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NATIONAL COUNCIL FOR AIR AND STREAM IMPROVEMENT

GREENHOUSE GAS AND FOSSIL FUEL REDUCTION BENEFITS OF USING BIOMASS MANUFACTURING RESIDUALS FOR ENERGY PRODUCTION IN FOREST PRODUCTS FACILITIES

TECHNICAL BULLETIN NO. 1016

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PRESIDENT'S NOTE

NCASI continues its work to address the United States Environmental Protection Agency's expressed interest in the life cycle greenhouse gas (GHG) benefits associated with using biomass. The regulatory decisions EPA makes on this topic have the potential to greatly affect the costs of doing business and the perception of the forest industry's products in the marketplace. The forest products industry, therefore, has a great deal at stake in ensuring that the agency's deliberations on this topic are well informed.

In an earlier report, NCASI examined the life cycle greenhouse gas and non-renewable energy benefits of using black liquor in the kraft recovery system. In the study described herein, NCASI extends this work to other types of biomass-based manufacturing residuals used for energy generation within the industry (woody mill residuals, waste water treatment plant residuals, and paper recycling residuals). While there are numerous studies examining the life cycle impacts of biomass energy, none has applied the comprehensive approach used here by NCASI to characterize the impacts of the industry's use of energy produced from biomass residuals.

In this study, NCASI has compared systems involving the use of biomass-based manufacturing residuals for energy to comparable systems relying on fossil fuels. The results indicate that the use of residuals examined in this study produces significant reductions in atmospheric GHGs. Combining the results of this study with the results of the previous NCASI study on black liquor reveals that each year's use of manufacturing residuals, including black liquor, in the US forest products industry avoids the emission of approximately 181 million metric tons of CO_2E, an amount approximately three times that of the annual direct emissions of CO_2 from fossil fuel combustion in the industry.

This study is one of a series of ongoing NCASI projects having the objective of helping the forest products industry and its stakeholders better understand the greenhouse gas and energy impacts of using forest biomass as a raw material and fuel.

Ronald A. Yeske

October 2013

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NOTE DU PRÉSIDENT

NCASI poursuit son travail dans le contexte de l'intérêt exprimé par la United States Environmental Protection Agency (EPA) pour les bénéfices en terme de gaz à effet de serre (GES) de l'utilisation de la biomasse, et ce en adoptant une perspective cycle de vie. Les décisions réglementaires de l'EPA à ce sujet ont le potentiel d'affecter considérablement le coût de faire des affaires et la perception des produits forestiers dans le marché. L'industrie des produits forestiers a, par conséquent, beaucoup en jeu pour assurer que les délibérations de l'EPA sur ce sujet soient bien informées.

Dans un rapport antérieur, NCASI a examiné les bénéfices du cycle de vie pour les GES et la consommation d'énergie non-renouvelable lié à la récupération de la liqueur noire. Dans l'étude décrite ici, NCASI étend ce travail à d'autres types de résidus de fabrication de produits forestiers utilisés pour la production d'énergie dans cette même industrie (résidus d'usine ligneux, résidus de traitement des eaux usées et résidus de recyclage du papier). Bien qu'il existe de nombreuses études sur les impacts du cycle de vie associés à la production d'énergie à partir de biomasse, aucune n'a appliqué l'approche globale utilisée ici par NCASI pour caractériser les impacts de la production d'énergie produite à partir de résidus de biomasse de l'industrie.

Dans cette étude, NCASI a comparé des systèmes impliquant l'utilisation des résidus de fabrication à base de biomasse pour l'énergie à des systèmes comparables utilisant plutôt des combustibles fossiles. Les résultats indiquent que l'utilisation des résidus examinés dans cette étude génère des réductions significatives des GES. La combinaison des résultats de cette étude avec les résultats de l'étude précédente de NCASI sur la liqueur noire révèle que l'utilisation annuelle de résidus de fabrication, y compris la liqueur noire, dans l'industrie des produits forestiers des États-Unis permet d'éviter l'émission d'environ 181 millions de tonnes d'équivalents CO_2, une quantité environ trois fois supérieure à celle des émissions annuelles directes de CO_2 provenant de la combustion de combustibles fossiles par cette industrie.

Cette étude fait partie d'une série de projets en cours de NCASI ayant pour objectif d'aider l'industrie des produits forestiers et ses parties prenantes à mieux comprendre les impacts pour les GES et la consommation énergétique de l'utilisation de la biomasse forestière comme matière première et combustible.

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Octobre 2013

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TECHNICAL BULLETIN NO. 1016
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ABSTRACT

This study examined the life cycle greenhouse gas (GHG) and fossil fuel-related implications of using various manufacturing biomass residuals for energy production at pulp and paper mills and wood products manufacturing facilities. Woody mill residuals (e.g., bark, sawdust, etc.), wastewater treatment plant (WWTP) residuals, and paper recycling residuals were studied. Results from an earlier study of black liquor were also included and extended. Two product systems were compared: a product system in which the biomass residuals are burned for energy in a forest products industry facility (biomass energy system), and a product system in which the biomass residuals are disposed of and fossil fuels are used instead (non-use system). The systems were compared on the basis of a functional unit of 1 GJ energy output in same form for each system. For each residual type, various scenarios were evaluated, including one (the typical scenario) that best represents the industry average. A variety of residual characteristics were subjected to sensitivity analyses. The impacts of the systems were characterized dynamically, using cumulative radiative forcing attributable to the GHG emissions from each system over time. Impacts were calculated in terms of the differences between the biomass and non-use systems over 100 years, expressed as CO_2E, as well as the time required for the net difference in cumulative radiative forcing to reach zero (i.e., the break-even time). Reductions in consumption of fossil fuels were also computed.

In the case of woody mill and WWTP residuals, the systems using residuals for energy produced GHG emissions, not including biogenic CO_2, that were more than 98% lower than those from the systems disposing of the residuals. Paper recycling residuals and black liquor resulted in significant, but lower, benefits (86.4% and 90.5% reductions in GHG emissions, respectively, in the typical scenario). Even when biogenic CO_2 was included in the analysis, over 100 years, the GHG impacts for typical scenarios involving a) woody mill residuals, b) WWTP residuals, c) paper recycling residuals, and d) black liquor solids were lower than the comparable non-use systems by 116 kg CO_2E/GJ, 295 kg CO_2E/GJ, 112 kg CO_2E/GJ, and 184 CO_2E/GJ, respectively. Relative to the comparable fossil fuel-based systems, fossil fuel consumption was found to be lower by more than 99% for all residuals examined in this study, except black liquor, for which the reduction was 89.8%. Break-even times ranged from 0 to 1.2 years under typical scenarios.

A gate-to-gate analysis addressing only biogenic GHGs, not considering fossil fuel substitution benefits, was also performed. In this case, the net GHG impacts over 100 years for typical scenarios involving a) woody mill residuals, b) wastewater treatment plant residuals, c) paper recycling residuals, and d) black liquor were lower than the comparable non-use systems by 8.5 kg CO_2E/GJ, 190 kg CO_2E/GJ, 132 kg CO_2E/GJ, and 0 kg CO_2E/GJ, respectively. The break-even times ranged from 0 years for black liquor, which comprises 57% of the biomass used by the industry for energy, to 19.5 years for woody mill residuals, which comprise 37%. For several residuals, the results were shown to be very sensitive to the parameter value describing the extent to which residuals decompose in mill landfills, a parameter with significant uncertainty.

KEYWORDS

biomass residuals, energy, greenhouse gases, life cycle assessment

RELATED NCASI PUBLICATIONS

Technical Bulletin No. 984 (April 2011). *Greenhouse gas and non-renewable energy benefits of black liquor recovery*.

RÉDUCTION DES ÉMISSIONS DE GAZ À EFFET DE SERRE ET DE LA CONSOMMATION D'ÉNERGIE FOSSILE DUE À L'UTILISATION DE RÉSIDUS MANUFACTURIERS DE BIOMASSE POUR LA PRODUCTION D'ÉNERGIE PAR LES USINES DE PRODUITS FORESTIERS

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RÉSUMÉ

Cette étude a examiné les implications pour les gaz à effet de serre (GES) et l'utilisation de combustibles fossiles de l'utilisation de divers résidus de biomasse provenant de la fabrication de produits forestiers pour la production d'énergie à ces usines de fabrication. Les résidus d'usine ligneux (par exemple, l'écorce, la sciure de bois, etc.), les résidus de traitement des eaux usées et les résidus de recyclage du papier ont été étudiés. Les résultats d'une étude antérieure portant sur la liqueur noire ont également été inclus et étendus. Deux systèmes de produit ont été comparés: un système de produit dans lequel les résidus de biomasse sont brûlés à une usine de fabrication de produits forestiers pour produire de l'énergie (système "énergie de biomasse") et un système de produit dans lequel les résidus de biomasse sont éliminés et des combustibles fossiles sont utilisés à la place (système "non utilisation"). Les systèmes ont été comparés sur la base d'une unité fonctionnelle de production de 1 GJ d'énergie utilisable et ce, sous la même forme pour chacun des systèmes comparés. Pour chaque type de résidus, divers scénarios ont été évalués dont un, le scénario typique, qui représente le mieux la moyenne de l'industrie. Une variété de caractéristiques des résidus a été soumise à des analyses de sensibilité. Les impacts des systèmes ont été caractérisés de façon dynamique, en utilisant le forçage radiatif cumulatif attribuable aux émissions de GES de chaque système dans le temps. Les impacts ont été calculés sous forme de différences observées sur 100 ans entre les systèmes "énergie de biomasse" et "non utilisation", exprimés en CO_2E. Le temps nécessaire pour observer les bénéfices pour les GES liés à l'utilisation de la biomasse et la réduction de la consommation de combustibles fossiles ont également été calculés.

Dans le cas des résidus d'usine ligneux et des résidus de traitement des eaux usées, les systèmes utilisant les résidus pour la production d'énergie produisent des émissions de GES plus de 98% inférieures à celles des systèmes disposant des résidus lorsque le CO_2 biogénique est exclus. Les résidus de recyclage du papier et la liqueur noire présentent aussi des réductions significatives, mais moins élevées (86.4% et 90.5% de réduction des émissions de GES, respectivement, dans le scénario typique). Lorsque le CO_2 biogénique est inclus dans l'analyse, les réductions de GES observées sur 100 ans, dans le cas du scénario typique sont de 116 kg de CO_2E/GJ, 295 kg CO_2E/GJ, 112 kg CO_2E/GJ et 184 CO_2E/GJ pour les résidus d'usine ligneux, les résidus du traitement des eaux usées, les résidus de recyclage du papier et la liqueur noire, respectivement. La consommation de combustibles fossiles est plus de 99% inférieure dans les systèmes "énergie de biomasse" que dans les systèmes "non utilisation" à l'exception du cas de la liqueur noire pour lequel la réduction observée est de 89,8%. Dans les scénarios typiques, le temps nécessaire pour observer les bénéfices liés aux GES varie entre 0 et 1.2 années.

Une analyse plus restreinte, ne portant que sur les émissions de GES biogénique et ne considérant pas la substitution des combustibles fossiles, a également été réalisée. Dans ce cas, les réductions de GES (systèmes "énergie de biomasse" versus systèmes "non utilisation") observées sur 100 ans dans les scénarios typiques sont de 8.5 kg CO_2E/GJ, 190 kg CO_2E/GJ, 132 kg CO_2E/ GJ et 0 kg CO_2E/GJ pour les résidus d'usine ligneux, les résidus du traitement des eaux usées, les résidus de recyclage du papier

et la liqueur noire, respectivement. Le temps nécessaire pour observer ces réductions varie de 0 an pour la liqueur noire qui représente 57% de l'énergie produite à partir de biomasse par l'industrie forestière à 19.5 ans pour les résidus d'usines ligneux qui en représente 37%. Pour plusieurs résidus, les résultats se sont avérés être très sensibles à la valeur du paramètre décrivant la mesure dans laquelle les résidus se décomposent dans les sites d'enfouissement, un paramètre avec une incertitude importante.

MOTS-CLÉS

résidus de biomasse, énergie, gaz à effet de serre, analyse du cycle de vie

PUBLICATIONS DE NCASI RELIÉES

Bulletin Technique No. 984 (Avril 2011). *Avantages pours les émissions de gaz à effet de serre et la consommation d'énergie non renouvelable de la récupération de liqueur noire.*

GREENHOUSE GAS AND FOSSIL FUEL REDUCTION BENEFITS OF USING BIOMASS MANUFACTURING RESIDUALS FOR ENERGY PRODUCTION IN FOREST PRODUCTS FACILITIES

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EXECUTIVE SUMMARY

Wood handling and processing activities in log yards, sawmills, pulp and paper mills, and other forest products activities produce a significant amount of residuals, most of which consist of black liquor, bark, sawdust, shavings, and other woody debris. These currently available residuals have long been used as a source of renewable energy in the forest products industry. In this study, the greenhouse gas (GHG) impacts attributable to the industry's use of these materials for energy, compared to not using them, were assessed.

ES.1 Significance of Findings

Combining the results of this study with the results of the previous NCASI study on black liquor reveals that, when considering biogenic and non-biogenic life cycle GHG emissions, each year's use of manufacturing residuals in the US forest products industry avoids the eventual release of approximately 181 million tonnes of CO_2E. The break-even times (i.e., the times required for the GHG impacts of using biomass to be the same or less than the impacts of using an alternative source of energy) range from 0 to1.2 years under typical scenarios, depending on the residual.

An analysis addressing only biogenic GHGs, not considering fossil fuel substitution benefits, was also performed. Even ignoring fossil fuel avoidance benefits, the annual use of manufacturing residuals, including black liquor, avoids the eventual release of 5 million tonnes CO_2E with the break-even times ranging from 0 years for black liquor, which comprises 57% of the biomass used by the industry for energy, to 19.5 years for woody mill residuals, which comprise 37%.

These results have been developed by comparing the GHG emissions from systems using manufacturing residuals for energy in the forest products industry to the emissions from alternative systems producing the same amount of energy from fossil fuels while disposing of the residuals by landfilling or a combination of landfilling and incineration. In cases where it is assumed that the alternative to burning manufacturing residuals for energy is incineration, the break-even times for all residuals are zero, whether or not fossil fuel substitution is considered. Where landfilling is assumed to be the alternative, the results can be very sensitive to assumptions about the degree to which biomass carbon decomposes in landfills, a parameter with large uncertainty.

Because manufacturing residuals have been used for energy in the forest products industry for many years, estimates were also made of the time required to show net benefits from ongoing use of residuals for energy. The results provided strong evidence that the ongoing use of manufacturing residuals for energy in the forest products industry has been yielding net benefits for many years.

ES.2 Objective

The overall objective of this study was to evaluate the life cycle (cradle-to-final energy analysis) greenhouse gas and fossil fuel reduction benefits of using forest products manufacturing-related biomass residuals for energy in forest products manufacturing facilities in contrast to disposal of these

residuals coupled with production of the same quantity and form of energy using fossil fuels. This study also incorporates and expands upon the results of a previous NCASI study that analyzed the greenhouse gas reduction benefits of using spent pulping liquor, known as black liquor, for energy in the forest products industry

This study also included two secondary objectives: 1) to analyze the emissions of biogenic GHGs directly released from the units in which the residuals are managed (i.e., combustion units or landfills, also called a gate-to-gate analysis)[1] and 2) to analyze the cumulative emissions attributable to the use of the residuals for energy as an ongoing, long-standing practice (both in terms of cradle-to-final energy and gate-to-gate boundaries).

The biomass residuals specifically studied in this project were

- woody mill residuals (e.g., bark, sawdust and other similar manufacturing residuals from sawmills, panel plants, and pulp and paper mills);
- wastewater treatment plant (WWTP) residuals;
- paper recycling residuals (e.g., old corrugated container (OCC) rejects)[2]; and
- black liquor (based on the results of an earlier NCASI study).

ES.3 Methods

ES.3.1 Methods for the Cradle-to-Final Energy Analysis

For each type of residual, the study compared two different product systems:

1) one in which the biomass residuals are burned for energy (**biomass energy system**); and
2) one in which the biomass residuals are disposed of and fossil fuels are used instead to generate an identical amount and form of energy (**non-use system**).

More specifically, the methodology used in this study followed life cycle principles by calculating emissions from "cradle to final energy," including fuel conversion efficiency. The primary functional unit employed in this study was ***the production of 1 GJ of energy.*** It is important to note that whether manufacturing residuals are used for energy or disposed of, the same number of trees would be harvested and the same quantity of resources would be required to produce the related forest products.

The overall analysis approach employed in this study is as follows. First, for each system component of the study (size reduction, biomass energy production, alternative fate of the residuals, and fossil fuel displaced), several scenarios were defined. These scenarios were intended to represent a broad range of conditions in the US forest products industry. Then, a typical scenario was defined for each residual type representing the best estimate of average conditions in the US in terms of the system components mentioned above. The typical scenario was analyzed to determine 1) typical benefits obtained by using a given residual type, 2) the contribution of each different system component to the overall results, 3) the sensitivity of various parameters (i.e., biomass properties such as higher heating value, water content, etc.) to the results, and 4) the timing of emissions. Where possible, each parameter was analyzed using a base case, low, and high value. Finally, a number of system configuration scenarios were also analyzed.

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[1] In this gate-to-gate analysis, the benefits of avoided fossil fuel use are not included.
[2] Paper recycling residuals are materials removed during processing to eliminate contaminants and yield reusable fiber. They generally consist of a fiber and plastic fraction.

The difference in greenhouse gas impact (GHGI) between product systems was determined by calculating the differences in annual GHG emissions from the systems and determining the cumulative radiative forcing impacts associated with these differences over time, out to 100 years. The difference in GHGI between the two systems was calculated twice, once with biogenic CO_2 included in the analysis and once with biogenic CO_2 excluded. In addition to characterizing the total difference in GHGI over 100 years, this study examined the implications of using biomass residuals for energy as a function of time. When residuals are burned for energy, the biogenic carbon is immediately released to the atmosphere. In contrast, residuals placed into landfills degrade and release the carbon over time.[3] In such cases, the emissions from the biomass energy system could sometimes be higher in the short term than those from the non-use system, but the emissions from the non-use system typically overtake those from the biomass energy system relatively quickly. For each residual, this study computed the number of years required for the cumulative radiative forcing associated with the emissions from the non-use system to equal the cumulative radiative forcing associated with the emissions from the biomass energy system (referred to as the "break-even time" in this report). After this point, the cumulative radiative forcing associated with the non-use system remains higher than that associated with the biomass energy system for the remainder of the 100-year period. Dynamic calculations of cumulative radiative forcing were used in the analysis rather than conventional global warming potentials because the intent was to capture the time-dependent impacts of each system, which is not possible using global warming potentials which assess cumulative radiative forcing over a single period (e.g., 100 years).

The difference in fossil fuel consumption between the two systems was also calculated.

ES.3.2 Methods for Additional Analyses

In addition to the life cycle analyses described above, two secondary analyses were undertaken.

The first involved limiting the analysis to the fate of the biomass carbon, without regard to fossil fuel substitution benefits. In this analysis, the two compared systems (i.e., the biomass energy system and the non-use system) were compared in terms of the emissions coming directly out of the units receiving the residuals (i.e., combustion units or landfills). In the case of paper recycling residuals, only the fiber fraction was considered as the focus here was on the fate of the biomass carbon. The results were computed for two indicators: difference in GHGI over 100 years and break-even time.

The second analysis consisted of changing the frame of analysis to evaluate the cumulative emissions attributable to the ongoing use of the residuals. For this analysis, a different functional unit was used, defined as ***the yearly production of 1 GJ of energy as an ongoing practice***. The differential GHGI indicator was computed on a yearly basis so as to estimate when in the past the practice would have had to begin in order for the difference in GHGI to become zero in 2014. These results were computed both for the full life cycle (i.e., including fossil fuel substitution) and for the more constrained analysis looking only at the biogenic GHG emissions from the units receiving the residuals.

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[3] The results of an earlier study of the benefits of using black liquor are also included in this report. For black liquor, it is difficult to construct an alternative fate scenario because the material is integral to pulp production. Nonetheless, in the earlier study it was assumed that, if not used in the kraft recovery cycle, black liquor would be incinerated or treated in aerobic wastewater treatment plants. In both cases, the carbon returns to the atmosphere far too rapidly for carbon storage to be important in the calculations. It was assumed that all carbon is emitted as biogenic CO_2. If, however, some of the carbon was emitted as methane, the benefits of using the liquor in the kraft recovery cycle would be greater than estimated in the previous study.

ES.4 Results from the Cradle-to-Final Energy Analysis, Including the Benefits of Displacing Fossil Fuels

ES.4.1 Difference in GHGI, Including Biogenic CO_2

Table ES.1 summarizes the differences in life cycle GHG impact, over 100 years, between the systems using residuals for energy and the systems using fossil fuels when biogenic CO_2 is included in the emissions. The negative values in this table indicate that the biomass energy system produced less impact (a reduction) compared to the non-use system. The weighted average reduction observed in the biomass energy system compared to the non-use system (including all residuals and black liquor) was 158 kg CO_2E/GJ. Given current fuel consumption, this means that the annual use of manufacturing residuals (including black liquor) in the industry avoids the eventual release of approximately 181 million tonnes CO_2E . The reduction occurs across a range of system configuration scenarios (boiler type, assumptions about the displaced fossil fuel, the GHG intensity of the electricity grid, and the level of cogeneration at forest products facilities) and without affecting the amount of wood harvested or the amount of forest products produced.

Table ES.1 Difference in Total Life Cycle GHG Emissions (including Biogenic CO_2) over 100 Years: Biomass Energy System Compared to Comparable Fossil Fuel-Based System Where the Residuals are Disposed

Residual Type	Differential GHGI: Difference in Emissions Impact for Typical Scenario (kg CO_2E/GJ)
Woody mill residuals	-116*
WWTP residuals	-295
Paper recycling residuals	-112
Spent liquor (incl. black liquor)†	-184
Weighted average	-158

* The results for woody mill residuals are very sensitive to the parameter used to characterize the extent to which these residuals decompose in landfills. The results shown here are based on the most conservative (i.e., least decomposition in the landfill) of several parameter values used by EPA for various purposes. Other values used by EPA, based on IPCC guidelines, yield far larger benefits (-295 kg CO_2E/GJ). †The various analyses were performed for black liquor only, which represents approximately 92% of the total spent liquor. In computing the weighted averages, it was assumed that black liquor was representative of any spent liquor.

ES.4.2 Relative Difference in GHGI, Excluding Biogenic CO_2

Table ES.2 summarizes the differences in life cycle GHG impacts, over 100 years, between the systems using residuals for energy and the systems using fossil fuels when biogenic CO_2 is excluded from the life cycle emissions. The negative results in this table indicate that the biomass energy system produces a smaller greenhouse gas impact than the non-use system. Using woody mill residuals and WWTP residuals for energy produces a reduction in impact from non-biogenic CO_2 GHGs of more than 98% compared to the non-use systems. Paper recycling residuals also result in significant, but lower, benefits (86.4% reduction in the typical scenario) mainly because these residuals are comprised of a portion of plastic. The previous study of black liquor by NCASI showed emissions of non-biogenic CO_2 GHGs that were lower by 90.5% for a system using black liquor in the kraft recovery system compared to a comparable system based on fossil fuels. The weighted average reduction in non-biogenic CO_2 GHG impact observed in the biomass energy system compared to the non-use system (including woody mill residuals, WWTP residuals, recycling residuals and black liquor) was 93.7% when compared to the non-use systems.

Table ES.2 Life Cycle GHG Emissions (Not Including Biogenic CO_2) over 100 Years: Percent Difference in GHG Impact between the Biomass-Based System and the Comparable Fossil Fuel-Based System Where the Residuals are Disposed

Residual Type	Relative GHGI: Difference in Typical Scenarios (%)
Woody mill residuals	-98.7*
WWTP residuals	-98.7
Paper recycling residuals	-86.4
Spent liquor (incl. black liquor)	-90.5
Weighted average	-93.7

* The results for woody mill residuals are sensitive to the parameter used to characterize the extent to which these residuals decompose in landfills. The results shown here are based on the most conservative (i.e., least decomposition in the landfill) of several parameter values used by EPA for various purposes. Other values used by EPA, based on IPCC guidelines, yield a difference of -99.2%.

ES.4.3 Emissions Timing

While not traditionally considered in LCA studies, the timing of emissions can be an important consideration for certain policy discussion/design contexts. When residuals are burned for energy, the biogenic carbon is immediately released to the atmosphere. In contrast, residuals placed into landfills release carbon over time. This delay is one of the reasons why forest biomass energy systems could initially emit more GHGs than the corresponding fossil fuel systems which dispose of the residuals. In a relatively short period, however, the cumulative radiative forcing associated with emissions from the fossil fuel systems becomes greater than that from the corresponding biomass systems due to the GHGs (including methane) produced by the decaying residuals and the GHG emissions from fossil fuel combustion. An assessment performed to address the timing of benefits produced the results summarized in Table ES.3. The results indicate that, when fossil fuel substitution is considered, it takes from 0 to 1.2 years for the cumulative radiative forcing associated with the biomass energy system to be less than that associated with the non-use system.

Table ES.3 Time for Biomass Energy Systems to Have Lower Cumulative Radiative Forcing from GHG Emissions (Including Biogenic CO_2) Than the Corresponding Non-Use Systems

Residual Type	Break-Even Time: Typical Scenarios (years)
Woody mill residuals	1.2*
WWTP residuals	0
Paper recycling residuals	0
Spent liquor (incl. black liquor)	0
Weighted average	0.5

* The results for woody mill residuals are sensitive to the parameter used to characterize the extent to which these residuals decompose in landfills. The results shown here are based on the most conservative (i.e., least decomposition in the landfill) of several parameter values used by EPA for different purposes. Other values used by EPA, based on IPCC guidelines, yield a break-even time of 0.5 years.

ES.4.4 Fossil Fuel Consumption

Table ES.4 summarizes the results obtained for the Fossil Fuel Consumption indicator. The negative values in this table indicate that the biomass energy systems use less fossil fuel than the corresponding non-use systems. For all residual types analyzed in this report (not including black liquor), considering all system configuration scenarios and sensitivity analyses performed, it was shown that fossil fuel consumption was lower by more than 99% in the biomass energy systems compared to the non-use systems. Note that a previous study by NCASI showed 89.8% lower fossil fuel consumption for a system using black liquor when compared to a scenario based on fossil fuel. The weighted average reduction in fossil fuel consumption observed in the biomass energy system compared to the non-use system (including all residuals and black liquor) was 93.8% when compared to the non-use systems.

Table ES.4 Fossil Fuel Consumption: Percent Difference between the Biomass-Based Systems and the Comparable Fossil Fuel-Based Systems Where the Residuals are Disposed

Residual type	Relative Fossil Fuel Consumption: Difference in Typical Scenarios (%)
Woody mill residuals	-100
WWTP residuals	-99.3
Paper recycling residuals*	-99.9
Spent liquor (incl. black liquor)	-89.8
Weighted average	-93.8

*Considering that the plastic fraction of paper recycling residuals is not a new input of fossil fuel.

ES.5 Results from Additional Analyses

ES.5.1 Analysis of Biogenic GHGs, Ignoring Fossil Fuel Displacement (Gate-to-Gate Analysis)

The results presented above were computed using a life cycle approach that considered the fossil fuels being displaced by biomass residuals. The typical scenarios for the two product systems (one system using residuals for energy and the other system managing the residuals by some other means) have also been compared in terms of the emissions coming directly out of the units receiving the residuals (i.e., combustion units or landfills). In this analysis, the benefits of fossil fuel substitution were ignored.

As shown in Table ES.5, even in this highly constrained analysis, using the biomass residuals for energy generation resulted in lower GHG impact. A previous, similarly constrained analysis on black liquor assumed that the alternative management scenario would involve returning the biogenic carbon in the liquor to the atmosphere. To be conservative, it was assumed in that study that the carbon would return to the atmosphere as CO_2 via incineration or treatment in aerobic wastewater treatment plants. This resulted in net zero biogenic GHG releases for energy production compared to an alternative fate. The reduction in biogenic GHG emissions impact over 100 years associated with the use of all manufacturing residuals (weighted according to usage), including black liquor, was shown to be 4.6 kg CO_2E/GJ. Given current fuel consumption, this means that the annual use of manufacturing residuals (including black liquor) in the industry avoids approximately 5 million tonnes CO_2E.

When the benefits of fossil fuel displacement are ignored, it takes longer for the biomass energy systems to arrive at the point where cumulative radiative forcing is lower than for the corresponding non-use systems. Considering only biogenic emissions, the break-even times ranged from 0 to 19.5 years.

Table ES.5 Results of Analysis of Biogenic GHGs, Ignoring Fossil Fuel Displacement

Residual Type	Differential GHGI (kg CO_2E/GJ)	Break-Even Time (years)
Woody mill residuals	-8.5*	19.5*
WWTP residuals	-190	5.9
Fiber fraction of paper recycling residuals†	-132	7.7
Spent liquor (incl. black liquor)	0	0
Weighted average	-4.6	7.6

* The results for woody mill residuals are very sensitive to the parameter used to characterize the extent to which these residuals decompose in landfills. The results shown here are based on the most conservative (i.e., least decomposition in the landfill) of several parameter values used by EPA for various purposes. Other values used by EPA, based on IPCC guidelines, yield far larger benefits (-187 kg CO_2E/GJ) and far shorter break-even times (6.6 years). † In addition to biomass, paper recycling residuals contain plastics which are produced from fossil fuels. For the purpose of the biomass carbon fate analysis, only the biomass fraction was considered.

ES.5.2 GHG Emissions from Ongoing Use of Residuals for Energy Production

The analysis above examined the impact over time associated with producing 1 GJ of energy on a one-time basis. The practice of burning residuals for energy, however, is a long-standing one in the forest products industry. It is also of interest, therefore, to examine the net impact from using residuals for energy on an ongoing basis. To do this, one can compare two facilities that are identical, except that one burns residuals for energy year after year while the other facility disposes of the residuals and uses fossil fuels for energy instead. Table ES.6 below, based on the typical scenarios used elsewhere in this study, shows the year when ongoing practices would have to have been initiated in order for the facilities using the residuals for energy production to show net benefits, in terms of cumulative radiative forcing, in 2014. The table also contains information on the industry's past use of these materials for energy. In the worst case, the use of woody mill residuals for energy without considering avoided fossil fuel emissions, the practice would have had to have started in the late 1970s in order for the "carbon debt" to be eliminated. In fact, woody mill residuals have been used for energy in the solid wood industry since the 1800s and in the paper industry since the early decades of the 1900s. The evidence is strong, therefore, that any carbon debt that might have been incurred in using manufacturing residuals for energy was eliminated long ago.

