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NATIONAL COUNCIL FOR AIR AND STREAM IMPROVEMENT

GREENHOUSE GAS AND
NON-RENEWABLE ENERGY BENEFITS
OF BLACK LIQUOR RECOVERY

TECHNICAL BULLETIN NO. 984

APRIL 2011

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PRESIDENT'S NOTE

In several recent announcements, the Environmental Protection Agency has made known its interest in understanding the life cycle greenhouse gas benefits associated with using biomass in order to support the development of various programs governing the use of biomass and releases of greenhouse gases. The decisions EPA makes on this topic have the potential to increase greatly the costs of doing business as well as to impair the perception of 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.

Black liquor solids comprise about half of the fuel used by the pulp and paper industry. Yet, among the various types of biomass used by the industry, the life cycle benefits of using black liquor solids are the least well understood, having been essentially ignored in the life cycle studies of biomass published to date. To remedy this lack of understanding of the life cycle greenhouse gas and non-renewable energy benefits of using black liquor solids in the kraft recovery system, NCASI undertook such a study, the results of which are contained in this report.

In this study, NCASI has compared a system using black liquor solids in the kraft recovery system to a fossil-fuel based system providing an equal amount of energy as well as chemicals for pulping. The results indicate that fossil fuel-related greenhouse gas emissions and non-renewable energy consumption are approximately 90% lower when black liquor solids are used in the kraft recovery system than in a comparable fossil fuel-based system. More than half of the benefits are attributable to the highly efficient production of pulping chemicals from black liquor solids in the kraft recovery system.

Based on 2004 data, approximately 100 million tonnes of fossil-fuel derived CO_2 emissions are avoided per year by using black liquor solids at US kraft mills. These avoided greenhouse gas emissions are approximately equal to the total of the forest products industry's emissions from fossil fuel combustion plus the emissions from electric power companies attributable to electricity purchased by the industry. These results do not depend on the accounting method for biogenic carbon (because biogenic CO_2 emissions are the same for the systems compared) and the results are valid across a range of assumptions.

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

April 2011

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MOT DU PRÉSIDENT

Dans plusieurs annonces récentes, l'Agence de protection de l'environnement des États-Unis (EPA) a fait connaître son intérêt pour la compréhension des avantages liés à de l'utilisation de la biomasse en ce qui concerne les émissions de gaz à effet de serres et ce, en adoptant une approche cycle de vie. Ceci à pour but de soutenir le développement de divers programmes régissant l'utilisation de la biomasse et les émissions de gaz à effet de serre reliées. Les décisions potentielles de l'EPA sur ce sujet ont le potentiel d'accroître considérablement les coûts pour les entreprises ainsi que de nuire à la perception des produits de biomasse dans le marché. L'industrie des produits forestiers, par conséquent, a intérêt à ce que les délibérations de l'EPA sur ce sujet soient bien informées.

Les solides de la liqueur noire représentent environ la moitié du carburant utilisé par l'industrie des pâtes et papiers. Pourtant, parmi les différents types de biomasse utilisés par l'industrie, les avantages du cycle de vie de l'utilisation des matières solides de la liqueur noire sont les moins bien compris. En effet, à ce jour, essentiellement aucune étude n'a été publiée à ce sujet. Pour remédier à ce manque de compréhension des avantages cycle de vie (gaz à effet de serre et énergie non-renouvelable) de l'utilisation des solides de la liqueur noire dans le cycle de récupération des produits chimiques de la pâte kraft, NCASI a entrepris une telle étude, dont les résultats sont contenus dans le présent rapport.

Dans cette étude, NCASI a comparé un système utilisant les solides de la liqueur noire dans le système de récupération des produits chimiques de la pâte kraft à un système produisant la même quantité d'énergie et de produits chimiques, mais à partir de combustible fossiles. Les résultats indiquent que la récupération de la liqueur noire réduit les émissions gaz à effet de serre de source fossile et la consommation d'énergie non-renouvelable d'environ 90%. Plus de la moitié de cette réduction est généralement attribuable à la production efficace de produits chimiques de mise en pâte dans le cycle de récupération de la liqueur noire.

Sur la base de données de 2004, environ 100 millions de tonnes d'émissions de CO_2 de source fossile fossiles sont évitées par an en utilisant les solides de la liqueur noire dans les usines de pâte kraft aux États-Unis. Ces émissions évitées de gaz à effet de serre sont à peu près égales au total des émissions de l'industrie des produits forestiers provenant de la combustion de combustibles fossiles ainsi qu'aux émissions dues à la production de l'électricité qu'elle achète. Ces résultats ne dépendent pas de la méthode de comptabilisation du carbone biogénique (parce que les émissions de CO_2 biogénique sont les mêmes pour les deux systèmes comparés) et sont valides pour toute une gamme d'hypothèses.

Cette étude fait partie d'une série de projets de NCASI dont l'objectif est d'aider l'industrie des produits forestiers et ses intervenants à mieux comprendre les émissions de gaz à effet de serre et la consommation d'énergie attribuables à l'utilisation de la biomasse forestière en tant que matière première et source d'énergie.

Ronald A. Yeske

Avril 2011

GREENHOUSE GAS AND NON-RENEWABLE ENERGY BENEFITS
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ABSTRACT

In this study, the life cycle greenhouse gas (GHG) and fossil fuel benefits of black liquor recovery are analyzed. These benefits are due to two effects: the production of energy that can be used in the pulping process or sold, and the recovery of the pulping chemicals that would otherwise need to be produced from other resources.

The fossil GHG emissions and non-renewable energy consumption for a system using black liquor solids in the kraft recovery system are approximately 90% lower than those for a comparable fossil fuel-based system. Across all scenarios, the systems relying on black liquor solids achieve a median reduction of approximately 140 kg CO_2 eq./GJ of energy produced, compared to the systems relying on fossil fuels to provide the same energy and pulping chemical production functions. The benefits attributable to the recovery of pulping chemicals vary from 44% to 75% of the total benefit. Applied to the total production of kraft pulp in the US, the avoided emissions are enough to offset all of the total Scope 1 and Scope 2 emissions from all mills in the US forest products industry. These results do not depend on the accounting method for biogenic carbon (because biogenic CO_2 emissions are the same for the systems compared) and the results are valid across a range of assumptions about the displaced fossil fuel, the GHG intensity of the grid, the fossil fuels used in the lime kiln, and the level of cogeneration at pulp and paper mills. The benefits occur without affecting the amount of wood harvested or the amount of chemical pulp produced.

KEYWORDS

black liquor, energy, greenhouse gases, life cycle assessment

RELATED NCASI PUBLICATIONS

None

AVANTAGES POUR LES ÉMISSIONS DE GAZ À EFFET DE SERRE ET LA CONSOMMATION D'ÉNERGIE NON RENOUVELABLE DE LA RÉCUPÉRATION DE LA LIQUEUR NOIRE

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RÉSUMÉ

Dans cette étude, les avantages de la récupération de la liqueur noire pour les émissions de gaz à effet de serre (GES) et la consommation d'énergie non renouvelable sont analysés en utilisant une approche cycle de vie. Deux causes permettent d'expliquer ces avantages : la production d'énergie pouvant être utilisée dans la fabrication de la pâte et du papier ou vendue, ainsi que la récupération des produits chimiques de mise en pâte qui, autrement, devraient être produits à partir d'autres ressources.

Les émissions de GES et la consommation d'énergie fossile non renouvelable pour un système utilisant les solides de la liqueur noire dans le système de récupération des produits chimiques de la pâte kraft sont environ 90% inférieurs à ceux d'un système comparable à base de combustibles fossiles. Lorsque tous les scénarios analysés sont pris en compte, la récupération de la liqueur noire produit une réduction moyenne d'environ 140 kg de CO_2 équivalents par gigajoule d'énergie produite, par rapport à un système produisant la même quantité d'énergie et de produits chimiques de mise en pâte, mais à partir de combustibles fossiles. Les avantages attribuables spécifiquement à la production de produits chimiques de mise en pâte varient entre 44% et 75% du total. Lorsqu'appliquées à la production totale de pâte kraft aux États-Unis, les émissions évitées sont suffisantes pour compenser la totalité des émissions de Scope 1 et de Scope 2 de l'industrie américaine des produits forestiers. Ces résultats ne dépendent pas de la méthode de comptabilisation du carbone biogénique (parce que les émissions de CO_2 biogénique sont les mêmes pour les deux systèmes comparés) et sont valables pour toute une gamme d'hypothèses incluant le type de combustibles fossiles déplacé, les émissions de GES produites par le réseau électrique, les combustibles fossiles utilisés dans les fours à chaux et le niveau de cogénération dans les usines de pâtes et papiers. Les avantages observés se produisent sans affecter la quantité de bois récolté ou la quantité de pâte chimique produite.

