarily include all relevant impacts with regard to the depth and breadth across the supply chain. Harmonization addresses inconsistent assumptions and key parameters of previously published LCAs in order to improve method consistency. The harmonization process can be viewed as improving the precision of life cycle GHG estimates. However, harmonization may not improve the accuracy of estimates. For instance, many studies neglect to even mention let alone account for the impacts of biomass losses along the supply chain in any great detail. Consistent neglect of certain contributors to life cycle GHG emissions across studies would bias results. The objective of harmonization was to improve the method consistency of previously published LCAs allowing for more consistent comparison and identifying the influence of harmonized parameters on life cycle GHG emissions.

The distribution of our results also cannot be considered a distribution of likelihood for actual life cycle GHG emissions for the technology or a formal sensitivity analysis. However, the magnitude of the change in life cycle GHG emission estimates can be considered indicative of the relative influence of examined parameters. The precision and range of results is improved with the large sample size evaluated here, but sample limitations affect the accuracy of the results compared to the "true" life cycle GHG emission range and central tendency of nuclear power under all potential conditions.

Remaining Major Sources of Life Cycle GHG Emission Variability

There are many remaining unharmonized sources of life cycle GHG emission variability. Existing literature indicates that the key remaining factors contributing to this variability are typically upstream of the biopower facility. Through an examination of existing uncertainty analysis and a cross study comparison, at least six major sources of life cycle GHG emission variability are apparent.

The most important upstream source of life cycle GHG emission variability for dedicated energy crops is feedstock yields and field input rates. Agricultural input manufacturing, primarily nitrogen, is often the single largest fossil fuel consumer in lignocellulosic crop based biopower systems (Herrara et al. 2008, Lu et al. 2010; Djomo et al. 2011) and the relative impact of field inputs on life cycle GHG emissions is modulated by biomass yields (Cherebini et al. 2009). The impact on life cycle GHG emissions of these parameters is complex because of the dynamic between biomass yields and field inputs (Herrara et al. 2008, Cherubini et al. 2009). For example, increases in field inputs can increase GHG emissions from fossil fuel use, but will raise yields which will have a mitigating impact on the level of GHG emission per unit of biomass.

Depending on the relationship between marginal field inputs and biomass yield an increase in field inputs could increase or decrease life cycle GHG emissions. Minimizing GHG emission at the field requires optimizing the relationship between field inputs and the biomass yield. Field inputs and biomass yield are also particularly important with regard to US biopower systems. Biomass yield and the background system (e.g., electric grid mix) used to produce field inputs are influenced by climate and location. Only about 20% of the collected literature on life cycle GHG emissions could be considered as applying to the US (i.e., focuses on the United States or North America).

Biopower systems that include an additional biomass processing step(s) tend to have higher life cycle GHG emissions. Several preprocessing methods for post-harvest biomass prior to combustion or gasification have been studied, such as pelletization, chipping, and pyrolysis. Pre-processing steps can have logistical and environmental benefits by reducing post-combustion wastes, increasing energy density, and increase flexibility of biomass use. However, additional preprocessing steps require fossil fuels that typically offset improvements in efficiency (Forsberg 2000; Damen and Faaij 2003).

Literature transportation modeling methods have been inconsistent, but generally indicate that transportation related GHG emissions are situationally dependent. Literature generally indicates that long distance importation of biomass can generate GHG emissions from large fossil inputs for long distance rail or ship transportation (Hacatoglu et al. 2011). For more centrally located biopower systems several studies model the bioenergy chain under a specific set of independent parameters including a transportation distance (Schaffner et al. 2002, Styles and Jones 2007). Other more recent detailed studies account for the dynamics between biopower system parameters. These studies evaluated the average or median transportation distance necessary to supply the biomass required to operate a biopower facility of a given biomass capacity. Such studies indicate that at lower generation capacities transportation GHG emissions are negligible (Searcy and Flynn 2008). Facilities with larger biomass capacities require a larger biomass resource basin and therefore the average or median transportation distance with increase lead to more significant fossil fuel consumption (Yoshioka et al. 2005; Roedl et al. 2010).

Biomass drying methods can either be an important or negligible direct source of life GHG emissions. Open air biomass drying requires little to no energy inputs and therefore few direct GHG emissions (Styles and Jones 2007). Mechanical drying requires energy inputs and GHG emissions can vary significantly depending on the level of drying required which depends on biomass moisture content, but also depending on inputs (i.e., fossil vs. renewable) (Sikkema et al. 2010; Forsberg 2000; Damen and Faaij 2003; Djomo et al. 2011). Initially, from an energy and GHG emission perspective this would seem to indicate that open air drying is preferred. However, open air drying could be an important indirect contributor to life cycle GHG emission variability through biomass losses.

Collected literature differed significantly on whether and how to account for biomass losses, but generally point two potential routes to increase life cycle GHG emissions. Biomass losses can reduce the “at facility gate” biomass yields (Corti and Lombardi 2004). The life cycle biopower system’s inputs per unit of biomass would then increase. A few studies also account for methane emissions resulting from biomass decay that might not have other wised occurred. Biomass losses are interrelated with biomass transportation, preprocessing, and drying life cycle phases and the length of travel from field to gate. The number of field to gate steps or the length of transportation distance increase the rate or likelihood of biomass losses. For example, a highly uncertain source of GHG emissions is biomass storage. Biomass air drying avoids mechanical drying fossil fuel inputs, but depending on the climate the biomass may begin to decay or even become infected with disease if left to dry at a slower pace (Forsberg 2000, Fan et al. 2011). Longer transportation distances increase the chance of biomass losses through leakage (Forsberg 2000).

A less studied potential significant life cycle GHG emission contributor is related to more detailed system boundary issues. Two examples seen in the literature related to soil quality and productivity at the field. Waste handling is generally a negligible life cycle phase so returning waste ashes to the field has little impact on reducing life cycle GHG emissions (Wihersaari 2005; Sebastian et al. 2010). However, waste ash recycling could significantly reduce non-nitrogen field nutrient inputs, reducing fossil fuel consumption (Malkki and Virtanen 2003; Daugherty 2001; Forsberg 2000). Other papers on biomass residues account for the soil quality impact by removing agricultural or forestry residues (Yoshioka et al. 2005; Cherubini et al. 2009; Bergsma et al. 2003). After quantifying the residue removal soil impact these studies assume fertilizers are applied to compensate for nutrient losses. The fossil fuel use to generate required field inputs would contribute to life cycle GHG emissions.

Remaining sources of life cycle GHG emission variability in biopower LCAs would be difficult to harmonize in existing literature. Many remaining sources of life cycle GHG emission variability are complex and interrelated. Since attempts to adjusting one parameter implies the adjustment of several others parameter, harmonization of literature in this manner would be difficult. A detailed examination of underlying modeling/methods and source data would be required to accurately examine these other sources of life cycle GHG emission variability in a quantitative manner. Furthermore, literature reporting limitations makes the assessment of the precise conditions of many studies, with regards to these factors—especially biomass losses and system boundaries—very difficult.

Comparison with Other Generating Technologies

Power generated from biomass, according to the literature reviewed, has a variable GHG. Generally, however, biopower compares favorably with other renewable energy sources, and is about an order of magnitude lower than natural gas based power. Figure 1-6 below, based on data from NREL, shows that renewable power is typically very attractive from a GHG perspective.

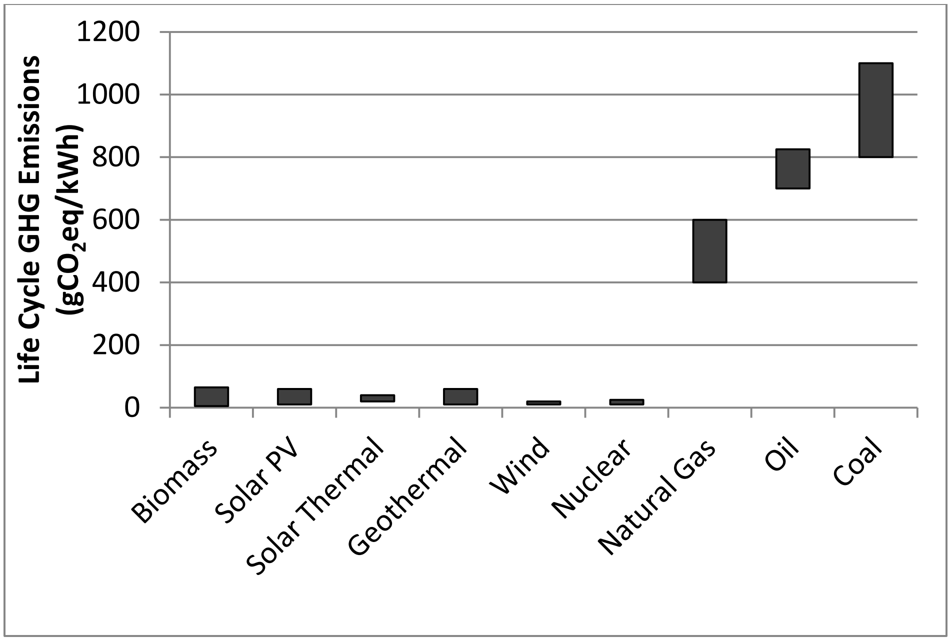


Figure 1-6
Life Cycle GHG Emissions

2
SUMMARY OF LITERATURE COUNTS OF OTHER LIFE CYCLE METRICS

Table 2-1 lists alternative life cycle GHG emission and sustainability indicators and metrics. Alternative life cycle GHG emission metrics that included avoided GHG emissions per unit of energy, land, or weight of biomass are omitted. These relative metrics are generally difficult to compare and were usually redundant with comparable absolute metrics. Metrics or indicators reported in only one study were also excluded. The existence of other GHG metrics and sustainability indicators within the 117 collected biopower LCA papers are noted below, and not assessed individually for quality. Therefore, in Table 2-1, the number of references containing the other metrics and indicators should be construed as an overestimate of usable original data.

Life cycle GHG emissions per kilowatt-hour are the most commonly-studied metric reported in the LCA literature. Table 2-1 lists other GHG emission metrics and sustainability indicators emphasize other measures of biopower sustainability. The non-life cycle GHG emission indicators categories listed in Table 2-1 are studied at a quantitative and qualitative level. Non-GHG sustainability indicators are aggregated into the broad categories that may include several different metrics. Metrics and indicators related to resources use (particularly energy), GHG emissions, criteria pollutants, and other impacts typically as pollutant releases have been well studied. Social and economic impacts were less studied in collected LCAs. However, it should be noted that studies exclusively on life cycle costing would have been excluded based on screening criteria.

Table 2-1
Number of References Addressing Alternative Metrics and Indicators

Alternative Life Cycle GHG Emission Metrics:	*Number of References*
GHG emissions per unit of land	5
GHG emissions per unit of biomass by weight	7
Displacement factor[5]	2
Carbon closure[6]	3
Costs per GHG emissions avoided	10
Non-Life Cycle GHG Emission Indicator Categories:	
Energy use indicators	54
Materials, renewable energy, and fossil fuel use	48
Criteria air pollutants	59
Water use	19
Land use	27
Human health risk assessment (for workers)	4
Monetary impacts of externalities	7
Social impacts (e.g., economic development)	6
Noise	5
Biodiversity	12
Other environmental impacts (e.g., generally other water, air, and soil pollutant releases)	56

[5] Displacement factor = (efficiency of bioenergy system/efficiency of fossil fuel system) x (CO_2carbon dioxide emissions of fossil system/CO2carbon dioxide from bioenergy).

[6] Carbon closure = $100 \times [1 -(C_{Net}–C_{Abs})]$; where C_{Net} is the amount (kg) of CO_2carbon dioxide released from the system as a result of the fossil fuel used in upstream processes, C_{Abs} is the amount (kg) of CO_2carbon dioxide absorbed by the biomass during growth.