Table ES.6 Ongoing Use of Residuals for Energy Production: Comparing Facilities Using Biomass Residuals for Energy with Similar Facilities Using Fossil Fuels for Energy and Disposing of the Residuals

Residual		Year in the Past When Ongoing Practice Would Have Had To Be Initiated for Cumulative Radiative Forcing from the Two Facilities To Be in 2014 (under typical scenario)	Past Industry Practice in Using the Residuals for Energy
Woody mill residuals	With benefits of the displaced fossil fuels	2012*	Wood residuals have been used in saw mills going back to the mid-1800s and in paper mills back to the early decades of the 1900s. AF&PA statistics date to 1971, at which point woody mill residuals represented 7% of the fuel (16% of the biomass) burned at pulp and paper mills.
	Without benefits of the displaced fossil fuels	1979*	
WWTP residuals	With benefits of the displaced fossil fuels	2014	NCASI statistics on WWTP residuals management go back to 1979, at which point 11% of these residuals was being burned for energy.
	Without benefits of the displaced fossil fuels	2004	
Paper recycling residuals	With benefits of the displaced fossil fuels	2014	NCASI has published information showing the use of recycling residuals for energy in 1975.
	Without benefits of the displaced fossil fuels†	2001	
Spent liquor (incl. black liquor)	With benefits of the displaced fossil fuels	2014	The burning of kraft black liquor for energy and chemicals dates to before the 1950s. Based on AF&PA statistics, in 1971, 35% of the fuel (84% of the biomass) burned at pulp and paper mills was black liquor. By 1980, this had increased to 40% of the fuel (79% of the biomass).
	Without benefits of the displaced fossil fuels	2014	

* The results for woody mill residuals are very sensitive to the parameter used to characterize the extent to which these residuals decompose in landfills. The results shown here are based on the most conservative (i.e., least decomposition in the landfill) of several parameter values used by EPA for various purposes. Other values used by EPA, based on IPCC guidelines, yield dates of 2013 and 2003 when the benefits of displaced fossil fuels are included and excluded, respectively.
†Fiber fraction only.

ES.6 Conclusions

In this study, the GHG and fossil fuel-related impacts of using woody manufacturing residuals, recycling residuals, and wastewater treatment plant residuals for energy production within the forest products industry have been analyzed using life cycle principles and other methods. A previous study of the use of black liquor for producing energy and pulping chemicals has also been updated and expanded. It has been shown that using all types of residuals for energy produces benefits both in terms of reduced fossil fuel consumption and reduced greenhouse gas emissions impacts. This result is valid across a range of system configuration scenarios (boiler type, assumptions about the displaced fossil fuel, the GHG intensity of the electricity grid, and the level of cogeneration at forest products facilities), residual characteristics (e.g., heating value, moisture content), and whether or not the

benefits from fossil fuel substitution are considered. These findings hold true whether biogenic CO_2 is included in the analysis or excluded by giving it an emission factor of zero (equivalent to what is sometimes called "carbon neutrality"). The benefits occur without affecting the amount of wood harvested or the amount of wood products produced.

It was shown that it takes from 0 to 1.2 years for the cumulative radiative forcing associated with emissions from the biomass energy system to be lower than that of the corresponding non-use system. Even ignoring the benefits of displacing fossil fuel and limiting the analysis to biogenic emissions, the cumulative radiative forcing impacts associated with emissions from the biomass energy systems are lower than those from the non-use systems in times ranging from 0 years for black liquor, which comprises 57% of the residuals used by the energy for industry, to 19.5 years for woody mill residuals which comprise 37% of that used by the industry.

These results have been developed by comparing the GHG emissions from systems using manufacturing residuals for energy in the forest products industry to the emissions from alternative systems producing the same amount of energy from fossil fuels while disposing of the residuals by landfilling or a combination of landfilling and incineration. In cases where it is assumed that the alternative to burning manufacturing residuals for energy is incineration, the break-even times for all residuals are zero, whether or not fossil fuel substitution is considered. Where the alternative is assumed to be landfilling, results can be very sensitive to assumptions about the degree to which biomass carbon decomposes in landfills, a parameter with large uncertainty.

When considered as an ongoing practice (e.g., ongoing production of 1 GJ energy per year), and when displaced fossil fuels are considered, net benefits from using residuals for energy are observed in less than two years. In the case where the benefits of displacing fossil fuels are ignored, the break-even times are longer. Even in the worst case, however, which is the ongoing use of woody mill residuals for energy without considering fossil fuel substitution, any "carbon debt" would be eliminated if the practice began before the late 1970s. Woody mill residuals have been used for energy in solid wood manufacturing since the 1800s and in paper mills since the early decades of the 1900s, providing strong evidence that any carbon debt incurred in the past from using manufacturing residuals for energy in the forest products industry was eliminated many years ago.

The GHG emissions reduction benefits of using manufacturing residuals for energy in the forest products industry are large. Given current fuel consumption, the use of manufacturing residuals (including black liquor) in the industry for one year avoids an emissions impact of approximately 181 million tonnes CO_2E, equal to approximately three times the annual direct emissions associated with the combustion of fossil fuels in the forest products industry.

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GREENHOUSE GAS AND FOSSIL FUEL REDUCTION BENEFITS OF USING BIOMASS MANUFACTURING RESIDUALS FOR ENERGY PRODUCTION IN FOREST PRODUCTS FACILITIES

1.0 INTRODUCTION AND BACKGROUND

1.1 Background

The use of wood for energy has attracted considerable attention as a greenhouse gas mitigation option (FAO 2008). The United States (US) and Canada are among the largest OECD[4] users of wood for industrial bioenergy, primarily from indirect sources including black liquor and other manufacturing residuals (FAO 2008, Steierer 2007). Wood harvesting and handling, as well as processing activities in log yards, pulp and paper mills, sawmills, and other forest products activities produce a significant amount of residuals, most of which consist of bark, sawdust, shavings, and harvest residuals and other woody debris. These residuals are increasingly being used as a source of renewable energy. Often, however, the residuals that are not beneficially used are either incinerated or placed in a municipal or on-site industrial landfill.

Recent years have seen a rise in both the interest in substituting biomass for fossil fuels and in the skepticism about the greenhouse gas (GHG) benefits of this substitution. While programs that promote the use of biomass as a substitute for fossil fuel have important connections to the issues of energy security and economic sustainability, it is the questions about greenhouse gas mitigation benefits that have been at the center of the debate on whether and how to increase the reliance on the use of biomass for energy.

An important distinction between biomass carbon (also known as biogenic carbon) and the carbon in fossil fuels is that biogenic carbon was only recently removed from the atmosphere. When biomass is burned, decays, or is otherwise oxidized, the resulting CO_2 is returned to the atmosphere. The net transfers of biogenic carbon to the atmosphere can be zero if the uptake of carbon (in CO_2) by growing trees is equivalent to the biogenic carbon released in the combustion and decay of biomass (sometimes referred to as representing "carbon neutrality"). Where the amounts of biogenic CO_2 that return to the atmosphere are less than the amounts removed, the difference represents increases in stocks of stored carbon (net removals from the atmosphere). Where net returns are greater than the amounts removed, the difference represents depleted stocks of stored carbon.

The net transfers of biogenic CO_2 to the atmosphere associated with the production and use of biomass can be used to characterize the GHG emissions associated with a biomass energy system, often called the "carbon footprint" of the system. Understanding the impacts of using biomass for energy, however, requires a different analytical framework than used for a carbon footprint. In studying the impacts of using biomass for energy, one must consider how that energy might be produced if biomass was not used and the fate of the biomass if not used for energy. In this study, the objective was to understand the impacts of using biomass for energy so the life cycle emissions from a system using biomass for energy are compared to the life cycle emissions from alternative systems where the biomass undergoes an alternative fate and fossil fuels are used to produce an equivalent amount of energy.

[4] Organisation for Economic Co-operation and Development.

1.2 Review of LCA Studies

In recent years, there has been a rapidly increasing number of life cycle assessment (LCA) studies of woody biomass residual energy systems. Table 1.1 provides an overview of the main studies recently published that compared woody biomass residual energy systems with fossil fuel-based energy systems and focused on direct energy production from the residuals, not including studies looking at liquid biofuels. Only studies published in the peer-reviewed literature are presented in this table. The overview does not purport to be exhaustive.

It can be seen from Table 1.1 that these studies have mainly focused on electricity generation and direct heating and that, in cases where the authors looked at the use of woody biomass residuals by forest products facilities (e.g., sawmills), they typically did not consider alternative fates for the residuals. It is also interesting to note that there are very few studies covering other manufacturing residuals from the forest products industry, such as wastewater treatment residuals and paper recycling residuals, and their use for energy production.

In addition, while not traditionally considered in typical LCA studies, the timing of emissions may be an important consideration for certain policy discussion/design contexts. When residuals are burned for energy, the biogenic carbon is immediately released to the atmosphere. In contrast, residuals placed into landfills or left on forest sites degrade slowly, releasing carbon over time. In these cases, the emissions from burning biomass for energy could be higher in the short term than those associated with disposing of the biomass, but this is generally compensated for relatively quickly by the benefits from fossil fuel substitution or benefits from avoiding the disposal emissions of the biomass residuals.

Table 1.1 Published Studies Regarding Life Cycle GHG Mitigation Benefits for Biomass Residuals Energy Systems

Study	Biomass Type	Fossil Fuel Offset	Type of Facility in Which the Biofuel Is Used	Alternative Fate Considered	GHG Mitigation*	Break-Even Time
Boman and Turnbull (1997)	Agricultural residuals, energy crops, forest harvest residuals and sawmill residuals	Coal (power)	US power plants/pulp mill	Not considered	> 90%	Not applicable
Mann and Spath (2001)	Various woody residuals	Coal (power, cofiring)	US power plants	46% landfilling, 54% mulch or conversion to short-lived products	123%†	Not available
Robinson et al. (2003)	Forest harvest and agriculture residuals	Coal (power, cofiring)	US power plants	Not considered	≈ 95%	Not applicable
Wihersaari (2005)	Forest harvest residuals	Coal, peat	Finnish power plant	Decomposition in forest	> 75%	Not available
Pehnt (2006)	Forest harvest residuals, woody biomass energy crops, waste wood	German energy mix (power, home heating)	German power plants and homes	Not considered	85-95%	Not applicable
Petersen Raymer (2006)	Fuel wood, sawdust, wood pellets, demolition wood, briquettes, bark	Coal (power, cofiring) and oil (home heating)	Power plants (imports to Norway), Norwegian homes, sawmills, large combustion facilities	Not considered	81-98%	Not applicable
Kirkinen et al. (2008)	Forest harvest residuals (other biomasses not considered here)	Coal, natural gas	Finnish energy sector	Decomposition in forest	Not available	< 20 years‡
Cherubini et al. (2009)	Forest harvest residuals	Various fossil fuels used for heat, power and CHP	Various	Unknown	70-98%	Not applicable

(Continued on next page. See notes at end of table.)

Table 1.1 (Cont'd)

Study	Biomass Type	Fossil Fuel Offset	Type of Facility in Which the Biofuel Is Used	Alternative Fate Considered	GHG Mitigation*	Break-Even Time
Froese et al. (2010)	Forest harvest residuals	Coal (power, cofiring)	US Great Lakes region power plants	Not considered	100%	Not applicable
Jones et al. (2010)	Forest harvest residuals	Natural gas, distillate oil (heat)	Unspecified	Burn at landing	≈ 40-50%‡	Not applicable
Puettmann and Lippke (2012)	Sawmill biomass residuals, pellets, forest harvest residuals	Natural gas (heat, power)	US sawmills	Not considered	57-66%§	Not applicable
Repo et al. (2012)	Forest harvest residuals	Coal, heavy oil, natural gas	Unspecified Finnish facility	Decomposition in forest	29-81%**	< 100 years
Ruhul Kabir and Kumar (2012)	Agricultural residuals, forest harvest residuals	Coal (power, cofiring)	Canadian power plants	Not considered	74-88%*	Not applicable
Zanchi et al. (2012)	Forest harvest residuals	Coal, oil, natural gas	Austrian power plants	Decomposition in forest	76-85%**	0 - 16 years
Gaudreault et al. (2012)	Black liquor	Coal, natural gas (heat and power); US electricity grid	US pulp and paper mills	Biogenic carbon released into CO_2	69-92%	Not applicable

*Percent for full substitution; for cofiring situations the mitigation pertains to the cofire rate (e.g., if 10% fossil fuel is replaced by biomass and emissions decrease by 9%, mitigation of 90% is assigned); includes all GHGs excluding biogenic CO_2. † Mitigation greater than 100% due to avoided end-of-life methane emissions. ‡Estimated. §One of the reasons why Puettmann and Lippke obtained lower mitigation results than other authors for manufacturing residuals is that they allocated a fraction of the load from manufacturing to the residuals. **Values at 100 years.

2.0 STUDY OBJECTIVES

The main objective of this study was to evaluate the life cycle (cradle-to-final energy analysis) greenhouse gas impact (GHGI) and fossil fuel reduction benefits of using various forms of forest biomass residuals (manufacturing-related) for energy production in forest products manufacturing facilities in contrast to no beneficial use of these residuals coupled with production of the same quantity and form of energy using fossil fuels. The total 100-year and yearly impacts were investigated.

The study also included two secondary objectives: 1) to analyze the greenhouse gas impact from the emissions of biogenic GHGs released from the units in which the residuals are managed (i.e., combustion units or landfills, gate-to-gate analysis); and 2) to analyze the cumulative greenhouse gas

impact associated with the net emissions attributable to the use of the residuals for energy as an ongoing, long-standing, practice (both in terms of cradle-to-final energy and gate-to-gate boundaries).

The biomass residuals studied in this project were

- woody mill residuals (e.g., bark, sawdust, and other similar manufacturing woody residuals from sawmills, panel plants, and pulp and paper mills);
- wastewater treatment plant (WWTP) residuals; and
- paper recycling residuals (e.g., old corrugated container (OCC) rejects)[5].

For each type of residuals, the study compared a base case of no beneficial use of residuals (including their alternative fates) with 100% use for energy generation. Note that whether or not these residuals are used for energy production, the same number of trees would be harvested and the same quantity of resources would still be required to produce the related forest products. In addition to heat production, the study also included combined heat and power (CHP) as a second option for using the residuals. Other options for processing or using the wood residuals (e.g., torrefaction, gasification, hydrolysis and fermentation, other beneficial uses) were not analyzed.

3.0 INTENDED APPLICATION AND TARGETED AUDIENCE

The intended application is to inform the discussion and development of policies that require an understanding of the impacts of using biomass-based manufacturing residuals for energy at forest products manufacturing facilities. The targeted audience of this report is individuals interested in understanding these impacts.

4.0 METHODS

4.1 Cradle-to-Final Energy Analysis

4.1.1 Overview Methodology Employed

Life Cycle Assessment (LCA) is the *"compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle,"* the life cycle being *"consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal"* (ISO 2006a, p. 2).

LCA principles and methodology are framed by a set of standards (ISO 2006a, b) and technical reports and specifications (ISO 2002, 2012a, b) from the International Organization for Standardization (ISO). ISO describes LCA methodology in four phases:

1) **Goal and scope definition,** in which the aim of the study, the product system under study, its function and functional unit, the intended audience, and the methodological details on how the study will be performed are defined;
2) **Life cycle inventory analysis (LCI),** which is the *"phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle"*(ISO 2006a, p. 2);

[5] Paper recycling residuals are materials removed during processing to eliminate contaminants and yield reusable fiber.

3) **Life cycle impact assessment (LCIA),** which is the "phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product" (ISO 2006a, p. 2); and
4) **Life cycle interpretation,** which is the *"phase of life cycle assessment in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations"* (ISO 2006a, p. 2).

This study

- used widely accepted LCA concepts, such as those described in LCA ISO standards 14040 and 14044 (International Organization for Standardization (ISO) 2006a, b);
- was built on the approaches by others [e.g., US Environmental Protection Agency (EPA), Consortium for Research on Renewable Materials (CORRIM)];
- was based on known and established competitive materials and alternative fates for biomass residuals; and
- did not consider any "export" of the residuals outside the forest products industry (e.g., to utilities).

More specifically, the methodology used in this study followed life cycle principles, by calculating emissions from "cradle to final energy" including fuel conversion efficiency. However, a simplified (streamlined) LCA methodology was applied. Streamlining generally can be accomplished by limiting the scope of the study or simplifying the modeling procedures, thereby limiting the amount of data or information needed for the assessment (Todd and Curran 1999). Many different streamlining approaches can be applied. In this study, two main approaches were taken: limiting the impact assessment to two indicators (global warming, fossil fuel consumption) and using generic information for the most part. Because of this, this study does not fully comply with ISO 14044 requirements for comparative assertions disclosed publicly. However, the study aligns as much as possible with this standard.

4.1.2 Functions and Functional Units

In this study, the primary functional unit was ***the production of 1 GJ of energy.*** The product systems being compared also fulfilled an additional implicit function, which is the management of the quantity of residuals required to produce 1 GJ of energy. This is further discussed in Section 4.1.4.

4.1.3 Scenario and Sensitivity Analyses

The overall analysis approach employed in this study is depicted in Figure 4.1. First, for each system component of the study (size reduction, biomass energy production, alternative fates of the residuals and fossil fuel displaced), possible scenarios were defined. These scenarios were intended to represent a broad range of conditions in the US forest products industry.

Then, a typical scenario was established for each residual type as the best estimate for representing average conditions in the US in terms of the different system components mentioned above. The typical scenario was analyzed to determine typical benefits obtained by using a given residual type, the contribution of each different system component to the overall results, the sensitivity of various parameters (e.g., higher heating value, water content, etc.) to the results, and the effect of time on the results. Where possible, each parameter was analyzed using a base case, low, and high value, and the base case values were derived from EPA. Perturbation analyses were also performed. The general idea behind perturbation analyses is that perturbations of the input parameters propagate as smaller or

larger deviations to the resulting output (Heijungs and Kleijn 2001). The objectives of perturbation analyses are to provide 1) a list of those input parameters for which a small imprecision already leads to important changes in the results, and 2) interesting suggestions for improving the environmental performance of the system. For each parameter tested in sensitivity analysis, a perturbation analysis was also performed and a sensitivity ratio was calculated as outlined below.

Sensitivity ratio = Percent change in output variable/Percent change in input variable

The input variable is the parameter tested in sensitivity analysis while the output variable is a given environmental indicator (see more detail in Section 4.1.6). For instance, a sensitivity ratio of +1.0 means that the score of the environmental indicator increases by 1% when the parameter value is increased by 1%. The more negative an environmental indicator score, the better the performance of the biomass energy system compared to the non-use system. The more positive or the more negative a sensitivity ratio is, the more sensitive a parameter is.

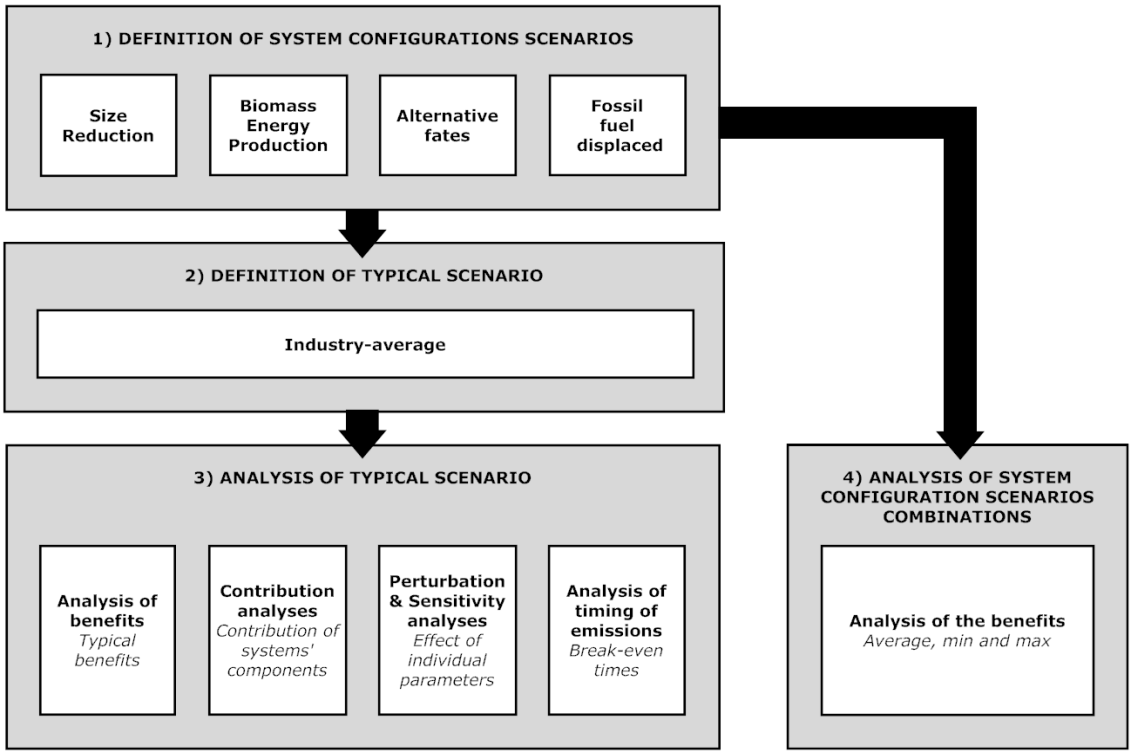


Figure 4.1 Study Overall Approach for the Life Cycle Based Analyses

4.1.4 Product Systems Studied, System Boundaries, and Allocation

For each type of residual, the study compared a base case of no beneficial use of residuals (while accounting for their alternative fate) with 100% use for energy generation. The different product systems studied and compared in this study are discussed next. The general approach was to include within the system boundary only the processes that were different between the biomass and non-use systems.

4.1.4.1 Woody Mill Residuals

Major sources of manufacturing residuals include sawmills, panel plants, and pulp and paper mills. These residuals consist primarily of bark and fine residuals (e.g., sawdust, planer shavings, sanderdust). In this study, all woody mill residuals were considered as a whole, in a single analysis. Sensitivity analyses were performed to encompass the variability in residual types (see Section 5.1).

Figure 4.2 illustrates the two product systems that were compared in the case of woody mill residuals.

1) **Biomass Energy System:** Production of 1 GJ of energy (heat or combined heat and power) using manufacturing residuals.
2) **Non-Use System:** Production of 1 GJ of energy (in the same form as in #1) using fossil fuels and alternative fate of the residuals.

Figure 4.2 also shows that the accounting started with the manufacturing-related biomass residuals and ended at the point at which the energy has been generated. All of these materials would be generated whether or not they would be used for energy generation, and thus there should be no effects on upstream processes attributable to the use of the materials for energy. Therefore, upstream emissions from the production of these materials were assumed to be the same for both systems and they were not included in the analysis.

In some cases, size reduction of manufacturing residuals is required. As depicted in Figure 4.2, three scenarios were considered regarding size reduction (SR0: no size reduction, SR1: size reduction in mobile chipper, and SR2: size reduction in stationary chipper). These processes, as well as any related upstream emissions, were included in the system boundary of the biomass energy system only as they were considered to be unnecessary in the non-use system. The system boundary of the biomass energy system also included the processes required to produce the energy at forest products facilities. Five system configuration scenarios were considered: heat production only in a stoker boiler (SB), heat production only in a fluidized bed boiler (FB), and three levels of combined heat and power (CHP1, CHP2, and CHP3) in which the heat is produced in a stoker boiler.

The non-use system included the upstream emissions for producing the fossil fuel and the energy production processes at forest products facilities or utilities. The energy produced was set to be in the same form as in the biomass energy system. Figure 4.2 shows the different system configurations that were analyzed regarding energy production in the non-use system. It was assumed that heat could be produced in forest products facilities using either coal (A) or natural gas (B). Electricity production at utilities (see Section 5.1) was assumed to be represented by the US average grid (C), coal (D), or natural gas combined cycle (E). When using woody mill residuals to produce 1 GJ of energy, an implicit secondary function is accomplished: the management of the quantity of residuals necessary to produce 1 GJ of energy (Q_R). For the two compared systems to be equivalent, it was necessary to expand the boundary of the non-use system to account for an alternative fate for these residuals. Figure 4.2 shows the two scenarios that were considered for the alternative fate of residuals in the non-use systems: 1) placed in landfills (MR1), and 2) incinerated without recovering the energy

(MR2). The typical scenario definition and rationale, and more details on the various unit processes involved in both systems, are provided in Section 5.1.

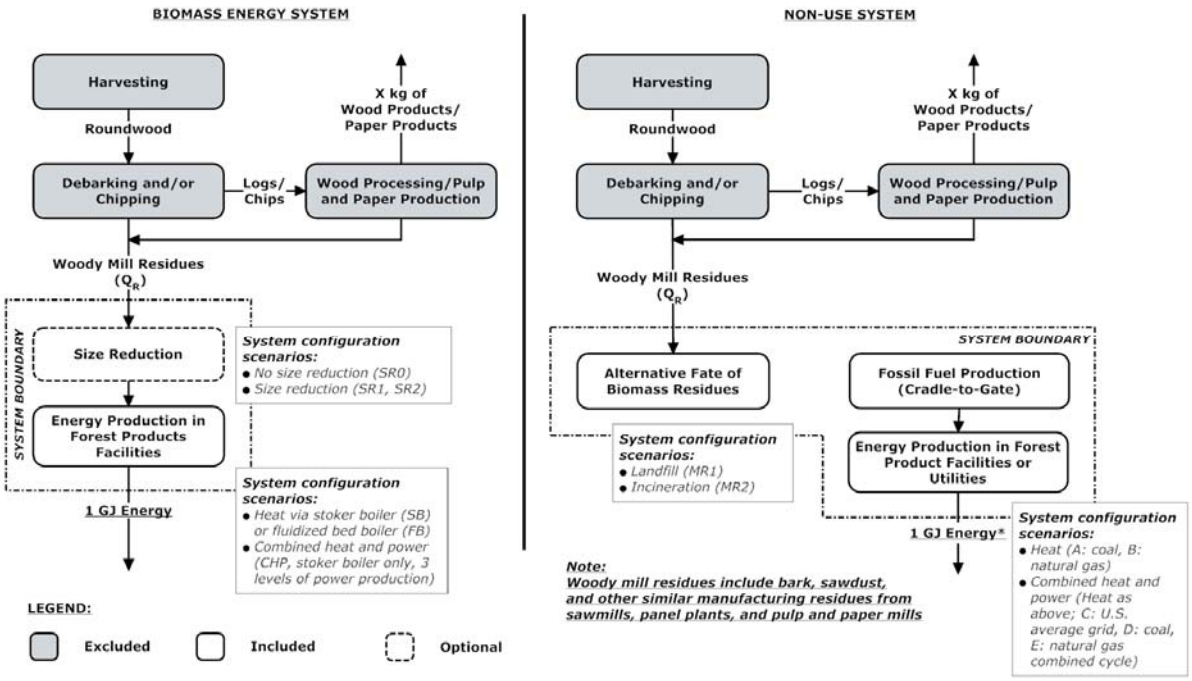


Figure 4.2 Compared Product Systems for Woody Mill Residuals

*4.1.4.2 **WWTP Residuals***

Another manufacturing residual that was included in the study is wastewater treatment plant (WWTP) residuals. Figure 4.3 illustrates the two systems that were compared for WWTP residuals.

1) **Biomass Energy System:** Production of 1 GJ of energy (heat, power or combined heat and power) using the WWTP residuals; and
2) **Non-use System:** Production of 1 GJ of energy (in the same form as in #1) using fossil fuels and alternative fate of the WWTP residuals.

Figure 4.3 also shows that the accounting started with the WWTP residuals and ended at the point at which the energy has been generated. WWTP residuals would be generated whether or not they are used for energy generation, and thus there should be no effects on upstream processes attributable to the use of these materials for producing energy. Therefore, upstream emissions from the production of these materials were assumed to be the same for both systems and they were not included in the analysis. It was also assumed that mechanical dewatering would be required whether the residuals would be used for energy generation or disposed of, and hence was not included in the study.

The system boundary of the biomass energy system included the processes required to produce the energy at forest products facilities. Four system configuration scenarios were considered: heat production only in a stoker boiler (SB), and three levels of combined heat and power (CHP1, CHP2, and CHP3) in which the heat is produced in a stoker boiler.

The non-use system included the upstream emissions for producing the fossil fuel and the energy production processes at forest products facilities or utilities. Figure 4.3 shows the different system

configurations that were analyzed. It was assumed that heat could be produced in forest products facilities using either coal (A) or natural gas (B). Electricity production at utilities (see Section 5.1) was assumed to be represented by the US average grid (C), coal (D), or natural gas combined cycle (E). When using WWTP residuals to produce 1 GJ of energy, an implicit secondary function is accomplished: the management of the quantity of residuals necessary to produce 1 GJ of energy (Q_R). For the two compared systems to be equivalent, it was necessary to expand the boundary of the non-use system to account for an alternative fate for these residuals. Figure 4.3 shows the two scenarios that were considered for the alternative fate of residuals in the non-use systems: 1) placed in landfills (MR1), and 2) incinerated without recovering the energy (MR2). The non-use system included the upstream emissions for producing the fossil fuel and the energy production processes at forest products facilities or utilities. The typical scenario definition and rationale, and more details on the various unit processes involved in both systems, are provided in Section 5.1.