MOTS CLÉS

Liqueur noire, énergie, gaz à effet de serre, analyse du cycle de vie

PUBLICATIONS DE NCASI RELIÉES

Aucune

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GREENHOUSE GAS AND NON-RENEWABLE ENERGY BENEFITS
OF BLACK LIQUOR RECOVERY

1.0 INTRODUCTION

Recent years have seen both a rise in the interest in substituting biomass for fossil fuels and increasing 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 and the carbon in fossil fuels is that the carbon in biomass-derived fuels 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. This aspect of the biogenic carbon cycle forms the basis for using a zero emission factor at the point of combustion for biomass-derived fuels (Abbasi and Abbasi 2010; Cherubini 2010; Cherubini et al. 2009; Lattimore et al. 2009; Robinson, Rhodes, and Keith 2003), and it represents an accepted benefit of using biomass-derived fuels rather than fossil fuels (Abbasi and Abbasi 2010; Froese et al. 2010; Schlamadinger et al. 1997). This is recognized by the ISO series of standards on life cycle assessment (ISO 2003, 35):

> *"The characterization model that describes the net-zero C emitted when burning biomass fuel is typically a recycling model, in which CO_2 from the atmosphere (and its C expression) are sequestered by the photosynthesis process [...]. [...] the CO_2 emissions from the combustion are considered equal to those already sequestered and those that will be subsequently sequestered. This is different from the CO_2 emissions of fossil fuel that result from the use of C from long-term carbon sinks rather than from the atmosphere. The characterization factor used is 0."*

There is a difference between the life cycle impacts (i.e., "footprint") of a biomass fuel and the emission factor (for an emissions inventory) of a biomass fuel. The emission factor of a biomass fuel pertains only to emissions that occur at the point of combustion. Life cycle impacts are based on these point of combustion emissions in combination with "upstream" (e.g., land use change, silvicultural/harvesting, transport, processing) and "downstream" (e.g., end-of-life) emissions. Because of these upstream, non-combustion emissions, the life cycle impacts assigned to biomass fuel use can be non-zero even where the release of biogenic CO_2 upon combustion is in balance with carbon uptake via regrowth (Abbasi and Abbasi 2010; Cherubini 2010). Where the amounts of 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.

There are different types of biomass used for energy and different regimes of land use/carbon stock changes associated with them. Biomass fuels obtained from residuals (agricultural, manufacturing, forestry residuals, etc.) are typically not associated with land use/carbon stock changes (Cherubini 2010; Mann and Spath 2001; Schlamadinger et al. 1997). Manufacturing residuals include many things such as wood manufacturing residues (e.g., bark, sawdust, planer shavings, sander dust from sawmills, panel plants, and pulp and paper mills, including material in on-site bark/hog piles).

Recent life cycle assessment (LCA) studies of wood residue-based energy systems, summarized in Table 1.1, typically demonstrate significant greenhouse gas mitigation benefits compared to energy derived from fossil fuels. Wood residues investigated in these studies included forest residuals (Cherubini et al. 2009; Froese et al. 2010; Mann and Spath 2001; Pehnt 2006; Robinson, Rhodes, and Keith 2003), mill residues (Mann and Spath 2001; Petersen Raymer 2006), urban "waste," or demolition wood (Mann and Spath 2001; Pehnt 2006; Petersen Raymer 2006).

Table 1.1 Life Cycle GHG Mitigation Benefits for Wood-Based Residues Energy Systems

Study	Biofuel Type	Fossil Fuel Offset	GHG Mitigation[a]
Froese et al. 2010	Forest residuals	Coal electricity (cofiring)	100%
Mann and Spath 2001	Various woody residuals	Coal electricity (cofiring)	123%[b]
Robinson et al. 2003	Forest and agriculture residues	Coal electricity (cofiring)	≈ 95%
Pehnt 2006	Forest wood, woody biomass energy crops, waste wood	Energy mix in Germany for electricity generation and home heating in 2010	85-95%
Cherubini et al. 2009	Forest residuals	Various fossil fuels used for heat and electricity production	70-98%
Petersen Raymer 2006	Fuel wood, sawdust, wood pellets, demolition wood, briquettes, bark	Coal electricity (cofiring) and heating oil	81-98%

[a] Percent for base case; 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).
[b] Mitigation greater than 100% due to avoided end-of-life methane emissions.

Black liquor solids, a by-product of the kraft pulping process, account for approximately half of the fuel used by the pulp and paper industry (AF&PA 2010). Yet, even in a time when the industry and its stakeholders are anxious to understand the benefits of using biomass fuels, there has been no comprehensive life cycle-based assessment of the benefits of using black liquor solids. Having identified this information need, NCASI recently undertook a life cycle study of the greenhouse gas and non-renewable energy impacts of using black liquor solids in the kraft recovery system. This report contains the results of that study.

2.0 GOAL AND SCOPE OF THE LIFE CYCLE STUDY

Life Cycle Assessment (LCA) is a *"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, 2).

LCA principles and methodology are framed by a set of standards (ISO 2006a, 2006b) and technical report specifications (ISO 2000, 2002, 2003) from the International Organization for Standardization (ISO). ISO describes LCA methodology in four phases (as illustrated in Figure 2.1):

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, 2);

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, 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, 2).
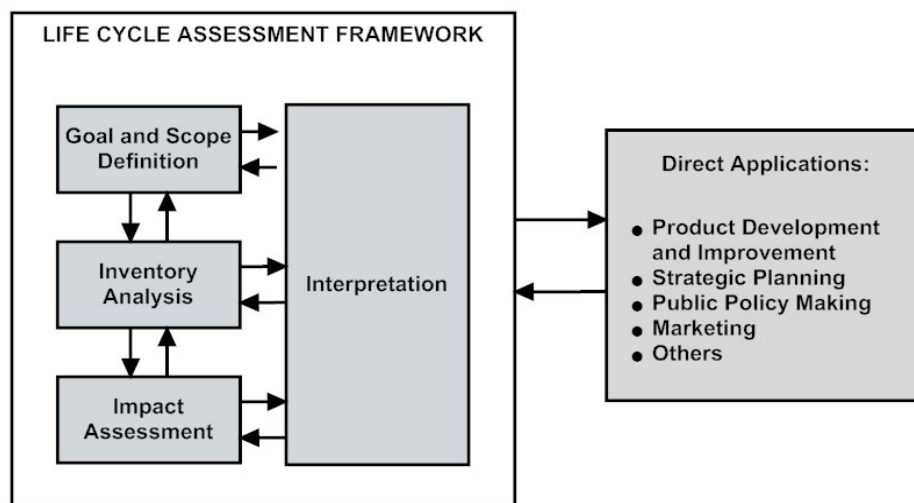
Figure 2.1 Life Cycle Assessment Phases (ISO 2006a)

In this study, a simplified (streamlined) LCA methodology has been 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, life cycle non-renewable energy demand), and using mainly site-generic information to model the fossil fuel system. Because of this, the study does not fully comply with ISO 14044 requirements for comparative assertions disclosed publically. However, the study aligns as much as possible with this standard.

2.1 Objective of the Study

The objective of this study is to characterize the GHG and non-renewable energy conservation benefits of using black liquor solids for energy production when compared to the GHGs from the fossil fuel it replaces.

2.2 Function and Functional Unit

The ISO 14044 standard requires that *"the scope of an LCA shall clearly specify the functions (performance characteristics) of the system being studied"* and that the *"functional unit shall be consistent with the goal and scope of the study"* (ISO 2006b, 8). The objective of this study is to

compare two alternative ways of producing energy (function) and the primary functional unit is defined as ***the production of 1 GJ of energy (heat and power)[1]***.

The production of energy using black liquor solids results in secondary functions that need to be dealt with. This is discussed below.

2.3   Description of the Systems Compared, System Boundaries, and Allocation

The methodology used in this study follows life cycle principles, by calculating emissions from "cradle to final energy" including end conversion efficiency. In other words, it is extended beyond the point of combustion to include transformation into electricity/steam (including transformation efficiency and distribution losses where applicable). Two different systems are compared and discussed hereinafter: a system in which 1 GJ of energy is produced from black liquor solids and an equivalent system in which the same amount of energy is produced from fossil fuels.