3

SUPPLEMENTAL HARMONIZATION METHODS

Life cycle GHG emission harmonization required the proportional adjustment of parameters related to aggregate system boundaries and facility operating parameters. The proportional adjustment is represented mathematically as follows:

Equation (1),

$$A = B + C \tag{2}$$

where

$A = Life\ Cycle\ GHG\ Emissions\ (g\ CO_2eq/kWh)$

$$B = \frac{Upstream\ Emissions\ (tons\ CO_2eq) +\ Downstream\ Emissions\ (tons\ CO_2eq)}{Capacity(MW) * Capacity\ Factor(\%) * System\ Life(yrs) * 365 * 24\ \left(\frac{hrs}{yr}\right)}$$

$$C = \frac{Ongoing\ Non\ Combustion\ Emissions\left(\frac{g\ CO_2eq}{Ib\ dry\ biomass}\right) + Combustion\ Emissions\left(\frac{g\ CO_2eq}{Ib\ dry\ biomass}\right)}{LHV\ \left(\frac{Btu}{Ib\ dry\ biomass}\right) * thermal\ efficiency\ (\%) * 0.293 * 10^{-3}\left(\frac{kWh}{Btu}\right)}$$

To proportionally adjust the estimates for a particular parameter, we multiply the estimate by a proportion that relates the standardized parameter value to the as-reported parameter value:

$$A' = (B + C) * \frac{x}{x'} \tag{3}$$

where

$A' = Harmonized\ Life\ Cycle\ GHG\ Emissions\left(\frac{g\ CO_2eq}{kWh}\right)$

$\frac{x}{x'} = \frac{LHV\ Reported\ in\ Study}{LHV\ Standardized}$

The proportional adjustment method can introduce a small error by harmonizing the upstream and downstream emissions (B) by a parameter that is not relevant to those emissions; in the example calculation: LHV. Wherever possible (i.e., life cycle GHG emission reported by life cycle phase) this error was avoided in calculations by first removing these GHG emissions. A small error is introduced where this was not possible. Harmonization of parameters relevant to B by proportional adjustment would introduce significant error and therefore were not harmonized by this method.

Parameters relevant to the upstream and downstream emissions were harmonized by proportional adjustment of just the upstream and downstream portion of the emissions. This required reporting of emissions by life cycle stage. This method is illustrated by equation (4):

$$A' = B * \frac{x}{x'} + C \tag{4}$$

Similarly, proportional adjustment of global warming potentials (GWPs) could be done only to estimates that reported life cycle emissions for each GHG species (CO_2, CH_4, and N_2O) individually. The following depicts this method, beginning with a slightly different representation of equation (2):

$$A = A1 + A2 * GWP + A3 * GWP \tag{5}$$

where

$A1 = Life\ Cycle\ Carbon\ Dioxide\ Emissions\ \left(\frac{gCO_2}{kWh}\right)$

$A2 = Life\ Cycle\ Methane\ Emissions\ \left(\frac{gCH_4}{kWh}\right)$

$A3 = Life\ Cycle\ Dinitrogen\ Oxide\ Emissions\ \left(\frac{gN_2O}{kWh}\right)$

The harmonization calculation

$$A' = A1 + A2 * GWP * \frac{x'}{x} + A3 * GWP \frac{y'}{y} \tag{6}$$

Note

$A' = Harmonized\ Life\ Cycle\ GHG\ emissions\ \left(\frac{g\ CO_2eq}{kWh}\right)$

$\frac{x'}{x} = \frac{CH_4\ GWP\ Standardized}{CH_4\ GWP\ Utilized\ in\ Study}$

$\frac{y'}{y} = \frac{N_2O\ GWP\ Standardized}{N_2O\ GWP\ Utilized\ in\ Study}$

Finally, in addition to the proportional adjustment method, an add-on method was employed for missing life cycle phases, construction and decommissioning. The add-on value was selected based on the median value for the pool of literature passing the second screen and reporting GHG emissions by life cycle phase. The adder method:

$$A' = (B + C) + (z' - z) \tag{7}$$

where

$$A' = Harmonized\ Life\ Cycle\ GHG\ Emissions \left(\frac{g\ CO_2eq}{kWh}\right)$$

$$z' = Average\ Fuel\ Cycle\ Emissions\ for\ the\ Pool\ of\ Collected\ Literature \left(\frac{g\ CO_2eq}{kWh}\right)$$

$$z = Reported\ Fuel\ Cycle\ Emissions \left(\frac{g\ CO_2eq}{kWh}\right)$$

4

SUMMARY OF PAPERS PUBLISHED FROM 2008 THROUGH JUNE 2011

Thirty-nine papers were published from 2008 through June 2011 covering various feedstocks, technologies, and sustainability metrics. Published LCAs of biopower also focused on many different timeframes (hypothetical versus projections) and regional contexts. The literature contains a wide variation of analysis perspectives from LCA review and meta-analysis, to policy analysis and quantification of negative externalities. Brief one-paragraph summaries published from 2008 through June 2011 that have passed quality and relevance screening criteria are provided below in alphabetical order. Paper summaries generally cover the bioenergy technologies and feedstocks analyzed, the primary life cycle metrics evaluated, and at least one primary key finding of the paper. However, because of the large body of topics covered or depending on the primary focus of the paper, some summaries do not have all these elements included or described in detail. Summaries were constructed from a distillation of a cursory overview, paper abstracts, and conclusion sections. Note that although some of the papers refer to non-U.S. cases and feedstocks, but some at least some of the insights and conclusions are applicable to the goal of sustainable biopower development in the United States.

Blanco and Azqueta 2008: This paper studied whether biopower can present opportunities for wheat and barley farmers based on a straw biopower plant in northern Spain. Results are based in part on environmental impact estimates (externality costs) from LCAs. The negative environmental impacts of electricity, including climate change, human health, property damage, and crop damage, produced with cereal straw are lower than fossil fuel alternatives and could justify the application of compensatory payment. However, study results depend critically on baseline assumptions.

Butnar et al. 2010: This LCA studied if poplar and Ethiopian mustard base biopower produced in Spain would be environmentally competitive energy alternatives. Alternative scenarios included different biopower plant capacity levels, biomass transport scenarios, and feedstock production productivity levels. Results show that Ethiopian mustard has higher impacts than Poplar when used for electricity production. Also, biomass transportation is an important life cycle phase to focus on in order to deliver maximum energy efficiency with the lowest environmental impact. Compared to fossil fuel alternatives, biomass has higher impacts in acidification, human toxicity, and photochemical oxidation while having lower impacts in climate change, abiotic depletion, and ozone layer depletion.

Cherubini and Strømman 2010: This LCA literature review investigated how key issues related to LCA methods, indirect environmental impacts, and uncertainties have been addressed in recent bioenergy LCA literature. The state of the literature is summarized followed by qualitative interpretation of the LCA results, with a focus on energy balance, GHG balance, and other impact categories. Most reviewed LCAs found a net reduction in GHG emissions and fossil energy consumption, but results were still fairly variable. The inclusion of specific local indirect effects (e.g., LUC) adds to this uncertainty.

Cherubini et al. 2009: This LCA meta-analysis of bioenergy systems is based on a review of published papers for which energy and GHG emission ranges are produced using a modeling system. The paper concludes that LCA results may differ even for apparently similar bioenergy systems because many key issues are site-specific and many factors can affect final outcomes. The article includes results for other bioenergy topic areas such as the biomass carbon cycle, selecting the appropriate reference system selection, and future bioenergy trends.

Djomo et al. 2011: This LCA meta-analysis of SRWC power and heat systems is based on a review of GHG emissions and energy yield data. Life cycle energy ratios and GHG emissions can vary significantly depending on system boundaries and methodological assumptions, but SRWC yields more energy and significantly reduces GHG emissions relative to coal. To reduce future variability this paper suggests a standardization of assumption documentation and development of a consensus framework for future analysis.

Fan et al. 2011: This LCA investigated pyrolysis-based processing from forest resources (i.e., forest wood, forest residues, and SRWC) to produce power. Combusting pyrolysis oil as a liquid biofuel to generate power can reduce the climate changing greenhouse emissions relative to fossil fuels. Several scenario analyses were conducted to determine effects of pyrolysis oil transportation distance, N-fertilizer inputs to energy crop plantations, and assumed electricity mixes for pyrolysis oil production. Improvements to the biopower system by minimizing inputs, reducing transportation distances, and shifting to renewable electricity can further reduce life cycle GHG emissions.

Faix et al. 2010: This LCA studied the biomass-to-oil process that involves forest residue wood chip conversion to pyrolysis oil and then combustion in a diesel engine. Results were compared with a diesel-fueled CHP system and showed lower greenhouse gas emissions, acidification, photochemical ozone formation, and ozone layer depletion. Eutrophication impacts were higher.

Froese et al. 2010: This LCA studied options for mitigating GHG emissions from electricity generation. Fossil energy demand and GHG emissions are compared among the options: a coal plant in Michigan that would co-fire biomass from forest residues, SRWC, or switchgrass; biologic sequestration in forest plantations; and geologic sequestration using carbon dioxide capture. Results showed that co-firing with forest residues is the most attractive option and geologic sequestration is the least attractive option. Biologic sequestration has intermediate impacts but is likely infeasible because of large land area requirements. Biomass feedstock potentials from land and forest resources are not limiting, but a combination of options might better optimize sustainability outcomes.

Fthenakis and Kim 2009: This LCA review presents normalized life cycle land use impacts. Estimates varied with region and technology, but biopower requires the largest amount of land relative to other conventional and renewable energy options.

Fthenakis and Kim 2010: This LCA review studied water demand factors across the lifecycle for conventional and renewable energy options. Also discussed was the scarcity of data on upstream water factors, assumption discrepancies, and water metric inconsistencies across datasets. Estimates varied with region and technology, but biopower had moderate-to-high water requirements relative to other studied conventional and renewable energy options.

Gärtner 2008: This large project report (of the New Energy Externalities Developments for Sustainability project) is an overview of the development of technologies for biomass electricity systems from the present to the remote future (i.e., 2050). Future bioenergy pathways for three different scenarios (i.e., pessimistic, optimistic-realistic, and very optimistic) are constructed. Since such an outlook cannot be very exact, the focus is primarily on the most significant bioenergy technologies, biomass types, and elements of the lifecycle. A large body of conclusions are available on a variety of biopower topics, including life cycle costs, technology development pathways, environmental and social impacts, and biomass potentials.

Gaunt and Lehmann 2008: This LCA studied the potential optimization options for slow pyrolysis-based bioenergy systems that produce biochar using switchgrass, miscanthus, forage corn, wheat straw, or corn stover. Results showed that the avoided emissions are between about two and five times greater when biochar is applied to agricultural land compared to systems only generating energy. Therefore, slow pyrolysis that produced biochar offers an energy efficient way to produce bioenergy that can achieve significant GHG emission reductions.

Gmünder et al. 2010: This LCA studied an Indian decentralized power generation plant fuelled by Jatropha oil in 2006. This system was compared to PV, grid connection and a diesel-fuelled power generator based on eco-toxicity, global warming potential, fossil fuel consumption, eutrophication, acidification, photochemical oxidation, and particulate matter. Overall environmental performance is only slightly improved compared to grid connection and the diesel-fuelled power generator while worse than PV. These results also depended on whether the Jatropha was cultivated on marginal land or existing crop land.

Goglio and Owende 2009: This "screening" LCA studied two small-scale electricity generation pathways based on willow SRWC. The impact assessment was based on net energy production, energy output-input ratio, and the related carbon dioxide emissions. Results showed that the key energy efficiency and environmental impact determining factors were the drying technique, fertilizer type and application technique, and the biomass conversion plant type. Chip transportation over distances in excess of 38 km lead to a significant drop in system energy efficiency.

Guinee et al. 2009: This hypothetical LCA case study on wood residue biopower was used to illustrate the effects of different choices and solutions for biogenic carbon balances and the treatment of co-products and recycling. The results indicate that there are several methodological choices that have not sufficiently been addressed by available standards and guidelines for LCAs, given the potentially large effects these methodological choices can still have on results.

Hactatoglu et al. 2011: This LCA analyzed a bioenergy system based on woody and herbaceous crops built around the Great Lakes St. Lawrence Seaway transportation corridor. The potential to use the Great Lakes St. Lawrence Seaway as a means of diversifying Canada's energy supply mix and reducing GHG emissions is substantial. Conditions that would make production economical without government subsidies include high energy prices, a cost on GHG emissions and/or a renewable fuel standard for solid biofuels.