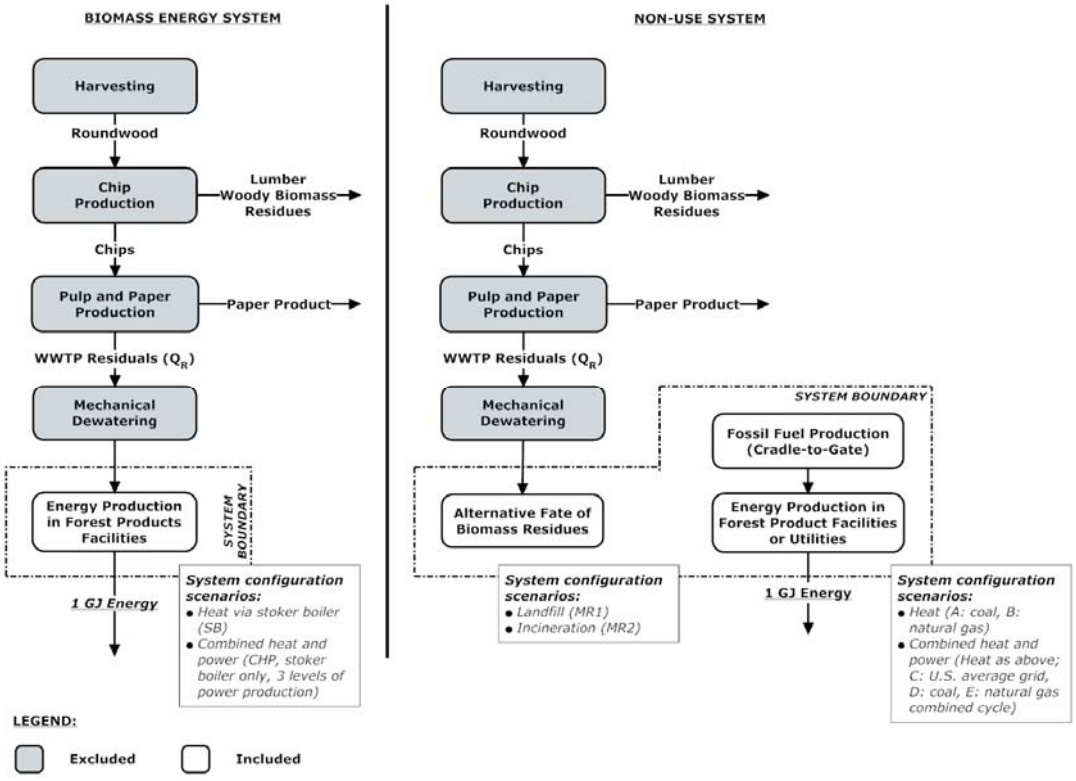


Figure 4.3 Compared Product Systems for WWTP Residuals

4.1.4.3 ***Paper Recycling Residuals***

The last manufacturing residual that was included in the study is paper recycling residuals, and more specifically old corrugated container (OCC) rejects. Figure 4.4 illustrates the two systems that were compared for paper recycling residuals.

1) **Biomass Energy System:** Production of 1 GJ of energy (heat, power or combined heat and power) using the paper recycling residuals.
2) **Non-Use System:** Production of 1 GJ of energy (in the same form as in #1) using fossil fuels and alternative fate of the paper recycling residuals.

Figure 4.4 also shows that the accounting started with the paper recycling residuals and ended at the point at which the energy has been generated. Paper recycling residuals would be generated whether

or not they would be used for energy generation, and thus there should be no effects on upstream processes attributable to the use of the materials for energy. Therefore, upstream emissions from the production of these materials were assumed to be the same for both systems and they were not included in the analysis.

The system boundary of the biomass energy system included the processes required to produce the energy at forest products facilities. Four system configuration scenarios were considered: heat production only in a stoker boiler (SB), and three levels of combined heat and power (CHP1, CHP2, and CHP3) in which the heat is produced in a stoker boiler.

The non-use system included the upstream emissions for producing the fossil fuel and the energy production processes at forest products facilities or utilities. Figure 4.4 shows the different system configurations that were analyzed. It was assumed that heat could be produced in forest products facilities using either coal (A) or natural gas (B). Electricity production at utilities (see Section 5.1) was assumed to be represented by the US average grid (C), coal (D), or natural gas combined cycle (E). When using paper recycling residuals to produce 1 GJ of energy, an implicit secondary function is accomplished: the management of the quantity of residuals necessary to produce 1 GJ of energy (Q_R). For the two compared systems to be equivalent, it was necessary to expand the boundary of the non-use system to account for an alternative fate for these residuals. Figure 4.4 shows the two scenarios that were considered for the alternative fate of residuals in the non-use systems: 1) placed in landfills (MR1), and 2) incinerated without recovering the energy (MR2). The non-use system included the upstream emissions for producing the fossil fuel and the energy production processes at forest products facilities or utilities. The typical scenario definition and rationale, and more details on the various unit processes involved in both systems, are provided in Section 5.1.

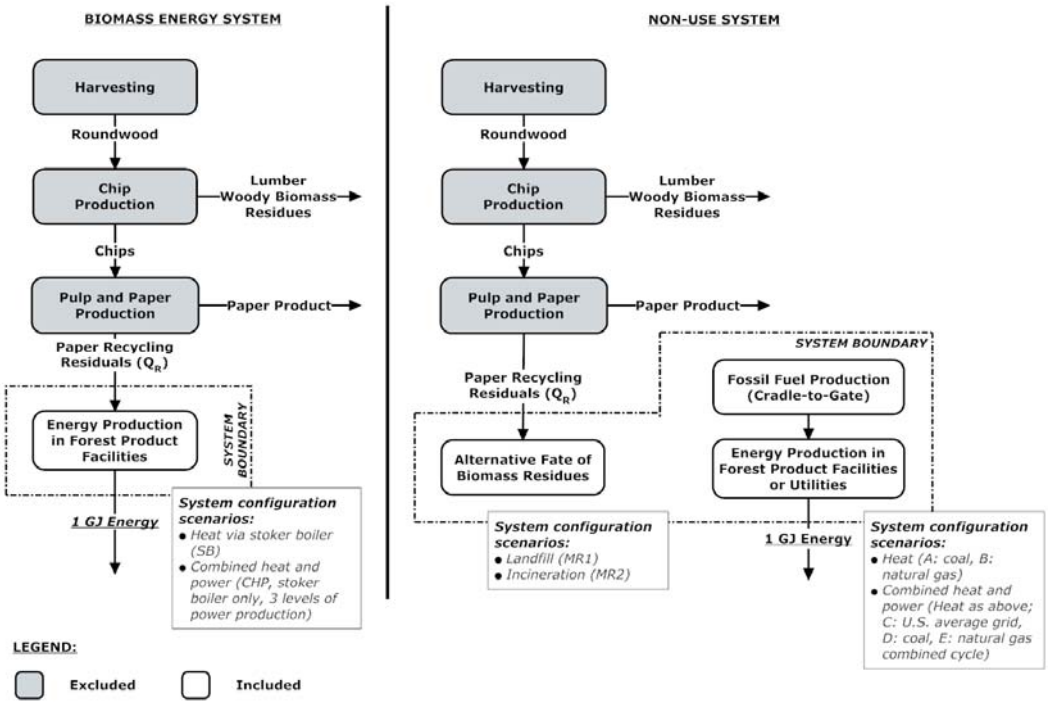


Figure 4.4 Compared Product Systems for Paper Recycling Residuals

4.1.5 Exclusions and Cut-Off Criteria

For each of the groups described above, the following components of each product system were not included in this study: manufacture of capital equipment, human activities, and unit processes common to the systems compared.

All required data were available. No cut-offs were applied.

4.1.6 Environmental Indicators Analyzed

Two main environmental aspects were studied in this study: greenhouse gases (GHGs) and fossil fuel consumption.

Note that in LCA studies, environmental indicator results are relative expressions and do not predict impacts on category endpoints, nor the exceeding of thresholds, safety margins, or risks.

4.1.6.1 Greenhouse Gas Impact (GHGI)

In this report, the term "greenhouse gas impact" is used to describe the cumulative radiative forcing over a period of time that is attributable to emissions of greenhouse gases. Various approaches can be used to calculate the greenhouse gas impact. The most common approach is to use the 100-year global warming potentials (GWPs) published by the Intergovernmental Panel on Climate Change (IPCC 2006a). The 100-year global warming potentials calculated by IPCC represent the cumulative radiative forcing over 100 years attributable to a pulse release of a GHG relative to the forcing attributable to a pulse release of the same mass of CO_2. Using this approach, the 100-year greenhouse impact is assumed to occur the same year as the pulse emission. The results are typically expressed as kilograms of CO_2 equivalents (kg CO_2E). GWPs are useful in developing GHG inventories in a way that allows the impacts associated with different types of emissions to be compared over 100 years, or some other period. IPCC has published GWPs for periods of 20, 100, and 500 years. In this study, the timing of impacts was of particular interest, which required a dynamic calculation of cumulative radiative forcing as a function of time. To accomplish this, a dynamic carbon footprinting approach developed by Levasseur (2013) and Levasseur et al. (2010) was used. This approach produces time-dependent global warming results based on the cumulative radiative forcing concept. The same scientific models are used in the dynamic carbon footprinting approach as used by IPCC to develop global warming potentials but the equations are integrated continuously over time with the exception of one element (see below). Although the results are typically expressed in units of radiative forcing (Wm^{-2}), they can also be presented in terms of kg CO_2E, especially if the objective is to compare the results to those obtained using GWPs. Approaches similar to the approach proposed by Levasseur et al. (2010) have been used elsewhere (e.g., Alvarez et al. 2012).

A difference between the dynamic approach proposed by Levasseur et al. (2010) and IPCC's scientific models was mentioned above. The approach proposed by Levasseur et al. includes the radiative forcing associated with CO_2 formed when methane decomposes in the atmosphere while IPCC's GWPs for methane do not (IPCC 2007, Chapter 2, paragraph 2.10.3). Because this study is attempting to identify the difference in total impacts between systems over time, it is appropriate to include the radiative forcing associated with CO_2 produced from the decomposition of methane in the atmosphere. Simulations performed by NCASI comparing the method of Levasseur et al. to IPCC global warming potentials indicate that the effect of this difference on results is relatively small over periods of interest in this study (i.e., 100 years and less). Table 4.1 shows the results of applying the dynamic approach compared to 100-year global warming potentials from IPCC (IPCC 2006a). The results using both approaches are also shown in several places in this report.

Table 4.1 Comparison of IPCC GWPs to Results Obtained Using the Dynamic Carbon Footprint Calculator by Levasseur et al.

GHG	20-Year		100-year		500-year	
	IPCC GWPs	**Dynamic Calculator**	**IPCC GWPs**	**Dynamic Calculator**	**IPCC GWPs**	**Dynamic Calculator**
Methane	72	72.9	25	27.5	7.6	10.3
Nitrous Oxide	289	289	298	298	153	153

In this study, the results for the GHGI indicator have been computed in three different ways, both for the IPCC 100-year GWPs and using the dynamic calculator.

First, the absolute difference in impact attributable to releases of GHGs over 100 years, including biogenic CO_2 emissions and removals[6] was used to calculate the results of the greenhouse gas impact indicator ("Differential GHGI") as follows:

Differential GHGI (kg CO_2E/GJ) = Total greenhouse gas impact caused by GHG releases, including biogenic CO_2 emissions and removals, for energy production using residuals – Total greenhouse gas impact of GHG releases, including biogenic CO_2 emissions and removals, for energy production using fossil fuels, including alternative fate of residuals,

or in a shorter form,

$$\textit{Differential GHGI (kg } CO_2E/GJ) = [\textit{Total GHGI}^r]_{\textit{Biomass system}} - [\textit{Total GHGI}]_{\textit{Non-use system}}$$

Second, the greenhouse gases impact was computed using the percent difference in radiative forcing or GHGI impact calculated using IPCC GWPs attributable to GHGs released over 100 years, not including biogenic CO_2 ($BioCO_2$), of the biomass energy system compared to the non-use system ("Relative Non-$BioCO_2$ GHGI") as follows:

Relative Non-$BioCO_2$ GHGI (%) = (greenhouse gas impact caused by GHG releases, not including biogenic CO_2, for energy production using residuals – greenhouse gas impact caused by GHG releases, not including biogenic CO_2, for energy production using fossil fuels, including alternative fate of residuals)/(greenhouse gas impact caused by GHG releases, not including biogenic CO_2, for energy production using fossil fuels, including alternative fate of residuals),

or in a shorter form,

$$\textit{Relative Non-}BioCO_2\textit{ GHGI (\%)} = [(\textit{GHGI, excl. } BioCO_2)_{\textit{Biomass energy system}} - (\textit{GHGI, excl. } BioCO_2)_{\textit{Non-use system}}]/ (\textit{GHGI, excl. } BioCO_2)_{\textit{Non-use system}}$$

[6] As described in Figures 4.2 to 4.4, the system boundary for the product systems did not include harvesting and forest-related activities because they are the same in the biomass and non-use systems. This means that the associated forest-related CO_2 removals, i.e., the sequestration or absorption of CO_2 from the atmosphere by the trees, were not included in this study.

[7] In this report, "Total GHG releases" is used as a short form for the sum of non-biogenic CO_2 GHGs and biogenic CO_2 GHGs.

Third, while not traditionally considered in typical LCA studies, the timing of emissions and of greenhouse gas impact may be an important consideration for certain policy discussion/design contexts. For instance, in the context of this study, timing may be important in cases where the alternative to using residuals is allowing them to decay in waste disposal sites. Therefore, this study examined the life cycle implications of using biomass residuals for energy as a function of time. For each residual, the study computed the number of years it would take for the cumulative greenhouse gas impact from the two systems to be equal (break-even time). After this time, the cumulative greenhouse gas impacts from the biomass systems remain lower than that from the non-use system for remainder of the 100-year period of study. While the Differential GHGI results are presented in terms of kg CO_2E to facilitate comparison with using the 100-year IPCC GWPs, the yearly differential impact is presented in terms of radiative forcing because the graphical results are much easier to interpret when presented in terms of radiative forcing units (Wm^{-2}).

Notes:

- The materials being examined are biomass residuals. Their use was assumed to have no effect on carbon in growing biomass or gross removals of carbon from the atmosphere by the forest.
- Carbon in products-in-use was not modeled in this study because the fate of carbon in products is not affected by the fate of the residuals.

4.1.6.2 Fossil Fuel Consumption

Fossil fuel used in the life cycle of each of the product systems studied was computed. The relative fossil fuel consumption ("Relative FF CON") was calculated as follows:

Relative FF CON (%) = (fossil fuel consumption score for energy production using residuals – fossil fuel consumption score for energy production using fossil fuels, including alternative fate of residuals)/(fossil fuel consumption score for energy production using fossil fuels, including alternative fate of residuals)

Fossil fuel consumption indicators are not based on an impact assessment model but rather on a quantification of the energy inputs to the studied product system. The cumulative energy demand method (Hischier and Weidema 2009) was used to quantify fossil fuel consumption because it is the most consistent with the life cycle inventory database used in this study. This method uses higher heating values in an attempt to characterize the total amount of energy consumed rather than only the energy directly used within the system being studied. The cumulative energy demand method tracks energy from the point of extraction.

Note: In this report, when a percent reduction is discussed, it is compared to the non-use system as defined in this study, unless otherwise mentioned.

4.1.7 Temporal Boundary

The temporal boundary describes the time horizon within which the results of the LCA are analyzed. The temporal boundary applies to inventory data and to the impact assessment. In this study, a temporal boundary of 100 years was selected because anything beyond that was judged to be too uncertain in relation to the goal of the study. This means that emissions were considered within 100 years after the residuals are used for energy or discarded. The greenhouse gas impact was also analyzed within this same 100-year time frame. When using IPCC GWPs, the greenhouse gas impact of an emission over 100 years is assumed to occur in the same year as the emissions. As a result, when using 100-year GWPs to study systems where emissions occur over time, some of the impacts associated with emissions occurring after year 1 actually occur after the 100-year period is ended.

4.2 Methodology for Additional Analyses

In addition to the life cycle analyses described above, the study also included two secondary analyses: a gate-to-gate analysis of the fate of biomass carbon, and one of the GHG emissions from the ongoing use of residuals for energy production.

4.2.1 Gate-to-Gate Analysis of Biogenic GHGs

The gate-to-gate analysis consisted of a more constrained analysis of the emissions of biogenic GHGs (mainly CO_2, CH_4, and N_2O) in isolation from any fossil fuel substitution benefits. In this analysis, the two compared systems (the biomass energy system and the non-use system) have been compared in terms of the emissions coming directly out of the units receiving the residuals (combustion units or landfills). In the case of paper recycling residuals, only their fiber fraction was considered because the focus here was on the fate of the biomass carbon. In this analysis, the system boundary for the various product systems was limited to the units receiving the residuals (i.e., "Energy Production in Forest Products Facilities" and "Alternative Fate of Biomass Residuals" in Figure 4.2 to Figure 4.4). The results were computed for two indicators described previously: differential GHGI and break-even times. A temporal boundary of 100 years was also used for that analysis.

4.2.2 GHG Emissions from Ongoing Use of Residuals for Energy Production

The analyses presented above focused on the one-time production of 1 GJ of energy (the functional unit) and looked forward in time to estimate the number of years it will take before the emissions impact attributable to the one-time use of biomass for energy is less than the emissions impact from a comparable system that disposes of the residuals. The practice of burning residuals for energy, however, is a long-standing one in the forest products industry. Therefore, it was also of interest to examine the net greenhouse gas impact over time attributable to the use of manufacturing residuals for energy on an ongoing basis. To look at the greenhouse gas impact from the ongoing use of biomass for energy production, a different functional unit is required. The functional unit used to assess emissions from ongoing practice is ***"the yearly production of 1 GJ of energy using biomass residuals as an ongoing practice."***

The definition of the temporal boundary is slightly different when analyzing the emissions attributable to ongoing practice. In fact, the time it takes for the cumulative greenhouse gas impact from a facility using residuals for energy on an ongoing basis to equal the cumulative greenhouse gas impact of a facility disposing of those residuals needs to be considered.

Data from AF&PA and NCASI were used to document the forest product industry's practices related to the use of biomass residuals for energy production.

4.3 Summary of Data Sources

North American data were used where possible and data gaps were filled using European data. The main data sources are summarized in Table 4.2.

Table 4.2 Data Sources

Process	Data Source
Direct combustion of wood residuals	NCASI, USEPA emission factors, literature
Direct combustion of WWTP residuals	Literature, NCASI
Combined heat and power from direct combustion	NCASI data
Landfilling	USEPA, IPCC, NCASI
Production of energy using fossil fuels	US-EI Database* (EarthShift 2009) modified to US 2010 power grid
Transportation distances	US Census 2002 (United States Department of Transportation and United States Department of Commerce 2004)
Transportation processes	US-EI Database (EarthShift 2009)

* The US-EI database (EarthShift 2009) bridges the current gap in the US LCI database (National Renewable Energy Laboratory 2008) and applies US electrical conditions to the ecoinvent database (ecoinvent Centre 2010). The database includes modified processes for the 423 processes contained in the US LCI database (version 1.6) and for the 3,974 unit processes contained in the ecoinvent database (version 2.2). Specifically, for the US LCI Database, most dummy processes (processes for which no life cycle information was available) were replaced with ecoinvent proxies using US electricity. Some of the dummy processes were not replaced if they were not available in the ecoinvent data set. For the ecoinvent data set, all processes using electricity from Switzerland or one of the European regions (RER, UCTE, CENTREL or NORDEL) were indirectly adapted to instead use US electricity. This was done by rerouting data for electricity production/distribution to data for US electricity production/distribution. NCASI also updated the data for electricity production to the most recent available data. The main data sets from the US-EI database that were used in this study are documented in this report. A data set with the "WITH US ELECTRICITY" mentioned in its title was originally developed by ecoinvent, while a data set with the "NREL" mentioned in its title was originally developed by the US LCI database.

4.4 Data Quality Goals

The ISO 14044 Standard (ISO 2006b) characterizes various aspects related to data quality and data quality analysis. It lists three critical data quality requirements: time-related coverage, geographical coverage, and technology coverage. The geographic coverage for this study is related to energy produced in US forest products facilities and utilities. When feasible, the most current available data were collected, which were most frequently for 2010. For data from secondary sources (literature, databases), the most current publicly available data for North America were used. A data quality goal of this study was to depict the GHG benefits of using biomass residuals within the forest products industry in a way that is representative of current average technology across the entire industry. Data were most frequently available from the members of the American Forest and Paper Association (AF&PA) and/or NCASI. Data obtained from these members were considered representative of the broader industry. The precision of the data is discussed where appropriate.

4.5 Energy Considerations

Energy requirement calculations were made using higher heating values (HHVs). HHVs account for the total heat content of the fuel when it is burned, some of which provides useful energy to the system in which the fuel is burned and some of which is used to evaporate the water in the combustion products. The latter is generally not available for use. For life cycle purposes, HHV is a more complete method of energy accounting compared to using the lower heating value (LHV), as LHV does not account for the energy content of the fuel that was used to evaporate the water. For this reason, HHVs were used in this study.

4.6 Software Package

This modeling for this study was performed using SimaPro™ version 7.3.3 and DynCO_2 (Levasseur 2013).

4.7 Critical Review and Public Use of the Results

Section 5.2 of ISO 14044 (ISO 2006b, p. 28) specifies that *"when results of the LCA are to be communicated to any third party (i.e., interested party other than the commissioner or the practitioner of the study), regardless of the form of communication, a third-party report shall be prepared".* This Technical Bulletin is intended to serve as a third-party report. The Standard also specifies that *"in order to decrease the likelihood of misunderstandings or negative effects on external interested parties, a panel of interested parties shall conduct critical reviews on LCA studies where the results are intended to be used to support a comparative assertion intended to be disclosed to the public"* (ISO 2006b, p. 31). This study constitutes a comparative assertion of biomass and non-use systems. However, no formal peer review was performed, meaning that the study is not fully compliant with the ISO 14044 Standard.

5.0 DETAILED DATA SOURCES AND STUDY ASSUMPTIONS

This section describes the life cycle inventory step of the LCA, in which the typical scenarios studied are described, as are the unit processes modeled, the related system configuration scenarios, and sensitivity analyses.

5.1 Detailed Description of Unit Processes, System Configurations and Sensitivity Analyses

Table 5.1 presents an overview of the individual components that were combined into the various system configurations scenarios that were studied in this project. All possible combinations were studied, with a few exceptions that are discussed later in this section of the report, as appropriate. From these possible configurations, a typical scenario was also constructed for each of the biomass residuals studied. These are presented in Section 5.1.2.5. The next paragraphs describe in detail each of the unit processes that were involved in the various system configurations and typical scenarios.

Table 5.1 Summary of Components Used to Derive Possible System Configurations

Pre-Processing		Energy Produced at Forest Products Facilities Using Biomass Residuals		Energy Produced at Forest Products Facilities Using Fossil Fuels		Alternative Fate of Residuals	
SR0	No size reduction	SB	Heat from stoker boiler	A	Heat from natural gas	MR1	Landfill
		FB	Heat from fluidized bed	B	Heat from coal		
SR1	Size reduction	CHP1	Combined heat and power: low power to steam ratio*	C	Power from average US grid	MR2	Incineration
		CHP2	Combined heat and power: medium power to steam ratio*	D	Power from coal		
		CHP3	Combined heat and power: high power to steam ratio*	E	Power from natural gas combined cycle		

*All CHP scenarios were based on the use of a stoker boiler to produce the heat from biomass residuals. CHP configurations vary from facility to facility. In some cases, the turbines used to produce the power receive steam from all boilers of the facility (biomass and fossil fuel boilers). In other cases, they receive steam only from specific boilers (biomass or fossil fuel). Analyzing a case where the same amount of CHP would be achieved using biomass or fossil fuel boilers would have led to results that are very similar to those obtained for cases where it was assumed there was only heat produced because the only difference would have been due to energy losses in the CHP system. Therefore, in this project, a more useful CHP scenario for comparison is one where there would be CHP production only in the biomass energy system; if biomass residuals would not be used for energy production at wood products facilities, then the facility would have burned fossil fuel without CHP and would have to purchase the power from local utilities.

5.1.1 Size Reduction of Biomass Residuals

In some cases, additional size reduction is necessary before using biomass residuals for energy production. In this study, it was assumed that size reduction would sometimes be required for woody mill biomass residuals fuel and other similar manufacturing biomass residuals and never required for WWTP and paper recycling residuals.

Size reduction is typically accomplished by means of chippers, hogs, and shredders. Chippers can slice logs and mill residuals and produce chips with two surfaces and clean edges of pre-specified dimensions. Hogs (e.g., hammermills) and shredders reduce wood particles through impact force, and thus produce coarse and multi-surface particles. Hybrid size reduction equipment, such as rotary knife hogs or pan-and-disc grinders, combine the durability of hogging equipment with the sharp cutting action of chippers to produce wood chunks with cleaner edges than those produced by shredders or hogs.

A few data sets, summarized in Table 5.2, were found in the literature concerning size reduction of wood. These served as the basis for this study. More specifically, size reduction-related emissions were modeled using the US-EI database, modified with the use of diesel and electricity as presented in this table. The following US-EI data sets were used:

- **Mobile chipper:** "Wood chopping, mobile chopper, in forest/RER WITH US ELECTRICITY"; and
- **Stationary chipper:** "Industrial residual wood chopping, stationary electric chopper, at plant/RER WITH US ELECTRICITY."

Table 5.2 Various Available Data Sets for Size Reduction and Assumptions Made in This Study

Source	Operation		Diesel (L/BDmT)	Lubricants (L/BDmT)	Electricity (kWh/BDmt)
Johnson et al. (2012)	Grinding of logging residuals		2.51 - 3.76	0.05 - 0.07	0
Johnson et al. (2012)	Chipping of thinnings		1.08 - 1.62	0.02 - 0.03	0
Werner et al. (2007)	Chopping of wood in mobile choppers		3.89*	0.06†	0
Werner et al. (2007)	Chopping in stationary chopper		0	0.002†	20
Jones et al. (2010)	Grinding of thinnings		2.42	N/Av.‡	0
System Configuration Scenarios and Sensitivity Analyses Considered in This Study					
SR0	No additional size reduction		0	0	0
SR1	Additional size reduction in mobile chipper	BC	2.49§	0.05	0
		Low	1.08	0.02	0
		High	3.89	0.07	0
SR2	Additional size reduction in stationary chipper	BC	0	0.002	20

*Werner et al. report 0.141 MJ of diesel burned per kg of residues and Kellenberger et al. (2007), 0.0234 kg of diesel per MJ. Using a density of 847.31 kg/m^3 (American Petroleum Institute 2009), this is equivalent to 3.89 L per BDmt. † Assuming a density of 900 kg/m^3.‡Not available. §Base case was taken as the middle of the range.

5.1.2 Energy Production Processes

5.1.2.1 Combustion of Woody Mill Residuals

Combustion of woody mill residuals is one of the unit processes that needed to be modeled to analyze the effects of producing energy using biomass residuals. Two types of boilers were modeled. First, a stoker boiler was assumed as it is the most commonly used firing method for burning woody biomass in the US forest products industry (NCASI 2011a). Stoker boiler efficiencies vary as a function of water content of the fuel. This is depicted in Figure 5.1. Sensitivity analyses were performed on water content and higher heating values. Second, to analyze the effect of the technology choice, a fluidized bed was also modeled using a single average residual water content and a single average higher heating value. Because smaller particles are required for a fluidized bed boiler, the analyses always incorporated size reduction. Table 5.3 summarizes the parameters that were varied for the modeling of manufacturing biomass residual combustion.

In addition, woody mill residuals are either used for energy production in the facility where they are generated or transported to another wood products facility. No transportation has been considered for the base case and transportation by truck over 130 km (United States Department of Transportation and United States Department of Commerce 2004, Table 14 available online only, value for trucking wood chips and particles) was modeled as a sensitivity analysis. The US-EI data set for single unit truck ("Transport, single unit truck, diesel powered NREL/US"), originally a US LCI Database data set, was used in this study.

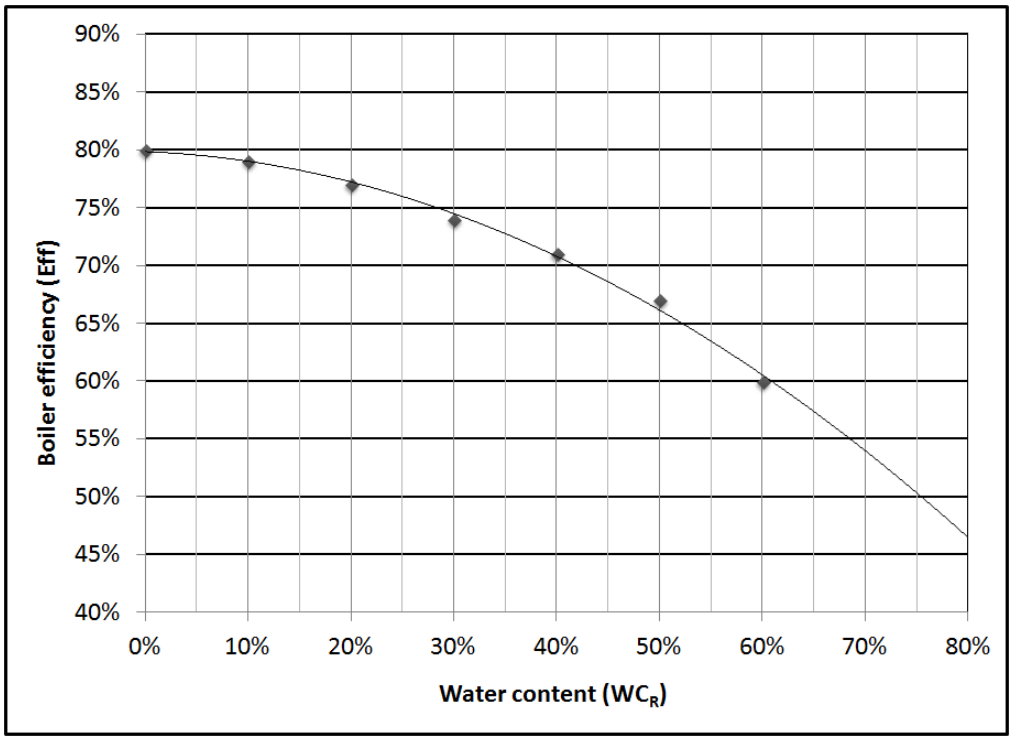


Figure 5.1 Stoker Boiler Efficiency as a Function of Fuel Water Content (WC_R)
[Based on Kostiuk and Pfaff (1997)]

The amount of residuals (Q_R) in dry tonnes required to produce a given amount of usable energy was calculated as follows:

$$Q_R = \frac{E_{DC}}{HHV \times Eff}$$

Where:

E_{DC}: Usable energy from direct combustion (GJ);
HHV: Higher heating value (GJ HHV/BDmT); and
Eff: Boiler efficiency (fraction between zero and 1).

GHG emissions due to biomass residual combustion were modeled using emission factors from USEPA (2009, Tables C-1 and C-2), converted to physical units[8]:

- 1,807 kg $BioCO_2$[9]/BDmT;
- 0.617 kg CH_4/BDmT; and
- 0.0809 kg N_2O/BDmT.

Ashes (2%) were assumed to be disposed of in facility landfills. Landfilling of wood ashes was modeled using data from the US-EI database ("Disposal, wood ash mixture, pure, 0% water, to sanitary landfill/CH WITH US ELECTRICITY U").

[8] Heating value and emission factors for wood and wood residuals specified by USEPA are as follows: 15.38 mmBtu HHV/short ton @12% water, 93.80 kg CO_2/mmBtu, 3.2E-2 kg CH_4/mmBtu and 4.2E-3 kg N_2O/mmBtu.
[9] $BioCO_2$: biogenic CO_2.