2.3.1   *Black Liquor Product System*

2.3.1.1   *Description of the Product System*

A schematic of the kraft pulping process is presented in Figure 2.4. Kraft pulping involves cooking wood chips in an aqueous solution of pulping chemicals, resulting in the extraction of cellulose from the wood by dissolving the lignin that binds the cellulose fibers together. In the kraft process, white liquor containing sodium hydroxide (NaOH) and sodium sulfide (Na_2S) is used to cook the chips in digesters at elevated temperature and pressure. The cooked chips are blown from the digester and washed to separate the spent cooking chemicals and dissolved organics, which together comprise "black liquor solids," from the fibers. The black liquor solids are sent for further processing in the kraft recovery system. The recovery system is critical to the economic viability of kraft pulping. It has two main functions: the recovery and regeneration of the inorganic pulping chemicals, and the combustion of the dissolved organic material with recovery of the energy content as process steam and electrical power. In some cases, it is also used to recover valuable organic by-products such as turpentine and tall oil.

Weak black liquor from pulp washing is sent to multiple-effect evaporators to increase its solids content to around 50%. The evaporation process requires a significant amount of energy. The resulting strong (concentrated) black liquor is sent to concentrators to increase the solids content further to between 65 and 80% (some older mills use direct contact evaporators instead of concentrators to increase the solids content to about 65%). The black liquor solids are then burned in a furnace known as a recovery boiler. Energy is produced in the oxidative zone of the boiler from organic matter in the liquor. This energy drives the chemical reactions in the reduction zone of the furnace, converting spent pulping chemicals into a molten smelt. Kraft black liquor solids are typically generated at a rate of between 1,300 and 1,900 kg of dry solids per metric tonne of pulp (2,600 to 3,800 lb/short ton). They have a higher heating value, ranging from about 12.6 to 15.2 GJ/tonne of black liquor solids (5,400 to 6,600 Btu/lb), so they are a significant source of energy for the pulp mill. Generally, the high pressure steam produced from recovery boilers is used to generate electricity through a process called combined heat and power (CHP) or cogeneration. With CHP or cogeneration, the high pressure steam turns a turbine to make electricity. Useful thermal energy (low or medium pressure steam) is also extracted from the turbine and used in the manufacturing process.

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[1] The heat to power ratio depends on the mill scenario investigated and is equivalent in the two systems compared.
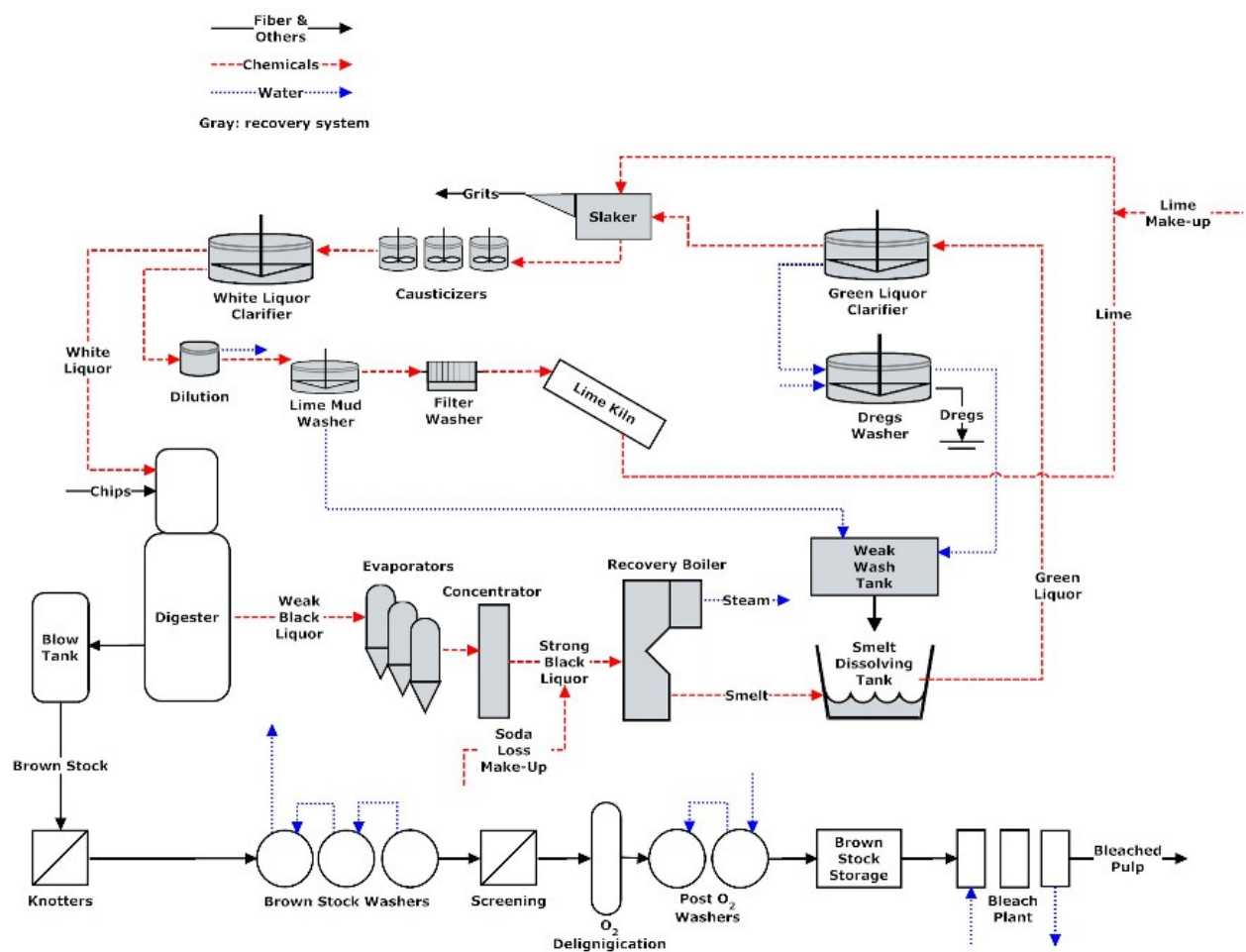
Figure 2.2 Flow Diagram of a Typical Kraft Pulping Process, Including Recovery and Bleaching
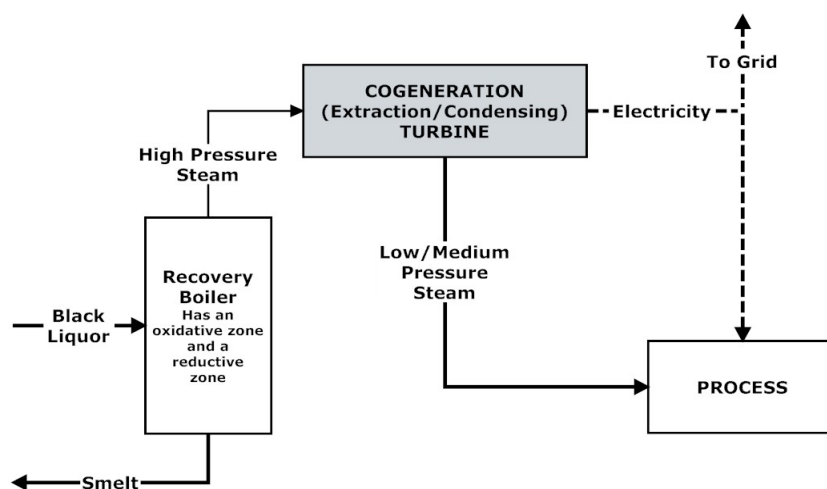
Figure 2.3 Cogeneration from Steam Produced in Recovery Boilers