Herrera et al. 2008: This LCA studied the environmental impacts of wheat-straw-based biopower compared to natural gas and a mixed plant using both biomass and natural gas. Results show reductions in energy use and GHG emissions from utilizing biomass; however, other metrics such as ozone depletion, eutrophication, and acidification were higher than the reference system.

Jeswani et al. 2011: This LCA investigated the co-firing of biomass from perennial grasses, SRWC, agricultural residues and waste forestry wood. Environmental and economic impacts were evaluated. All biomass options lead to a substantial reduction in environmental impacts compared to the coal-only power generation. Overall the use of waste wood appears to be environmentally the most sustainable option. In comparison to direct combustion, biomass gasification has higher global warming potential due to the higher consumption of biomass and energy for gasification. The results of the life cycle economic costing show that electricity from biomass is economically less attractive than coal. Direct biomass firing is two times more expensive than coal and biomass gasification is up to three times higher.

Kharecha et al. 2010: This paper includes an LCA review and outlines technology options for phasing out coal in the United States by 2030 in order to, among other purposes, reduce GHG emissions. Efficiency measures and substitution of coal with renewables and third generation nuclear plants were most effective in reducing GHG emissions. Elimination of fossil fuel subsidies and a substantial rising price on carbon emissions are the root requirements for a clean, emissions-free future.

Kiatkittipong et al. 2009: This LCA studied the environmental impacts (i.e., acidification, eutrophication, greenhouse gas emissions, and photochemical oxidation) of various alternatives for dealing with bagasse waste from sugarcane in Thailand. The four waste management scenarios were: landfilling with landfill gas use, anaerobic digestion with biogas production, incineration for power generation, and pulp production. Incineration showed better environmental performance than conventional biogas collection, but the use of bagasse in pulp mills might be the most environmentally benign alternative.

Kim and Fthenakis 2008: Conference paper that duplicates results (with less detail) of Fthenakis and Kim 2009.

Kimming 2011: This LCA is the thesis version of Kimming et al. 2011.

Kimming et al. 2011: This study used consequential life cycle assessment (LCA) to analyze two potential energy self-sufficient systems for organic arable farms, based on agricultural residues. The impact categories used are energy balance, resource use and greenhouse gas (GHG) emissions. The bioenergy systems utilize ley or straw as the substrate for energy production. Results show that it is possible to supply the village or the farm with energy through the systems described without competing with food production. Ley-based scenarios require higher energy input than scenarios based on Salix, but lower inputs relative to the straw scenario.

Kirkinen 2010: Project report that largely duplicates results of Kirkinen et al. 2008. Kirkinen et al. 2008 provides greater detail on the biopower lifecycle, while this report provides greater detail on the relative radiative forcing commitment (RRFC) metric.

Kirkinen et al. 2008: This paper proposes a new GHG emission metric called RRFC, which is applied to the combustion of reed canary grass and forest residues for use in Finland. RRFC accounts for the energy absorbed in the earth system due to life cycle GHG emissions. The use of forest residues and reed canary grass for energy has the lowest greenhouse impacts relative to comparison systems from natural gas, coal, or peat. The length of the time horizon had an impact on the RRFC values and, to some extent, the relative positions of various bioenergy sources.

Lenzen and 2010: This LCA review attempted to provide more information on critical technical aspects of technologies and to capture the most recent LCA findings from international literature. This review covers many renewable and conventional technologies including biopower. Results from life cycle studies of bioenergy production can be highly variable under different feedstock type, location, land use, baseline, and scope/boundary assumptions.

Lu and Zhang 2010: This LCA studies various environmental and economic issues associated with a large set of energy conversion technologies that use crop residues in China. The results show that the return of crop residues to the fields, silo/amination, and anaerobic digestion offer the greatest environmental benefit. However, if a positive net income is most important, the co-firing of crop residues with coal and crop residue gasification for power offers greater economic and technical feasibility.

Macknick et al. 2011: This LCA review of renewable energy systems provides estimates of operational water withdrawal and water consumption factors for electricity generating technologies in the United States. The impacts of the power sector on freshwater availability can be reduced by utilizing dry cooling or by using non-freshwater sources for cooling. Very little data exists for biomass, but water consumption and withdrawals are on the medium to high end relative to other electricity generating technologies.

Mai Thao et al. 2011: This LCA evaluates the life cycle GHG emissions of rice husks under eighteen bioenergy scenarios. The analysis results reveal that CH4 and N2O emissions from open burning contribute largely to the current GHG emissions. Therefore, the cessation of open burning alone has a large GHG mitigation potential. The use of briquettes, even though GHG is emitted during the production stage, can still contribute to GHG emission mitigation as the production is more efficient than rice husk burning or dumping. In the power generation scenarios, most GHG emissions were derived from the combustion process. Therefore, gasification which has a small GHG emission contribution from combustion is the most efficient GHG mitigator.

Manomet Center for Conservation Sciences (MCCS) 2010: This paper addresses a wide array of scientific, environmental, economic, and technological issues related to the use of forest biomass for bioenergy in Massachusetts. The study attempts to answer the following highly complex questions: (1) What are the implications of shifting energy production from fossil fuel sources to forest biomass on the terrestrial carbon cycle?; (2) How much forest wood is available for use?; (3) What are the potential ecological impacts of increased forest biomass use by the Massachusetts Commonwealth; and (4) What, if any, policies are needed to ensure sustainability of the bioenergy system? Significant controversy over the results of this study and its use by the Massachusetts Department of Energy Resources for defining new Renewable Portfolio Standards related to biopower have led to extensive review of this study by many parties.

McKechnie et al. 2011: This paper integrated LCA and forest carbon analysis to assess forest bioenergy GHG emissions over time. Application of this method wood pellet and forest biomass ethanol cases reveals a substantial reduction in forest carbon due to bioenergy production. In all cases, overall GHG emissions increased. In the long term, biopower reduces GHG emissions relative to coal. Forest carbon losses delay net GHG mitigation by 16-38 years, depending on the biomass resource. Forest carbon more significantly influences GHG emissions when biomass is sourced from standing trees as compared to residues. Although forest carbon dynamics can't be generalized it is recommended that a combined LCA and forest carbon approach be undertaken for bioenergy studies.

Pettersson and Harvey 2010: Black liquor gasification is currently being developed as an alternative technology for energy and chemical recovery at chemical pulp mills. This LCA studies how assumptions regarding systems surrounding the pulp mill affect the carbon dioxide emission balances for black liquor gasification to motor fuels and electricity generation. Results show that the potential to reduce carbon dioxide emissions is much higher for a pulp mill rather than an integrated pulp and paper mill. Electricity generation is favored when assuming high grid electricity carbon dioxide emissions.

Ramjeawon 2008: This LCA studied the environmental and resource impacts of electricity generated from the combustion of sugar cane bagasse in Mauritian sugar mills. Bagasse-derived electricity performs well in terms of GHG emissions, acidification, and non-renewable energy inputs but poorly in water consumption and eutrophication.

Renouf et al. 2010a: This LCA is the first half of two papers covering the full life cycle of Australian sugarcane production (including electricity production from bagasse). See Renouf et al. 2010b for full life cycle result discussion.

Renouf et al. 2010b: This LCA is the second half of two papers covering the full life cycle of Australian sugarcane production (including electricity production from bagasse). LCA environmental impact results for sugarcane were heavily influenced by how sugarcane was processed, variability in how it was grown, and the co-product allocation method selected. Results imply that environmental impacts are dependent on regional conditions as well as the selected methodological approach.

Rettenmaier et al. 2010: This screening LCA of thirteen energy crops summarizes the work of the European Commission -funded project "4F CROPS – Future Crops for Food, Feed, Fiber and Fuel. The thirteen dedicated energy crops are combined with processing and use options to generate 120bioenergy chains. All bioenergy chains show energy use and GHG emission improvements relative to fossil fuel replacements, but disadvantages with regard to other environmental impacts. However, results vary significantly across locations, assumptions about co-products and the fossil reference system. Environmental tradeoffs are necessary when considering among various bioenergy systems.

Rio Carrillo and Frei 2009: This study analyzed the water needs for Spanish energy production. Hypothetical scenarios simulating the risks of various energy policies are also analyzed. Results show that the combination of energy resources used in Spain is projected to consume 25% more water in 2030 than in 2005. Renewable energy technologies are mixed in terms of their water supply impacts. Wind power can reduce water withdrawal, but bioenergy production is water intensive.

Roedl 2010: This LCA studied the GWP, eutrophication, photochemical ozone creation, and acidification impacts of SRWC used to produce power and heat (and Fischer-Tropsch diesel) compared to the average German grid mix. SRWC can reduce environmental burdens (with the exception of eutrophication) if it is used for bioenergy. The environmental impacts of heat and power are less than those for Fischer-Tropsch diesel.

Schubert et al. 2008: This large project report (from the Wissenschaftlicher Beirat der Bundesregierung) aims to show through a synthesis of literature that sustainable bioenergy use is possible, and it also outlines potential opportunities or methods for minimizing the risks of negative outcomes. As a part of this report, LCA is conducted on straw, wood residues and SRWC combusted directly or co-fired with coal. This report presents results on a variety of other topics including life cycle costs, policy, biomass potentials, LUC, defining and measuring sustainability metrics and criteria, and much more.

Searcy and Flynn 2008: This LCA studied GHG emissions from four renewable energy systems using straw/corn stover. The largest impact on avoided GHG emissions arises from the substitution of biomass for fossil fuel. Relative to this, the impact of emissions from processing fossil fuel and processing biomass to produce electricity or transportation fuels is minor.

Sebastián et al. 2011: This LCA evaluated large-scale biomass electricity generation based on direct biomass fired power plants, or co-firing in an existing coal power plant. Sensitivity analysis indicates that the factors which have a greater influence on GHG emissions for the co-firing case are biomass pretreatments that are required and the coal utility boiler efficiency decrease when it is fed with a fuel for which it was not originally designed. Efficiency is the most important factor for the direct fired case.

Sikkema et al. 2010: This LCA compared wood pellet chains from sawmills used in heat or electricity production. Cost structures, primary energy inputs, and avoided GHG emissions are reviewed for: district heating, residential heating, and electricity production. The paper concluded that wood pellets can achieve substantial GHG savings, especially when replacing coal, but are relatively expensive.

Steubing et al. 2011: This LCA assessed synthetic natural gas (SNG) from biomass used for heating, electricity generation, and transportation. SNG systems were compared to fossil and conventional wood reference systems and sensitivity analysis for expected technological improvements was completed. Substituting fossil technologies with SNG systems reduced global warming and for particular technologies other aggregated environmental impacts. However, eutrophication, ecotoxicity, and respiratory disease caused by inorganics do increase. The efficient use of process heat and technological improvements such as efficiency could improve environmental benefits.

Tabata et al. 2011: In this LCA the impact of GHG reduction from semi-carbonized fuel produced by woody biomass co-firing with coal in thermal power plants is evaluated for the Wakayama prefecture, Japan. In this study, a new business is considered whose operations would co-fire the woody biomass with coal. The life cycle inventory takes into account processes such as cutting timber, manufacturing semi-carbonized fuel, and coal co-firing. The spatial distribution of the woody biomass was ascertained using a geographic information system, and the location of several facilities and a road transportation network were determined. An annual reduction in GHG emissions of approximately 46,700 tonnes is possible. Environmental impacts were reduced, relative to business as usual, when taking into account climate change, acidification and land use.

Thornley 2008: This LCA modeled the combustion and gasification of willow SRWC and miscanthus to evaluate carbon monoxide, nitrous oxides, particulates, and hydrocarbons. Results indicate that harvesting and tractor transport are potentially the most significant contributors to these pollutants.

Thornley et al. 2009: This LCA analyzed the technical, environmental, economic, and social impacts of biopower. The results show that similar GHG emission savings are achieved under a variety of conditions, but to achieve those savings land use efficiency varied substantially.