Table 5.3 Base Case and Sensitivity Analyses for Manufacturing Biomass Residual Combustion

Technology Scenario		Parameter Analyzed	Value Analyzed		Comments
SB	Stoker boiler	Water content (W_R)	BC	50% (Eff = 66%)	The range of water content for wood residuals was based on rounded values from a literature review by NCASI (2011a) and assumed to be representative of the full range of wood residuals (e.g., chips, sawdust, etc.). The base case was selected as 50% because the moisture content of as-fired wood is typically near 50% for the pulp, paper and lumber industries (USEPA 1995). Efficiencies were based on Forintek (Kostiuk and Pfaff 1997). According to NCASI's literature review, water content of residuals can be as high as 75%, but this is not very realistic.
			Low	10% (Eff = 79%)	
			High	60% (Eff = 60%)	
		Higher heating value (HHV)	BC	20 GJ/BDmT	The range of heating values is based on a literature review by NCASI (2011a) and is assumed to be representative of the full range of wood species (hardwood and softwood). USEPA (2009, Tables C-1 and C-2) proposed heating value for wood is 20.3 GJ/BDmT (see below for more details).
			Low	13 GJ/BDmT	
			High	26 GJ/BDmT	
FB	Fluidized bed	Water content	50% (Eff = 80%)		Water content was assumed the same as above. Efficiency for the fluidized bed was from a NCASI literature review (2011a).
		Higher heating value	20 GJ/BDmT		

*5.1.2.2 **Combustion of Wastewater Residuals***

Residuals from pulp and paper mill wastewater treatment plant (WWTP) operations are often burned in mill boilers both to recover energy and for solid waste minimization.

Table 5.4 presents example characteristics of WWTP residuals that can affect their suitability for combustion. From this table, it can be seen that characteristics of residuals vary significantly. In this study, sensitivity analyses for residuals combustion were set to account for this variation.

Co-firing with bark in a stoker boiler was assumed; however, only the fraction of heat from the WWTP residuals was analyzed. Burning WWTP residuals is more difficult than burning bark mainly because of their high ash and low oxygen content. To compensate for the effects of higher ash and lower oxygen contents, the moisture of the residuals must be lower to produce the same efficiency in stoker boilers (Kraft and Orender 1993). The authors suggested that for sludge to burn like bark, the equivalent of 5 moisture points must be compensated for in some way. Switching from all bark to all residuals is worth 5 equivalent moisture points (1 moisture point being the same as 1% water content) and

- co-firing 90% bark with 10% sludge is worth 0.5 moisture points; and
- co-firing 80% bark with 20% sludge is worth 1.0 moisture point.

In this study, the latter, which is more conservative, was assumed. However, as mentioned above, only the heat fraction from the residuals was analyzed. Only stoker boilers were analyzed.

Table 5.4 Characteristics of WWTP Residuals

Source	WWTP Residual	Ash Content (%wt, dry basis)	Carbon Content (%wt, dry basis)	Water Content (%wt, wet basis)	Heat Content (GJ HHV/BDmT)*
Durai-Swami et al. (1991)	Recycled paper mill and kraft mill	5.5 - 18.9	47.2 - 48.2	49.5 - 62.4	20.6 - 24.1
James and Kane (1991)	Kraft mill	8.0	48.0	37.5	19.8
Nickull et al. (1991)	Clarifier and dredged from sulfite mill	1.9	48.7	66.6	20.1
Kraft (1994), Kraft and Orender (1991, 1993)	Deinking, pulp mill, unspecified	11.3 - 48.1	28.8 - 51.8	58.0 - 60.6	5.0 - 21.5
Aghamohammadi and Durai-Swamy (1993)	Recycled paper and cardboard	2.8 - 3.0	48.4 - 48.6	50 - 85	20.6 - 20.8
Douglas et al. (1994)	Deinking	31.9 - 33.2	32.7 - 38.2	42.7 - 68.6	12.3 - 15.3
Frederik et al. (1996)	Recycled paper mill	43.8	16.1	42.0	8.38
La Fond et al. (1997)	Secondary	N/Av	49.3	N/Av	23.1
Hischier (2007)	Mechanical, primary and secondary Deinking	36.4 - 67.3 (deink only, wet)	19.0 - 35.8	25 - 70.6	2.6 - 8.6 GJ (LHV)
NCASI (2005a) and USEPA (ERG 2002)	Bleached kraft, unbleached kraft, unbleached kraft colored, deinked, mechanical, groundwood, chemi-mechanical – mixed and secondary	9.9 - 56.8	37.4 - 45.5	36.2 - 80.6†	7.6 - 18.1†
USEPA GHG Reporting Rule (2009, Tables C-1 and C-2)	Wastewater from paper mills	N/Av	N/Av	N/Av	20.3§
Woodruff et al. (2012)	Pulping, deinking	10 - 50	N/Av	50 - 60	9.3 - 23.3
NCASI unpublished lab experiments	Bleached kraft combined, deinking combined, non-integrated combined, non-integrated primary, deinking primary	26.1 - 74.4	23.1 - 37.3	N/Av	N/Av
IPCC (2006b, Chapter 2, Section 2.3.2)	"Industrial sludge" including WWTP residuals from pulp and paper industry	N/Av	27**	N/Av	N/Av

*When unknown, assumed to be HHV. †Includes dewatered and not dewatered residuals. ‡Assuming USEPA values are expressed in Btu HHV/lb. §According to USEPA (2010b, p. 79138), wood residuals means materials recovered from three principal sources: municipal solid waste (MSW); construction and demolition debris; and primary timber processing. Wood residuals recovered from MSW include wooden furniture, cabinets, pallets and containers, scrap lumber (from sources other than construction and demolition activities), and urban tree and landscape residuals. Wood residuals from construction and demolition debris originate from the construction, repair, remodeling and demolition of houses and non-residential structures. Wood residuals from primary timber processing include bark, sawmill slabs and edgings, sawdust, and peeler log cores. Other sources of wood residuals include, but are not limited to, railroad ties, telephone and utility poles, pier and dock timbers, wastewater process sludge from paper mills, trim, sander dust, and sawdust from wood products manufacturing (including resinated wood products residuals), and logging residuals. **Example from Japan.

Water content of WWTP residuals (WC_R, primary and secondary treatment, deinking residuals) can vary widely; see Table 5.4. Residuals are typically mechanically dewatered. The general objective of dewatering is to remove water to the extent that the solids volume is reduced and the resulting residuals behave as a solid and not as a liquid. Residuals dewatering is accomplished at pulp and paper facilities by incorporating equipment and practices that result in increased WWTP residuals solids content. Employing residuals dewatering a) reduces the costs associated with residuals hauling, b) maximizes the use of remaining landfill capacity, c) makes residuals a more attractive fuel for combination fuel-fired boilers, and d) makes residuals more attractive for beneficial use opportunities (NCASI 2008). WWTP residuals can be dewatered using several technologies, of which belt filter presses and screw presses are the most frequently used in the US industry (NCASI 2008). Solids contents achievable using belt filter and screw presses are over 30% (WC_R < 70%[10]) and 40% (WC_R < 60%), respectively. A lower value of 50% water was also analyzed.

In this study, it was assumed that WWTP residuals were dewatered to 40% solids content, whether they were to be burned or landfilled, i.e., dewatering is assumed to happen both in the biomass and non-use systems. For this reason, dewatering was not included in the study. Ashes from residuals combustion were assumed to be landfilled on site. Landfilling of sludge ashes was modeled using the US-EI database (Disposal, wood ash mixture, pure, 0% water, to sanitary landfill/CH WITH US ELECTRICITY), assuming landfilling of wood ash could be taken as a proxy. Sensitivity analyses were performed on water content, heating value, and ash content. These are summarized in Table 5.5. Efficiencies have been derived from Figure 5.1 (assuming WC_R + 1%).

Table 5.5 Scenarios/Sensitivity Analyses for WWTP Residual Combustion

Parameter Analyzed	Value Analyzed		Rationale/Sources
Water content (WC_R)	BC	60% (Eff =60%)	BC and high values are based on achievable dry contents for screw presses. NCASI analysis of data in Table 5.4 was used to determine the low value by eliminating less probable drier residuals.
	Low	50% (Eff =66%)	
	High	70% (Eff =53%)	
Higher heating value (HHV)	BC	15 GJ/BDmT	BC, low, and high values are based on NCASI analysis of data in Table 5.4.
	Low	10 GJ/BDmT	
	High	20 GJ/BDmT	
Ash content	BC	30%	BC, low, and high values are based on NCASI analysis of data in Table 5.4.
	Low	10%	
	High	50%	

According to USEPA (2009), emission factors for wood and wood residuals should be used for WWTP sludge. However, the carbon content of WWTP residuals can vary significantly depending on the type of residuals. In this study, USEPA emission factors are used as a base case and sensitivity analyses are performed to accommodate the variability in the carbon content of WWTP residuals. This is summarized in Table 5.6. It is also assumed that the higher carbon contents are associated with the higher HHVs.

[10] WC_R: water content of residuals.

Table 5.6 Emission Factors for Burning WWTP Residuals

Parameter Analyzed		Value Analyzed		Rationale/Sources
Biogenic CO_2	kg CO_2/BDmT	BC	1,807 (CC = 49%)	According to USEPA (2010b, p. 79138), wood residuals include WWTP residuals. Hence, the same emission factor as for woody mill residuals was used (USEPA 2009, Tables C-1 and C-2).
		Low	733 (CC = 20%)	Low and high values are based on NCASI analysis of data in Table 5.4.
		High	2017 (CC = 55%)	
CH_4	kg CH_4/BDmT	BC	0.617	According to USEPA (2010b, p. 79138), wood residuals include WWTP residuals. Hence, the same emission factor as for woody mill residuals was used (USEPA 2009, Tables C-1 and C-2).
N_2O	kg N_2O/BDmT	BC	0.0809	

5.1.2.3 ***Combustion of Paper Recycling Residuals (OCC Rejects)***

Paper recycling residuals, and more specifically OCC rejects, are often burned in boilers at pulp and paper mills that process recovered paper. This is done both for volume reduction and for energy recovery. Table 5.7 presents some general characteristics of OCC rejects, as well as the assumptions that were made in this study. OCC rejects were considered representative of the broader paper recycling residuals category. Ranges provided in the table are based on typical characteristics at a number of mills. They are intended to capture the breadth of anticipated variation for these materials.

Paper recycling residuals are a mix of fiber and plastic. In a stoker boiler, the fiber fraction is likely to behave as WWTP residuals (lower efficiency than that for wood biomass residuals). The plastic fraction is likely to behave like a fossil fuel (higher efficiency than that for woody biomass residuals). In this study, it was assumed that the boiler efficiency would be the same as that for woody biomass residuals at similar water content. Only stoker boilers were analyzed.

Ashes from residuals combustion were assumed to be landfilled on site. Landfilling of paper recycling residuals ashes was modeled using the US-EI database (Disposal, wood ash mixture, pure, 0% water, to sanitary landfill/CH WITH US ELECTRICITY), under the assumption that landfilling of wood ash could be taken as a proxy.

Table 5.7 General Characteristics of OCC Rejects and Sensitivity Analyses

Parameter		Range	Source	Range Analyzed in This Study		
				BC	Low	High
Fiber	% dry wt.	30 - 95	NCASI (2000)	60	30	90
Plastics	% dry wt.	5 - 70	NCASI (2000)	40	10	70
Ashes	% dry wt.	1 - 10	NCASI (2000)	5		
Biogenic CO_2 emissions when burning fiber fraction of OCC	kg CO_2/kg fiber	1.807*-1.833†	USEPA (2009, Tables C-1 and C-2)	1.807	N/A	N/A
CH_4 emissions when burning fiber fraction of OCC	kg CH_4/kg fiber		Estimated*	6.17E-5*		
N_2O emissions when burning fiber fraction of OCC	kg N_2O/kg fiber		Estimated*	8.09-6*		
Fossil CO_2 emissions when burning plastic fraction	kg CO_2/kg plastic	2.30	US-EI (EarthShift 2009)‡	2.30		
CH_4 emissions when burning plastic fraction of OCC	kg CH_4/kg plastic	6.38E-6	US-EI (EarthShift 2009)‡	6.38E-6		
N_2O emissions when burning plastic fraction of OCC	kg N_2O/kg plastic	2.58E-5	US-EI (EarthShift 2009)‡	2.58E-5		
Higher heating value	GJ HHV/BDmT	18.8-27.7	NCASI (2000)	Fiber fraction: 19.1 Plastic fraction: 40.9		
Water content (boiler efficiency)	% wet wt. (%)	35-70	NCASI (2000)	55(63)	40 (71)	70 (54)

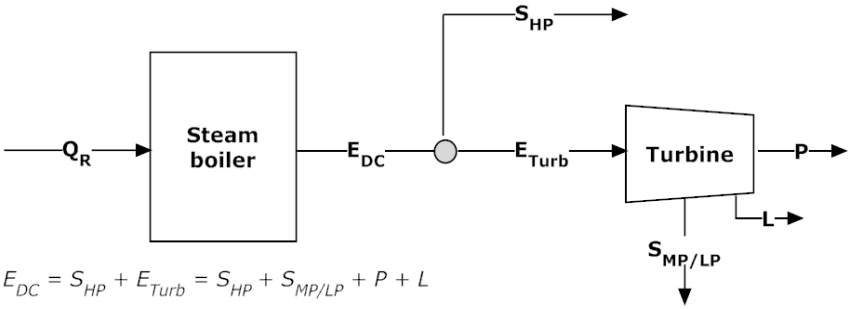
NOTE: Ranges are based on NCASI analysis of the literature. Base case is selected as the middle of the range unless otherwise selected.
* USEPA (2009) emission factors for wood and wood residuals, expressed based in physical units, are used for the fiber fraction of OCC rejects. † Assuming all carbon emitted as CO_2. ‡Disposal, plastics, mixture, 15.3% water, to municipal incineration/CH WITH US ELECTRICITY.

The carbon dioxide produced when plastics are burned is commonly accounted for using the same methods as for carbon dioxide produced in burning fossil fuels (USEPA 2010c, Table C-1 and Section 98.33(e)). For the gate-to-gate analyses of the biogenic GHG releases, it is only the accounting methods for biogenic carbon that are in question. For this reason, for these analyses, only the fiber fraction of paper recycling residuals was considered.

The heating values of the individual plastic and fiber fractions were presented in Table 5.7. There is no available information for the individual water contents of each of the fractions. However, it was shown in Table 5.7 that water content of paper recycling residuals varies significantly and it can be assumed that, while the plastic fraction of the residuals may contain some water, most of it would be found in the in the fiber fraction. In this analysis, the same water content as paper recycling residuals was applied to its fiber fraction. This resulted in 66% water for base case condition, which is very similar to WWTP residuals.

*5.1.2.4 **Combined Heat and Power (CHP)***

In this study, a hypothetical combined heat and power configuration (CHP) representative of those commonly used in the forest products industry was modeled. This system, depicted in Figure 5.2, consisted of a biomass-fired boiler with high pressure steam routed to a back pressure turbine.



$E_{DC} = S_{HP} + E_{Turb} = S_{HP} + S_{MP/LP} + P + L$

$S_{HP} + S_{MP/LP} + P = 1\ GJ$

Legend:
$\mathbf{Q_R}$: Quantity of wood residues, $\mathbf{E_{DC}}$: Usable energy from direct combustion,
$\mathbf{E_{Turb}}$: Steam to turbine, $\mathbf{S_{HP}}$: High pressure steam to process,
$\mathbf{S_{MP/LP}}$: Extraction steam to process, **P**: Power, and **L**: Losses

Figure 5.2 Hypothetical CHP Configuration Considered in This Study

The relationship between Q_R and E_{DC} is described above in Section 5.1.2.1. Three scenarios were considered: 1) one representing an older pulp and paper mill (CHP1), 2) one representing a newer pulp and paper mill (CHP2), and 3) one considering the maximum power production through use of a condensing turbine. This last scenario could be considered representative of cases where very little steam is required. All three scenarios are presented in Table 5.8.

All the CHP scenarios were performed with base case stoker boiler conditions.

Table 5.8 CHP Scenarios

Scenario #	E_{DC}	E_{Turb}	S_{HP}	P	$S_{MP/LP}$	$S_{HP}+S_{MP/LP}$	L
	(GJ)						
CHP1	1.0499	0.9974	0.05 E_{DC} = 0.0525	0.18 E_{Turb} = 0.1795	0.77 E_{Turb} = 0.7680	0.8205	0.05 E_{Turb} = 0.0499*
CHP2	1.0499	0.9974	0.05 E_{DC} = 0.0525	0.29 E_{Turb} = 0.2892	0.66 E_{Turb} = 0.6583	0.7108	0.05 E_{Turb} = 0.0499*
CHP3	1.0499	0.9974	0.05 E_{DC} = 0.0525	0.95 E_{Turb} = 0.9475	0	0.0525	0.05 E_{Turb} = 0.0499*

* Used for sootblowing.

*5.1.2.5 **Energy Production Using Fossil Fuels***

Two possible options for producing energy from biomass residuals were considered: heat and combined heat and power. This means that an equivalent system needed to be studied regarding fossil fuels. For cases where the biomass energy system included heat production at the forest products facility, it was assumed that in the fossil fuel-based system an equivalent quantity of heat would be produced at the facility using either coal (A) or natural gas (B).

A somewhat different approach was taken for cases where combined heat and power would be applied to the biomass energy system. CHP configurations vary from facility to facility. In some cases, the turbines used to produce power receive steam from all boilers at the facility (i.e., both biomass and fossil fuel boilers). In other cases, they receive steam only from specific boilers (biomass or fossil fuel). Analyzing a case where the same amount of CHP would be achieved using biomass or fossil fuel boilers would have led to results that are very similar to those that were obtained for the case where it was assumed there was only heat produced, because the only difference would have been due to energy losses in the CHP system, which are typically very small. Therefore, in this project, a more useful CHP scenario for comparison is one where there would be CHP production only in the biomass energy system; if biomass residuals were not used for energy production at forest products facilities, then the facility would have burned fossil fuel without CHP and would have to purchase the power from local utilities. Three scenarios were analyzed: C) US average electrical grid mix, D) power generated using coal, and E) power generated using natural gas combined cycle. These scenarios were selected in order to cover a large spectrum of possible mill situations.

All energy production processes from fossil fuel-related processes were modeled using the US-EI database. In specific, the following data sets were used for heat production:

- **Heat from coal:** "Bituminous coal, combusted in industrial boiler NREL/US" (this data set includes transportation of the coal to the boiler); and
- **Heat from natural gas:** "Natural gas, combusted in industrial boiler NREL/US" (this data set includes transportation of the natural gas to the boiler).

Both these data sets are expressed based on the quantity of fuel burned and not on the quantity of energy produced. To calculate the energy produced, the following was assumed:

- **Coal:** boiler efficiency of 85% and higher heating value of 24.93 MMBtu per short ton (29.0 GJ/tonne); and
- **Natural gas:** boiler efficiency of 80% and HHV of 1.028E-3 MMBtu per cubic feet (0.0383 GJ/m^3).

Heating values were obtained from USEPA (2009, Table C-1). GHG emission factors were also derived from EPA. The emission factors for natural gas are 93.4 kg CO_2, 1.1E-2 kg CH_4 and 1.6E-3 kg N_2O per MMBtu. The emission factors for coal are 53.02 kg CO_2, 1.0E-3 kg CH_4 and 1.0E-4 kg N_2O per MMBtu.

The following data sets were used for electricity production at utilities:

- Electricity, bituminous coal, at power plant NREL/US; and
- Electricity, natural gas, at turbine, 10MW/GLO WITH US ELECTRICITY.

The US average consumption grid mix was also modeled using processes from the US-EI Database. It was calculated by considering the quantity of power produced in the US by type of fuel, the quantity of power exported, and the quantity imported from Canada and Mexico. The production mix for the United States was calculated using 2010 data from the US Department of Energy, Energy Information Administration (EIA 2012, Forms EIA-906, EIA-920 and EIA-923). Data for 2009 from the International Energy Agency were used for Mexico (IEA 2013), as these were the most recent data available. Since electricity imports from Mexico represent less than 3% of the total energy consumed in the US, these data are not expected to have a significant effect on the results. Canadian data were taken from Statistics Canada (2013a, b, c). Table 5.9 presents the fuel mix for US average electricity consumption as well as the US-EI data sets that were used to model it.

Table 5.9 US Average Electricity Grid Fuel Consumption Mix

Fuel Type	%	US-EI Data Set Used
Coal (including CHP)	45	Electricity, bituminous coal, at power plant NREL/US
Petroleum	1	Electricity, residual fuel oil, at power plant NREL/US
Natural gas (including CHP)	24	Electricity, natural gas, at power plant NREL/US
Nuclear	20	Electricity, nuclear, at power plant NREL/US
Hydroelectric	7	Electricity, hydropower, at power plant/SE WITH US ELECTRICITY U (89%), and Electricity, hydropower, at pumped storage power plant/US WITH US ELECTRICITY U (11%)
Wind	2	Electricity, at wind power plant/RER WITH US ELECTRICITY
Wood and wood derived fuels (CHP)	1	Electricity, biomass, at power plant NREL/US

Note that this US average grid mix was also used for the background electricity consumption of all processes modeled with the US-EI database.

Different fuels may be associated with different energy requirements for air emissions control of combustion units. In this study, it was assumed that the differences in energy requirements for emissions control were insignificant compared to the energy produced by the combustion units. This assumption was tested using sensitivity analyses.

5.1.3 Alternative Fates

5.1.3.1 Landfilling of Manufacturing Residuals

In landfills, a fraction of the biogenic carbon in wood-based material decays, primarily into gas. The remaining fraction is non-degradable under anaerobic conditions. The non-degradable fraction varies by type of product, being generally higher in materials with more lignin. In this study, the degradable fraction of the biogenic carbon in landfills was assumed to decay according to a first order decay equation, with a variable rate constant. This approach is recommended by IPCC (IPCC 2006b) and used by EPA (2010a, 2014a) for a number of purposes.

Reported decay rates are highly variable from one material to another and from one study or program to another. The factors that affect the rate of decomposition in landfills include waste management and processing variables (such as the size of the waste particles), the waste properties, factors that influence bacterial growth (such as moisture, available nutrients, pH, and temperature), and the design of the landfill (Micales and Skog 1997). EPA tested 52 municipal solid waste landfills and found decay rates that varied on average from 0.020 to 0.057, depending on precipitation conditions (USEPA 2014a, Annex 3.14, Table A-262). Published values for wood product and pulp and paper waste, branches, and solid wood products vary from 0.01 to 0.1 (De la Cruz and Barlaz 2010, IPCC 2006b, Chapter 3, Table 3.3, Micales and Skog 1997, NCASI 2005b, Section 14.2, Skog 2008, U.S. EPA 2012a, U.S. EPA 2013, Table TT-1, U.S. EPA 2014a, Annex 3.14). These values were mostly derived from laboratory experiments. NCASI knows of no published data, however, on decay rates specific to forest products industry manufacturing residuals in industry landfills based on actual measurements. Therefore, in this study, the EPA decay rates for municipal solid waste (MSW) were used (US EPA 2014a, Annex 3.14, Table A-262). These were used because 1) 50 to 60% of the biodegradable material in discarded MSW in the US (after recovery for recycling) is paper, paperboard, wood, and yard trimmings (USEPA 2014b, Table 3), 2) unlike most of the decay rates

found in the literature, these decay rates are derived from field data instead of laboratory experiments, and 3) they are based on a robust data set, having been derived from 52 representative landfills from across the United States with varying amounts of precipitation. These EPA MSW decay rates are somewhat higher than those used in the EPA GHG emissions reporting program for pulp, paper, and wood products mill landfills, somewhat lower than those used for pulp and paper mills in the EPA national GHG inventory, and are within the range of those reported elsewhere for forest-derived materials.

The fraction of material degradable under anaerobic conditions must also be known in order to estimate GHG emissions from landfills receiving manufacturing residuals. Data are available for some of the specific residuals in this study; the parameter values used to characterize the extent of decomposition are discussed below in the sections dealing with individual types of residuals.

Under anaerobic conditions, about one-half of the degradable carbon is converted to biogenic CO_2 while the other half is converted to CH_4. Under aerobic conditions (e.g., in shallow unmanaged landfills), a much smaller fraction of the gas consists of CH_4. The methane correction factor (MCF, fraction between zero and 1) is used to reflect the fraction of material that is degraded under anaerobic conditions.

Another factor influencing the releases of landfill CO_2 and CH_4 methane to the atmosphere is the extent to which CH_4 is oxidized to biogenic CO_2 before exiting the landfill. Even in the absence of systems designed to capture and destroy methane, it is commonly assumed that about 10% of the methane is oxidized as it moves through the surface layers of the landfill (IPCC 2006b, Chapter 3, Table 3.2, U.S. EPA 2014a, Section 8.1). Finally, some landfills are equipped with cover systems to collect and destroy methane by burning, and assumptions need to be made regarding the fraction of the methane that is collected and burned. In this study, it was assumed that manufacturing residuals are landfilled in a landfill receiving primarily forest product industry waste and that for these landfills there is no methane capture, assumptions consistent with current practice in the industry and with the approach used by EPA to calculate landfill emissions from pulp and paper mills landfills for the national inventory (USEPA 2014a, Annex 3.14).

Cumulative quantities of carbon dioxide and methane from mill landfills emitted at a given time are calculated as follows.

Quantity of Carbon Converted to Gas at a Given Time Under Anaerobic Conditions:

$$Q_{C\rightarrow Gas,ana} = MCF \times Q_R\left(1 - e^{-kt}\right) \times CC \times (1 - F_{CCND})$$

where Q_R is the quantity of residuals required to produce a given amount of usable energy in the biomass product system, t the time in years, CC the carbon content of residuals, F_{CCND} the fraction of carbon that is non-degradable under anaerobic condition, and k the decay rate.

Quantity of Carbon in Gas Converted to Methane ($Q_{C->CH4}$):

$$Q_{C\rightarrow CH4} = Q_{C\rightarrow Gas,an} \times F$$

where F is the fraction of gas converted to methane under anaerobic conditions.

Quantity of Methane Not Collected and Burned (Q_{CH4NCB})

$$Q_{CH4NCB} = Q_{C\rightarrow CH4} \times \frac{16}{12}(1 - F_{CH4CB})$$

where F_{CH4CB} is the fraction of methane collected and burned or oxidized.

Quantity of Methane Released to the Environment ($Q_{CH4,Landfill}$):

$$Q_{CH4,Landfill} = Q_{CH4NCB} \times (1 - F_{CH4OX})$$

where F_{CH4OX} is the fraction of methane oxidized in landfill covers.

Quantity of Carbon Converted to Gas at a Given Time Under Aerobic Conditions:

$$Q_{C \rightarrow Gas,ae} = (1 - MCF) \times Q_R\left(1 - e^{-kt}\right) \times CC$$

Total Quantity of Gas at a Given time:

$$Q_{C \rightarrow Gas} = Q_R\left(1 - e^{-kt}\right) \times CC \times [1 - MCF * F_{CCND}]$$

Quantity of Carbon Dioxide Released to the Environment ($Q_{CO2,Landfill}$):

$$Q_{CO2,Landfill} = \left(Q_{C \rightarrow Gas} - Q_{CH4,landfill} \times \frac{12}{16}\right) \times \frac{44}{12}$$

Other environmental loads related to landfilling activities were modeled using the US-EI database (Disposal, wood untreated, 20% water, to sanitary landfill/CH WITH US ELECTRICITY).

5.1.3.1.1 Woody Mill Residuals

As mentioned above, an important factor in calculating emissions from landfills is the fraction of the original biogenic carbon that is non-degradable under anaerobic conditions. There is a wide variation of values for this parameter in the case of wood and wood-derived materials. Values published in the literature for woody materials vary from 50% (IPCC 2006b) to over 90% (Wang et al. 2011). Values for paper-based materials can be significantly lower than those for woody materials (USEPA 2012a). In this study, the value used in the EPA GHG Inventory for wood products disposed in MSW landfills was used in the typical scenario. This was done because 1) in the context of this study, it is more conservative than lower values sometimes used by EPA (i.e., it results in lower methane emissions from landfilling, reducing the relative benefits of burning for energy); and 2) given recent studies (e.g., Wang et al. 2011), it is likely more realistic than lower values sometimes used by EPA. There is large uncertainty in this parameter however. Materials like bark and sawdust that comprise woody mill residuals have not been studied to NCASI's knowledge. Landfill parameter values selected in this study for woody mill residuals are summarized in Table 5.10.

Table 5.10 Parameters Affecting Emissions from Landfilling of Woody Mill Residuals

Parameter Analyzed	Value Analyzed		Rationale/Source(s)
Biogenic carbon content (CC)	BC	50%	IPCC (2006c, Table 12.4, default value for carbon fraction of wood residues)
Non-degradable carbon under anaerobic conditions (F_{CCND})	BC	77%	USEPA (2014a, Annex 3.13); see rationale above
	Low	50%	IPCC (2006b, Chapter 3, p. 3.13) and USEPA (2010a, p. 39773, 2013, Table TT-1) recommend using a default value of 50% for the fraction of carbon that decomposes under anaerobic conditions for all waste
	High	90.0%	Mid-point of the range for wood and wood products (Wang 2011, Table 2)
Decay rate (k)	BC	0.038 yr^{-1}	USEPA (2012b), value representative of 52 US municipal solid waste landfills and various precipitation conditions; see rationale above
	Low	0.020 yr^{-1}	
	High	0.057 yr^{-1}	
Methane correction factor (MCF) i.e., fraction of landfill under anaerobic conditions	BC	1	IPCC (2006b), methane correction factors set up to be representative of managed anaerobic
Fraction of gas converted to methane under anaerobic conditions (F)	BC	0.5	IPCC (2006b)
Fraction of methane oxidized in landfill covers (F_{CH4OX})	BC	10%	IPCC (2006b)
Fraction of methane burned or oxidized (F_{CH4CB})	BC	0%	Assuming no mill landfill is equipped with methane collection systems (USEPA 2014a)

5.1.3.1.2 WWTP Residuals

Assumptions made to model GHG emissions from landfilling WWTP residuals are summarized in Table 5.11. Detailed calculations were presented in Section 5.1.3.1. Other environmental loads from landfilling of WWTP residuals were modeled using the US-EI database (Disposal, sludge from pulp and paper production, 25% water, to sanitary landfill/CH WITH US ELECTRICITY).