The smelt, containing mainly sodium sulfide and sodium carbonate, is dissolved in weak wash (from the mud washing system) in the smelt dissolving tank to produce green liquor. The green liquor is clarified to remove solids (green liquor dregs) and sent to the slaker, which is then followed by a series of causticizers. Reburned lime (CaO) from the lime kiln (see below) or fresh lime is added to the slaker where it is slaked to form calcium hydroxide. The calcium hydroxide reacts with sodium carbonate present in the green liquor within the causticizers to form sodium hydroxide and calcium carbonate, the latter precipitating due to its low solubility. The resulting white liquor is clarified to remove calcium carbonate (lime mud) and inerts (slaker grits) prior to being sent to the pulp mill for use in the digester. The lime mud from the clarifier is washed, filtered, and sent to the lime kiln to convert calcium carbonate back into calcium oxide for reuse in the slaker. In the lime kiln, lime mud (about 55% to 80% calcium carbonate, with the balance being water) is calcined to form lime (CaO) and CO_2. The source of heat for this reaction is typically natural gas or fuel oil. Occasionally, petroleum coke is also used. A simplified representation of the chemistry in the kraft pulping and chemical recovery system is illustrated in Figure 2.4.
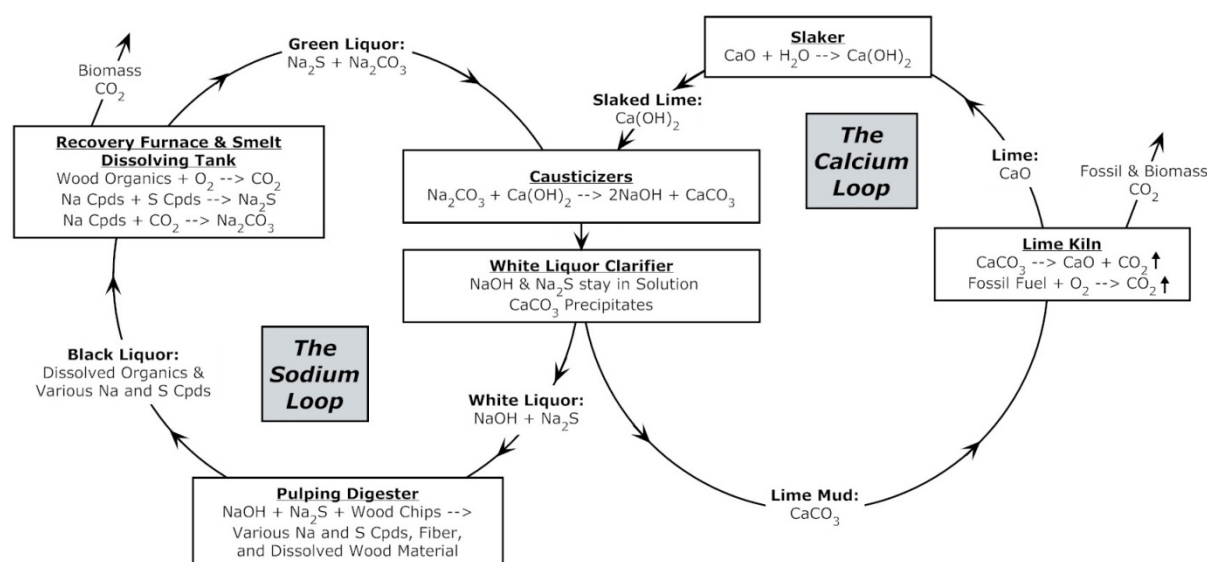
Figure 2.4 Chemistry of the Kraft Pulping Process

2.3.1.2   *System Boundary and Allocation*

When performing an LCA, the product system needs to be defined and the system boundary established. When several products (or functions) from different product systems share the same unit process or group of unit processes, an allocation problem is encountered. The allocation problem consists of the need to attribute the environmental load among each of the products (or functions) delivered by the shared process, which are sometimes referred to as multifunctional processes. Two types of co-products can be differentiated: co-products that are used within the investigated system, and co-products that are used in other product systems.

Several strategies can be used when an allocation problem is encountered. The ISO 14044 standard (ISO 2006b) on LCA recommends the following hierarchy of approaches, in preferential order:

1) Avoid allocation through
   a. System subdivision or
   b. System expansion;
2) Perform allocation using an underlying physical relationship; or
3) Perform allocation using another relationship.

When applying the ISO 14044 standard, system subdivision and system expansion strategies should be selected over allocation wherever possible. System expansion is possible and advantageous in this context, so it is applied. The advantage of system expansion in this study is that it allows the consideration of existing benefits outside the studied system. This is required in order to fully account for the potential benefits of the chemicals produced in the kraft recovery system as co-products of the energy produced in that system.

Two allocation problems are encountered in life cycle of energy production using black liquor. First, the black liquor solids that are the primary raw material for producing the energy do not exist in isolation but rather are a co-product of kraft pulp production. In other words, the kraft pulping unit process is shared between the kraft pulp and the black liquor solids. Second, the kraft recovery system, in which the energy is produced, also generates chemicals that are reused within the kraft pulping process (i.e., the kraft recovery system is shared between the energy and the chemicals). The application of a system expansion approach to these allocation problems discussed below explains the final system boundary as will then be illustrated in Figure 2.7.

System Expansion for the Kraft Pulping Process

A simplified schematic of the kraft pulping allocation problem is illustrated in Figure 2.5. In order to apply system expansion to that allocation problem, it is necessary to determine which of the three following statements best describes the case of black liquor.

1) Black liquor solids and kraft pulp are produced independently.
2) The production of kraft pulp is dependent on the production of black liquor solids.
3) The production of black liquor solids is dependent on the production of kraft pulp.

Statement #3 is the one which best describes the black liquor solids case. The production of both products (kraft pulp and black liquor solids) is determined by the demand for kraft pulp. Black liquor solids are produced because of that demand, and management actions chosen for black liquor solids will have little effect on the amount of pulp (and black liquor solids) produced. This is illustrated by the definition, for comparison purposes, of a parallel fossil fuel system in which kraft pulping remains constant (see Section 2.3.2 for more details). Using more black liquor solids for energy production will not affect the production of pulp. Instead, in theory[2], increased use of black liquor solids for energy results in less black liquor solids going to alternative management processes. For those specific situations, system expansion best practices (Ekvall and Weidema 2004) present two options:

1) exclude the shared process from the system boundary of the product under investigation and subtract from it equivalent alternative management process; or
2) exclude the shared process from the system boundary of the product under investigation and add an equivalent alternative management process to the system being compared.

Option 2 is used in this study because it gives systems that are more easily understood (see Section 2.3.2 for more details).

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[2] In practice, black liquor is always almost fully utilized for energy production.
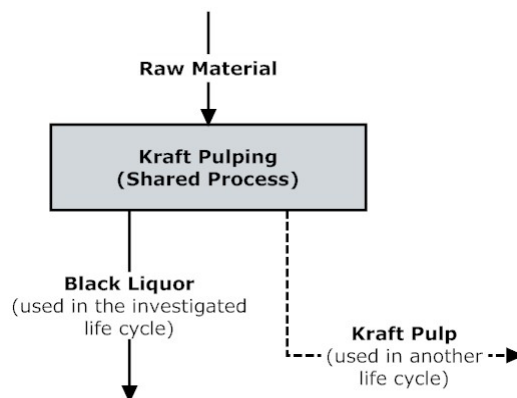
Figure 2.5 Kraft Pulping Allocation Problem

System Expansion for the Kraft Recovery System

A simplified schematic of this second allocation problem is shown in Figure 2.6a. Once again, it is necessary to determine which of the following statements best applies to the case of the energy.

1) Energy and pulping chemicals are produced independently.
2) The production of chemicals is dependent on the production of energy.
3) The production of energy is dependent on the production of pulping chemicals.

Black liquor solids are burned in the recovery boiler to recover the inorganics in a suitable chemical form to regenerate the pulping chemicals and energy is produced at the same time. One could decide not to recover the energy and this would not have an effect on the regeneration of chemicals. At the same time, one could, in theory, decide to burn the black liquor solids for the energy and not to recover the chemicals. Therefore, Statement #1 is the one which best describes the kraft recovery system. In this case, best system expansion practices recommend subdividing the shared process into its individual components. In doing so, two subprocesses specific to each of the products (energy and pulping chemicals) are defined: the energy recovery subprocess (evaporation, concentration, burning in recovery boilers), and the chemical recovery subprocess (smelt dissolution, green liquor clarification, causticizing, lime reburning, white liquor clarification). The energy recovery process is now shared between the energy and the smelt that is used as a raw material for pulping chemical production. This is illustrated in Figure 2.6b. It is still necessary to determine which of the following statements best applies to the case of the energy.

1) Energy and smelt are produced independently.
2) The production of smelt is dependent on the production of energy.
3) The production of energy is dependent on the production of smelt.
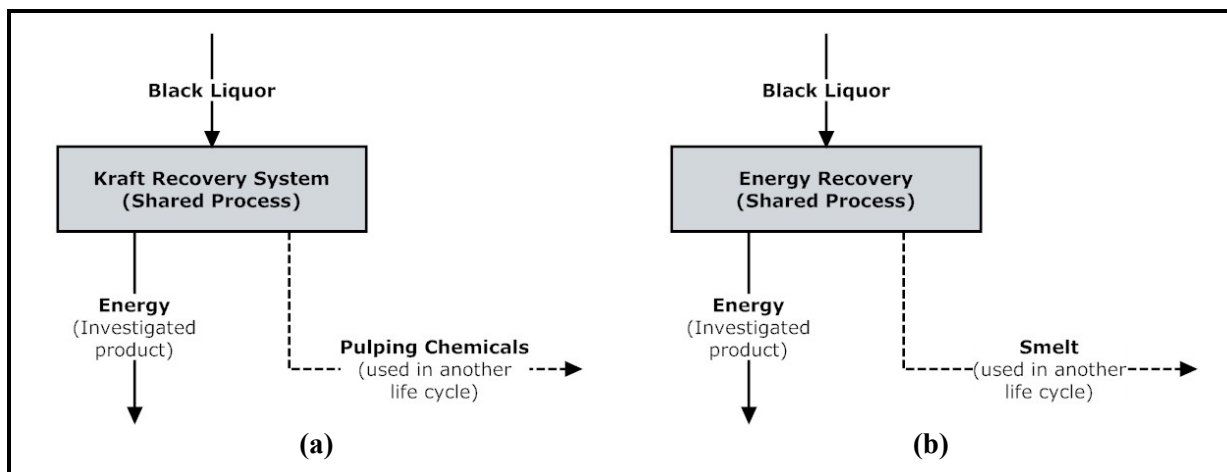
Figure 2.6 Kraft Recovery System Allocation Problem as Portrayed at
a) System Level, b) Energy Recovery Level

The production of smelt is now clearly dependent on the production of energy, which is the investigated product of this study. Reducing the combustion of black liquor solids that would otherwise be used to produce energy would reduce the production of smelt and pulping chemicals that would have to be produced otherwise. System expansion best practices for this situation are to include the shared process (energy recovery) in the system boundary and to include in the system boundary any other process that would be affected by a change in smelt production. This can be done by two different means:

1) expanding the system boundary to include the production of pulping chemicals using smelt and subtracting the alternative pulping production; or
2) expanding the system boundary to include the production of pulping chemicals using smelt and adding the alternative pulping chemical production to the compared system.