Tiwary and Colls 2010: This LCA studied secondary aerosol generation potential of various bioenergy systems from the photochemical interactions of precursor gases. The second part of the paper proposed mitigation options to minimize those impacts. These options included biomass gasification prior to combustion, delaying biomass harvest, and decreasing the geographical distance between the biomass plant and field. Results indicate gasification of miscanthus provides the best option to minimize acidic emissions from the combustion plant. The other options only lead to marginal aerosol emission improvements.

van Dam et al. 2009: This paper studied the feasibility of using a socio-economic and environmental impact analysis for large-scale bioenergy production, based on a set of defined criteria and indicators in an Argentina case study. It is difficult to give a final conclusion about whether a bioenergy chain is sustainable or not. Sustainability depends not only on the previous land use system but also on other factors such as the selection of the bioenergy crop, the suitable agroecological zone, and the agricultural management system applied. The results also imply that it is possible to steer towards sustainability performance of a bioenergy chain during project development and implementation.

Varun and Prakash 2009: This review paper studied energy and carbon dioxide LCAs of renewable electricity generation systems. Results indicate that carbon emissions from renewable energy are lower than fossil fuel systems but not zero.

Wicke et al. 2008: This LCA studied GHG emissions of crude palm oil (CPO) and palm fatty acid distillate (PFAD) production in northern Borneo (Malaysia), their transport to the Netherlands, and their co-firing with natural gas for electricity production. Results demonstrate that LUC is the most decisive factor in overall GHG emissions. Palm oil energy chains based on land that was previously natural rainforest or peatland emitted significant GHG emissions. However, if CPO production takes place on degraded land, management of CPO production is improved, or if the by-product PFAD is used for electricity production, these systems may be sustainable.

Zhang et al. 2010: This LCA evaluated 100% wood pellet direct biomass combustion and co-firing with coal in Ontario, Canada. GHG and criteria air pollutant emissions are compared with current coal and hypothetical natural gas combined cycle facilities. 100% pellet utilization provides the greatest GHG benefit on a kilowatt-hour basis. Results suggest that biomass utilization in coal facilities should be considered for its cost-effective GHG emission mitigation potential.

Zhong et al. 2010: This LCA analyzed flash pyrolysis to determine whether a flash pyrolysis plant set up locally (in Singapore) would be environmentally friendly. The results obtained show that the process of flash pyrolysis of wood waste has little negative contribution to the environment.

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Phase B

6
BIOPOWER LIFE CYCLE GREENHOUSE GAS EMISSION SENSITIVITY ANALYSIS

Introduction

Phase A reviewed life cycle assessment (LCA) literature to assess the central tendency and variability of biopower's life cycle greenhouse gas (GHG) emissions. In that study, "harmonization" was achieved by aligning several common facility performance parameters and generalizing system boundaries. This helped facilitate comparison across studies and provided a better picture of central tendency and variability of prior life cycle GHG emission estimates. However, several important remaining sources of life cycle GHG emission variability in the biomass supply chain upstream of the biopower facility were identified. A better understanding of these major sources of life cycle GHG emission variability could help inform the design of biopower systems and predict their GHG emission effects.

A "harmonization" approach for examining remaining major sources of life cycle GHG emission variability would have been difficult and time-consuming. Many sources of life cycle GHG emission variability, such as thermal efficiency, are more complex and interrelated than biopower facility assumptions. In addition, literature reporting on biopower systems presents another important limitation. Exploring remaining major sources of life cycle GHG emission variability requires another analysis approach. To this end, Warner and Mann (2012) constructed a simplified LCA model in Excel to calculate the emissions of the greenhouse gases (GHG) carbon dioxide (CO_2), methane (CH_4), and dinitrous oxide (N_2O). The LCA model is now coded into NREL's Systems Advisor Model (SAM)[7]. SAM is a tool for calculating the levelized costs of energy (LCOE) for renewable power technologies. SAM was selected for the development of the GHG calculator tool because of its regional biomass resource availability, technical specifications for biomass combustion, and regional climate estimation capabilities.

Using the newly constructed life cycle GHG emission module, we conducted a sensitivity analysis based on optimistic and pessimistic scenarios derived from literature collected in Phase A. The life cycle sensitivity analysis is intended to help:

- Identify important assumptions determining the magnitude of life cycle GHG emissions
- Better explain observed life cycle GHG emission variability
- Better identify differences between biomass feedstock categories obscured by confounding factors observed during the course of the literature review
- Facilitate and examine alternative biomass supply chain designs that were studied in few papers (e.g., mechanical biomass drying)
- Explore dynamics between related parameters.

[7] https://sam.nrel.gov/content/downloads

Using this simplified life cycle GHG emission calculator, we can explore remaining questions about how biopower systems differ under a range of conditions and system designs, and more fully explain results found in the literature review of Phase A.

Scope and Methods

System Boundaries of the Life Cycle Impact Module

Prior to this project, SAM contained data and equations for multiple biomass residues and wastes and combustion technologies (with or without coal co-combustion) in order to calculate biopower levelized costs of energy (LCOE). SAM can calculate LCOEs for biomass combustion systems based on one of several system designs (e.g., grate stoker furnace and fluidized bed combustor,) and multiple biomass waste and residue feedstocks (i.e., barley straw, wheat straw, rice straw, corn stover, forest residues, urban residues, and mill residues) (Jorgenson et al. 2011). Facility operation ambient conditions and biomass resource availability are based on a database of local conditions (e.g., climate) for many locations nationally in the United States (Jorgenson et al. 2011). SAM structure was expanded to include new alternative biopower generation systems and biomass feedstocks for user selection. The SAM now includes the lignocellulosic crops, short rotation wood crops (SRWC) and herbaceous crops, and biomass gasification technology.

The SAM life cycle impact module includes all major GHG emissions sources along the biomass supply chain (i.e., LUCs and/or other market-mediate impacts are not included). Major sources of direct and indirect life cycle GHG emissions included within SAM's systems boundaries are biomass production (or avoided use for wastes and residues), harvest or collection, transport, preprocessing, drying, dry matter losses along the supply chain, and conversion to power. GHG emissions from facility construction, operations, and decommissioning were typically negligible contributors to GHG emissions (Phase A of this report) and were therefore excluded. Presuming best practices are followed (i.e., prevention of biomass decomposition), biomass storage emissions are also a negligible GHG emitter (Phase A of this report). However, fossil energy use for storage was easily modeled and occurred in tandem with other life cycle phases, such as biomass drying, and were therefore included. N_2O, and in some instances, CH_4, have been identified as important contributors to life cycle GHG emission results (Phase A of this report). CH_4 is primarily emitted in biomass decomposition (e.g., in landfills) of waste biomass and is included when applicable. Only N_2O emissions from fossil fuel use are included in current calculations.

Sensitivity Analysis – Base Case Biomass Feedstock Category Scenarios

The feedstock categories are more generalized than are potentially available in SAM because of literature data limitations. Available data was non-existent, limited, or of poor quality for the several biomass feedstock categories included in SAM (Phase A of this report). Base case scenarios were constructed for the following generalized categories:

- Agricultural residues, modeled as SAM's corn stover
- Forest residues
- Wood wastes, modeled as SAM's primary mill residues
- SRWC, primarily based on collected Poplar and Salix data
- Herbaceous crops primarily based on collected switchgrass data.

To the extent possible, data on more detailed biomass categories are captured within the optimistic and pessimistic ranges established for each parameter used for the corresponding scenarios of the sensitivity analysis. One benefit of the feedstock category simplification is that these general categories more closely align with those analyzed in Phase A and can be used for comparison.

Assumptions about the conditions of the biopower life cycle used in base case scenarios come from SAM's default assumptions as documented in Warner and Mann (2012) and Jorgenson et al. (2011). Power generation conditions based on Jorgenson et al. (2011) used Fargo, North Dakota, ambient conditions. These ambient conditions apply to both the operation of the biopower facility and biomass drying to equilibrium moisture concentration (EMC), when applicable. Conditions and parameters selected for non-power generation life cycle phases are based on recent high-quality analyses and represent reasonable current or near-future conditions. Data collection included review of papers from our prior literature review (Phase A of this report); the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (GREET); and recent biofuel literature featuring Monte Carlo analyses.

We extended our search beyond outside the biopower literature because it lacked detailed Monte Carlo analyses or deep discussion of several aspects of the life cycle such as GHG emissions from fertilizer production. Base cases are constructed mostly from Hsu et al. (2011) and the most recent version of GREET (ANL 2012). These resources tended to involve more current U.S. field practices, and in some cases, a wider range of potential biomass supply chain conditions than what was available in reviewed biopower literature. This is primarily due to the dearth of U.S. centric LCAs found in the biopower literature (Phase A of this report). Relative to the LCA literature, current conditions are predicted to generally skew optimistic to the range of potential conditions that were found in the literature that could have been used to t estimate GHG emission estimates f because of inevitable improvement in technology or background conditions (e.g., shifting to lower GHG emitting electricity).

Beyond the conditions under which the supply chain operates (e.g., energy efficiencies), several system boundary and supply chain design issues needed to also be established for the base case. Supply chain design options were mostly selected based on typical systems found in the literature review as documented in Warner and Mann (2012). However, waste wood life cycle estimates were calculated without avoided biomass decomposition emissions (ABDE), which are associated with CH_4 released through landfilling and decomposition of the biomass. SAM assumes these default conditions, but their inclusion prevents easy comparison across biomass feedstock categories. The implications of accounting for ABDE was explored in additional scenarios in the results section. Table 6-1 shows base case, pessimistic, and optimistic scenario parameters used in the sensitivity analysis across all feedstock categories. Feedstock-specific parameters are shown in Tables 6-2 through 6-6. Pessimistic and optimistic cases were constructed based on a re-review of collected literature, but base case data is taken from Warner and Mann (2012).

Table 6-1
Data Used in the Construction of Base Case, Pessimistic, and Optimistic Scenarios Across All Biomass Feedstock Categories

All Biomass Feedstocks	Units	Base Case	Source(s)	Pessimistic Case	Source(s)	Optimistic Case	Source(s)
Thermal Efficiency	*%*	28	[20]	12	[11]	50	[5]
Drying Methods		Dried to EMC	[20]	Mechanical Drying w/ Natural Gas	[1, 31, 41]	Biomass Fed as Received	[20]
Truck Diesel Use Efficiency	*mi/gge*	4.7	[1]	0.74	[31]	13	[19]
Preprocessing Methods		Light Grinding or Chipping	[32]	Heavy Grinding	[41]	No Preprocessing	-
Truck Capacity	*tons*	25	[1]	4.4	[40]	44	[17]
Life Cycle Electricity CO_2 Intensity	*g CO_2/kWh*	640	[26, 28]	1100	[39]	13	[8]
Transportation Distance by Truck	*mi*	60	[13]	220	[3]	3.1	[22]
Biomass Losses	*%*	5	[19]	20	[4]	1	[6]
Life Cycle Biodiesel Use in Place of Diesel		Diesel	[1]	Diesel	[1]	Biodiesel	[1]

Table 6-2
Data Used in the Construction of Base Case, Pessimistic, and Optimistic Agricultural Residue Scenarios

Agricultural Residues	Units	Base Case	Source(s)	Pessimistic Case	Source(s)	Optimistic Case	Source(s)
Biomass Moisture Content	*%*	30	[20]	60	[19]	10	[27]
Biomass Yield	*collected tons/acre*	1.5	[19]	0.1	[15]	13	[11]
Fertilization - N	*lbs/ton harvested biomass*	18	[19]	33	[10]	0	[19]
Fertilization - P_2O_5	*lbs/ton harvested biomass*	2	[19]	23	[33]	1.4	[19]
Fertilization - K_2O	*lbs/ton harvested biomass*	30	[19]	69	[10]	4.5	[22]
Fertilization - Lime	*lbs/ton harvested biomass*	0	[1]	0	[1]	0	[1]
Biomass Collection Diesel Use	*mmBtus/acre*	0.068	[15]	0.49	[33]	0.054	[15]

Table 6-3
Data Used in the Construction of Base Case, Pessimistic, and Optimistic Forest Residue Scenarios