Table 5.11 Parameters Affecting Emissions from Landfilling of WWTP Residuals

Parameter Analyzed	Value Analyzed		Source(s)
Biogenic carbon content (CC)	BC	49%	See Table 5.6.
	Low	19%	
	High	55%	
Non-degradable carbon under anaerobic conditions (F_{CCND})	BC	50%	From NCASI unpublished experiments
	Low	40%	
	High	60%	
Decay rate (k)	BC	0.038	USEPA (2012b), value representative of 52 US municipal solid waste landfills and various precipitation conditions, see rationale above
	Low	0.020	
	High	0.057	
Methane correction factor (MCF)	BC	1	IPCC (2006b), methane correction factors set up to be representative of managed anaerobic landfills
Fraction of gas converted to methane under anaerobic conditions (F)	BC	0.5	IPCC (2006b)
Fraction of methane oxidized in landfill covers (F_{CH4OX})	BC	10%	IPCC (2006b)
Fraction of methane burned or oxidized (F_{CH4CB})	BC	0%	Assuming no mill landfill is equipped with methane collection systems

5.1.3.1.3 Paper Recycling Residuals

Assumptions made to model GHG emissions from landfilling the fiber fraction of OCC rejects are summarized in Table 5.12. Detailed equations were provided in Section 5.1.3.1. Other environmental emissions related to the use of resources for landfilling the fiber fraction, as well as for landfilling the plastic fraction of OCC rejects, were modeled using the US-EI database.

- **Fiber fraction of residuals:** Disposal, sludge from pulp and paper production, 25% water, to sanitary landfill/CH WITH US ELECTRICITY, assuming WWTP residuals are representative of the fiber fraction of the paper recycling residuals
- **Plastic fraction of residuals:** Disposal, paper, 11.2% water, to sanitary landfill/CH WITH US ELECTRICITY

Table 5.12 Parameters Affecting Emissions from Landfilling the Fiber Fraction of OCC Rejects

Parameter Analyzed	Value Analyzed		Source(s)
Biogenic carbon content (CC)	BC	50%	IPCC (2006b)
Non-degradable carbon under anaerobic conditions (F_{CCND})	BC	61%	Based on NCASI (2004)
	Low	40%	Based on lower value for WWTP residuals (see Table 5.11)
Decay rate (k)	BC	0.038	USEPA (2012b), value representative of 52 US municipal solid waste landfills and various precipitation conditions, see rationale above
	Low	0.020	
	High	0.057	
Methane correction factor (MCF)	BC	1	IPCC (2006b), methane correction factors set up to be representative of managed anaerobic
Fraction of gas converted to methane under anaerobic conditions (F)	BC	0.5	IPCC (2006b)
Fraction of methane oxidized in landfill covers (F_{CH4OX})	BC	10%	IPCC (2006b), assuming no mill landfill is equipped with methane collection systems
Fraction of methane burned or oxidized (F_{CH4CB})	BC	0%	Assuming no mill landfill is equipped with a methane collection system

*5.1.3.2 **Incineration of Woody Mill Residuals***

Incinerating the woody mill residuals without recovering the energy is modeled in this study as a way to illustrate the simplest way by which biogenic carbon can return to the atmosphere. Emissions from incineration are assumed the same as those for combustion for energy generation (see Section 5.1.2.1).

*5.1.3.3 **Incineration of WWTP Residuals***

Emissions from incineration are assumed to be the same as those related to combustion for energy generation (see Section 5.1.2.2).

*5.1.3.4 **Incineration of Paper Recycling Residuals***

Emissions from the incineration of paper recycling residuals are assumed to be the same as those related to combustion for energy generation (see Section 5.1.2.3).

5.2 Definition of Typical Scenarios

5.2.1 Current Energy Use and Waste Management Practices at Forest Products Facilities

Energy production and waste management data were compiled for the US forest products facilities (both pulp and paper and wood products) using data collected by AF&PA, NCASI, and the American Wood Council (AWC) and are summarized in Table 5.13 and

Table 5.14. Most data are from 2010. Waste management data for the wood products facilities were compiled through 2008 only. For this reason, to produce a representative number for the entire forest products industry in 2010, the ratio of management options in 2008 was applied to 2010 production data. There are no "waste management" data available for bark, sawdust, and similar woody mill residuals produced at pulp and paper facilities, as they are not a waste but rather almost always being burned for energy.

Table 5.13 US Forest Products Facilities Estimated Fuel Mix
(Not Including Purchased Power and Steam)

Fuel Type	Paper Products Facilities	Wood Products Facilities	Forest Products Industry (AF&PA, NCASI and AWC members used as a proxy for the entire US industry)
	%		
Biomass fuels	**70.9**	**90.1**	**72.1**
Fossil fuels	**29.1**	**9.9**	**27.9**
Natural gas	13.9%	8.6%	13.5%
Coal	10.9%	0.3%	10.2%
Other fossil	4.4%	0.9%	4.1%
Power produced through combined heat and power	**GJ/GJ fuel input**	0.06	

Table 5.14 Waste Management Practices at US Forest Products Facilities

Waste Type	% Beneficial Use	Disposal		
		Total	% Landfill (% of disposal)	% Burning* (% of disposal)
Paper Products Facilities				
WWTP residuals	32.5%	67.5%	44.4% (65.8%)	23.1% (34.2%)
All others (causticizing wastes, general mill trash, construction debris, OCC rejects, landfilled broke, bark, wood residual, sawdust, knots, metal and other recyclable)	26.9%	73.1%	68.4% (93.6%)	4.7% (6.4%)
Wood Products Facilities				
All waste types (incl.: unusable sawdust, shavings, bark, garbage, recyclables, used oil, pallets, etc.)	96.2%	3.8%	3.8% (100%)	Negligible
Forest Products Industry (AF&PA and NCASI members used as a proxy for the whole US industry)				
Other waste from pulp and paper facilities and all waste from wood products facilities	57.8%	42.2%	39.6% (93.8%)	2.6% (6.2%)

*This does not include burning for energy.

Typical scenarios were modeled to be as representative as possible of current practices within US forest products manufacturing facilities using the information in the tables above. In addition, all parameters were set to their base case values for typical scenarios.

5.2.2 Woody Mill Residuals

The typical scenario considered for woody mill residuals is summarized in Table 5.15. A stoker boiler was assumed in the typical scenario as it is the most commonly used firing method for burning woody biomass (NCASI 2011a). Size reduction is sometimes required to process oversized particles prior to burning. Stoker boilers can be used to burn biomass residuals for a broad spectrum of sizes (NCASI 2011a). Woody mill residuals are generally found in sizes suitable for stoker boilers (NCASI 2011a). For this reason, as a typical scenario, no size reduction was considered. The ratio of steam to power produced was set based on industry data for CHP (from AF&PA, NCASI, and AWC). This study analyzed only cases where steam and electricity would be produced via CHP using biomass boilers and not fossil fuel boilers. Therefore, it was assumed that, at the industry level, the total power produced from CHP would be generated from biomass and fossil fuels in forest products facilities in the same ratio as overall fuel usage, and only the fraction from biomass was considered. Power to heat ratio ($P/S_{MP/LP}$) assumed for the CHP1 scenario above was assumed for the typical scenario as a conservative assumption. The actual heat/CHP configuration assumed for this system is depicted in Figure 5.3.

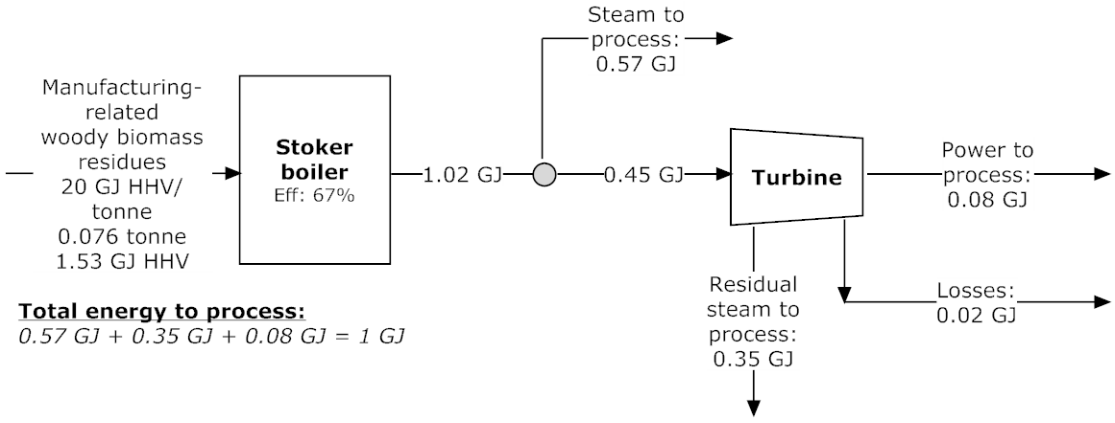


Figure 5.3 Heat/CHP Configuration Considered in the Typical Scenario for Woody Mill Residuals

The typical scenario considered was based on the data presented earlier in Table 5.13 for the entire forest products industry. It can be seen from this table that natural gas and coal are the main fossil fuels used by the US forest products industry. Therefore, in the typical scenario, only those two were considered in the ratio used by the industry. It was hence assumed that 57% of the steam produced from biomass would displace heat from natural gas and 43% would displace heat from coal. All (100%) of the displaced power was assumed to be from the US power consumption grid mix average. As shown previously in

Table 5.14, when woody mill residuals are disposed of, they are either landfilled (94%) or burned (6%). However, as the burning reported by NCASI/AF&PA members most likely involves recovery of energy, this was not considered to be an alternative fate for the typical scenario. Instead, 100% landfilling was considered. It should be noted however, that there are very few data on what would be a reasonable "typical" alternative fate for woody mill residuals as it is not a common practice of the industry to dispose of these.

Table 5.15 Typical Scenario for Woody Mill Residuals

Pre-Processing			Energy Produced at Forest Products Facilities/Utilities				Alternative Fate of Residuals		
			Biomass Residuals		Corresponding Fossil Fuels				
SR0	No size reduction	100%	Heat from stoker boiler and residual steam from CHP	92%	Heat from natural gas	57%	MR1	Landfill	100%
					Heat from coal	43%			
SR1	Size reduction - Mobile chipper	0%	Power from CHP	8%	US average power consumption mix	100%	MR2	Incineration	0%
SR2	Size reduction - Stationary chipper	0%							

5.2.3 WWTP Residuals

The typical scenario considered for WWTP residuals is summarized in Table 5.16. A stoker boiler was also assumed in the typical scenario as a conservative assumption. The ratio of steam to power produced was set based on industry data (from AF&PA, NCASI, and AWC) regarding CHP. This study analyzed only cases where CHP would be produced using biomass boilers and not fossil fuel boilers. Therefore, it was assumed that, at the industry level, the total power produced from CHP would be generated from biomass and fossil fuels in forest products facilities in the same ratio as overall fuel usage and only the fraction from biomass was considered. Power to heat ratio ($P/S_{LP/MP}$) assumed for the CHP1 scenario above was used for the typical scenario as a conservative assumption. The actual heat/CHP configuration assumed for this system is depicted below in Figure 5.4.

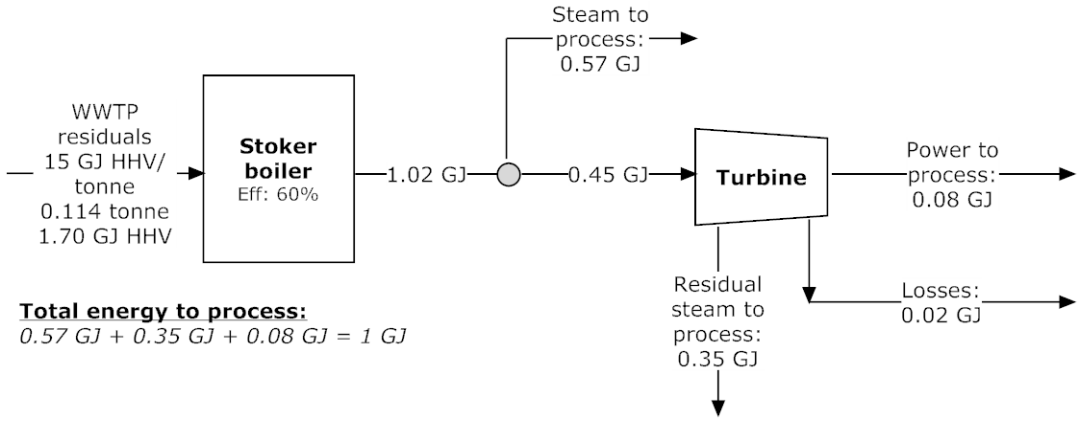


Figure 5.4 Heat/CHP Configuration Considered in the Typical Scenario for WWTP Residuals

The typical scenario considered was based on the data presented in Table 5.13 for the whole industry. It can be seen from this table that natural gas and coal are the main fossil fuels used by the US forest products industry. In the typical scenario, therefore, only these two fuels were considered in the ratio used by the industry. It was hence assumed that 57% of the steam produced from biomass would

displace heat from natural gas and 43% would displace heat from coal. All (100%) of the displaced power was assumed to be from the US power consumption grid mix average. Finally, as shown previously in Table 5.14, WWTP residuals that are not beneficially used are typically landfilled (66%) or burned (34%). As it is not necessary that burning residuals would involve recovery of energy (for instance, in cases where the heating value would be too low), this ratio was assumed in the typical scenario.

Table 5.16 Typical Scenario for WWTP Residuals

Energy Produced at Forest Products Facilities/Utilities				Alternative Fate of Residuals		
Biomass Residuals		Corresponding Fossil Fuels				
Heat from stoker boiler and residual steam from CHP	92%	Heat from natural gas	57%	MR1	Landfill	66%
		Heat from coal	43%			
Power from CHP	8%	US average power consumption mix	100%	MR2	Incineration	34%

5.2.4 Paper Recycling Residuals

The typical scenario considered for paper recycling residuals is summarized in Table 5.17. A stoker boiler was assumed in the typical scenario as a conservative assumption. The ratio of steam to power produced was set based on industry data (from AF&PA, NCASI, and AWC) for CHP. This study analyzed only cases where CHP would be produced using biomass boilers and not fossil fuel boilers. Therefore, it was assumed that, at the industry level, the total power produced from CHP would be generated from biomass and fossil fuels in forest products facilities in the same ratio as overall fuel usage and only the fraction from biomass was considered. Turbine efficiency assumed for the CHP1 scenario above was used for the typical scenario as a conservative assumption. The actual heat/CHP configuration assumed for this system is depicted below in Figure 5.5.

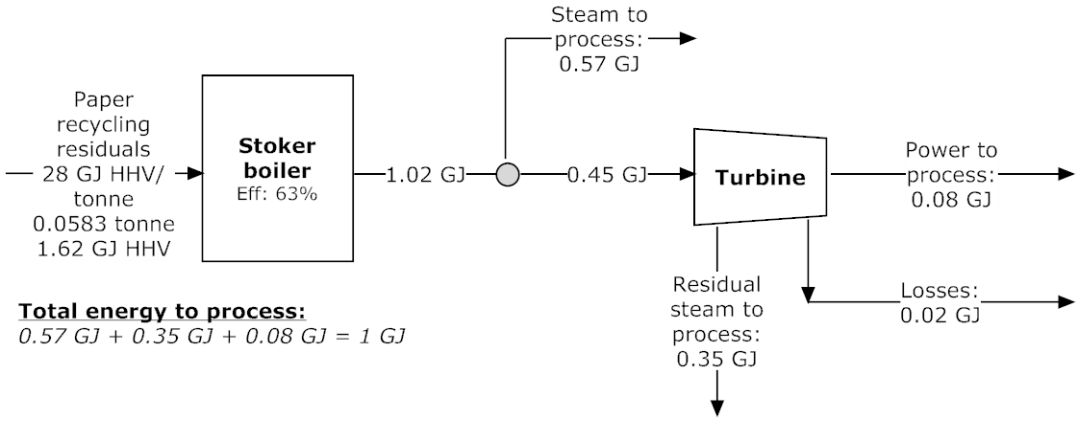


Figure 5.5 Heat/CHP Configuration Considered in the Typical Scenario for Paper Recycling Residuals

The typical scenario considered was based on the data presented above in Table 5.13 for the whole industry. It can be seen from this table that natural gas and coal are the main fossil fuels used by the US forest products industry. In the typical scenario, only those two were considered in the ratio used by the industry. It was hence assumed that 57% of the steam produced from biomass would displace heat from natural gas and 43% would displace heat from coal. All (100%) of the displaced power was assumed to be from the US power consumption mix average. Finally, as shown in Table 5.14, paper

recycling residuals that are not beneficially used are typically landfilled (93.6%) or burned (6.4%). As it is not necessary that burning residuals would involve recovery of energy (for instance if they were disposed of in municipal facilities), this ratio was assumed in the typical scenario.

Table 5.17 Typical Scenario for Paper Recycling Residuals

Energy Produced at Forest Products Facilities/Utilities				Alternative Fate of Residuals		
Biomass Residuals		Corresponding Fossil Fuels				
Heat from stoker boiler and residual steam from CHP	92%	Heat from natural gas	57%	MR1	Landfill	93.6%
		Heat from coal	43%			
Power from CHP	8%	US average power consumption mix	100%	MR2	Incineration	6.4%

6.0 RESULTS AND DISCUSSION: CRADLE-TO-FINAL ENERGY

This section discusses the results of the cradle-to-final energy analysis, including fossil fuel substitution.

Note: For the GHGIs indicators, the results at 100 years developed by applying the dynamic carbon footprinting approach are compared with those obtained using the IPCC 100-year GWPs. Because the comparisons reveal that the differences at 100 years are small, for simplicity, the contribution, scenarios, and sensitivity analyses results are presented using only 100-year GWPs.

6.1 Woody Mill Residuals

This section presents the results for the woody mill residuals.

6.1.1 Typical Scenario: Base Case Results

The typical scenario was first analyzed with all parameters at their base case values.

6.1.1.1 Greenhouse Gas Impact: Differential GHGI

When using the dynamic carbon footprinting approach, the biomass energy system produces, after 100 years, a greenhouse gas impact that is **116 kg CO_2E lower**[11] per gigajoule of energy produced compared to the defined non-use system. This reduction is **111 kg CO_2E** when applying IPCC 100-year GWPs.

Figure 6.1 presents the 100-year differential GHGI for the biomass energy system compared to the non-use system as well as the contribution of each system component to the results using IPCC 100-year GWPs. In this figure,

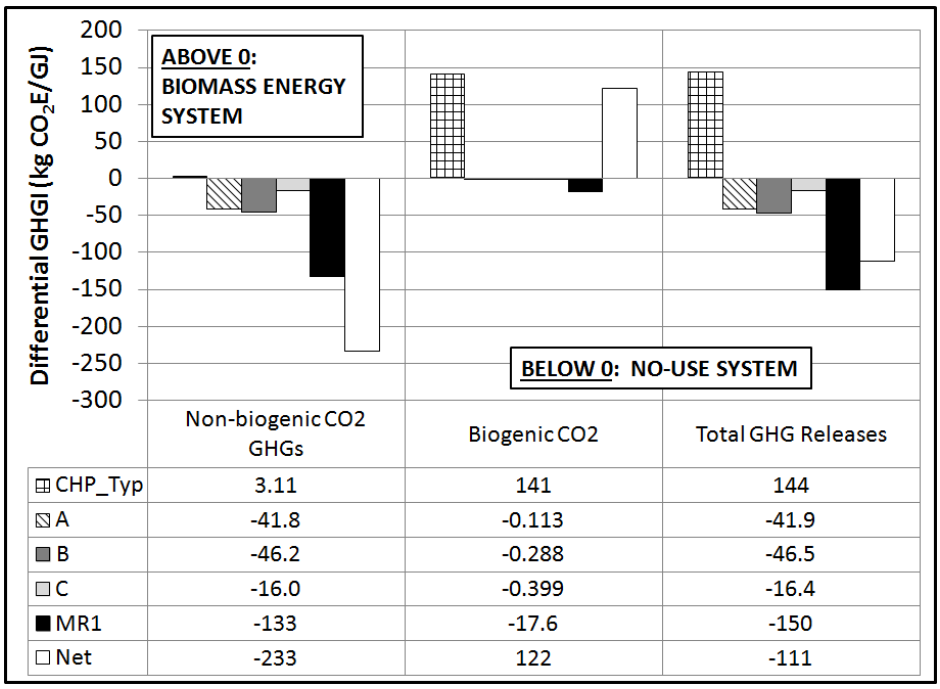
- the GHGI indicator results from the non-biogenic CO_2 releases [which include fossil fuel-related CO_2, CH_4 and N_2O as well as biomass-related CH_4 and N_2O and other GHGs (fossil

[11] Results in this report are always presented as differences (i.e., biomass energy system minus non-use system). The "Relative GHGI" indicator does not include biogenic CO_2. The "Differential GHGI" indicator includes emissions and removals of biogenic CO_2.

fuel- and biomass-related)], the GHGI indicator results from biogenic CO_2 releases and the total GHG releases[12] are depicted separately;
- the results from the biomass energy system are shown as positive numbers;
- the results from the non-use system are shown as negative numbers (because they are avoided);
- the "net" bars represent the sum of the different system components; and
- a net positive indicates that the biomass energy system impacts are greater than the non-use system and a net negative indicates that the biomass energy system impacts are lower than the non-use system (in other words, the more net negative the indicator result, the more beneficial is the biomass energy system).

As shown in this figure, a significant fraction of the difference between the biomass energy and non-use systems is attributable to non-biogenic CO_2 GHGs, i.e., GHGs other than biogenic CO_2. More specifically, the methane emissions from landfills (most of MR1) avoided when burning residuals to produce energy is responsible for a large portion of the benefits from the biomass energy system. Reducing energy production from fossil fuels [i.e., heat from coal (A), heat from natural gas (B), and US average power grid (C)] also contributes to the difference, but to a lesser extent. The greenhouse gas impact caused by the emissions of biogenic CO_2 is different in the two systems (i.e., the net is not zero) for two reasons. First, much of the biogenic carbon is released as methane in the non-use system (included within non-biogenic CO_2 GHGs) and mostly as carbon dioxide in the biomass energy system. Second, some of the carbon is stored in landfills in the non-use system.

[12] In this report, "Total GHG releases" is used as a short form for the sum of non-biogenic CO_2 GHGs and biogenic CO_2 GHGs.



	Non-biogenic CO2 GHGs	Biogenic CO2	Total GHG Releases
CHP_Typ	3.11	141	144
A	-41.8	-0.113	-41.9
B	-46.2	-0.288	-46.5
C	-16.0	-0.399	-16.4
MR1	-133	-17.6	-150
Net	-233	122	-111

Figure 6.1 Contribution Analysis for the Differential GHGI (at 100 Years) for Woody Mill Residuals - Typical Scenario
[In the figure, the different components of the biomass energy system are depicted as follows: CHP system as described in Figure 5.3 (CHP_Typ). The components of the non-use system are depicted as follows: heat from coal (A), heat from natural gas (B), US average power grid (C), residuals in landfills (MR1). Results reflect the use of 100-year GWPs.]

6.1.1.2 Greenhouse Gas Impact: Relative Non-BioCO_2 GHGI

The result for the "Relative Non-BioCO_2 GHGs" indicator is -98.7%[13] for both the dynamic carbon footprinting approach and IPCC 100-year GWPs, meaning that the biomass product system generates almost no GHGs when ignoring biogenic CO_2.

6.1.1.3 Greenhouse Gases: Timing of Impacts

When residuals are burned for energy, the biogenic carbon is immediately released to the atmosphere. In contrast, residuals placed into landfills degrade relatively slowly, releasing the carbon (both CO_2 and CH_4) over time.

Figure 6.2 shows the annual radiative forcing attributable to greenhouse gas emissions from producing 1 GJ of energy in the biomass energy and non-use systems. These values have been calculated based on the dynamic radiative forcing approach, described in Section 4.1.6.1 of this report.[14] An explanation of the factors contributing to the radiative forcing is shown in Table 6.1.

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[13] Non-biogenic CO_2 GHGs only. Calculated as follows: (CHP_Typ - A - B - C - MR1)/(A+B+C+MR1).
[14] In Figure 6.2 and Figure 6.3, radiative forcing due to the GHG emissions is plotted in units of Wm^{-2} instead of units of CO_2E because, when using dynamic radiative forcing calculations, the relationship between annual and cumulative results is much easier to illustrate visually using units of Wm^{-2}. For other residuals addressed later in this report, only the differential cumulative results are shown.

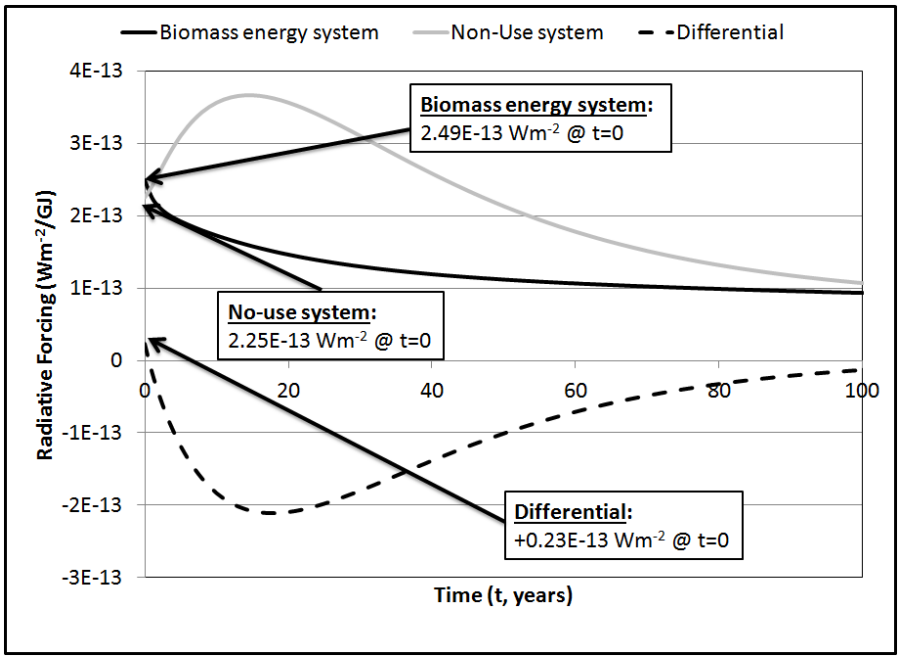


Figure 6.2 Annual GHG Impact for the Biomass Energy and Non-Use Systems: Woody Mill Residuals - Typical Scenario

Table 6.1 Explanation of Annual Emissions, Woody Mill Residuals, Dynamic Carbon Footprinting

Time (years)	Biomass Energy System	Non-Use System	Differential (i.e., biomass energy system minus non-use system)
t = 0	The woody residuals are burned, releasing GHGs, which result in radiative forcing at the time of combustion of 2.49E-13 Wm^{-2}.	The fossil fuels are burned, releasing GHGs, which result in radiative forcing at the time of combustion of 2.25E-13 Wm^{-2}. Biomass residuals are placed in landfills. There are no releases from the landfills at time 0.	The differential radiative forcing is positive (0.23E-13 Wm^{-2}) because at time 0 there is more forcing from the emissions released by the biomass energy system than from the non-use system.
$0 < t < \infty$	There are no additional emissions from the biomass energy system. The radiative forcing caused each year by GHGs released in year 0 slowly declines as these GHGs degrade (e.g., CH_4) or are removed from the atmosphere (e.g., CO_2).	Although there are no additional emissions from combustion, residuals start degrading in landfills releasing GHGs. In each year, there is radiative forcing from landfill GHGs released in the current year plus forcing due to GHGs released in previous years that are still in the atmosphere. During the period that landfill emissions are high, annual radiative forcing increases because the forcing from new emissions increases faster than previously emitted GHGs are removed from the atmosphere. Over time, however, the GHG releases from landfills decline and approach zero and the GHGs in the atmosphere degrade (e.g., CH_4) or are removed from the atmosphere (e.g., CO_2). As a result, the annual radiative forcing approaches zero.	The differential radiative forcing goes through a minimum and then increases, approaching zero, because the emissions from both systems eventually degrade or are removed from the atmosphere.

While Figure 6.2 shows the annual radiative forcing, Figure 6.3 shows the same data but plotted as cumulative radiative forcing, in units of Wm^{-2}, associated with emissions of GHGs in the biomass energy and non-use systems for woody mill residuals as a function of time. An explanation of the sources of this radiative forcing is provided in Table 6.2. Figure 6.3 shows that the differential radiative forcing is initially positive because the forcing due to the emissions from the biomass energy system is higher than that for the non-use system. The differential cumulative greenhouse gas impact quickly becomes negative, however, as landfill emissions increase in the non-use scenario. The figure shows that, under the typical scenario assumptions (e.g., alternative fate is 100% landfill), it takes 1.2 years before the cumulative radiative forcing due to GHG releases in the biomass energy system is less than the radiative forcing due to releases in the non-use system.

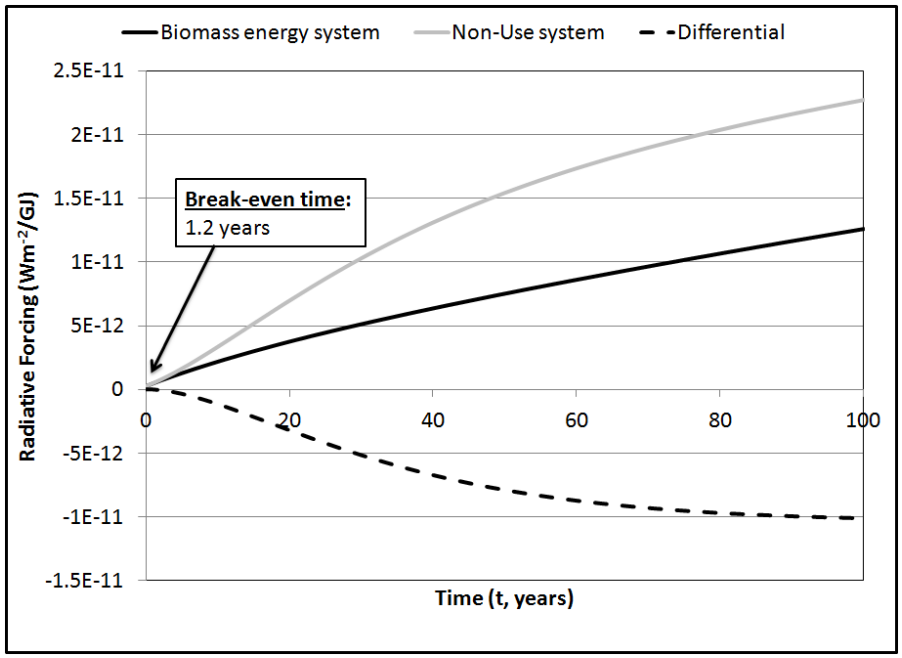


Figure 6.3 Cumulative GHG Impact for the Biomass Energy and Non-use Systems: Woody Mill Residuals - Typical Scenario

Table 6.2 Explanation of Cumulative Emissions, Woody Mill Residuals

Time (years)	Biomass Energy System	Non-Use System	Differential (i.e., biomass energy system minus non-use system)
t = 0	The woody residuals are burned, releasing GHGs, which result in radiative forcing at the time of combustion of 2.49E-13 Wm^{-2}.	The fossil fuels are burned, releasing GHGs, which result in radiative forcing at the time of combustion of 2.25E-13 Wm^{-2}. Biomass residuals are placed in landfills. There are no releases from the landfills at time 0.	The differential radiative forcing is positive (0.23E-13 Wm^{-2}) because at time 0, there is more forcing from the emissions released by the biomass energy system than from the non-use system.
$0 < t < 1.2$	There are no new emissions from the biomass energy system. The initially released GHGs remain in the atmosphere for a period of time, so each year, the cumulative radiative forcing increases.	Biomass residuals placed in landfills start to degrade, releasing GHGs. The cumulative GHG emissions, and their cumulative radiative forcing, increase rapidly.	The difference in cumulative radiative forcing decreases as the forcing associated with the non-use system increases more rapidly that that associated with the biomass energy system.
t = 1.2	Cumulative radiative forcing reaches 5.2E-13 Wm^{-2}.	Cumulative radiative forcing reaches 5.2E-13 Wm^{-2}.	The cumulative differential radiative forcing is 0 (break-even time).
$1.2 < t < \infty$	There are no new emissions from the biomass energy system but cumulative forcing continues to increase until all GHGs are removed from the atmosphere.	The emissions from the landfill continue for a considerable period. Cumulative radiative forcing continues to increase until all GHGs released from fossil fuel combustion and from disposal operations are removed from the atmosphere.	At 100 years, the difference in cumulative radiative forcing is -1.01E-11 Wm^{-2}. The difference changes only slowly after this point.