Option 2 is used in this study. The final system boundaries for the black liquor system are shown in Figure 2.7. The implications for the compared systems are discussed below.
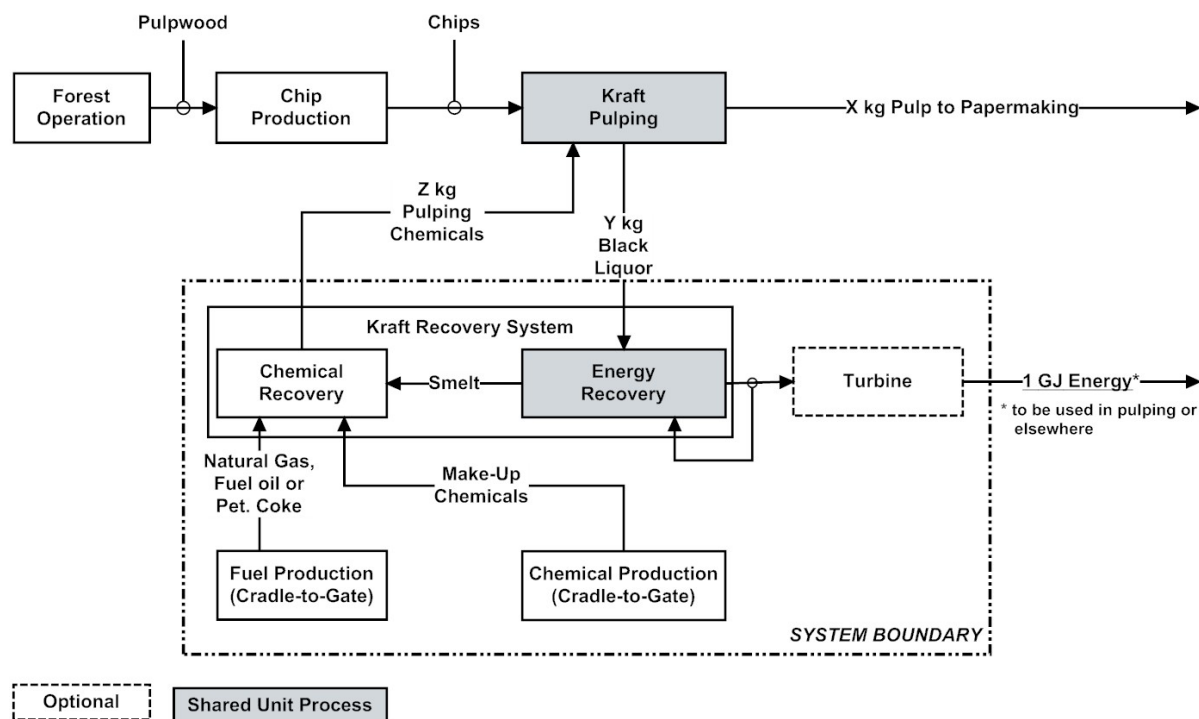
Figure 2.7 System Boundary for Energy Production Using Black Liquor Solids

Additional Functions

The primary functional unit of the system depicted in Figure 2.7 is the production of 1 GJ of energy. However, using the system expansion approach the investigated system has been expanded to include two secondary functions:

- the production of a fixed amount of pulping chemicals; and
- the management of black liquor solids.

2.3.1.3 *Summary of Processes Included and Excluded*

The system boundary includes the production and transportation of material (mainly make-up chemicals) and energy used in the kraft recovery process (mainly fuels for the lime kiln operations), as well as all other related upstream processes, the kraft recovery process itself and the turbine where applicable. It is assumed that the heat requirement for the kraft recovery system is satisfied internally. Capital equipment is not included.

2.3.2 *Fossil Fuel Product System*

To assess the potential benefits of the kraft recovery system, a parallel fossil fuel system has been defined. The ISO standard requires that in comparative studies "systems shall be compared using the same functional unit and equivalent methodological considerations […]." For this reason, the fossil fuel system needs to encompass the same primary functional unit and the same two secondary functional units as the black liquor system:

- the production of 1 GJ of energy (in the same form as for the black liquor system);
- the production of a fixed amount of pulping chemicals; and
- the management of black liquor solids.

This is illustrated in Figure 2.8. The system boundary includes the extraction, processing, and transportation of fossil fuels prior to their conversion to energy, as well as the conversion processes themselves. The system boundary is expanded to include the alternative production of pulping chemicals and management of black liquor solids.
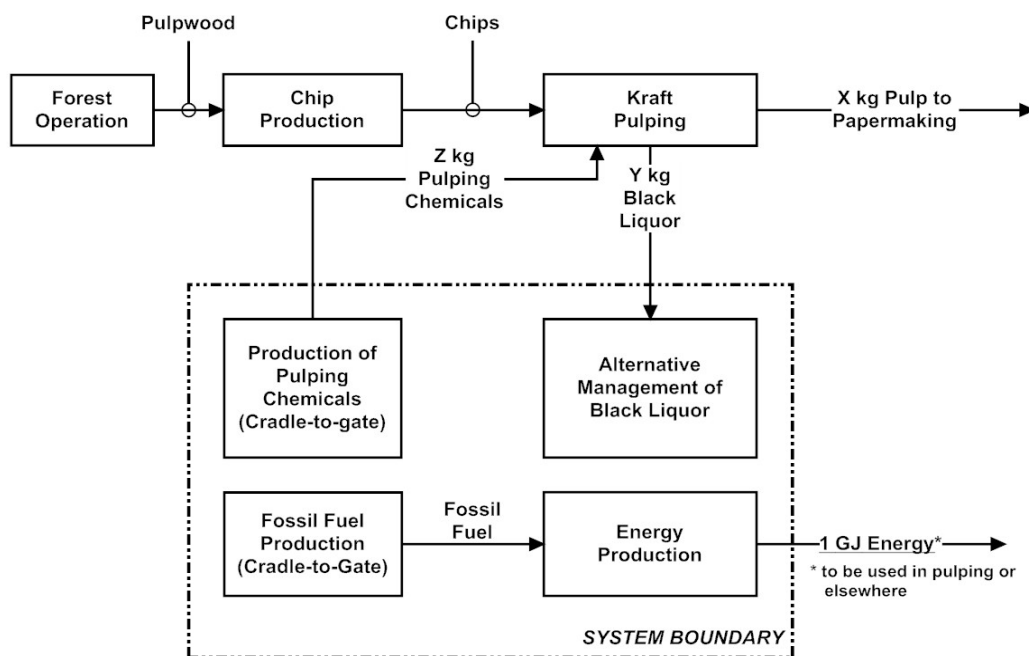
Figure 2.8 System Boundary for Energy Production Using Fossil Fuels

2.4   Impact Assessment and Other Indicators

Two indicators are characterized in this study: global warming, and life cycle non-renewable energy demand. More detail concerning these indicators is given in Table 2.1.

Table 2.1 Indicators Characterized

Indicator	Method	Unit	Description
Global warming	Intergovernmental Panel on Climate Change – 100 years (IPCC 2006)	kg CO_2 eq.	This indicator refers to the potential change in the earth's climate caused by the buildup of GHGs that trap heat radiated from the earth that would have otherwise passed out of the earth's atmosphere.
Life cycle non-renewable energy demand (NRE)	ecoinvent cumulative energy demand (Frischknecht et al. 2007; Goedkoop et al. 2008)	MJ	The objective of this indicator is to investigate the energy use throughout the life cycle of a good or service. This includes the direct uses as well as the indirect consumption of energy due to the use of, for example, construction materials or raw materials. The method includes renewable energy demand and non-renewable energy demand. Only the latter component is included in this study.