Forest Residues	Units	Base Case	Source(s)	Pessimistic Case	Source(s)	Optimistic Case	Source(s)
Biomass Moisture Content	*%*	44	[20]	60	[12]	15	[14]
Biomass Yield	*collected tons/acre*	7.6	[15]	0.23	[7]	24	[30]
Fertilization - N	*lbs/ton harvested biomass*	0	[1]	0	[1]	0	[1]
Fertilization - P_2O_5	*lbs/ton harvested biomass*	0	[1]	0	[1]	0	[1]
Fertilization - K_2O	*lbs/ton harvested biomass*	0	[1]	0	[1]	0	[1]
Fertilization - Lime	*lbs/ton harvested biomass*	74	[7]	74	[7]	0	[1]
Biomass Collection Diesel Use	*mmBtus/acre*	0.1	[7]	0.1	[7]	0.1	[7]

Table 6-4
Data Used in the Construction of Base Case, Pessimistic, and Optimistic Wood Waste Scenarios

Wood Waste	Units	Base Case	Source(s)	Pessimistic Case	Source(s)	Optimistic Case	Source(s)
Biomass Moisture Content	*%*	48	[20]	60	[6]	35	[37]
Biomass Yield	*collected tons/ acre*	N/A	N/A	N/A	N/A	N/A	N/A
Fertilization	*lbs/ ton collected biomass*	N/A	N/A	N/A	N/A	N/A	N/A
Biomass Collection Diesel Use	*mmBtus/ton collected biomass*	0.013	[7]	0.013	[7]	0.013	[7]

Table 6-5
Data Used in the Construction of Base Case, Pessimistic, and Optimistic Case Woody Crop Scenarios

SRWC	Units	Base Case	Source(s)	Pessimistic Case	Source(s)	Optimistic Case	Source(s)
Biomass Moisture Content	*%*	34	[20]	60	[25]	15	[14]
Biomass Yield	*harvest tons/acre*	6.2	[7]	2	[34]	11	[2]
Fertilization - N	*lbs/ton harvested biomass*	72	[7]	190	[9]	13	[4]
Fertilization - P_2O_5	*lbs/ton harvested biomass*	4.3	[7]	74	[9]	6.5	[4]
Fertilization - K_2O	*lbs/ton harvested biomass*	22	[7]	130	[9]	2.7	[11]
Fertilization - Lime	*lbs/ton harvested biomass*	120	[34]	120	[34]	33	[7]
Biomass Collection Diesel Use	*mmBtus/acre*	0.81	[7]	2	[15]	0.44	[7]

Table 6-6
Data Used in the Construction of Base Case, Pessimistic, and Optimistic Herbaceous Crop Scenarios

Herbaceous Crops	Units	Base Case	Source(s)	Pessimistic Case	Source(s)	Optimistic Case	Source(s)
Biomass Moisture Content	*%*	34	[20]	50	[34]	12	[18]
Biomass Yield	*harvest tons/acre*	5.3	[19]	1.2	[29]	16	[10]
Fertilization - N	*lbs/ton harvested biomass*	120	[19]	390	[33]	0.89	[19]
Fertilization - P_2O_5	*lbs/ton harvested biomass*	11	[19]	45	[21]	4.3	[19]
Fertilization - K_2O	*lbs/ton harvested biomass*	140	[19]	180	[21]	0.89	[19]
Fertilization - Lime	*lbs/ton harvested biomass*	170	[34]	500	[24]	140	[10]
Biomass Collection Diesel Use	*mmBtus/acre*	0.69	[33]	2.8	[10]	0.47	[7]

Sensitivity Analysis – Optimistic and Pessimistic Scenarios

We conducted analysis to assess the sensitivity of the overall results to variation in individual contributing parameters based on ranges from “optimistic” to “pessimistic”. The life cycle GHG emission sensitivity analysis mostly derived supply chain operating parameters from the previously completed literature review of biopower LCAs, but it also included recent biofuel papers, as outlined in the previous section. From the literature review conducted for Phase A, about 70 papers were re-reviewed for life cycle parameters that could be used to create optimistic and pessimistic scenarios for each SAM parameter. SAM life cycle impact module parameters collected across the biopower life cycle include fossil fuel consumption rates, fertilizer application rates, transportation distance, fossil fuel carbon intensities, and other considerations, as more fully documented in the SAM life cycle impacts user guide (Warner and Mann 2012).

Optimistic and pessimistic sensitivity analysis scenarios are based on the minimum and maximum values (where applicable) of collected literature data. Technological efficiency parameters (e.g., diesel use efficiency in farming and transportation) are mainly taken from newer and older papers, representing the pessimistic and optimistic cases, respectively. Monte Carlo analyses from Hsu et al. (2011) and Spatari and MacLean (2011) also significantly contributed to other minimum and maximum values (e.g., fertilizer application and biomass yields). Several biomass supply chain design options that did not fit neatly within the pessimistic and optimistic framework because of intermediate impacts (e.g., mechanical drying with renewable energy) were also explored outside the core sensitivity scenarios; these can be found in the Results and Discussion section.

To simplify and streamline the sensitivity analysis, not all potential SAM parameters were analyzed. Highly detailed assumptions about the operation of a biopower facility were not; they were already included in the range of thermal efficiencies taken from the literature and used in the sensitivity analysis. We already examined biopower facility operation to a significant extent in Phase A. Storage electricity consumption efficiencies were ignored because they are a negligible source of GHG emissions (Phase A of this report), presuming good storage practices. GHG emission intensities of individual transportation fuels were only analyzed through a replacement of high carbon intensity fossil fuels with lower carbon intensity biofuels (where applicable) rather than specific value changes (e.g., diesel with biodiesel). A detailed analysis of potential life cycle GHG emission intensities of various transportation fuels is beyond the purview of this analysis. Long-distance transportation of biomass using rail or barge represents neither the highest nor lowest GHG-emitting transportation options and is instead explored in separate alternative scenarios.

Data limitations in the literature also prevented analysis of some SAM life cycle parameters. Few papers reported preprocessing energy consumption. Due to the general lack of high-quality data needed to construct a realistic range (Zhang et al. 2011), preprocessing was instead examined by the extent to which biomass was preprocessed rather than the energy efficiency of the system. Pelletization was not examined in the core scenarios but in separate alternative scenarios. Because of the significant energy requirements for more extensive preprocessing systems, actual energy consumption could be significantly higher or lower than the scenarios investigated here. Parameters associated with fertilizer manufacturing (e.g., natural gas use), collection and/or harvest of forest residues and wood wastes, and lime application for some biomass feedstocks were not analyzed due to data availability or inapplicability to the Phaseicular feedstock category. Variation in life cycle GHG emissions from fertilizer production is indirectly examined through scenarios with varying electricity GHG emission intensity, but these effects are negligible and have a larger influence on preprocessing steps.

Biomass gasification and multiple combustion technologies were not specifically explored in the sensitivity analysis. We evaluated biomass conversion technologies in Phase A, and the effective impact of using these systems is alternative thermal efficiencies. For the combustion technologies, these efficiencies are already captured in established ranges taken from the LCA literature. Gasification systems typically have a higher thermal efficiency (i.e., median of 38% from Phase A) than combustion systems and would, on average, emit less life cycle GHG emissions due to increased biomass conversion efficiency. Gasification engine systems usually have a slightly lower thermal efficiency than combustion systems and would emit more life cycle GHG emissions on average. However, biomass drying would be dependent on and internal to the gasification process (i.e., flue gas drying), thus negating the need for a drying phase in the life cycle. Therefore, drying scenarios examined are not relevant to gasification systems. Since biomass drying is a negligible contributor to GHG emissions unless mechanically dried, and the base case scenario uses air drying, biomass gasification would not deviate significantly from the biomass combustion base case scenarios.

Results and Discussion

Base Case Scenarios and Sensitivity Analysis

Base case scenarios results are shown in Figure 6-1 along with related sensitivity analysis in Figure 6-2 and represented numerically in Table 6-7. In Figure 6-2, lines between sensitivity analysis points and the base case should not be considered actual values or a linear relationship between those parameters and life cycle GHG emissions. However, the slope can be used to estimate the magnitude of influence the parameter has on resulting life cycle GHG emissions. Life cycle GHG emission results, from smallest to largest, were 13 g/kWh for waste wood (w/o

ABDE), 30 g/kWh for forest residues, 40 g/kWh for woody crops, 55 g/kWh for agricultural residues, and 64 g/kWh for herbaceous crops.

Wood wastes have the lowest life cycle GHG emissions because of the lack of fertilizer inputs to offset waste biomass collection. Forest residues were essentially the same as wood wastes except removal from forest land was assumed to require significant lime application for nutrient compensation. However, relative to agricultural residues, this compensation is much less due to major carriers of nutrients (e.g., needles) often being left behind in forest residue collection (Hartmann et al. 1999). In practice impacts of forest residue removal will differ depending on prior conditions. While rarely examined forest residues could have been burned on site in which case there would be substantial GHG emission benefits for using forest residues as an energy feedstock, similar to wood wastes as examined in alternative scenarios in the "Optimistic and Pessimistic Life Cycle Operating Assumptions" section.

Lower fertilizer application for wood wastes and forest residues are partially offset by higher diesel inputs for biomass collection. Agricultural residues require the lowest diesel inputs for biomass collection, but more fertilizer application is required to offset removal of nutrients from the soil. While agricultural residue fertilizer application and fuel consumption is lower than SRWCs, agricultural residues have the lowest heating value according to SAM feedstock assumptions (Jorgenson et al. 2011). Herbaceous crops with higher fertilizer inputs and lower yields than SRWCs generated the highest life cycle GHG emission estimate among the feedstock categories examined.