Figure 6.4 compares the timing of differential cumulative GHGI results obtained using the dynamic carbon footprinting approach with those obtained using IPCC 100-year GWPs, both in units of kg CO_2E. In both approaches, the difference in emissions between the two systems is computed for each year. The dynamic approach calculates the environmental impact in terms of the radiative forcing that is associated with GHGs remaining in the atmosphere attributable to all current and past emissions. Each year's forcing is added to past years to obtain cumulative radiative forcing. The IPCC approach calculates impact by assigning each year's emissions an impact equal to the cumulative radiative forcing occurring over 100 years, using 100-year GWPs. Both approaches consider the timing of emissions but only the dynamic approach accurately characterizes the timing of the warming associated with those emissions.

The first observation that can be made from Figure 6.4 is that the differential cumulative GHGI results decline faster when using the dynamic carbon footprinting approach than with IPCC GWPs. In other words, more short-term benefits from using biomass residuals for energy production are observed when applying dynamic carbon footprinting. The break-even time is 1.2 years using dynamic carbon footprinting and 7.5 years when using IPCC global warming potentials. The difference is due to the methane released from the landfills under the non-use scenario. Methane is a potent greenhouse gas but it has a short lifetime in the atmosphere so its greenhouse gas impact is

concentrated in the years immediately following its release, as opposed to carbon dioxide, which is much more persistent. This short-term warming effect of methane is captured by the dynamic approach but not by the use of 100-year GWPs.

Because both approaches are affected by the timing of emissions, and because methane emissions are higher in the earlier years of the simulation, both approaches show the benefits (i.e., negative differential impacts) increasing more rapidly in the early years. Because the 100-year GWPs approach is affected only by emissions timing, the curve flattens out as methane generation slows. In the case of the dynamic approach, the benefits accrue more rapidly in the early years but diminish later in the simulation as methane in the atmosphere decomposes to CO_2, exerting a lower radiative forcing effect and reducing the differences between the biomass energy and non-use systems. As methane generation ceases and all of the methane in the atmosphere decomposes to CO_2, the results for the two approaches converge.

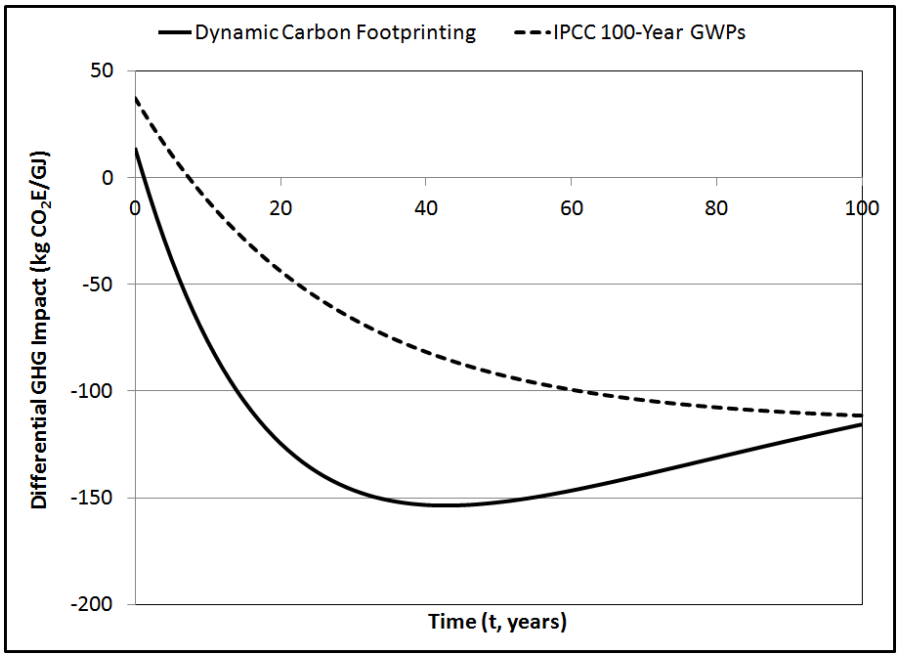


Figure 6.4 Emissions Timing: Comparing Results Based on Dynamic Carbon Footprinting and IPCC 100-Year GWPs

6.1.1.4 ***Consumption of Fossil Fuels***

Figure 6.5 shows the relative consumption of fossil fuels ("Relative FF CON," biomass energy system compared to non-use system). It can be seen from the figure that fossil fuel use in the biomass energy system is 100% lower; virtually no fossil fuels are used in the biomass energy system. It can also be seen from the figure that the main contributor to the difference between the systems is the heat from natural gas in the non-use system.

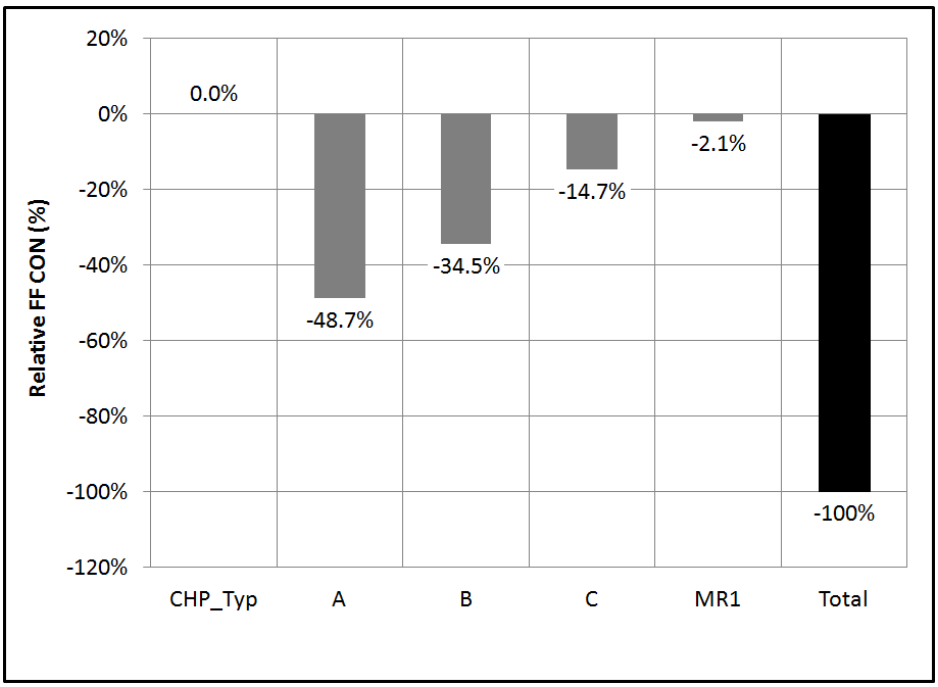


Figure 6.5 Relative Consumption of Fossil Fuels for Woody Mill Residuals - Typical Scenario [In the figure, the different components of the biomass energy system are depicted as follows: CHP system as described in Figure 5.3 (CHP_Typ). The components of the non-use system are depicted as follows: heat from coal (A), heat from natural gas (B), US average power grid (C), residual in landfills (MR1).]

6.1.2 Typical Scenario: Perturbation and Sensitivity Analyses

6.1.2.1 Perturbation Analyses

As mentioned in Section 4.1.3, sensitivity ratios represent the percent change in an output variable caused by a 1% change in one given input variable. For simplicity and given that the GHGI results do not vary significantly over a 100-year period depending on the approach used, perturbation analyses were performed using IPCC 100-year GWPs. Figure 6.6 shows the sensitivity ratios for the four indicators analyzed in this study, for woody mill residuals. The following input variables were tested in sensitivity analyses: transportation distance of the residuals (Distance), their water content (WC_R), their heating value (HHV), and the fraction of their carbon content that is non-degradable carbon (F_{CCND}).

The results depicted in Figure 6.6 should be interpreted as follows. A sensitivity ratio of +1.0 means that value of the output variable increases by 1% when the input variable value is increased by 1%. The greater the absolute value of the sensitivity ratio, the more intrinsically sensitive a parameter was.

It can be seen from Figure 6.6 that transportation distance of residuals to the boiler had very little effect on the "Differential GHGI" indicator results when compared to the other studied parameters. The fraction of non-degradable carbon (F_{CCND}) had the most significant effect on the results, with sensitivity ratios of 4.5. The positive ratio means that when increasing the value of the parameter, the indicator result is also increased, indicating a declining performance of the biomass energy system compared to the non-use system. Increasing the water content of the residuals, and thus reducing the boiler efficiency, produced a negative sensitivity ratio, i.e., a positive effect on the results. This is because on a per gigajoule basis, more residuals are required to produce the energy and thus more

landfilling, and associated methane emissions from landfills, are avoided. The opposite can be seen when increasing the higher heating value.

The time for the biomass energy system to have lower cumulative emissions than the non-use system ("break-even time" in Figure 6.6) was significantly affected, relatively speaking, by the various parameters analyzed, except for the transportation distance of residuals.

Finally, overall, the relative GHGI and relative fossil fuel consumption (FF CON) indicator results were not significantly affected by the parameters analyzed.

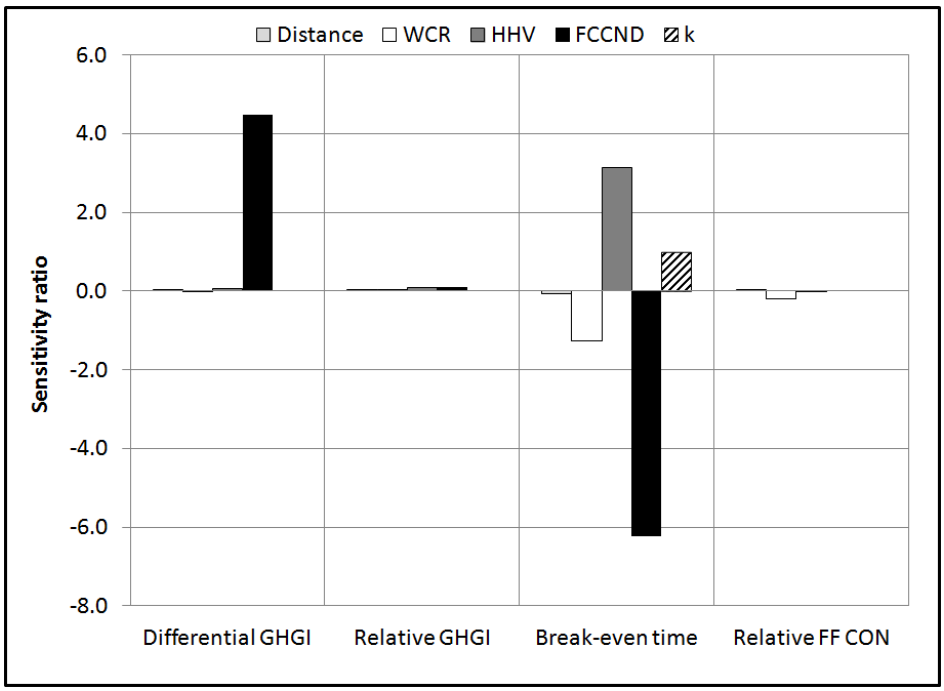


Figure 6.6 Sensitivity Ratios for Woody Mill Residuals

6.1.2.2 ***Sensitivity Analyses***

Table 6.3 shows the results of sensitivity analyses considering the actual possible ranges of variation for each parameter. It is shown that the range of the fraction of carbon in woody mill residuals that is non-degradable under anaerobic conditions (F_{CCND}) had the most effect on the results. With the higher fraction considered, smaller benefits are observed from the combustion of woody mill residuals, whereas with the lower value of F_{CCND}, benefits are far higher and break-even times far shorter than those calculated in the typical scenario.

Table 6.3 Sensitivity Analyses on Indicator Results for the Typical Scenario, Woody Mill Residuals

Parameter	Differential GHGI* (kg CO_2E/GJ)			Relative Non-BioCO_2 GHGI* (%)			Break-Even Time* (years)			Relative FF CON (%)		
	Typ	Min	Max	Typ	Min	Max	Typ	Min	Max	Typ	Min	Max
WC_R	-111†	-110	-112	-98.7‡	-98.6	-98.8	7.5§	3.2	9.6	-100	-100	-100
HHV		-110	-115		-98.4	-98.8		1.1	17.6		-100	-100
F_{CCND}		-27.2	-286		-97.5	-99.2		3.2	22.0		-100	-100
Transp. of residuals		-109	-111		-97.8	-98.7		7.5	7.9		-98.2	-100
k		-94.1	-114		-98.6	-98.7		1.3	3.5		-100	-100

*Computed using IPCC 100-Year GWPs. †-116 kg CO_2E/GJ using dynamic modeling of cumulative radiative forcing. ‡ -98.7% using dynamic modeling of cumulative radiative forcing. §1.2 years using dynamic modeling of cumulative radiative forcing.

6.1.3 System Configuration Scenarios

In Section 5.0, various system configuration scenarios were presented. For instance, it was noted that the alternative fate of woody mill residuals was difficult to determine. System configuration scenarios were used to analyze those system configuration assumptions that were uncertain.

All possible scenario combinations presented in Section 5.1 were analyzed (132 combinations). The calculations were performed using IPCC 100-year GWPs. Results are presented in Table 6.4 for cases where parameters would be at their base case value. GHG releases and fossil fuel consumption are significantly lower for all scenarios. Maximum differences were obtained in scenarios in which

- there is no size reduction;
- combined heat and power with maximum power production is produced;
- coal is being displaced (for both heat and power production);
- there is no transportation; and
- alternative fate is landfilling.

Minimum differences were obtained in scenarios in which

- there is size reduction;
- only heat is produced;
- natural gas is being displaced (for both heat and power production);
- there is transportation; and
- alternative fate is incineration.

Results in Table 6.4 also show that the time for the biomass energy system to have lower cumulative emissions than the non-use system varies between 0 and 9.7 years, the lowest being observed when incineration is the alternative fate.

Table 6.4 Indicator Results for Various System Configuration Scenarios, Woody Mill Residuals

Indicator	Unit	Typical	Min	Max
Differential GHGI*	kg CO_2E/GJ	-111†	-78.4	-312
Relative non-BioCO_2 GHGI*	%	-98.7‡	-94.9	-99.3
Break-even time*	years	7.5§	0	9.7
Relative FF CON	%	-100%	-98.5	-100

*Computed using IPCC 100-Year GWPs. † -116kgCO_2E/GJ using dynamic modeling of cumulative radiative forcing. ‡ -98.7% using dynamic modeling of cumulative radiative forcing. §1.2 years using dynamic modeling of cumulative radiative forcing.

6.2 WWTP Residuals

This section presents results for the WWTP residuals.

6.2.1 Typical Scenario: Base Case Results

The typical scenario was first analyzed with all parameters at their base case values.

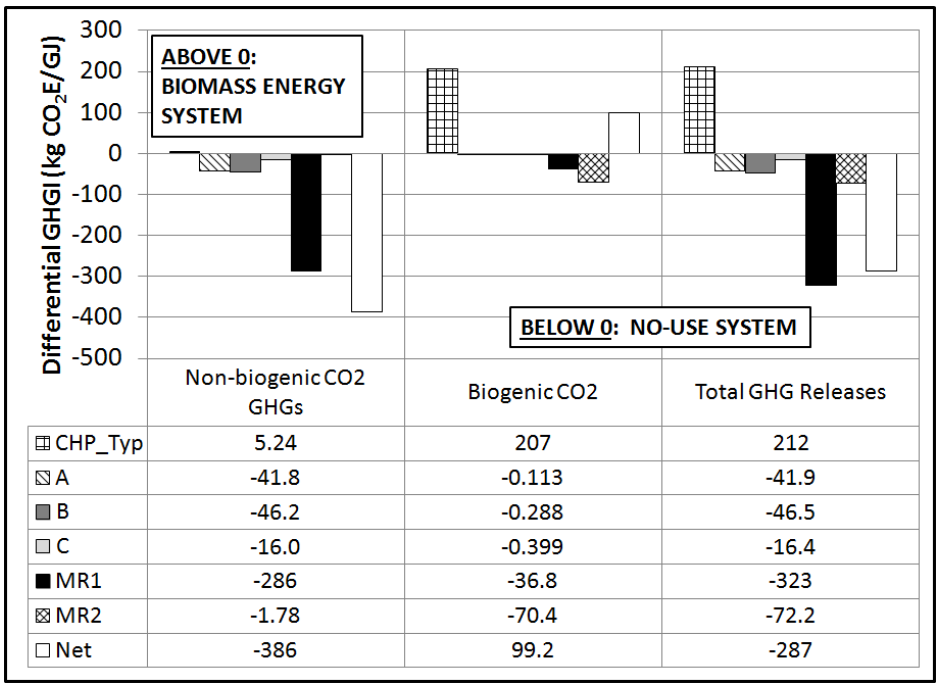
6.2.1.1 Greenhouse Gases: Differential GHGs

When using the dynamic carbon footprinting approach, the biomass energy system produces, after 100 years, a greenhouse gas impact that is **295 kg CO_2E lower**[15] per gigajoule of energy produced compared to the defined non-use system. This reduction is **287 kg CO_2E** when applying IPCC 100-year GWPs.

Figure 6.7 presents the 100-year differential GHGI for the biomass energy system compared to the non-use system as well as the contribution of each system component to the results using IPCC 100-year GWPs. In this figure, emissions from the non-use system are shown as a negative number because to obtain the Differential GHGs indicator overall result, the emissions of the non-use scenario were subtracted from those of the biomass energy system.

The figure shows that non-biogenic CO_2 GHGI is mostly lower because when burning residuals to produce energy, there are no methane emissions from landfills. The fact that there is less heat generated from fossil fuels also contributes to the lower impact, but to a lesser extent. Emissions of biogenic CO_2 are different in the two systems for two reasons. First, much of the biogenic carbon is released as methane in the non-use system (included within non-biogenic CO_2 GHGs) and mostly as CO_2 in the biomass energy system. Second, some of the carbon is stored in landfills in the non-use system.

[15] Results in this report are always presented as differences (i.e., biomass energy system minus non-use system). The "Relative GHGI" indicator does not include biogenic CO_2. The "Differential GHGI" indicator includes emissions and removals of biogenic CO_2.



	Non-biogenic CO2 GHGs	Biogenic CO2	Total GHG Releases
CHP_Typ	5.24	207	212
A	-41.8	-0.113	-41.9
B	-46.2	-0.288	-46.5
C	-16.0	-0.399	-16.4
MR1	-286	-36.8	-323
MR2	-1.78	-70.4	-72.2
Net	-386	99.2	-287

Figure 6.7 Contribution Analysis for the Differential GHGI (at 100 Years) for WWTP Residuals - Typical Scenario

[In the figure, the different components of the biomass energy system are depicted as follows: CHP system as described in Figure 5.4 (CHP_Typ). The components of the non-use system are depicted as follows: heat from coal (A), heat from natural gas (B), US average power grid (C), residual in landfills (MR1), incineration of residuals (MR2). Results reflect the use of 100-year GWPs.]

6.2.1.2 Greenhouse Gases: Relative Non-BioCO_2 GHGs

The result for the "Relative Non-BioCO_2 GHGs" indicator is -98.7%[16] (-99.1% using IPCC GWPs), meaning that the biomass energy system generates almost no GHGs when ignoring biogenic CO_2 and hence, produces a significant reduction when compared to the non-use system.

6.2.1.3 Greenhouse Gases: Timing of Impacts

When WWTP residuals are burned for energy, the related biogenic carbon is released to the atmosphere immediately. In contrast, WWTP residuals placed into landfills degrade slowly, releasing the related biogenic carbon (both CO_2 and CH_4) over time. Figure 6.8 presents the results of the "Differential GHGI" indicator over time using U.S. EPA's decay rates for materials placed in municipal landfills, for the typical scenario. These results were developed using the dynamic carbon footprinting approach described in Section 4.1.6.1 of this report and are expressed in units of radiative forcing (Wm^{-2}). The net difference is initially negative (i.e., the impact from the biomass energy system is lower than that from the no-use system from time equals zero, meaning that the break-even time is zero) and then declines over time as the material degrades in landfills. When using IPCC 100-year GWPS, the difference in impact is initially positive and the break-even time is observed at 1.8 years.

[16] Non-biogenic CO_2 GHGs only. Calculated as follows: (CHP_Typ - A - B - C - MR1- MR2)/ (A+B+C+MR1+MR2).

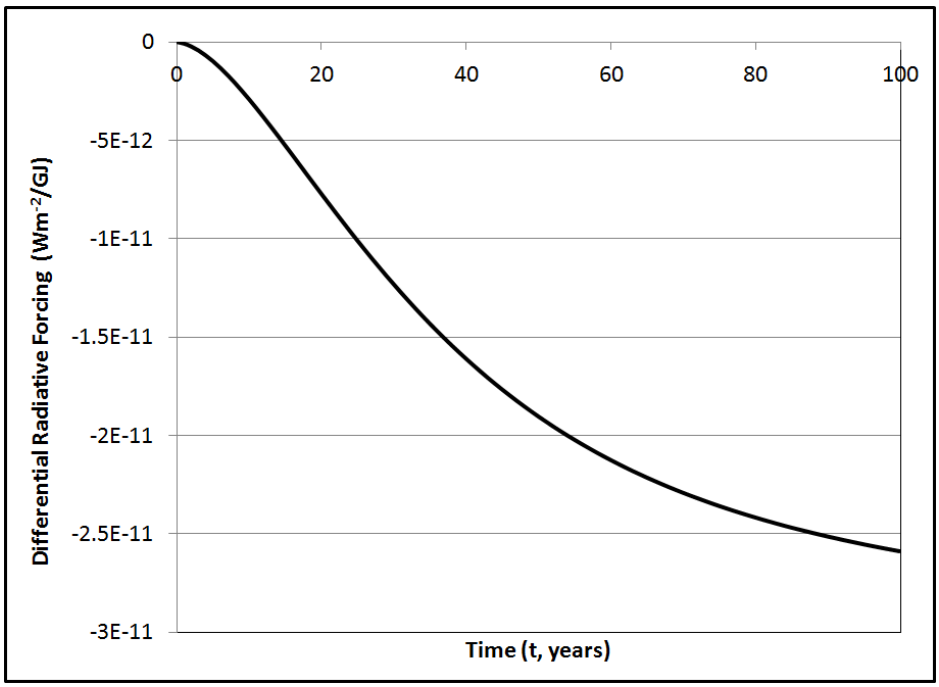


Figure 6.8 Cumulative Differential GHGI Indicator Results as a Function of Time for WWTP Residuals - Typical Scenario

6.2.1.4 ***Consumption of Fossil Fuels***

Figure 6.9 shows the results for the relative consumption of fossil fuels indicator ("Relative FF CON," biomass energy system compared to non-use system).

It can be seen from Figure 6.9 that the biomass energy system used 99.3% less fossil fuel when compared to the non-use system defined in this study. This is due to the fact that virtually no fossil fuels are used in the biomass energy system. It can also be seen from the figure that the main contributor to the lower emissions is avoided heat from natural gas.

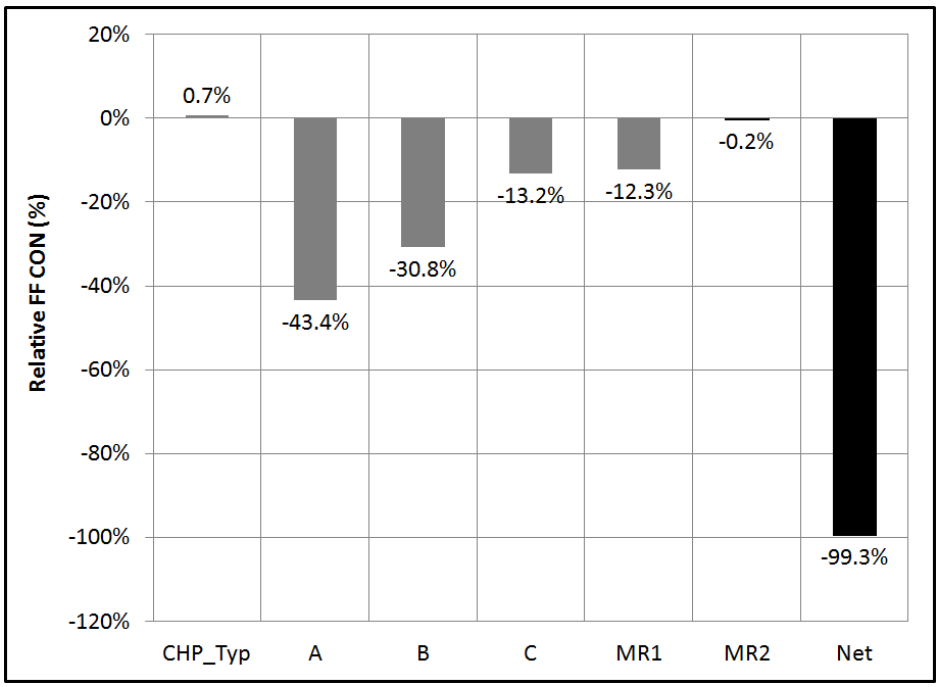


Figure 6.9 Relative FF CON Indicator Results for WWTP Residuals - Typical Scenario
[In the figure, the different components of the biomass energy system are depicted as follows: CHP system as described in Figure 5.4 (CHP_Typ). The components of the non-use system are depicted as follows: heat from coal (A), heat from natural gas (B), US average power grid (C), residual in landfills (MR1), incineration of residuals (MR2).]

6.2.2 Typical Scenario: Perturbation and Sensitivity Analyses

6.2.2.1 Perturbation Analyses

Various parameters were analyzed in perturbation analyses. For each of these parameters, a sensitivity ratio was calculated (see Section 4.1.3). For simplicity and given that the GHGI results do not vary significantly over a 100-year period depending on the approach used, perturbation analyses were performed using IPCC 100-year GWPs.

Sensitivity ratios for the parameters tested in this study are presented in Figure 6.10. It can be seen from that figure that the carbon content of the residuals has the most significant effect on the GHGI results, with a sensitivity ratio of -1.3. The negative ratio means that when increasing the value of the parameter, the score is decreased, indicating an improving performance of the biomass energy system compared to the non-use system. The fraction of non-degradable carbon (F_{CCND}) also has a significant effect on the Differential GHGs results, with a sensitivity ratio of 1.1. The positive ratio means that when increasing the value of the parameter, the score is also increased, indicating a declining performance of the biomass energy system compared to the non-use system. Increasing the water content of the residuals, and thus reducing the boiler efficiency, produced a negative sensitivity ratio, i.e., a positive effect on the results. This is because on a per gigajoule basis, more residuals are required to produce the energy; thus, more landfilling and associated methane emissions from landfills are avoided. The opposite can be seen when increasing the higher heating value. Overall, Relative GHGs and fossil fuel consumption results were not significantly affected by the parameters analyzed. Break-even time was shown, relatively speaking, to be highly sensitive to all parameters tested, with the exception of the ash content.

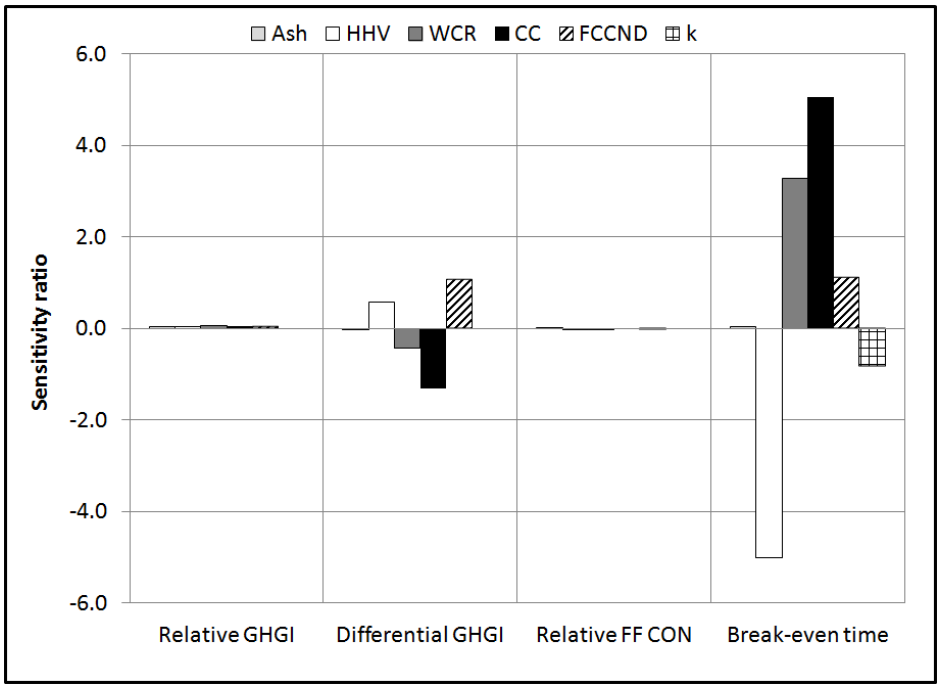


Figure 6.10 Sensitivity Ratios for WWTP Residuals

*6.2.2.2 **Sensitivity Analyses***

Above, perturbation analyses were applied to determine which parameters were intrinsically the most sensitive to the results without considering the actual ranges of possible values for these parameters. In Table 6.8, the results of sensitivity analyses considering the actual possible ranges of variation for each parameter are presented. It is shown that the range of possible heating values and carbon content for WWTP residuals had the most effect on the results. Also, even in the worst conditions, the GHG benefits of the biomass energy system compared to the non-use system are still considerable.