Net benefits are calculated as follows:

$$\text{Net GHG benefits } (\%) = \frac{\text{GHG}_{\text{Black liquor system}} - \text{GHG}_{\text{Fossil fuel system}}}{\text{GHG}_{\text{Fossil fuel system}}} \times 100$$

$$\text{Net resource benefits } (\%) = \frac{\text{NRE}_{\text{Black liquor system}} - \text{NRE}_{\text{Fossil fuel system}}}{\text{NRE}_{\text{Fossil fuel system}}} \times 100$$

2.5   Scenarios

Multiple scenarios are defined concerning 1) level of cogeneration from black liquor steam, 2) the fuel burned in lime kilns, 3) the heat energy displaced, and 4) the electricity displaced (see Table 2.2). The base case scenario (1.1, AI) assumes that all the steam produced from recovery boilers is sent to cogeneration turbines to produce electricity, that residual fuel oil is burned in lime kilns, that heat energy displaces energy from coal, and that cogenerated electricity displaces average electricity in the US (average grid). All scenarios are listed in Table 2.2. All possible combinations were analyzed, for a total of 36 scenarios.

Table 2.2 Scenarios Analyzed

Level of Cogeneration		Fuel Burned in Lime Kilns		Electricity		Heat Displaced	
1	Full	1	Residual fuel oil	A	Average US grid	I	Coal
2	None	2	Natural gas	B	Coal mix	II	Natural gas
		3	Petroleum coke	C	Natural gas combined cycle		

3.0 MODELING AND ASSUMPTIONS

3.1   Black Liquor System

3.1.1 *General Process Modeling*

A modular process simulation model using WinGEMS[3] was created to represent the material and energy flows in the digester, brown stock washing, recovery area, and steam and power system. The model simulates a bleached kraft pulp mill producing 1500 air-dried metric tonnes (admt) of bleached kraft pulp per day. A schematic of the full mill simulation is included in Appendix A. The sodium, potassium, sulfur, and chloride balance for the kraft pulping, oxygen delignification, and recovery areas is provided in Appendix B. The uncoated freesheet (UFS) results from the North American life cycle assessment report for printing and writing paper products served as the basis for tuning the base case simulation model for energy use and self-generated electricity amounts (NCASI 2010). There are 31 North American mills included in the UFS category in the North American life cycle assessment report. Of these 31 mills, energy inputs to 19 integrated[4] U.S. mills were used to tune the base case simulation model. The summary energy source information for the 19 US integrated mills producing primarily UFS product and the corresponding base case simulation fuel inputs and on-site electricity

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[3] WinGEMS is a process simulation program designed to model pulp and paper processes.
http://www.metso.com/automation/pp_prod.nsf/WebWID/WTB-050701-2256F-46EA1
[4] Integrated mills produce kraft pulp on site that is used to manufacture uncoated freesheet on site.

production amounts are given in Table 3.1. The major non-steam generating use of fuels is the energy requirements for lime kilns.

Based upon typical equipment operating conditions within the industry, the base case simulation model was used to quantify the material flows of cooking chemicals (NaOH and Na_2S), the steam and electricity generated by the black liquor recovery boiler and turbine system, and the energy consumed within the recovery area. Six simulation cases were constructed to provide cooking chemical material flow values and recovery area steam and electricity generation and consumption values for the life cycle modeling. The six simulation cases were divided into two subsets; one subset of the simulation model included cogeneration of electricity (i.e., a steam turbine generator system was integrated into the simulations), and one subset did not include cogeneration. The cases with and without cogenerated electricity were constructed to quantify the effects of cogenerated electricity on the life cycle results. Three simulation cases were constructed within the subsets by selecting different primary fuels in the lime kiln: residual fuel oil, natural gas, and petroleum coke. The three different lime kiln fuel simulations were constructed to provide complete coverage of the most common fuels used in lime kilns within the US pulp and paper industry.

Details of the key input parameters and output results for the simulation cases are provided in Appendix C.

Table 3.1 Production-Weighted Mean (PWM) Fuel Input and Electricity Production Values of 19 US Integrated Mills Producing Primarily Uncoated Freesheet Compared to Base Case Simulation Values

	PWM of UFS Mills		**Base Case Simulation Values**	
Black liquor solids fuel energy	18.55	GJ/admt	20.9	GJ/admt
Hogged fuel energy	6.39	GJ/admt	6.39	GJ/admt
Coal fuel energy	3.64	GJ/admt	3.64	GJ/admt
Natural gas fuel energy	4.02	GJ/admt	0.00	GJ/admt
Residual fuel oil	0.63	GJ/admt	1.78	GJ/admt
Total	33.2	GJ/admt	32.7	GJ/admt
Onsite electricity production	700	kWh/admt	703	kWh/admt

3.1.2 *Lime Kiln Fuel Energy*

The fuel mix for lime kilns operating at pulp and paper mills within the US, based on the NCASI combustion source database (NCASI 2005), is presented in Table 3.2.

Table 3.2 Fuel Mix for US Lime Kilns (NCASI 2005)

Fuel	Proportion in Mix[a] (%)
Natural gas	40.3
Residual fuel oil	56.4
Petroleum coke	3.3

[a] On an energy content basis.

The elemental composition, moisture content, and higher heating value (HHV) are required fuel specifications for the WinGEMS lime kiln model. Built-in fuel information for residual fuel oil and natural gas were adopted for the simulation and are presented in Table 3.3. Petroleum coke fuel

specifications were not available within the WinGEMS lime kiln model, and therefore literature value were used (Lee et al. 1997, 1999).

Table 3.3 Lime Kiln Fuel Specifications

Specification	Residual Fuel Oil	Natural Gas	Petroleum Coke
Carbon (wt. %)	85.8	74.8	86.3
Hydrogen (wt. %)	11	25.2	3.5
Nitrogen (wt. %)	-	-	1.6
Sulfur (wt. %)	3	-	5.5
Oxygen (wt. %)	0.45	-	0.5
Ash (wt. %)	0.05	-	0.3
Moisture (wt. %)	-	-	2.3
HHV (MJ/kg)	40.6	55.6	34.9

3.1.3 *Kraft Mill Steam Requirements*

Table 3.4 shows the department-level medium and low pressure steam requirements in the base case simulation model (residual fuel oil, with cogeneration). The small amount of high pressure steam used for recovery and power boiler sootblowing is not included in Table 3.4. Existing benchmarking results (Bruce 2000) indicate typical mill steam consumption values of between 17 GJ/admt for a 1990s vintage North American softwood bleached kraft mill to 22 GJ/admt for a 1980s vintage North American softwood bleached kraft mill.

Table 3.4 Department Medium and Low Pressure Steam Requirements—Base Case Simulation

Department	Steam Requirement (GJ/admt)
Medium pressure steam	
Digester	2.9
Oxygen delignification	1.7
Low pressure steam	
Pulp dryer	4.2
Evaporators	5.3
Steam stripper	1.5
Other[a]	2.4
Bleach plant	1.2
Digester	1.5
ClO_2 plant	0.2
Total medium and low pressure steam	20.9

[a] Other includes steam to deaerator, chiller, and other miscellaneous steam uses.

3.1.4 *Kraft Mill Electricity Requirements*

Steam and material flows were characterized within the simulation model. Kraft mill electricity requirements have been reviewed in a number of energy benchmarking studies involving hypothetical

model mills and data compiled from operating mills. The departmental electricity requirements from four studies are presented in Table 3.5. The "typical" 1990s North American mill in Bruce (2000) is based upon results from 1990s vintage operating mills. Other study results (Francis, Tower, and Browne 2002; Nygaard 1992) are based upon hypothetical model mills and would represent electricity consumption given best available technology.

Table 3.5 Departmental Electricity Requirements for Bleached Kraft Mills

Department[a]	**Model Bleached Market Kraft Pulp Mill** (Francis et al. 2002)	**"Typical" 1990s North American Mill** (Bruce 2000)	**1980s US Mill** (Nilsson et al. 1995)	**1990 Model Mill** (Nygaard 1992)
	(kWh/admt)			
Chip conveying	20	24	25	55
Digester	40	168	43	85
Washing and screening	30	-	103	-
Oxygen delignification	75	-	47	40
Bleaching[b]	100	124	42[*]	55
Screening and storage	-	-	74	45
Pulp machine	141	155	153	120
Black liquor evaporators	30	125	66	35
Steam stripping	-	-	-	-
Power plant	60	191	125	70
Kiln and recausticizing	50	30	42	60
Hot water supply	32	68	-	10
Wastewater treatment	30	-	-	30
Miscellaneous	30	-	61	20
Chemical preparation and oxygen	-	59	-	5
Total	638	944	781	630
***Total – Kraft recovery only*[c]**	180	514	276	250

[a] Electricity consumption, mostly by pumping and air handling systems (Larson and Nilsson 1991), was not explicitly considered in the simulation model. Bleached kraft mill benchmarking studies from the literature were used to characterize the electricity requirements associated with the kraft recovery system, so these electricity requirements could be considered in the life cycle modeling.