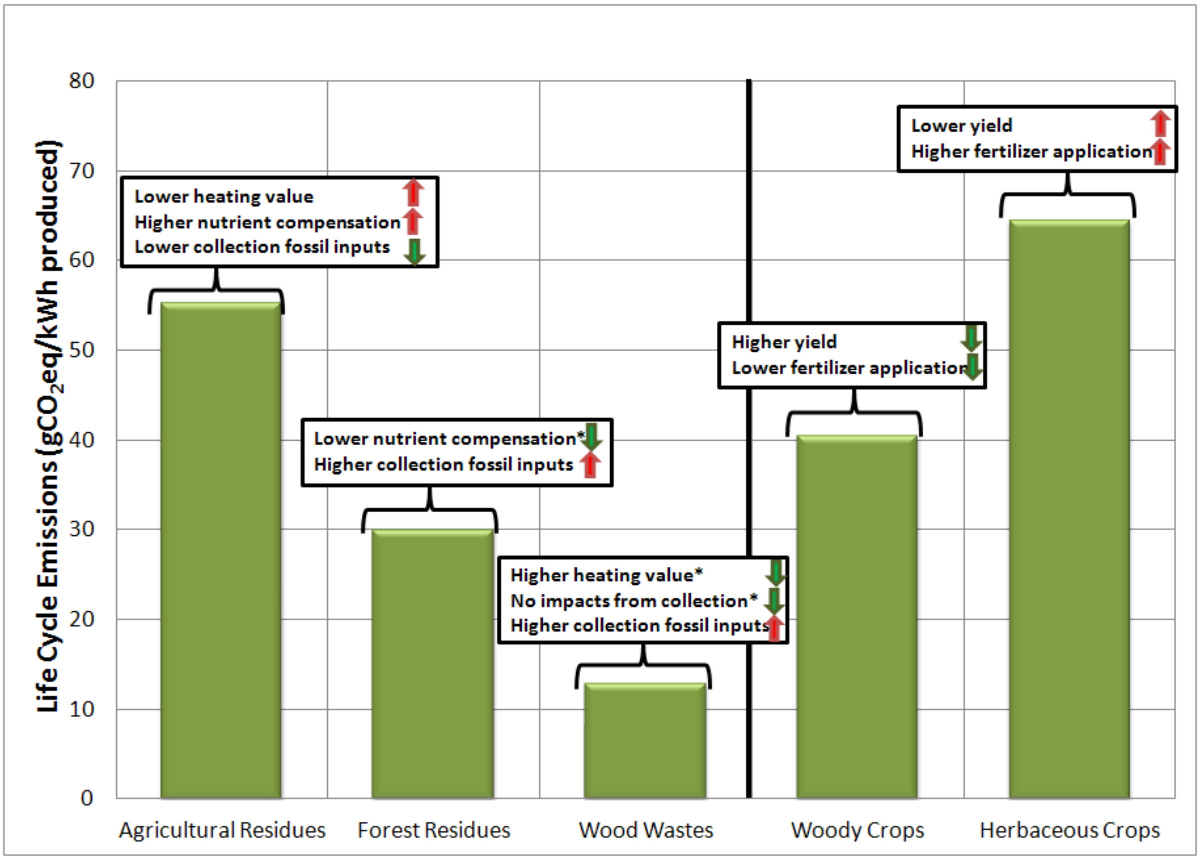


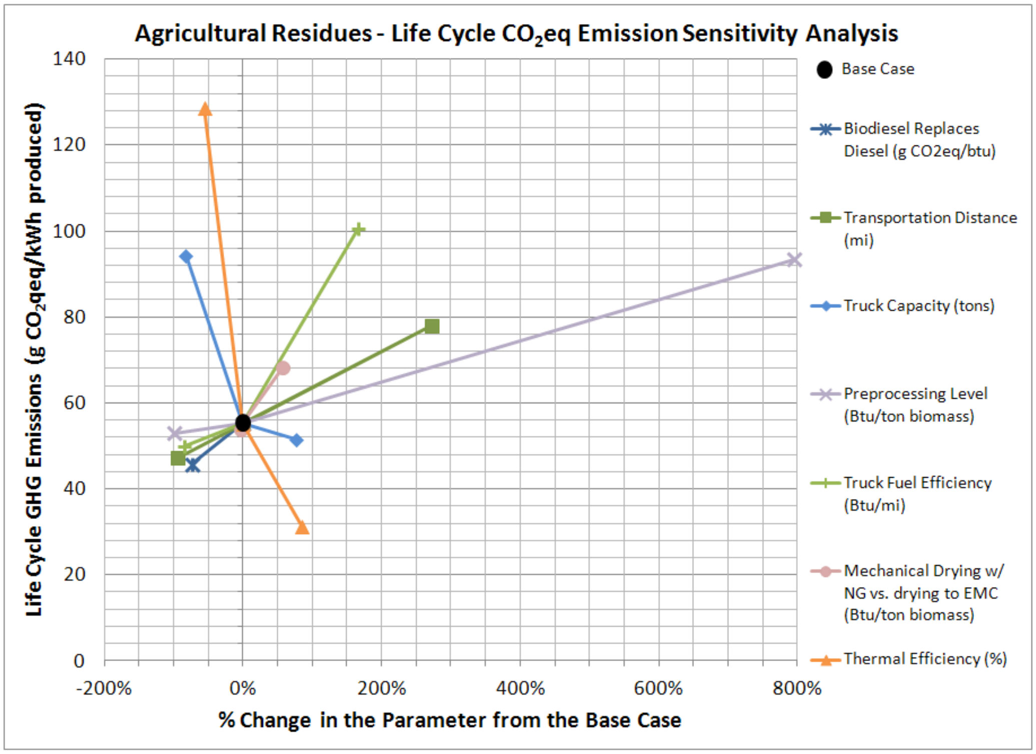
Figure 6-1
Base case scenario life cycle greenhouse emissions w/o land use change. Red and green arrows indicate major contributors to higher and lower greenhouse gas emissions relative to other feedstock systems. *Alternative assumptions reasonably established in the literature.

Life cycle GHG emission results from base cases are similar, but do differ somewhat from the median estimates found in our previous literature review (i.e., Phase A). The median harmonized estimates of life cycle GHG emissions found in the literature were 15, 34, 37, 43, and 50 g CO_2eq/kWh for primary mill wastes, forest residues, agricultural residues, woody crops, and herbaceous crops. Base case scenario life cycle GHG emission estimates for primary mill residues, forest residues, and SRWCs are fairly close at 13, 30, and 40 g CO_2eq/kWh, respectively. The greater GHG emissions from herbaceous crops are most likely due to the much higher base case fertilizer inputs assumed. Base case assumptions are higher than the median fertilizer application estimates found in the literature (e.g., 120 versus 77 lb N/acre), especially compared to SRWC. The most likely explanation: Our agricultural residue scenarios are assumptions about nutrient removal from the field through biomass collection.

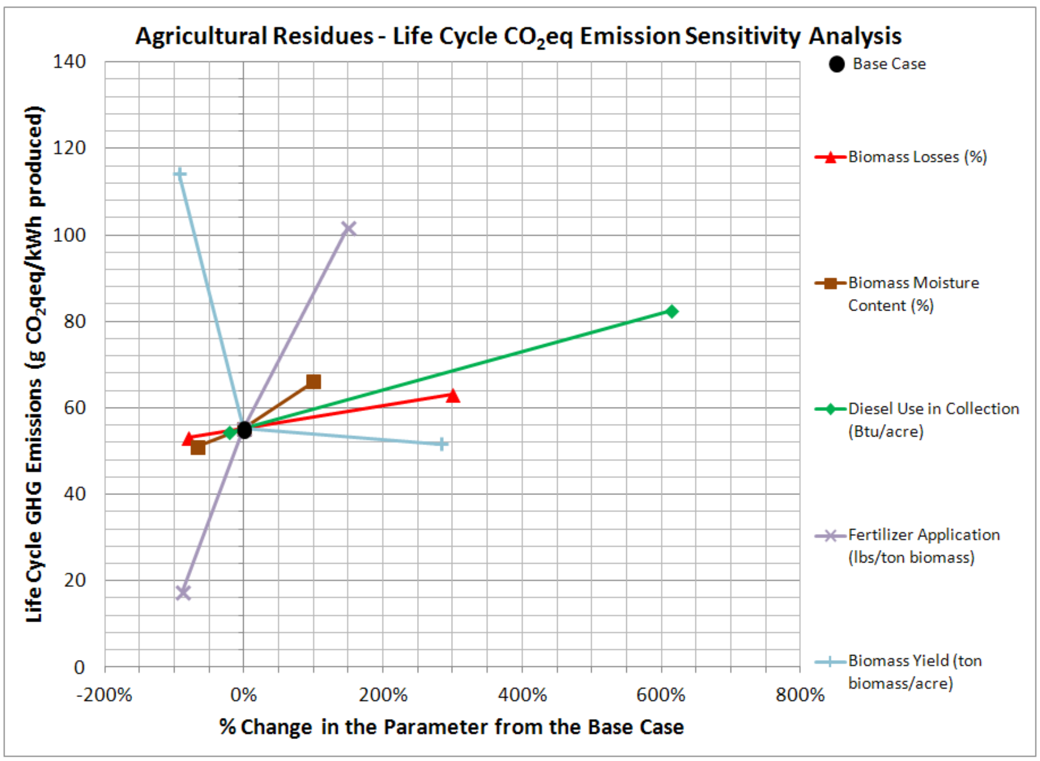
Base case scenarios assume that biomass residue removal is always offset by fertilizer application, but the literature differed on accounting for this impact. Even ignoring differences in fertilizer application rates, more recent papers such as Elsayed et al. (2003) and Zhang et al. (2007) include fertilizer application to compensate for nutrient loss within the LCA system boundaries. Other papers, typically older ones such as SECDA (1994) and Hartmann and Kaltschmidt (1999), did not address fertilizer application and estimated lower GHG emissions.

Papers excluding and including fertilizer application estimated life cycle GHG emissions around 10–20 g CO_2eq/kWh lower and higher than our base case results. The median life cycle GHG emission estimate from our literature review (i.e., 40 g CO_2eq/kWh) is likely a composite of papers split between these methods.

Results indicate that base case scenarios appear to be optimistic relative to the range of potential assumptions for parameters studied in this sensitivity analysis. Selected base case scenario parameters that are directly or indirectly related to energy efficiency (e.g., truck fuel efficiency and capacity) are on the low end of range of data collected from literature. A likely explanation for this result is that since data used in the SAM are from recent papers, technological improvements over 20 years have led to a wide range of potential assumptions. In a couple cases, the pessimistic assumptions are not only taken from older papers—they are also pessimistic scenarios. Base case assumptions not expected to highly deviate over time with technological improvements (e.g., average transportation distances and fertilizer application) are much closer to average or median conditions found in the literature.



(A)

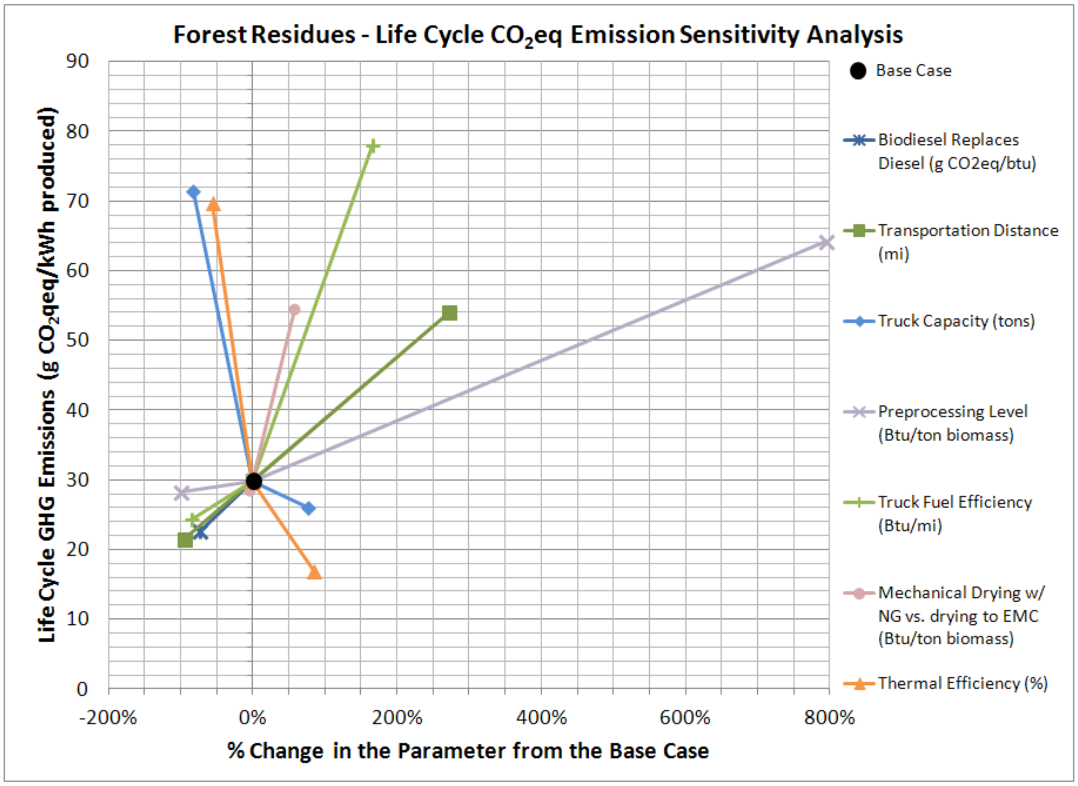


(B)

Figure 6-2
Agricultural residues life cycle GHG emission sensitivity analysis

EMC = atmospheric equilibrium moisture concentration; NG = natural gas.