Table 6.5 Sensitivity Analyses on Indicator Results for the Typical Scenario, WWTP Residuals

Para-meter	Differential GHGI* (kg CO_2E/GJ)			Relative Non-BioCO_2 GHGI* (%)			Break-Even Time* (years)			Relative FF CON (%)		
	Typ	Min	Max	Typ	Min	Max	Typ	Min	Max	Typ	Min	Max
WC_R	-287†	-271	-310	-99.1 ‡	-98.6	-98.7	1.8§	1.0	3.0	-99.3	-99.2	-99.4
HHV		-242	-378		-98.5	-98.8		0	5.6		-99.0	-99.5
Ash		-287	-288		-98.5	-98.8		1.9	3.0		-98.8	-99.8
CC		-178	-309		-97.7	-98.8		0	3.0		-99.3	-99.3
F_{CCND}		-226	-349		-98.4	-98.8		1.6	2.4		-99.3	-99.3
k		-287	-287		-98.7	-98.7		1.3	3.5		-99.3	-99.3

*Computed using 100-year GWPs.†-295 kg CO_2E/GJ using dynamic modeling of cumulative radiative forcing. ‡-98.7% using dynamic modeling of cumulative radiative forcing. §0.0 years using dynamic modeling of cumulative radiative forcing.

6.2.3 System Configuration Scenarios

In Section 5.0, various system configuration scenarios were presented. All relevant scenario combinations were analyzed (40 combinations). Results are presented in Table 6.6 for scenarios where parameters would be at their base case values. Results obtained for the typical scenarios are also reproduced in this table for comparison purposes. GHG releases and fossil fuel consumption are significantly lower for all scenarios. Maximum differences were obtained in scenarios in which

- combined heat and power with maximum power production is produced;
- coal is being displaced (for both heat and power production); and
- alternative fate is landfilling.

Minimum differences were obtained in scenarios in which

- only heat is produced;
- natural gas is being displaced (for both heat and power production); and
- alternative fate is incineration.

Table 6.6 Indicator Results for Various System Configuration Scenarios - WWTP Residuals

Indicator	Unit	Typical	Min	Max
Differential GHGI*	kg CO_2E/GJ	-287†	-79.5	-589
Relative Non-BioCO_2 GHGs *	%	-99.1‡	-93.9	-99.3
Break-even time*	years	1.8§	0	6.4
Relative FF CON	%	-99.3	-99.1	-99.7

*Computed using 100-year GWPs.†-295 kg CO_2E/GJ using dynamic modeling of cumulative radiative forcing. ‡-98.7% using dynamic modeling of cumulative radiative forcing. §0.0 years using dynamic modeling of cumulative radiative forcing

6.3 Paper Recycling Residuals

6.3.1 Typical Scenario: Base Case Results

The typical scenario was first analyzed with all parameters at their base case values.

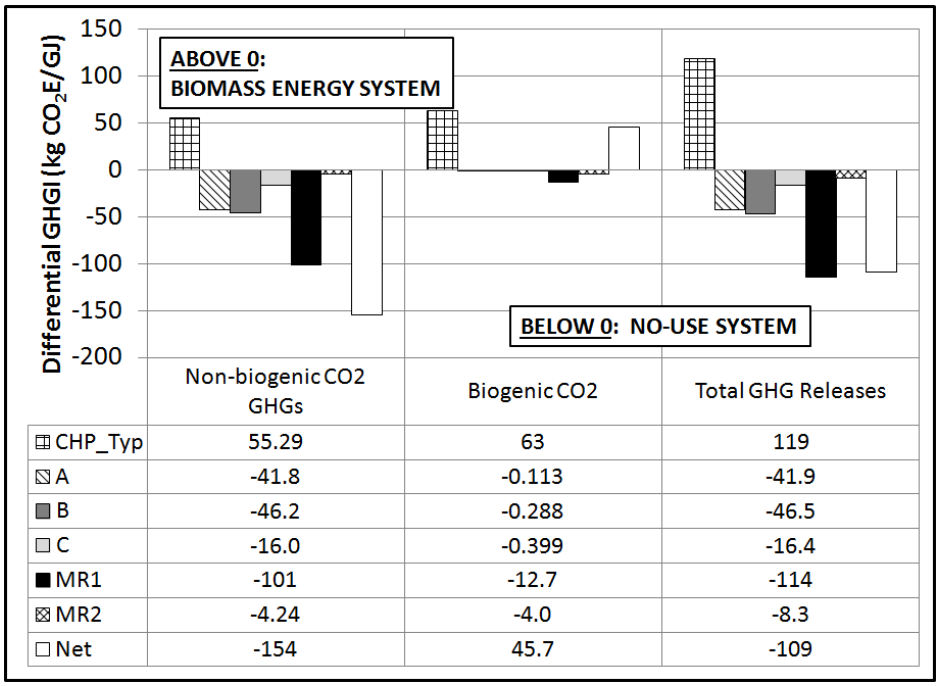
6.3.1.1 Greenhouse Gases: Differential GHGs

When using the dynamic carbon footprinting approach, the biomass energy system produces, after 100 years, a greenhouse gas impact that is **112 kg CO_2E lower**[17] per gigajoule of energy produced compared to the defined non-use system. This reduction is **109 kg CO_2E** when applying IPCC 100-year GWPs.

Figure 6.11 shows that the non-biogenic CO_2 GHGI is mostly lower because when burning residuals to produce energy, there are no methane emissions from landfills. Alone, the avoided methane emissions from landfills lower the impact by 154 kg CO_2E/GJ. The fact that there is less heat from fossil fuels also contributes to the lower impact, but to a lesser extent. Emissions of biogenic CO_2 are

[17] Results in this report are always presented as differences (i.e., biomass energy system minus non-use system). The "Relative GHGI" indicator does not include biogenic CO_2. The "Differential GHGI" indicator includes emissions and removals of biogenic CO_2.

different in the two systems for two reasons. First, much of the biogenic carbon is released as methane in the non-use system (included within non-biogenic CO_2 GHGs) and mostly as CO_2 in the biomass energy system. Second, some of the carbon is stored in landfills in the non-use system.



	Non-biogenic CO2 GHGs	Biogenic CO2	Total GHG Releases
CHP_Typ	55.29	63	119
A	-41.8	-0.113	-41.9
B	-46.2	-0.288	-46.5
C	-16.0	-0.399	-16.4
MR1	-101	-12.7	-114
MR2	-4.24	-4.0	-8.3
Net	-154	45.7	-109

Figure 6.11 Contribution Analysis for the Differential GHGI (at 100 Years) for Paper Recycling Residuals - Typical Scenario

[In the figure, the different components of the biomass energy system are depicted as follows: CHP system as described in Figure 5.5 (CHP_Typ). The components of the non-use system are depicted as follows: heat from coal (A), heat from natural gas (B), US average power grid (C), residual in landfills (MR1), incineration of residuals (MR2). Results reflect the use of 100-year GWPs.]

*6.3.1.2 **Greenhouse Gases: Relative Non-BioCO_2 GHGs***

The result for the "Relative Non-BioCO_2 GHGI" indicator is -86.4%[18] (-75.2% when using IPCC GWPs), meaning that the biomass product system generates almost no GHGs when ignoring biogenic CO_2. When compared to other types of residuals presented above (woody mill residuals and WWTP residuals), the use of paper recycling residuals presents significantly lower overall benefits. This is because paper recycling residuals are composed of an important fraction of plastic which, when combusted, releases fossil fuel GHGs.

*6.3.1.3 **Greenhouse Gases: Emissions Timing***

When paper recycling residuals are burned for energy, the biogenic carbon (both CO_2 and CH_4) is immediately released to the atmosphere. In contrast, residuals placed into landfills degrade slowly, releasing the carbon over time. Figure 6.12 analyzes the "Differential GHGI" indicator results over time using U.S. EPA's decay rate for materials placed in municipal landfills for the typical scenario.

[18] Non-biogenic CO_2 GHGs only. Calculated as follows: (CHP_Typ - A - B - C - MR1 - MR2)/ (A+B+C+MR1+MR2).

It shows that the differential impact is initially slightly negative (i.e., the impact from the biomass-based system is lower than that from the fossil fuel-based system, meaning that the break-even time is zero) and declines over time as the material degrades in landfills. When using the IPCC GWPs, the break-even time is also zero years.

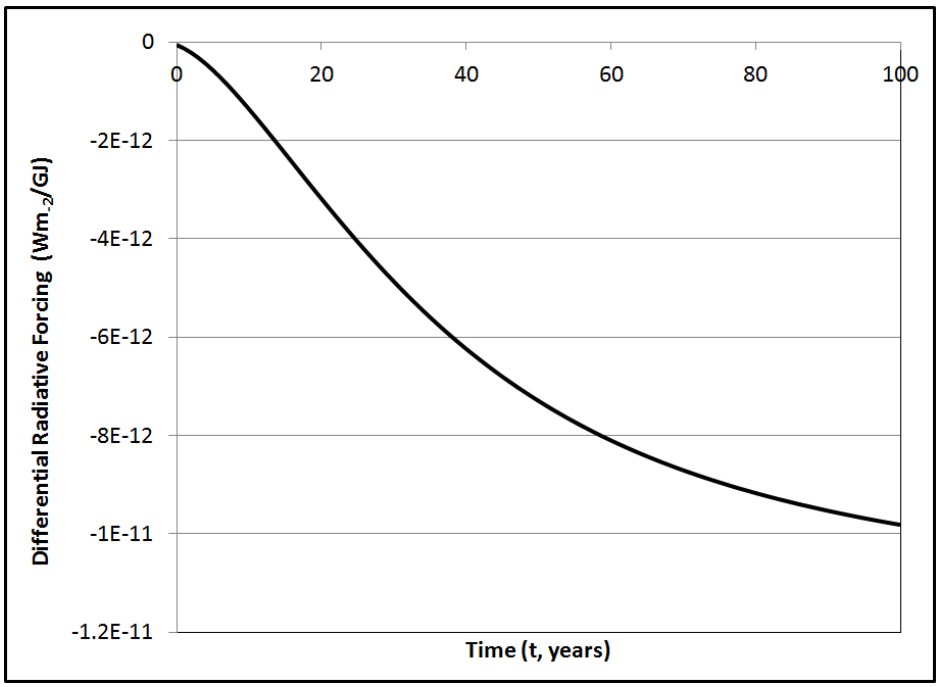


Figure 6.12 Cumulative Differential GHGI Indicator Results as a Function of Time for Paper Recycling Residuals - Typical Scenario

6.3.1.4 ***Consumption of Fossil Fuels***

Figure 6.13 shows the relative consumption of fossil fuels ("Relative FF CON," biomass energy system compared to non-use system) for paper recycling residuals.

It can be seen from that figure that the biomass energy system uses 99.9% less fossil fuel than the non-use system. This is due to the fact that virtually no fossil fuels are used in the biomass energy system. It can also be seen from the figure that the main contributor to the lower emissions is avoided heat from natural gas. Note that the plastic fraction of paper recycling residuals was not considered to be fossil fuel.

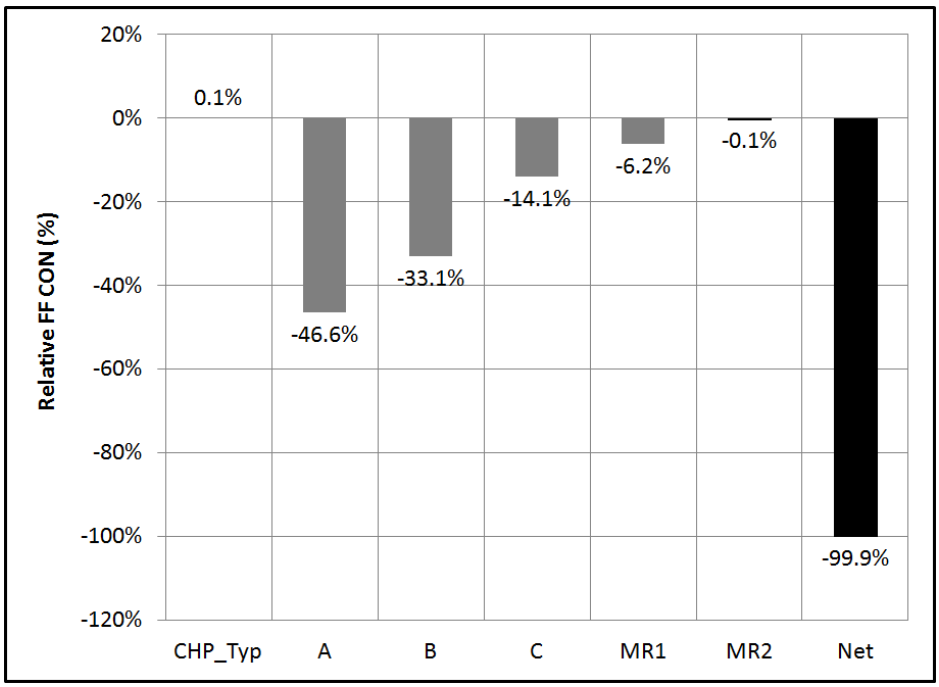


Figure 6.13 Relative Consumption of Fossil Fuels for Paper Recycling Residuals - Typical Scenario [In the figure, the different components of the biomass energy system are depicted as follows: CHP system as described in Figure 5.5 (CHP_Typ). The components of the non-use system are depicted as follows: heat from coal (A), heat from natural gas (B), US average power grid (C), residual in landfills (MR1), incineration of residuals (MR2).]

6.3.2 Typical Scenario: Perturbation and Sensitivity Analyses

6.3.2.1 Perturbation Analyses

Various parameters were analyzed in perturbation analyses. For each of these parameters, a sensitivity ratio was calculated (see Section 4.1.3). Sensitivity ratios for the parameters tested in this study are presented in Figure 6.14. Sensitivity ratios are not shown for break-even times as they were initially zero. It can be seen from Figure 6.14 that the fraction of non-degradable carbon (F_{CCND}) and the fiber fraction of paper recycling residuals have the most significant effect on the results, with sensitivity ratios up to 1.5. The positive ratio obtained for F_{CCND} means that when increasing the value of the parameter, the score is also increased, indicating a declining performance of the biomass energy system compared to that of the non-use system. Increasing the fiber fraction resulted in a negative sensitivity ratio. This means the biomass energy system generated lower emissions or consumed less fossil fuel than the non-use system. The water content of the residuals had little effect on the results compared to the other parameters. Finally, overall, fossil fuel consumption scores were not significantly affected by the parameters analyzed.

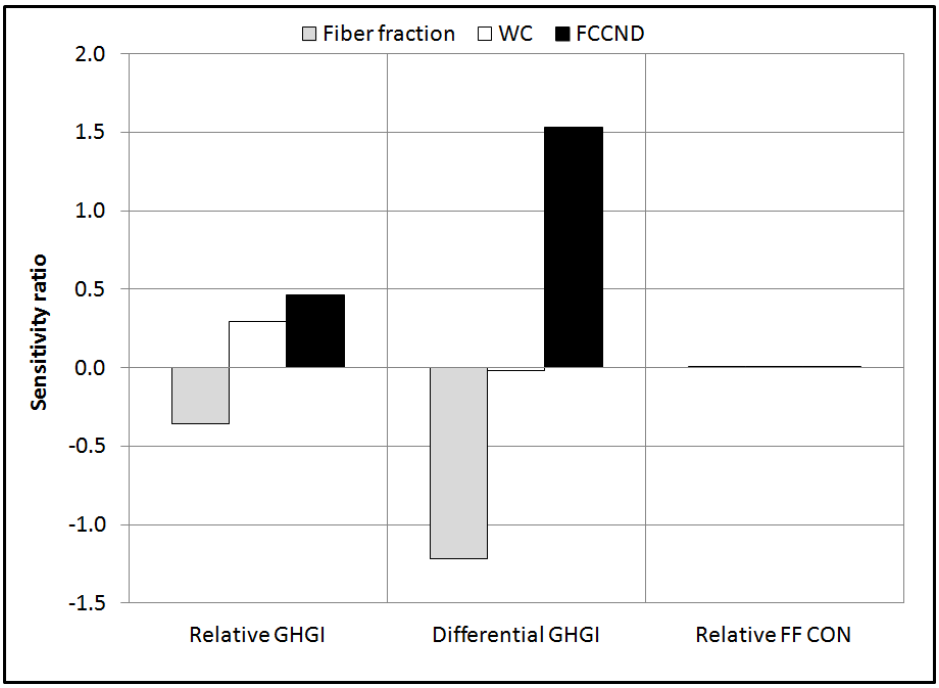


Figure 6.14 Sensitivity Ratios for Paper Recycling Residuals: Relative Non-BioCO_2 GHGs, Differential GHGs, and Relative FF CON

*6.3.2.2 **Sensitivity Analyses***

Above, perturbation analyses were applied to determine which parameters were intrinsically the most sensitive to the results without considering the actual ranges of possible values for these parameters. In Table 6.7, the results of sensitivity analyses considering the actual possible ranges of variation for each parameter are presented. It is shown that the range of possible heating values for paper recycling residuals had the most effect on the results. Also, even with the highest heating value for residuals, the GHG benefits of the biomass energy system compared to the non-use system are still considerable.

Table 6.7 Sensitivity Analyses on Indicator Results for the Typical Scenario, Paper Recycling Residuals

Para-meter	Differential GHGI* (kg CO_2E/GJ)			Relative Non-BioCO_2 GHGI* (%)			Break-Even Time* (years)			Relative FF CON (%)		
	Typ	Min	Max	Typ	Min	Max	Typ	Min	Max	Typ	Min	Max
Fiber fraction	-109 †	-57.8	-191	-75.2 ‡	-49.6	-93.2	0§	0	2.3	-99.9	-99.9	-99.9
WC_R		-108	-109		-71.5	-75.1		0	3.4		-99.9	-99.9
FCCND		-109	-166		-75.2	-78.7		0	0		-99.9	-99.9
K		-109	-109		-75.2	-75.2		0	-0.7		-99.9	-99.9

*Computed using 100-year GWPs. †-112 kg CO_2E/GJ using dynamic modeling of cumulative radiative forcing. ‡-86.4% using dynamic modeling of cumulative radiative forcing. §0 years using dynamic modeling of cumulative radiative forcing.

6.3.3 System Configuration Scenarios

In Section 5.0, various system configuration scenarios were presented. All relevant scenario combinations were analyzed (40 combinations). Results are presented in Table 6.8 for scenarios where parameters would be at their base case values. Results obtained for the typical scenarios are also reproduced in that table for comparison purposes. The biomass energy system resulted in lower GHG releases and fossil fuel consumption in all scenarios. Maximum differences were obtained in scenarios in which

- the fiber fraction of paper recycling residuals is higher;
- combined heat and power with maximum power production is employed;
- coal is being displaced (for both heat and power production); and
- alternative fate is landfilling.

Minimum differences were obtained in cases in which

- the plastic fraction of paper recycling residuals is higher;
- only heat is produced;
- natural gas is being displaced (for both heat and power production); and
- alternative fate is incineration.

Table 6.8 Indicator Results for Various System Configuration Scenarios - Paper Recycling Residuals

Indicator	Unit	Typical	Min	Max
Differential GHGs*	kg CO_2E/GJ	-109†	-82.9	-316
Relative GHGs *	%	-75.2‡	-62.5%	-86.3%
Break-even time*	years	0§	0	7.6
Relative FF CON	%	-99.9	-99.9	-100

*Computed using 100-year GWPs. †- 112 kg CO_2E/GJ using dynamic modeling of cumulative radiative forcing. ‡-86.4% using dynamic modeling of cumulative radiative forcing. §0 years using dynamic modeling of cumulative radiative forcing.

6.4 Black Liquor

In a previous study by NCASI (Gaudreault et al. 2012, NCASI 2011b), the benefits of recovering black liquor for production of energy and pulping chemicals that would otherwise need to be produced from other resources were analyzed. In that study, it was determined that developing a detailed model of the alternative fate of black liquor would have required too much speculation because black liquor is not disposed of. Its use in the kraft recovery cycle is integral to pulp production. Nonetheless, it was reasonable to assume that alternative management would involve returning the biogenic carbon in the liquor to the atmosphere, perhaps via incineration (in which case the carbon is emitted immediately), or aerobic wastewater treatment (in which case the carbon would be emitted over a period of hours to months depending on the type of treatment system in use). In either case, the carbon is returned to the atmosphere far too quickly to make carbon storage a significant factor in the calculations. To be conservative, it was also assumed that all of the carbon in the black liquor would be emitted as CO_2. If, in the alternative management scenario, some of the carbon was emitted as methane, the benefits of using black liquor in the kraft recovery cycle would be larger than estimated in the study.

The detailed results obtained for black liquor can be found in NCASI (2011b) and Gaudreault et al. (2012). These are summarized in Table 6.9. At the time of this earlier study, no dynamic carbon footprint approach was applied and the results were not limited to 100 years. The break-even time

would remain zero using dynamic carbon footprinting but limiting the analysis to 100 years would slightly reduce the GHG benefits.

Table 6.9 Summary of Indicator Results for Black Liquor

Indicator	Unit	Typical	Min	Max
Differential GHGI*	kg CO_2E/GJ	-182 (184‡)	-97.9	-192
Relative Non-BioCO_2 GHGI*	%	-90.5	-69.0	-92.4
Break-even time*,†	years	0	Not available	
Relative FF CON	%	-89.8	-71.1	-90.7

* Based on 100-year GWPs. † Break-even time was not analyzed in NCASI (2011b) and Gaudreault et al. (2012). However, assuming that the most likely alternative fate for black liquor is incineration, consistent with the conservative assumption made regarding carbon emission from this alternative fate, the break-even time would be zero years. ‡Computed using dynamic cumulative radiative forcing.

6.5 Comparison of the Residuals

Figure 6.15 compares the GHG benefits for the different types of biomass residuals on 1) a functional unit basis (i.e., 1 GJ of energy), and 2) a tonne of residual basis. "Differential GHGs" indicator results are depicted for the biomass energy system compared to the non-use system.

The figure shows that producing 1 GJ of energy using WWTP residuals produces greater benefits than does using woody mill residuals. This may seem counterintuitive, as WWTP residuals are a fuel of lesser quality than woody biomass residuals. This result was obtained because to produce 1 GJ of energy, more WWTP residuals are needed than when using woody biomass residuals, which also means diverting more WWTP residuals from landfills and hence avoiding more methane emissions. Paper recycling residuals generated relatively lower benefits than woody mill residuals and WWTP residuals on a per GJ basis. This was due to the plastic fraction of the residuals, which produce fossil fuel GHGs when burned.

On a per tonne of residual basis, fuels with higher HHV, lower water content, and greater degradable fraction in landfills led to greater benefits. The plastic fraction of paper recycling residuals was also an important factor explaining the lower benefits observed for this material.

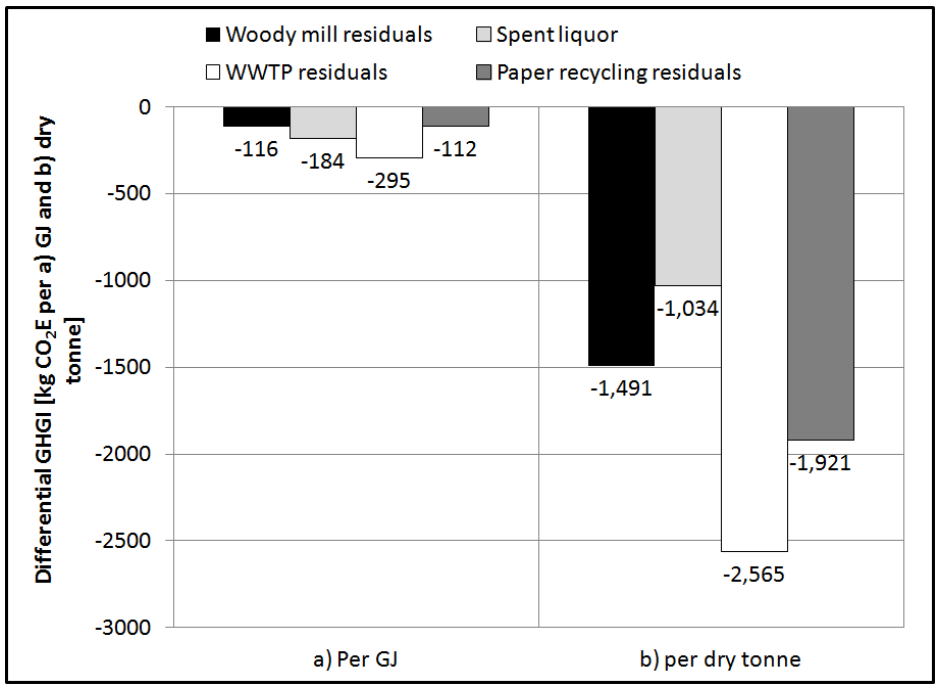


Figure 6.15 Comparison of the Differential Releases for the Different Residual Types a) per Gigajoule, b) per dry Tonne

It is also possible to use the numbers presented in Table 6.14 below to calculate typical scenario weighted average indicator results for all residuals included in this study. In calculating these averages, it was assumed that the results were the same for other spent liquor as for black liquor. Residuals other than black liquor and those analyzed in this study were not included. The weighted average results are presented in Table 6.10.

Table 6.10 Weighted Average Indicator Results, Typical Scenarios, Life Cycle Results

Indicator	Unit	Weighted Average Result (all manufacturing residuals)	
		Dynamic Carbon Footprint	IPCC GWPs
Differential GHGI	kg CO_2E/GJ	-158	-155
Relative non-bioCO_2 GHGI	%	-93.7%	-94.3%
Break-even time	Years	0.5	2.9
Relative FF CON	%	-93.8%	-93.8%

6.6 Additional Sensitivity Analysis on Air Emission Control Equipment

As mentioned in Section 5.1.2.1, it was assumed in this study that the difference in energy requirements for air emission control was negligible for boilers combusting biomass residuals, coal, and/or natural gas. There is very little information available regarding air emission control device energy requirements and what information is available is rarely in a format that is usable for this study. Some of the available information is summarized in Table 6.11. Table 6.12 presents common air emission control equipment used for various boiler types within the forest products industry.

Based on the information in Table 6.11 and Table 6.12, two sensitivity analyses were performed to test the significance of the differences in control equipment and are summarized in Table 6.13. The results of the sensitivity analyses, presented in Figure 6.16, indicate that neglecting the differences in energy requirements for air emission control has likely led to a slight overestimation (of less than 3%) of the benefits related to the biomass energy system, especially in the context of fossil fuel consumption benefits.

Table 6.11 Power Consumption for Various Air Emission Control Devices

Air Emission Control Equipment	Power Consumption (% of energy output)	Applicability	Reference
Electrostatic precipitator	0.1 - 1.8%	Power utilities	European Commission (2006)
	0.2%*	Heat from coal	NCASI (1998)
	0.3%†	Heat from biomass	NCASI (1998)
	≈ 0.6%	Heat from coal‡	USEPA (2002)
Wet scrubber	≤ 3.0%	Power utilities	European Commission (2006)
Dry scrubber	0.3% - 1.0%	Power utilities	European Commission (2006)
	0.5% - 1.0%	Heat production	Kitto (1996)
Unspecified scrubber	1.0%*	Heat from coal	NCASI (1998)
	1.0%†	Heat from biomass	NCASI (1998)
Selective catalytic reduction (SCR)	0.5%	Power utilities	European Commission (2006)
Selective non-catalytic reduction (SNCR)	0.1 - 0.3%	Power utilities	European Commission (2006)

*Assuming 0.04 - 1.3 W/acfm, 0.5 acfm/(lb steam/hr) and 1.52E-03 GJ/lb steam. †Assuming 0.04 - 1.3 W/acfm, 0.92 acfm/(lb steam/hr) and 1.27E-03 GJ/lb steam. ‡Assuming 8640 hr/yr, 0.06$/kWh, 9780dscf/MMBtu, 3% O_2 at T=325°F.

Table 6.12 Common Combustion-Related Air Emission Control Equipment

Fuel Burned	Most Common Control Equipment
Coal	ESP, low NO_x burner
Biomass	ESP, wet scrubber (newer boilers have SNCR for NO_x control)
Natural gas	Low NO_x burner, flue gas recirculation

Table 6.13 Sensitivity Analyses on Air Emission Control Equipment

#	Electricity Consumption for Air Emission Control (% of heat output)		
	Biomass	Natural Gas	Coal
S1	0.3%	0.0%	0.2%
S2	2.1%	0.0%	1.8%

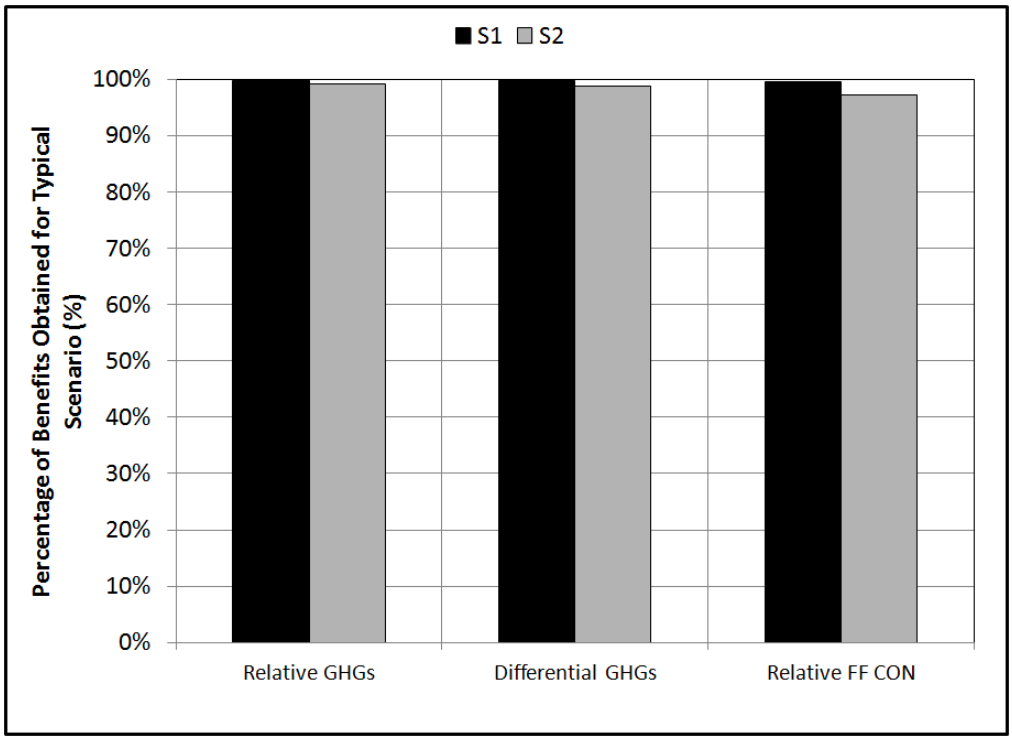


Figure 6.16 Sensitivity Analyses on Air Emission Control Equipment - Manufacturing-Related Woody Biomass Residuals - Typical Scenario

6.7 Life Cycle Results in Context

In this study, the life cycle GHG emissions and non-renewable energy consumption associated with the US forest products industry's use of biomass residuals (biomass energy system) have been compared to the GHG emissions and the non-renewable energy consumption that would occur if fossil fuels were used instead (non-use system). The results have been calculated in terms of the differences between these two systems, expressed in terms of value chain GHG emissions. In this section of the report, the calculated GHG benefits are put in the context of total emissions from the forest products industry value chain.