[b] Three-stage bleaching.

[c] An average value was used in this study.

3.1.5 *Process Simulation Results*

The simulation results on a per air-dried metric tonne (admt) of bleached pulp and a per gigajoule (GJ) of energy output are summarized in Table 3.6 and Table 3.7, respectively.

Table 3.6 Process Simulation Results (unit/admt of Bleached Pulp)

Material	Unit	Scenario					
		1.1	1.2	1.3	2.1	2.2	2.3
Inputs							
Black liquor solids	bdmt[a]	1.52	1.54	1.54	1.54	1.52	1.54
NaOH, 100%	kg	11.7	13.4	13.4	13.4	11.7	13.4
$Na_3H(SO_4)_2$ addition from R8/R10 plant	kg	18.6	16.3	16.2	16.3	18.6	16.2
Make-up lime (CaO)	kg	0.0162	0.0162	0.0162	0.0162	0.0162	0.0162
Steam	GJ	6.80	6.80	5.50	5.40	5.70	5.90
Natural gas	GJ	1.90	0.00	0.00	1.78	0.00	0.00
Fuel oil	GJ	0.00	1.78	0.00	0.00	1.90	0.00
Petroleum coke	GJ	0.00	0.00	1.70	0.00	0.00	1.70
Electricity	GJ	0.834	0.834	0.834	0.834	0.834	0.834
Outputs							
Steam	GJ	14.5	14.4	14.4	16.1	16.1	16.1
Electricity	GJ	1.60	1.60	1.60	0.00	0.00	0.00
NaOH, 100%, to pulping	kg	328	332	333	333	328	333
Na_2S, to pulping	kg	114	124	124	124	114	124

[a] Bone dry metric tonne.

Table 3.7 Process Simulation Results (unit/GJ of Net Energy Output)

Material	Unit	Scenario					
		1.1	1.2	1.3	2.1	2.2	2.3
Inputs							
Black liquor solids	bdmt[a]	0.178	0.182	0.158	0.143	0.148	0.151
NaOH, 100%	kg	0.00	0.00	0.00	0.00	0.00	0.00
$Na_3H(SO_4)_2$ addition from R8/R10 plant	kg	2.19	1.92	1.67	1.51	1.78	1.59
Make-up lime (CaO)	kg	0.00191	0.00191	0.00166	0.00150	0.00156	0.00162
Steam	GJ	0.00	0.00	0.00	0.00	0.00	0.00
Natural gas	GJ	0.223	0.00	0.00	0.650	0.00	0.00
Fuel oil	GJ	0.00	0.211	0.00	0.00	0.182	0.00
Petroleum coke	GJ	0.00	0.00	0.174	0.00	0.00	0.167
Electricity	kWh	0.00	0.00	0.00	0.00	0.00	0.00
Outputs							
Net energy output[b]	GJ	1.00	1.00	1.00	1.00	1.00	1.00
Steam	%	90.5	90.6	91.8	100	100	100
Electricity	%	9.50	9.40	8.20	0.00	0.00	0.00
NaOH, 100%, to pulping	kg	37.2	37.8	32.8	29.8	30.3	31.3
Na_2S, to pulping	kg	13.5	14.7	12.7	11.5	11.0	12.1

[a] Bone dry metric tonne.
[b] Energy output from which energy inputs have been subtracted.

3.1.6   *Chemicals and Fuels Used in Black Liquor System*

Chemicals and fuel consumed in the black liquor system were modeled based on data from a commercial life cycle inventory database (U.S. LCI). The datasets used are presented in Table 3.8.

Table 3.8 Data Sources for Chemicals and Fuels Used in Black Liquor System

Material	Database	Dataset
Natural gas	U.S. LCI	Natural gas, combusted in industrial equipment/RNA
Fuel oil	U.S. LCI	Residual fuel oil, combusted in industrial boiler/US
Petroleum coke	U.S. LCI	Petroleum coke, at refinery/kg/US, CO_2 combustion emissions from NCASI
Make-up lime	U.S. LCI	Quicklime, at plant/US

NOTE: RNA=North America.

3.2   Fossil Fuel System

3.2.1   *General Modeling Assumptions*

The fossil fuel system has been modeled using data from commercially available databases (U.S. LCI, ecoinvent). These databases include energy production efficiencies. For electricity, it was assumed that transmission losses were 7% of the produced power (U.S. Energy Information Agency 2010). Datasets used are presented in Table 3.9.

Table 3.9 Data Sets Used for the Fossil Fuel System

Energy type	Database	Dataset
Heat from coal	U.S. LCI	Bituminous coal, combusted in industrial boiler/US
Heat from natural gas	U.S. LCI	Natural gas, combusted in industrial boiler/US
Average U.S. electricity	U.S. LCI/ecoinvent	Based on 2006 fuel mix: Electricity, coal mix, at power plant/US (U.S. LCI); Electricity, residual fuel oil, at power plant/US (U.S. LCI); Electricity, natural gas, at power plant/US (U.S. LCI); Electricity, nuclear, at power plant/US (U.S. LCI); Electricity, hydropower, at power plant/SE (ecoinvent); Electricity, at wind power plant 800kW/RER (ecoinvent); Electricity, production mix photovoltaic, at plant/US (ecoinvent); Electricity, biomass, at power plant/US (U.S. LCI); No data for geothermal
Coal-based electricity	U.S. LCI	Electricity, coal mix, at power plant/US
Electricity from natural gas combined cycle	ecoinvent	Natural gas, burned in gas turbine/DE

NOTES: SE=Sweden, DE=Germany.

3.2.2   *Alternative Chemical Production*

The recovery of black liquor solids results in the production of two essential chemicals for the pulping process: sodium hydroxide (NaOH) ("caustic") and sodium sulfide (Na_2S). To make the fossil fuel system equivalent to the black liquor system, it is necessary to include an equivalent alternative chemical production in the fossil fuel system.

Life cycle data for caustic production are from the U.S. LCI database (see Table 3.10).

No life cycle data are available for sodium sulfide production. For this reason, a data set was constructed. Industrially, sodium sulfide can be produced through several different process pathways. In this study, it was assumed that sodium sulfide is produced by the reduction of sodium sulfate (Na_2SO_4) with carbon (charcoal). This process pathway was selected because it already takes place in pulp and paper mills given that sodium sulfate is often used as a make-up chemical. Resource and energy requirements were estimated from stoichiometry and heat of reaction:

$$Na_2SO_4 + 4C \xrightarrow{H_R = -12966 \text{ kJ/kg}} Na_2S + 4CO$$
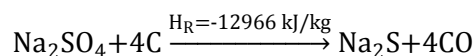
Also, since this reaction occurs at high temperatures (900°C-1000°C), an additional energy requirement (2215 kJ/kg Na_2S) for bringing the reactants to the appropriate temperature was included. The energy was assumed to be provided by natural gas. Natural gas life cycle information was obtained from the U.S. LCI database while sodium sulfate and charcoal life cycle information was obtained from the ecoinvent database (see Table 3.10).

There are several process pathways to produce sodium sulfide, but it is unlikely that the choice of pathway has a significant impact on energy requirements. For instance, in contrast to the pathway selected above, a different pathway involves the saturation of a caustic soda solution with hydrogen sulfide (H_2S) and further reaction with caustic. This pathway has an enthalpy of reaction very similar to the previous one. It does not require as high a temperature but the solution produced with caustic and sodium sulfide needs to be concentrated before further reaction. Furthermore, the life cycle GHG emissions associated with the chemicals used in this latter pathway are similar to those in the previous pathway.

Table 3.10 Data Sources for Alternative Chemical Production

Material	Database	Dataset
Caustic	U.S. LCI	Sodium hydroxide, production mix, at plant/kg/RNA
Sodium sulfate	ecoinvent	Sodium sulphate, powder, production mix, at plant/RER
Carbon	ecoinvent	Charcoal, at plant/GLO, assuming charcoal is 95% carbon
Natural gas	U.S. LCI	Natural gas, combusted in industrial equipment/RNA

NOTES: RNA= North America, RER=average Europe, GLO=global.