(A)



(B)

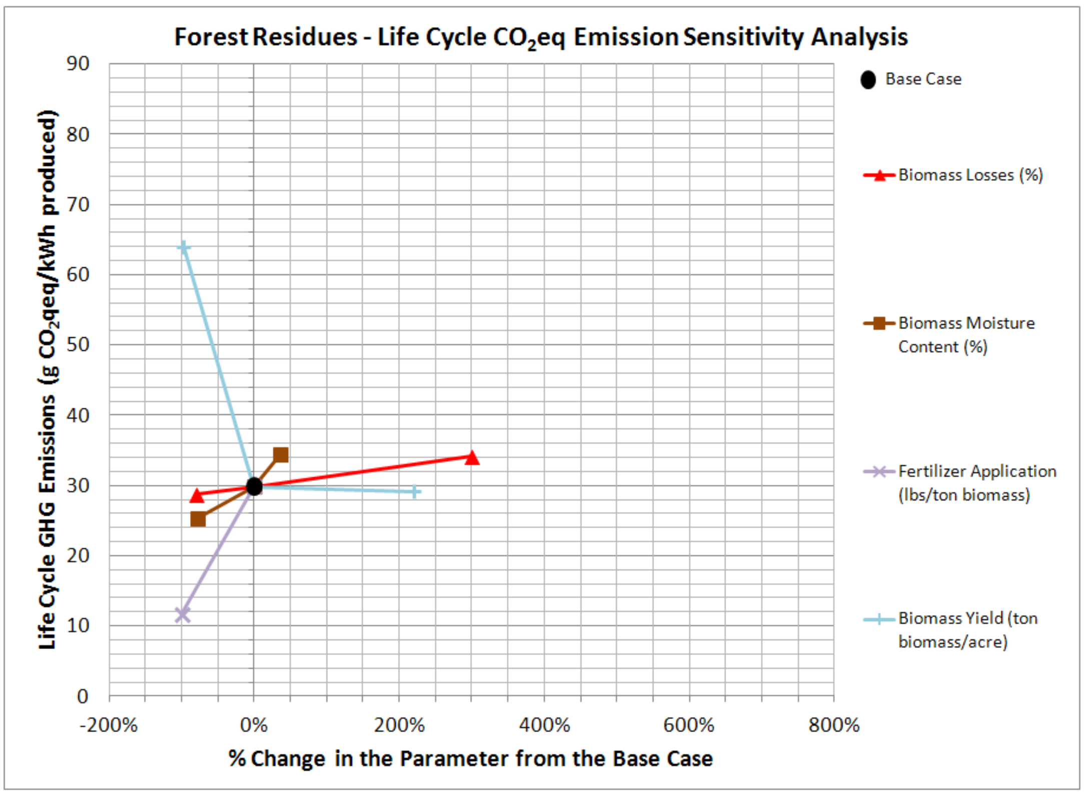


Figure 6-3
Forest residues life cycle GHG emission sensitivity analysis

EMC = atmospheric equilibrium moisture concentration; NG = natural gas.

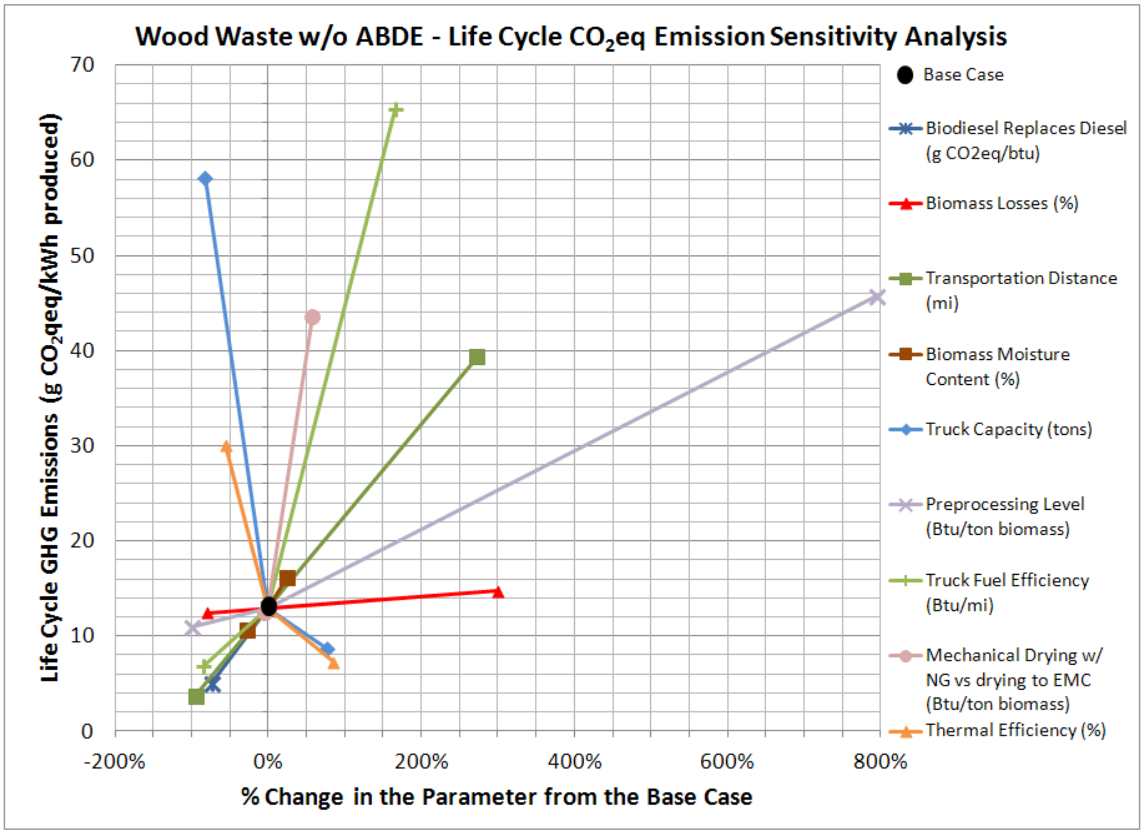


Figure 6-4
Wood wastes life cycle GHG emission sensitivity analysis

EMC = atmospheric equilibrium moisture concentration; NG = natural gas.

Table 6-7
Sensitivity Analysis Parameter Changes and Results for All Biomass Feedstock Categories

Parameter or Biomass Supply Chain Design Option Varied	Agricultural Residue			Forest Residue			Wood Wastes			SRWC			Herbaceous Crops		
	g CO_2eq /kWh Decrease	g CO_2eq /kWh Increase	Total Change	g CO_2eq /kWh Decrease	g CO_2eq /kWh Increase	Total Change	g CO_2eq /kWh Decrease	g CO_2eq /kWh Increase	Total Change	g CO_2eq /kWh Decrease	g CO_2eq /kWh Increase	Total Change	g CO_2eq /kWh Decrease	g CO_2eq /kWh Increase	Total Change
Thermal Efficiency	31	129	98	17	70	53	7	30	23	23	94	71	36	188	151
Biomass Yield	52	114	63	29	64	35				27	109	82	27	190	162
Drying Methods	54	68	15	29	54	26	12	44	31	39	55	16	62	78	16
Fertilization	17	102	84	12		18				24	75	52	27	155	128
Truck Diesel Use Efficiency	50	101	51	24	78	54	7	65	59	36	80	44	60	104	44
Preprocessing Methods	53	93	40	28	64	36	11	46	35	39	74	35	62	96	33
Collection Diesel Use	54	82	28							36	56	20	61	95	34
Truck Capacity	52	94	43	26	71	45	9	58	49	37	75	37	61	99	37
Biomass Moisture Content	51	66	15	25	35	9	11	16	6	37	47	10	60	69	9
Transportation Distance by Truck	47	78	31	21	54	33	4	39	36	33	60	27	57	84	27
LC Biomass Losses	53	63	10	29	34	5	12	15	2	39	46	7	62	73	12
LC Biodiesel Use in Place of Diesel	46		9	23		-23	5		35	28		-28	51		17
	Parameter % Change	Parameter % Change	Total Change	Parameter % Change	Parameter % Change	Total Change	Parameter % Change	Parameter % Change	Total Change	Parameter % Change	Parameter % Change	Total Change	Parameter % Change	Parameter % Change	Total Change
Thermal Efficiency	-56%	85%	141%	-56%	85%	141%	-56%	85%	-141%	-56%	85%	141%	-56%	85%	141%
Biomass Yield	-93%	283%	376%	-97%	220%	317%				-69%	79%	147%	-78%	305%	382%
Drying Methods	-3%	58%	60%	-4%	58%	62%	-4%	58%	62%	-3%	58%	60%	-3%	58%	61%
Fertilization	-88%	150%	238%	-100%		100%				-36%	141%	177%	-60%	82%	142%
Truck Diesel Use Efficiency	-84%	166%	251%	-84%	166%	251%	-84%	166%	251%	-84%	166%	251%	-84%	166%	251%
Preprocessing Methods	-100%	795%	895%	-100%	795%	895%	-100%	795%	895%	-100%	795%	895%	-100%	795%	895%
Collection Diesel Use	-21%	615%	637%							-46%	150%	196%	-32%	300%	332%
Truck Capacity	-82%	76%	159%	-82%	76%	159%	-82%	76%	159%	-82%	76%	159%	-82%	76%	159%
Biomass Moisture Content	-67%	100%	167%	-77%	36%	114%	-27%	25%	52%	-56%	76%	132%	-65%	47%	112%
Transportation Distance by Truck	-95%	273%	368%	-95%	273%	368%	-95%	273%	368%	-95%	273%	368%	-95%	273%	368%
LC Biomass Losses	-80%	300%	380%	-80%	300%	380%	-80%	300%	380%	-80%	300%	380%	-80%	300%	380%
LC Biodiesel Use in Place of Diesel	-73%		73%	-73%		73%	-73%		73%	-73%		73%	-73%		73%

Black cells indicated non-applicability.

Optimistic and Pessimistic Life Cycle Operating Assumptions

Despite significant differences across feedstock categories, our results indicate that certain parameters or supply designs are fairly consistent major or minor contributors to life cycle GHG emissions. Across all feedstock categories, where applicable, the consistently major contributors (i.e., >50 g CO_2eq/kWh of total change) to variability in life cycle GHG emissions are thermal efficiency, biomass yield, and fertilizer application. Results parallel prior speculation and conclusions from Phase A and help demonstrate that these assumptions are important to life cycle GHG emissions due to:

- Thermal efficiency's modulation of life cycle GHG emissions per kilowatt-hour
- Biomass yield's modulation of GHG emissions from the most important life cycle phase (i.e., biomass production or collection) per unit of biomass

- The most significant contributor to GHG emissions from biomass production or collection being fertilizer application
- Some advanced preprocessing methods consume substantial quantities of energy
- Inefficient transportation systems lead to large fossil fuel consumption.

Other less important contributors (i.e., >25 g CO_2eq/kWh of total change) to life cycle GHG emission variability included truck capacity, truck fuel use efficiency, transportation distance, biomass preprocessing, and biomass production or collection diesel use. In most cases, biomass losses along the supply chain, biomass moisture content, and the replacement of diesel fuel with biodiesel had little effect on life cycle GHG emissions. Biomass drying also had relatively little influence on life cycle GHG emissions, but results in practice may vary depending on the assumed biomass moisture content, natural gas use efficiency, and water removal efficiency. For example, a sensitivity estimate combining worst case moisture content for agricultural residues with natural gas drying would lead to 120 g CO_2eq/kWh.

Though results are largely consistent across feedstock categories, there are some notable trends between related parameters and differences between feedstocks. Biomass yields for herbaceous crops had a much larger impact on life cycle GHG emissions than other biomass categories because of higher fertilizer inputs relative to their yields. Mechanical drying was a more important contributor to life cycle GHG emissions for forest residues and waste wood relative to other biomass feedstocks due to higher assumed moisture content of the biomass. Higher moisture content also meant more collected or grown biomass was required to meet the same dry biomass requirements. Therefore, fertilizer inputs, diesel use in collection, and transportation prior to drying are increased per unit of biomass when drying conditions are used. Biodiesel use led to the largest GHG emissions reductions when life cycle diesel was used heavily (i.e., energy crops).

Many LCAs account for GHG emissions that are avoided by using waste wood for biopower that would have otherwise been emitted to the atmosphere. Sensitivity results are partially recalculated in Figure 6-5 with the inclusion of these ABDEs. The inclusion of avoided GHG emissions leads to a significant negative life cycle GHG impact of -1,487 g CO_2eq/kWh in the base case scenario. The magnitudes of the changes are similar, if smaller, when the avoided biomass use is considered in accounting for sensitivity analysis scenarios not displayed in Figure 6-5. The major differences in the scenarios displayed in Figure 6-5 are that biomass losses, moisture content, and drying methods have the opposite impact on life cycle GHG emissions when avoided biomass is not considered. These results can be traced to the SAM's accounting of the "dry" biomass that is fed to biopower facilities. Assumptions about biomass losses and biomass moisture content affect biomass collected to meet "dry" biomass requirements required. The greater the biomass losses or the greater the difference between "dry and "wet" biomass moisture content, the more biomass is required. As more waste wood collection occurs, more biomass decomposition emissions are avoided.