Table 6.13 presents data that allow calculation of the greenhouse gas benefits of using biomass residuals for energy generation. From this table, it can be seen that kraft black liquor and woody mill residuals represent 24.3% and 34.6%, respectively, of the total energy used by the industry, for an overall total of 58.9%.

Table 6.14 Various Contextual Data Regarding the US Forest Products Industry

Element	Value			Reference
Total energy consumption	2.58E9 GJ/yr			2010 data collected by AF&PA, NCASI, and AWC and scaled up to total US production* Total energy includes purchased power
Fraction of energy from various sources (may not sum to 100% due to rounding)	**Source**	**Biomass Energy**	**Total Energy**	2010 data collected by AF&PA, NCASI, and AWC and scaled up to total US production*
	Black liquor	52.3%	34.6%	
	Other spent liquor	4.6%	3.0%	
	Woody mill residuals	36.8%	24.3%	
	WWTP residuals	0.63%	0.42%	
	Paper recycling residuals	0.05%	0.03%	
	Others	5.7%	3.9%	
	Fossil fuels	N/A	33.7%†	
GHG benefits from black liquor recovery	Base Case	184 kg CO_2E/GJ in steam		The base case was recalculated in this report; min and max are from Gaudreault et al. (2012)
	Min	98 kg CO_2E/GJ in steam		
	Max	192 kg CO_2E/GJ in steam		
Value chain emissions of the US forest products industry	Scope 1	64.6 million tonnes CO_2E/yr (62.0 million tonnes CO_2E/yr from fossil fuels use)		Heath et al. (2010)
	Scopes 2 and 3	147 million tonnes CO_2E/yr		
	Net biogenic carbon flows	-109 million tonnes CO_2E/yr		
	Net value chain emissions	104 million tonnes CO_2E/yr		

*Together, AF&PA, NCASI, and AWC members comprise 96% of total US pulp production, 86% of total paper and paperboard production and 36% of wood products production. † Including purchased electricity, based on the energy content at the fence line (i.e., 3412 BTU per kWh) and assuming that it is 100% fossil fuel-based.

Based on the data in Table 6.10 and Table 6.14, it is possible to estimate the increase in value chain emissions that would accompany the forest products industry's changing from biomass manufacturing residuals (including black liquor) for energy to fossil fuels. Overall, the use of biomass manufacturing residuals (including black liquor) in the forest products industry for one year avoids, for typical scenarios, the emission of 181 million tonnes CO_2E. In an earlier study, it was determined that direct emissions of GHGs from fossil fuel combustion in the US forest products industry in 2004 were approximately 65 million tonnes CO_2E per year (Heath et al. 2010). The use of biomass-based manufacturing residuals for one year, therefore, avoids a quantity of GHG emissions approximately three times the annual fossil-fuel related direct GHG emissions from the forest products industry.

7.0 RESULTS AND DISCUSSION: ADDITIONAL ANALYSES

This section presents the results of the gate-to-gate analysis of biogenic GHGs and the analysis of the emissions of GHGs in the context of ongoing practices.

7.1 Gate-to-Gate Analysis of Biogenic GHGs

All the results presented above were computed using a life cycle approach that considered the fossil fuels being displaced by biomass residuals. The typical scenarios for the two product systems (one system using biomass for energy and the other system managing it by some other means) have also been compared in terms of the emissions coming directly out of the units receiving the residuals (i.e., combustion units or landfills). In this analysis, the benefits of fossil fuel substitution were ignored. For this gate-to-gate analysis, paper recycling residuals were analyzed in terms of their fiber fraction only.

Gate-to-gate Differential GHGI results are summarized in Table 7.1. These show that, even in this highly constrained analysis, using the biomass residuals for energy generation resulted in reductions in GHG releases. The results in Table 7.1 also highlight the effects of using dynamic modeling of radiative forcing instead of 100-year GWPs, with the effects being especially significant on estimated break-even times. A significant fraction of the emissions benefits were attributable to avoidance of landfill methane. A previous, similarly constrained analysis on black liquor assumed that the alternative management would likely involve returning the biogenic carbon in the liquor to the atmosphere. In order to be conservative, in that study, it was assumed that the carbon would return to the atmosphere as CO_2 via incineration or treatment in aerobic wastewater treatment plants. This resulted in net zero GHG releases for energy production from black liquor compared to an alternative fate. When not considering fossil fuel substitution, the weighted average reduction in GHG emissions considering all residuals is 4.6 kg CO_2E/GJ.

Because the benefits of displacing fossil fuels are not included, the times required for cumulative emissions impact from the biomass energy system to fall below the cumulative emissions impact from the non-use system are longer than calculated earlier in this report. Depending on the residual, it required 0 to 19.5 years for the cumulative emissions impact from the biomass system to become lower than the cumulative emissions impact from the non-use system.

A sensitivity analysis was also performed that uses the IPCC default value of 50% (instead of 77% in the typical scenario) for the percentage of carbon in woody mill residuals that is non-degradable under landfill anaerobic conditions. These results, presented in parentheses in Table 7.1, show that the results are highly affected by this parameter.

Table 7.1 Results of the Gate-to-Gate Analysis of Biogenic GHGs

Residual Type	Differential GHGs over 100 Years (kg CO_2E/GJ)		Break-Even Time (years)	
	Dynamic CF	IPCC 100-Year GWPs	Dynamic CF	IPCC 100-Year GWPs
Woody mill residuals	-8.5 (-187)†	-5.1	19.5 (6.6) †	77.0
WWTP residuals	-190	-182	5.9	13.4
Fiber fraction of paper recycling residuals*	-132	-126	7.7	18.2
Spent liquor (incl. black liquor)	0	0	0	0
Weighted average	-4.6 (-74.2) †	-3.3	7.6 (2.6) †	30.1

*In addition to biomass, paper recycling residuals contain plastics which are produced from fossil fuels. For the purpose of the biomass carbon fate analysis, only their fiber fraction was considered. †Numbers in parentheses were derived using IPCC default for fraction of carbon that is non-degradable under anaerobic conditions, that is 50% instead of 77%.

7.2 GHG Emissions from Ongoing Use of Residuals for Energy Production

Table 7.2 shows the times required for cumulative emissions from a facility using residuals for energy to be equal to the emissions from a facility disposing of the residuals, both for the cradle-to-energy (including fossil fuel substitution) and gate-to-gate (excluding fossil fuel substitution) analyses. The results are presented for the dynamic carbon footprint approach only. The table also indicates when in the past the ongoing practice would need to have begun in order for the cumulative emissions from the two systems to be equal in 2014. The table includes text describing the practices in the industry at points in the past. It should be noted that there is considerable uncertainty in the estimates of break-even times, especially where fossil fuel substitution is ignored. This is because, in cases where fossil fuel substitution benefits are ignored, the curve describing the difference in cumulative emissions between the two scenarios is relatively flat as it approaches zero (because the initial difference between the scenarios is large). The break-even time is equal to the point at which the curve passes through zero, so the results are sensitive to small changes in assumptions, particularly assumptions about landfill decay and methane production. By contrast, where fossil fuel substitution is considered, the curve is steeper where it passes through zero because of the smaller initial difference between the two scenarios, thus reducing the uncertainty about break-even time.

Table 7.2 The Use of Residuals for Energy as an Ongoing Practice

Residual		Years For Emissions from Facility Using Residuals for Energy on an Ongoing Basis to Be Equal to Emissions from a Facility Disposing of These Residuals (Under Typical Scenario)	Year in the Past When Ongoing Practice Would Have Had to Be Initiated for Emissions from the Two Facilities to Be Equal at the in 2014 (Under Typical Scenario)	Past Industry Practice in Using the Residuals for Energy
Woody mill residuals	w/ benefits of the displaced fossil fuels (cradle-to-energy)	1.9 (0.9)*	2012 (2013)*	The literature mentions the use of wood residuals in boilers used for wood drying at sawmills going back to at least 1920 and in steam engines in sawmills going back to the mid-1800s. Based on AF&PA statistics, in 1971, woody mill residuals represented 7% of the fuel (16% of the biomass) burned at pulp and paper mills. By 1980, this had increased to 11% of the fuel (21% of the biomass). Between 1987 and 1999, it varied between 15% and 18% of the fuel (25% to 29% of the biomass).
	w/o benefits of the displaced fossil fuels (gate-to-gate)	34.5 (10.4)*	1979 (2003)*	
WWTP residuals	w/ benefits of the displaced fossil fuels (cradle-to-energy)	0	2014	NCASI statistics on WWTP residuals management go back to 1979, at which point 11% of these residuals was being burned for energy. By 1988, this had increased to 21%.
	w/o benefits of the displaced fossil fuels (gate-to-gate)	9.3	2004	

(Continued on next page. See notes at end of table.)

Table 7.2 (Cont'd)

Residual		Years For Emissions from Facility Using Residuals for Energy on an Ongoing Basis to Be Equal to Emissions from a Facility Disposing of These Residuals (Under Typical Scenario)	Year in the Past When Ongoing Practice Would Have Had to Be Initiated for Emissions from the Two Facilities to Be Equal in 2014 (Under Typical Scenario)	Past Industry Practice in Using the Residuals for Energy
Paper recycling residuals	w/ benefits of the displaced fossil fuels (cradle-to-energy)	0	2014	There are different types of recycling residuals generated by mills using recovered paper. Some of these are combined with WWTP residuals and managed similarly to what is described above; i.e., in 1979 11% of WWTP residuals were burned for energy, increasing to 21% in 1988. OCC rejects, however, are often managed separately. NCASI has published information showing that using recycling residuals for energy started as early as 1975.
	w/o benefits of the displaced fossil fuels (gate-to-gate)	12.2	2001	
Spent liquor (incl. black liquor)	w/ benefits of the displaced fossil fuels (cradle-to-energy)	0	2014	Based on AF&PA statistics, in 1971, 35% of the fuel (84% of the biomass) burned at pulp and paper mills was black liquor. By 1980, this had increased to 40% of the fuel (79% of the biomass). Between 1987 and 1999, it varied between 43% and 46% of the fuel (71% to 75% of the biomass).
	w/o benefits of the displaced fossil fuels (gate-to-gate)	0	2014	

*Numbers within brackets were derived using IPCC defaults for the fraction of carbon in woody mill residuals that does not degrade under anaerobic conditions (50%) rather than that of U.S. EPA (77%).

8.0 UNCERTAINTY AND LIMITATIONS

This section provides further interpretation of the robustness of the results presented above.

8.1 Data Accuracy and Uncertainty

Evaluating data accuracy and uncertainty is an important aspect of LCA studies. An LCA is a complex model made up of thousands of data points and the accuracy of these data can significantly affect the results. Analyzing the uncertainty of such a complex model is not straightforward. Techniques such as Monte Carlo analysis can be used to evaluate uncertainty, but an important challenge is the lack of uncertainty data for the different variables that comprise the LCA model. Therefore, in many cases, the robustness of the results and conclusions of LCA studies are assessed using other methods. In this study, the parameters with potential effects on the results were analyzed using sensitivity analyses covering their most probable range of variation and results were discussed given these variations. However, without comprehensive uncertainty data, it was impossible to quantitatively assess the statistical significance of the differences between the compared systems.

The data collection process met the data quality goals as set out in Section 4.4.

8.2 Limitations

The main limitations of this study are summarized in this section. They relate primarily to the conformity of the study with ISO LCA standards (ISO 2006a, b) and to the data used and assumptions made.

8.2.1 ISO Conformity

As mentioned previously, a streamlined LCA methodology was used in this study. As a consequence, it was not possible to fully comply with ISO 14044 requirements for comparative assertions disclosed publicly. The main non-conformances are outlined below.

- Although the assumptions, models, and results were reviewed by a committee of stakeholders, no formal external critical review was performed.
- While the Standard requires that for studies intended to be used for publicly disclosed comparative assertions, a sufficiently comprehensive set of impact categories be employed, only two were used in this study, in accordance with the study objective.
- No formal uncertainty analysis was performed.

In addition, the gate-to-gate analyses need to be understood as additional information rather than as an LCA result.

8.2.2 Data and Assumptions

Some of the generic data sets used in this study were not specific to the US, although the study employed a version of these data sets modified to use US electricity production.

The relevant characteristics related to the residuals analyzed in this study are typically quite variable. This variability was analyzed in sensitivity analyses and results were shown for range of characteristic values sufficiently large to cover most of the variability.

The data identified for size reduction were fixed on a per tonne basis and did not account for the extent of size reduction. That said, size reduction was not found to significantly affect the study results.

Several assumptions were made regarding WWTP residuals that could have affected the study results. The main ones are discussed here.

- It was assumed that mechanical dewatering can achieve 40% solids, that this was sufficient for combustion, and that the same level of dewatering was also suitable for transporting them to a landfill disposal site. The main reason for this assumption was that no data were available concerning the energy consumption for additional dewatering. Assuming additional dewatering would have had two main effects on the results. First, this would have decreased the overall performance of the biomass energy system by increasing its consumption of energy and related releases. Second, assuming drier WWTP residuals would have increased boiler efficiency, and thus reduced the quantity of residuals required to produce 1 GJ of energy, which would have resulted in lower benefits when analyzing the results on a per gigajoule basis, but greater benefits on a per tonne of residuals basis.
- It was also assumed that WWTP residuals would be co-fired with bark in a 20:80 ratio. Based on this ratio, a boiler efficiency was calculated. Increasing the share of residuals in the mix burned would have decreased the boiler efficiency, while decreasing their share would have increased the efficiency. The effect of boiler efficiency on the results was discussed immediately above. The relationship between the share of WWTP residuals burned and boiler efficiency is also uncertain. The best available information was used.

Because paper recycling residuals are made up of a mix of materials that have characteristics similar to WWTP residuals (negative effect on boiler efficiency compared to woody biomass residuals) and plastic (positive effect on boiler efficiency compared to woody biomass residuals), it was assumed that paper recycling residuals would be burned in boilers with the same efficiency as woody biomass residuals at a given water content. Boiler efficiencies for these kinds of material are not known, however. The effect of boiler efficiency on the results was discussed above. Also, OCC rejects were considered to be representative of paper recycling residuals in general. In cases where, for instance, the plastic fraction of other paper recycling residuals is outside the range studied in this study, results would be slightly different. However, a broad range of characteristics was examined in this study to account for these potential variances.

The best available data for energy production using fossil fuels were used. These data were deemed representative of average US conditions. No sensitivity analyses were performed on that part of the modeling. As a consequence, the results of the study cannot be generalized to a broader set of conditions regarding energy production from fossil fuels. Also, it was assumed that the difference in energy requirements for air emissions control would not vary significantly from one fuel to another. If this were not the case, and in particular if the energy penalty for emissions control were lower for natural gas than for biomass, the benefits calculated for scenarios involving natural gas would be reduced. This is not, however, expected to be significant.

The results are very sensitive to landfill and waste decomposition characteristics and these characteristics are very uncertain. Sensitivity analyses were performed to address this issue. Results appear to be robust within the ranges assessed for those characteristics with the exception of woody mill residuals for which very different results can be obtained depending on the assumption made regarding the fraction of carbon that is non-degradable under anaerobic conditions. In this study, a value of 77% was used, obtained from the U.S. EPA GHG Inventory (2014a, Table 7.50). IPCC recommends using a default value of 50% and specifies that waste-specific information can be used instead but emphasizes that “[t]he reported degradabilities especially for wood, vary over a wide range and [are] yet quite inconclusive” (IPCC 2006b, Chapter 3, pp. 3.13-3.14). Table 8.1 compares the results using the two values. The results show that the selected value has significant effect on the results. Some studies have reported higher fractions of non-degradable carbon in wood than 77%

(Wang et al. 2011). Assuming a higher non-degradable fraction would significantly reduce the estimated benefits of using this material for energy.

Table 8.1 Comparison of Results Obtained for Woody Mill Residuals Using the EPA and IPCC Values for Fraction of Carbon Non-Degradable Under Anaerobic Conditions and Effect for Industry Average Results

Indicator	Unit	Fraction of Non-Degradable Carbon Under Anaerobic Conditions (FCCND)			
		Including Fossil Fuel Substitution (Cradle-to-Final Energy)		Excluding Fossil Fuel Substitution (Gate-to-Gate)	
		77% (EPA)	50% (IPCC)	77% (EPA)	50% (IPCC)
Woody mill residuals differential GHGI	kg CO_2E/GJ	-116	-295	-8.5	-187
Weighted average differential GHGI	kg CO_2E/GJ	-158	-228	-4.6	-74.2
Break-even time (woody mill residuals)	years	1.2	0.5	19.5	6.6
Weighted average break-even time	years	0.5	0.2	7.6	2.6
Break-even year for ongoing practice (woody mill residuals)	-	2012	2013	1979	2003
Industry-average benefit	million tonnes CO_2E/yr	181	261	5.3	84.9

In addition, the analysis of the timing of emissions depends heavily on landfill characteristics. In the absence of information more specific to forest products manufacturing residuals, U.S. EPA decay rates for municipal landfills were used. These decay rates were derived for a mix of wastes, i.e., not only for woody materials which may degrade more slowly. Therefore, the lower decay rates used in the scenarios are probably more representative of woody materials. Even considering this, the break-even times were short, with the exception of paper recycling residuals that contain a fraction of plastic.

Finally, the results of the assessment of ongoing practice are valid only in the context of two main assumptions: 1) assuming the same quantity and type of energy produced in every year, 2) assuming the same alternative fates and fossil fuels displaced in every year.

9.0 CONCLUSIONS

In this study, the GHG and fossil fuel-related benefits of using woody manufacturing residuals, recycling residuals, and wastewater treatment plant residuals for energy production within the forest products industry were analyzed using life cycle principles and additional analyses. It was shown that using all types of residuals for energy production produces benefits both in terms of reduced fossil fuel consumption and reduced greenhouse gas emissions. This result is valid across a range of system configuration scenarios (boiler type, assumptions about the displaced fossil fuel, the GHG intensity of the electricity grid, and the level of cogeneration at forest products facilities), residual characteristics (e.g., heating value, moisture content), and whether or not the benefits from fossil fuel substitution are considered. These findings hold true whether biogenic CO_2 is included in the analysis or excluded by giving it an emission factor of zero (equivalent to what is sometimes called “carbon neutrality”). The

benefits occur without affecting the amount of wood harvested or the amount of wood products produced.

It takes 0 to 1.2 years before the cumulative emissions impacts from the biomass energy systems are lower than those in the corresponding non-use systems. Even ignoring the benefits of displacing fossil fuel and limiting the analysis to biogenic emissions, the cumulative emissions impacts from the biomass energy systems associated with producing 1 GJ of energy are lower than those from the non-use systems in 0 to 19.5 years, depending on the residual.

These results were developed by comparing the GHG emissions from systems using manufacturing residuals for energy in the forest products industry to the emissions from alternative systems producing the same amount of energy from fossil fuels while disposing of the residuals by landfilling or a combination of landfilling and incineration. In cases where it is assumed that the alternative to burning manufacturing residuals for energy is incineration, the break-even times for all residuals are zero, whether or not fossil fuel substitution is considered. Where the alternative is assumed to be landfilling, the results can be sensitive to the parameter value describing the extent to which residuals decompose in mill landfills, a parameter with large uncertainty. The impact is especially significant for woody mill residuals.

When considered as an ongoing practice (e.g., ongoing production of 1 GJ energy per year), and when the benefits of displaced fossil fuels are considered, the typical cumulative impact of residuals used for energy in the industry becomes less than that of disposing of the residuals in less than two years. If the benefits of displaced fossil fuels are ignored, the typical cumulative impact of using the residuals becomes smaller than the impact associated with disposing of the residuals in less than 35 years for all of the residuals examined. In all cases, even ignoring the benefits of displaced fossil fuels, the ongoing use of the residuals predates, by a considerable period, the date when the practice would have needed to begin in order for the current use of manufacturing residuals to be showing net benefits.

The emissions benefits of using manufacturing residuals for energy in the forest products industry are large. Given current practice, the use of manufacturing residuals including black liquor in the industry for one year avoids the emission of approximately 181 million tonnes CO_2E, equal to approximately three times the annual direct emissions associated with the combustion of fossil fuels in the forest products industry.

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APPENDIX A

ACRONYMS AND NOMENCLATURE

General Acronyms and Nomenclature:

AF&PA:	American Forest and Paper Association
AWC:	American Wood Council
BC:	Base case
BDmT:	Bone-dry metric tonne
Bio:	Biomass
BioCO_2:	Biogenic CO_2
Biogenic GHGs:	Biogenic CO_2 as well as CH_4 produced from decomposing biomass and CH_4 and N_2O produced in biomass combustion
Biomass energy system:	Product system in which the biomass residuals are used for energy production
Break-even time:	Number of years required for the cumulative emissions from the non-use system to equal the cumulative emissions from the biomass energy system
CHP:	Combined heat and power
CORRIM:	Consortium for Research on Renewable Industrial Materials
CO_2:	Carbon dioxide
CO_2E:	CO_2 equivalents, i.e., measure for describing how much global warming a given type and amount of greenhouse gas may cause, using the functionally equivalent amount or concentration of carbon dioxide (CO_2) as the reference
Cradle-to-final energy analysis:	A cradle-to-final energy analysis can be defined as a specific LCA applied to the production of energy. It generally includes the extraction and production of fuels, their transportation and their combustion to produce energy.
Differential GHGs:	Absolute difference in releases of GHGs, including biogenic CO_2 emissions and removals
Eff:	Efficiency
EPA:	Environmental Protection Agency
FF:	Fossil fuel

Non-use system:	Product system in which the fossil fuels are used for energy production and in which an alternative fate for the biomass residuals is considered or in which only the alternative fate of the biomass residuals is considered
Gate-to-gate analysis:	A gate-to-gate analysis can be described as a partial LCA looking at only one value-added process in the entire production chain
GHG:	Greenhouse gas
GJ:	Gigajoule (1 GJ = 0.948 MMBtu)
GWP:	Global warming potential
HHV:	Higher heating value
H&P:	Heat and power
ISO:	International Organization for Standardization
LCA:	Life cycle assessment
LCI:	Life cycle inventory
LCIA:	Life cycle impact assessment
LHV:	Lower heating value
MSW:	Municipal solid waste
NG:	Natural gas
N/Av.:	Not available
OCC:	Old corrugated containers
OECD:	Organisation for Economic Co-operation and Development
Relative FF CON:	Relative difference in fossil fuel consumption of the biomass energy system compared to the non-use system
Relative Non-Bio CO_2 GHGs:	Relative difference in GHGs, not including biogenic CO_2, of the biomass energy system compared to the non-use system
Removals:	Sequestration or absorption of CO_2 from the atmosphere by the trees
US:	United States
WWTP:	Wastewater treatment plant

System Configuration Scenarios Nomenclature:

Alternative Fate Scenarios

MR1: Landfilling

MR2: Incineration

Boiler Type Scenarios

FB: Fluidized bed boiler

SB: Stoker boiler

Fossil Fuel Scenarios

A: Heat from coal

B: Heat from natural gas

C: US-average electricity

D: Electricity from coal

E: Fossil fuel scenario, electricity from natural gas combined cycle

Size Reduction Scenarios

SR0: Size reduction scenario, no size reduction

SR1: Size reduction scenario, mobile chipper

SR2: Size reduction scenario, stationary chipper

General Nomenclature:

CC: Biogenic carbon content

E_{DC}: Usable energy from direct combustion

E_{Turb}: Steam to turbine

F_{CCND}: Non-degradable carbon content under anaerobic conditions

F_{CH4CB}: Fraction of methane captured and burned

F_{CH4OX}: Fraction of methane oxidized in landfill covers

k: Decay rate

L: Losses

MCF: Methane correction factor

P: Power to process

Q_R: Quantity of residuals required to produced 1 GJ of usable energy

SHP: High pressure steam to process

SMP/LP: Extraction steam to process

WC_R: Water content of residuals

APPENDIX B

REPORT REVISIONS SINCE ORIGINAL PUBLICATION

This is the third version of this report. The first version was published in October 2013. A revised version was published in May 2014 to correct some of the data and make some clarifications to the text. NCASI found that the values describing the composition of biomass energy presented in Table 6.14 were calculated using the wrong method. These numbers affected the various weighted averages calculated throughout the report. In addition, NCASI calculated the total greenhouse gases avoided by the industry's use of woody mill residuals and black liquor to be 110 million tonnes CO_2E for woody mill residuals and 218 million tonnes CO_2E for combined woody mill residuals and black liquor. It was not clear in the report that other residuals were not included in this estimate. If the estimate had included other residuals, the avoided emissions benefit would have been slightly larger. Also, the report text was clarified in a few places. These changes did not affect the general conclusions of the report.

In July 2014, NCASI determined that the calculations pertaining to woody mill residuals were in error due to the use of an incorrect value for the fraction of carbon that degrades in landfills under anaerobic conditions. Specifically, NCASI used a value of 55% for this parameter while it had intended to use 77%, the value used by the United States Environmental Protection Agency in its Inventory of U.S. Greenhouse Gas Emissions and Sinks. NCASI has recalculated all of the results involving woody mill residuals and recomputed all industry-average numbers. The table below lists the changes in results and where they occur in the report. The table only identifies places where the changes involve calculations based on dynamic radiative forcing. The numbers calculated with the Intergovernmental Panel on Climate Change (IPCC) 100-year global warming potentials (GWPs) were also updated but this is not shown in the table. Note that the text of the report was also modified in several places (not listed here) to reflect the changes in these results. NCASI also provided more details concerning the available information on the decay rates of various manufacturing residuals and the fraction of non-degradable carbon in wood. In addition, a sensitivity analysis using the default value from IPCC (i.e., 50% of the carbon non-degradable under anaerobic conditions), also used by EPA in its greenhouse gas reporting rule, was added. (Table 8.1 was added to Section 8.2.2.) Note that many results presented in Table 8.1 were not in the original report.

In the table below, where a value is presented, for instance, in Section ES.6 in the new report, that result is typically presented in Section ES.5 in the previous version of the report. So, where “ES.6” is listed in the table, it pertains to the new version only and, for the previous version, should be “ES.5.” Note also that in some places information was removed from, or added to, a section compared to the previous version of the report.

Indicator	Unit	Including Fossil Fuel Substitution (Cradle-to-Final Energy)			Excluding Fossil Fuel Substitution (Gate-to-Gate)		
		Previous Version of the Report	**This Version of the Report**	**Places in the Report Where the Change Was Made**	**Previous Version of the Report**	**This Version of the Report**	**Places in the Report Where the Change Was Made**
Woody mill residuals differential GHGI	kg CO_2E/GJ	-261	-116	Abstract, Table ES.1 and relative text, Section 6.1.1.1	-154	-8.5	Table ES.5 and relative text, Abstract, Table 7.1 and relative text
Weighted average differential GHGI	kg CO_2E/GJ	-215	-158	Table ES.1 and relative text, Table 6.10	-61.4	-4.6	Table ES.5 and relative text, Table 7.1 and relative text
Woody mill residuals relative GHGI	%	-99.1	-98.7	Table ES.2 and relative text, Section 6.1.1.2	Not calculated in the report		
Weighted average mill residuals relative GHGI	%	-93.9	-93.7	Table ES.2 and relative text, Table 6.10			
Break-even time (woody mill residuals)	years	0.6	1.2	Abstract, Table ES.3 and relative text, ES.6, Figure 6.3, Section 6.1.1.3, Section 9.0	7.4	19.5	Abstract, ES.1 Table ES.5 and relative text, ES.6, Table 7.1 and relative text, Section 9.0
Weighted average break-even time	years	0.2	0.5	ES.4.3, Table 6.10, Section 9.0	2.9	7.6	Table ES.5 and relative text, Table 7.1 and relative text, Section 9.0
Break-even year for ongoing practice (woody mill residuals)	-	Unchanged*			1998†	1979†	Table ES.6 and relative text, Table 7.2
Industry-average benefit	million tonnes CO_2E/yr	218	181	President's Note, ES.1, ES.4.1, ES.6, 6.7, 9.0	The number was added to the text as it was not there previously.		

*The number of years to break-even changed from 1.3 to 1.9 but the year did not necessitate updating. †The number of years was also updated from 16.2 to 34.5.

Other analysis pertaining to woody mill residuals were also updated, including

- the contribution analysis depicted in Figure 6.1;
- the explanation of the timing of emissions in Figure 6.2, Table 6.1, Figure 6.3, Table 6.2, and Figure 6.4,
- the perturbation analyses in Figure 6.6, the sensitivity analyses in Table 6.3;
- the system configuration scenarios in Table 6.4;
- the comparison of the residuals in Figure 6.15;
- the industry-wide benefits from using woody mill residuals only (110 MT CO_2 E removed from the report); and
- the weighted average results in Table 6.10.

In addition, the following changes were also made to the report.

- The text of the abstract, executive summary conclusion, and conclusion were modified to better reflect the limitations of the study.
- A "Significance of Findings" section was added to the executive summary.
- The benefits from using black liquor were recalculated using dynamic radiative forcing. The number went from -182 to -184 kg CO_2E/GJ.
- The analyses on ongoing practices for all residuals type were recalculated using the radiative forcing curves instead of CO_2E curves, leading to some changes when excluding fossil fuel substitution (Table ES.6):
    - wastewater treatment plant (WWTP) residuals went from 2001 to 2004; and
    - paper recycling residuals went from 1997 to 2001.
- The weighted averages and annual values were removed from the ongoing practices tables.
- Some values derived from the literature were corrected and/or clarified and some choices made for the base case and sensitivity analyses for the different manufacturing residuals studied in this report were clarified by adding text in Tables 5.2, 5.3, 5.5, 5.6, and 5.7.
- The choice of the decay rates for all residuals was better justified.
- The equations for calculating emissions from landfill were clarified.