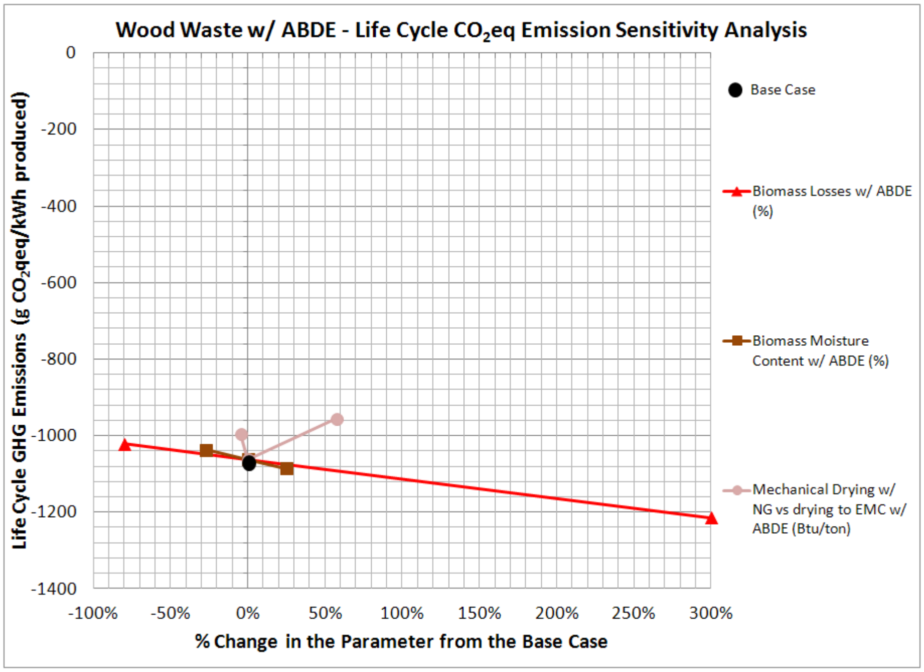


Figure 6-5
Extended wood wastes life cycle GHG emission sensitivity analysis with and without avoided biomass decomposition emissions (ABDE) accounting

EMC = atmospheric equilibrium moisture concentration; NG = natural gas.

Several other variations in the biomass supply chain that did not fit neatly with the optimistic and pessimistic scenario frameworks were explored to look at intermediate life cycle GHG emission conditions. Long distance transportation of agricultural residues led to about a 40% increase in life cycle GHG emissions. Switching to rail transport or barge long distance transportation after 60 miles instead led to about a 10% and 5% increase in life cycle GHG emissions, respectively, for the same total distance of about 220 miles. Mechanical agricultural residue drying using natural gas can lead to about a 25% increase in life cycle GHG emissions. For agricultural residues, the assumed moisture removed through drying is 20%, but this can vary depending on wet biomass composition assumptions. If drying uses a renewable resource such as biomass instead of natural gas, then mechanical drying actually decreases life cycle GHG emissions slightly, by 1%–2%. These results assume the alternative energy source has a carbon intensity of approximately 10 g CO_2eq/MJ. Preprocessing scenarios only explored heavy biomass grinding. Pelletization on top of heavy grinding of agricultural residues would shift the increase in life cycle GHG emissions from about a 70% increase to about a 120% increase. Alternatively, because these preprocessing steps are based on electricity consumption, a lower GHG-emitting background economy could significantly shift these results. Assuming heavy grinding of the agricultural residues and a 100% wind base electric grid, life cycle GHG emissions would actually be 3% less than the base case scenario. The negative change is due to the “cleaner” electricity consumption used in fertilizer manufacturing. A 100% coal-based electric grid would lead to 120% increase in life cycle GHG emissions. Similar resulting trends are found for all other feedstock categories.

Implications for Biopower Decision Making

Improvements in facility or field output efficiency are generally the most effective approaches to reduce GHG emission, but other more conditional sources of life cycle GHG emissions, such as from intermediate biomass supply chain assumptions, can also be significant contributors. Field and facility efficiencies show the most potential based on the slopes of the lines between variable parameters and thermal efficiencies. Yields (at least for crop-based biopower) modulate the fossil consumption and resulting GHG emissions over the life cycle on first a biomass and then on a power production basis. Intermediate steps such as transportation, preprocessing, and drying are generally negligible based on typical systems. However, actual practice may require more involved life cycle phases such as biomass pelletization. Under these conditions' intermediate steps can become just as significant in contribution to life cycle GHG emissions as field and facility assumptions. To limit life cycle GHG emissions from these sources, decision makers will need to consider the tradeoffs between GHG emissions and other goals (e.g., the economic market for biomass pellets). Decision makers can also investigate ways to reduce GHG emissions from these sources, such as those outlined in the alternative scenarios examined. For example, it might be better to use biomass integrated gasification and combined cycle system (IGCC) or mechanical drying using renewable energy if GHG emission from drying are a concern.

One potential government policy in which these life cycle GHG emissions may be of direct relevance is a direct or indirect (i.e., carbon price within a cap in trade system) carbon tax. A back-of-the-envelope calculation of the impact of a carbon tax on biopower using agricultural residues and multiple coal systems is used as a simple illustrative example of the policy impacts on LCOE calculations.[8] LCOE figures, life cycle GHG emissions, and carbon taxes are shown in Table 6-8 using Annual Energy Outlook 2010 30-year life and 7.4% real discount rate assumptions. Life cycle GHG emission estimates for pulverized and IGCC coal are taken from a recent LCA literature review (Whitaker et al. 2011). Results show that the LCOE of coal IGCC systems equal biomass systems at 10 $\$_{2009}$/ton CO_2eq and the LCOE of pulverized coal is equal to biomass at about \$40 /ton CO_2eq (2009\$). These results are in line with similar analyses reviewed for Phase A (e.g., Cottrell et al. 2003). As the sensitivity analysis illustrates, biopower life cycle GHG emissions can vary significantly. Thus, the results are somewhat uncertain. For example, the LCOE of waste wood assuming ABDEs would have a very low LCOE, even at a small carbon price. Conversely, if agricultural residues went through lengthy preprocessing and mechanical drying, the GHG emissions would lead to a much less competitive LCOE.

[8] The SAM calculations were not used for this assessment because of the lack of a comparable coal module and the AEO's LCOE estimates cannot be directly compared to SAM results due to differences in financial model assumptions.

Table 6-8
Coarse LCOE Calculations for Agricultural Biomass and Coal Systems With and Without Carbon Taxes

		LCOE	GHG Emission Intensity	Tax (real)	LCOE (w/ Carbon Tax)
	$\$_{2009}$/ ton CO_2eq	cents $_{2009}$/kWh	g CO_2eq/kWh	cents $_{2009}$/kWh	cents $_{2009}$/kWh
Agricultural Residue Combustion	10	11.3	60	0.033	11.3
Pulverized Coal		9.5	1100	0.46	9.96
IGCC Coal		10.9	840	0.37	11.3
Agricultural Residue Combustion	25	11.3	60	0.082	11.3
Pulverized Coal		9.5	1100	1.2	10.7
IGCC Coal		10.9	840	0.92	11.8
Agricultural Residue Combustion	40	11.3	60	0.13	11.4
Pulverized Coal		9.5	1100	1.9	11.4
IGCC Coal		10.9	840	1.5	12.4

LCOE taken from EIA (2011). Coal GHG emission intensity from Whitaker et al. (2011). Biomass GHG emission intensity from this paper.

Analysis Limitations

There are several important limitations to this analysis and the data collected with regards to the selected variables analyzed and the implicit limitations of the reviewed literature. The current version of the SAM is simplistic and does not feature a great deal of complex dynamics (e.g., moisture losses along the supply chain rather than only in drying). Nor does it consider the many sources of minor GHG emissions (e.g., herbicide application and facility construction) that might add up to a relatively large effect. Because of this, our results should only be considered as indicative of relationships between and relative impacts rather than as a precise number generator. To that end, more sophisticated modeling requires more details about the operations of the life cycle than is probably available in the collected LCA literature. The inclusion of several important sources of data used for biofuel LCAs greatly improved our analysis, but nonetheless emphasizes that the creation of a full LCA tool would require additional data resources.

Another possible limitation of this analysis is a lack of “best” and “worst” case scenarios in which all optimistic and pessimistic values are combined in a single case, respectively. These cases were generated, but then culminated in extremes that, once considered, were interpreted as being mostly inappropriate. The best case is essentially 0 g CO_2eq/kWh because system efficiencies are so high that little fossil energy is consumed per kilowatt-hour generated. Under worst case conditions, the biopower life cycle became so inefficient that the level of fossil energy consumption led to life cycle GHG emissions that greatly exceeded coal. The primary reason for this high level of GHG emissions is that many of the pessimistic assumptions for fossil fuel consumption levels were higher than anything seen in the literature. For example, in a transportation scenario, biomass losses might increase the needed biomass transport, and other assumptions reduce the truck’s capacity and fuel efficiency. Results could have been worse if we had assumed a higher GHG-emitting source of diesel, such as oil sands instead of crude oil.

A note of caution: The range of data collected from the literature does not represent a statistically independent population, and certainly does not represent the full potential range impacts as to how the technology has been or could be deployed. We gathered data from all available high-quality studies, but that does not guarantee that we captured all possible cases of manufacture, deployment, or use (i.e., our range may be narrower than the true range for the technology). Collected data may not necessarily include all relevant impacts with regard to the depth and breadth across the supply chain. The range of our results, together with our base case, cannot be considered a distribution of likelihood for actual life cycle GHG emissions for the technology. Nor can it be considered a formal sensitivity analysis. However, the magnitude of the change in life cycle GHG emission estimates can be considered indicative of the relative influence of examined parameters. The precision and range of results is improved with sample size, but sample limitations affect the accuracy of the results compared to the "true" life cycle GHG emission range and central tendency of biopower under all potential conditions.

Our analysis does not tackle any major issues associated with biomass feedstocks and the assumption about carbon neutrality. In the long-term emissions from the combustions of biomass are presumed to be up taken be regrowth of biomass for a net neutral impact. However, in practice the actual dynamics are much more complex, depending on the feedstock. For example, the removal of forest residues that would otherwise be left on the forest floor my take decades to be regrown. Essentially this study does not address the climatic implications of the short-term large carbon flux of combusting that biomass versus the longer-term sequestration for establishment and regrowth of the forest in which new residues would be collected.

The final major limitation of note that was covered in our previous literature review (Phase A of this report) is the lack of LUC. LUC was excluded to reflect the system boundaries of many of the papers we studied, but meaningful results with LUC would require a separate literature review to the extent that much of the LCA and LUC are non-overlapping.

7
CONCLUSIONS

Base case scenario runs constructed from recent literature generally look optimistic with respect to GHG emissions. These optimistic base case assumptions were usually technological efficiencies. Other assumptions were similar to median values found in the literature. Wood wastes and forest residues had the lowest GHG emission rates (11 and 34 g CO2eq/kWh), while herbaceous crops had the highest (at 75 g CO2eq/kWh). Agricultural residue and short rotation woody crop (SRWC) combustion led to 60 and 45 g CO2eq/kWh, respectively. Major feedstock differences mostly depended on fertilizer application practices and yields. Collection/harvest practices and the assumed agricultural residue heating values also played a role. The sensitivity analysis found that the major contributors (>50% change in GHG emissions from the base case) to variability are related to net output of the biopower facility (e.g., thermal efficiency), biomass production (i.e. crops) or collection (i.e., residues) yields, fertilizer inputs, and the inclusion of high energy use practices (e.g., natural gas drying of biomass or pelletization). Improvements in facility or field output efficiency are potentially the best approaches to GHG emission reduction because they modulate GHG emissions over the life cycle. However, intermediate steps can become just as important contributors to life cycle GHG emission variability when longer and more complex (e.g., pelletization and natural gas mechanical drying) supply chains are considered. Among other analysis limits, life cycle GHG emission calculations are simplistic relative to a full LCA. Our results should be considered as indicators of relationships and relative impacts rather than as precise estimates.

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