3.2.3   *Alternative Management of Black Liquor Solids*

The recovery of black liquor not only provides energy and chemicals for the pulp and paper process, it also allows disposing of the organic matter. For this reason, to make the fossil fuel- and black liquor-based kraft recovery systems equivalent, it is necessary to include an equivalent management of black liquor solids in the fossil fuel-based system.

A detailed model of alternative management of black liquor solids would have required too much speculation, but the management would almost certainly ultimately involve returning the biogenic carbon in the liquor to the atmosphere. In the best case, it would return as CO_2, so this is what has been modeled. The alternative management may involve greater emissions of GHGs if, for instance, some the biogenic carbon is returned to the atmosphere as methane or if fossil fuels were required. For this reason, the approach taken is conservative.

3.3   Other Supporting Information

3.3.1   *Transportation*

Data to estimate emissions related to transportation of materials are based on the U.S. LCI database where available or estimated from the 2002 U.S. Commodity Flow Survey (U.S. Department of Transportation and U.S. Department of Commerce 2004, Table 6), (http://www.census.gov/svsd/www/cfsdat/2002cfs-us.html)[5]. One-way trips were assumed. More information can be found in Table 3.11 and Table 3.12. Transportation processes were modeled using the U.S. LCI and ecoinvent databases (see Table 3.13).

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[5] Neglecting multimodal transportation.

Table 3.11 Transportation Distances and Modes Based on US LCI Database

Material	Unit	Truck tkm/unit	Rail tkm/unit	Water, Inland tkm/unit	Pipeline tkm/unit
Natural gas	m^3	0.199	0.0119	-	1.19
Fuel oil	L	0.00525	0.00336	0.0284	-
Petroleum coke	kg	0.0290	0.676	0.0470	-
Bituminous coal	kg	0.00676	1.04	-	0.00502

Table 3.12 Transportation Distances and Modes Based on Commodity Flow

SCGT 3-Digit Category	Used for	Truck %	Truck Distance (km)	Rail %	Rail Distance (km)	Water, Inland %	Water, Inland Distance (km)
Sodium hydroxide (caustic soda) and potassium hydroxide (caustic potash)	NaOH	41.3	230	39.7%	927	19.0%	776
Inorganic chemicals	CaO, Na$_2$S, sodium sulfate	73.7%	183	21.9%	1088	4.3%	489
Other wood product	Charcoal	100%	303	-	-	-	-

Table 3.13 Data Sets for Transportation Processes

Transportation Process	Database	Dataset
Truck	U.S. LCI	Transport, combination truck, average fuel mix/US
Rail	U.S. LCI	Transport, train, diesel powered/US
Water, inland	U.S. LCI	Transport, barge, average fuel mix/US
Pipeline	ecoinvent	Transport, natural gas, pipeline, long distance/RER Transport, crude oil pipeline, onshore/RER

3.3.2 *Heat Contents*

The process simulation produced energy balances in energy units while some U.S. LCI database combustion data are in mass units. Hence, heating values presented in Table 3.14 were used.

Table 3.14 Fuel Heating Values

Fuel	Unit	Heating Value (GJ LHV[a]/unit)
Natural gas	m^3	0.0351
Fuel oil	L	0.0420
Coal	kg	0.0295

[a] 1 GJ HHV ≈0.95 GJ LHV.

4.0 RESULTS

The main GHG mitigation benefits results are presented in Table 4.1. The results for the individual scenarios can be found in Appendix B.

These results show that for the base case scenario (full cogeneration, natural gas burned in the kilns, average US grid displaced, and heat from coal displaced), the recovery of black liquor produced a reduction of approximately 182 kg CO_2 eq./GJ, or 91% of fossil fuel CO_2.

When combining all scenarios, a median reduction of approximately 140 kg CO_2 eq./GJ, or 90% of fossil fuel CO_2, is estimated. When no cogeneration is considered about 90% of the benefit is reached. Finally, the benefits from the recovery of the chemicals vary from 44% to 75% of the total benefit.

Table 4.1 Summary of GHG Mitigation Benefits Results

Scenario/Case	Absolute Reduction (kg CO_2 eq./GJ)	Relative Reduction (%)	Contribution of Chemical Recovery (%)
Base case (1.1, AI)	182	90.5%	49.8%
Min	97.9	69.0%	74.9%
Median	142	88.0% (89.9%, 79.9%)[a]	54.3%
Max	192	92.4%	44.2%

[a] (with cogeneration, without cogeneration).

Table 4.2 frames the GHG emission reduction due to black liquor recovery in the context of the emissions of the entire US forest products industry. It shows that the reduction is essentially enough to fully offset Scope 1 (direct) and Scope 2 (purchased electricity) emissions.

Table 4.2 US Total GHG Emissions Reduction Due to Use of Black Liquor Solids

Energy from black liquor solids in US in 2004	1.05e09 GJ (Heath et al. 2010)
Total potential GHG reduction due to black liquor recovery	149 Tg CO_2 eq.[a]
Scope 1 & 2 GHG emissions (fossil) by the whole US forest products manufacturing facilities in 2004	108 Tg CO_2 (Heath et al. 2010)

[a] Calculated: 142 kg CO_2 eq./GJ x 1.05E09 GJ = 1.49E11 kg CO_2 eq. = 149 Tg CO_2 eq.

The main non-renewable energy consumption benefits results are presented in Table 4.3. The results for the individual scenarios can be found in Appendix E.

Table 4.3 Summary of Non-Renewable Energy Conservation Benefits Results

Scenario/Case	Absolute Reduction (GJ_{NR}/GJ)[a]	Relative Reduction (%)	Contribution of Chemical Recovery (%)
Base case (1.1, AI)	2.51	89.8%	55.2%
Min	1.49	71.1%	68.4%
Median	1.91	87.1% (89.2%, 77.0%)[b]	55.4%
Max	2.51	90.7%	47.0%

[a] GJ_{NR}: Life cycle non-renewable energy required to produce 1 GJ of energy.
[b] (with cogeneration, without cogeneration).

These results show that for the base case scenario (full cogeneration, natural gas burned at the kilns, average US grid displaced, and heat from coal displaced) , the recovery of black liquor solids produced a reduction of approximately 2.51 GJ non-renewable energy for each GJ of energy output (90% reduction). When considering all scenarios, a median reduction of approximately 1.91 GJ/GJ is achieved. When no cogeneration is considered, about 90% of the benefit is reached. The benefits from recovery of the pulping chemicals vary from 47% to 68% of the total benefit.

5.0 LIMITATIONS

The intent of this study was to improve the understanding of the GHG mitigation and fossil fuel conservation benefits of black liquor solids recovery. It is important to understand the limitations of the study before drawing conclusions. The main limitations of the study are the following:

- the use of assumptions regarding the types of energy displaced, and particularly the nature of the alternative chemical production processes, introduces uncertainty;

- the completeness and applicability of some of the inventory data used are open to question especially regarding:

  - the modeling of the production of sodium sulfide; and

  - the use of some secondary data from European LCI database (ecoinvent);

- the limited scope of the life cycle impact assessment precludes a comprehensive view of the life cycle impacts; and

- because LCIA indicator results are relative expressions they cannot be used to predict impacts on category endpoints, exceedances of thresholds, safety margins, or risk.

6.0 CONCLUSIONS

In this study, the life cycle GHG and fossil fuel-related benefits of black liquor solids recovery were analyzed. These benefits are due to two effects: the production of energy that can be used in the pulping process or sold, and the recovery of the pulping chemicals that would otherwise need to be produced from other resources.

The fossil GHG emissions and non-renewable energy consumption for a system using black liquor solids in the kraft recovery system are approximately 90% lower than those for a comparable fossil fuel-based system. When applying this reduction to the production of kraft pulp in the US, the avoided emissions are enough to offset all of the total Scope 1 and Scope 2 emissions from the entire US pulp and paper industry (all mills). This result does not depend on the accounting method for biogenic carbon because biogenic CO_2 emissions are the same for the systems compared and the result is valid across a range of assumptions about the displaced fossil fuel, the GHG intensity of the electricity grid, the fossil fuels used in the lime kiln, and the level of cogeneration at pulp and paper mills. The benefits occur without affecting the amount of wood harvested or the amount of chemical pulp produced.

REFERENCES

Abbasi, T. and S.A. Abbasi. 2010. "Biomass Energy and the Environmental Impacts Associated with ITS PRODUCTION and Utilization." *Renewable and Sustainable Energy Reviews* 14(3):919-937. doi:10.1016/j.rser.2009.11.006

American Forest & Paper Association (AF&PA). 2010. *2010 AF&PA Sustainability Report*. Washington DC: American Forest & Paper Association. http://www.afandpa.org/Sustainability/ (accessed April 2011).

Bruce, D.M. 2000. Benchmarking energy consumption and identifying opportunities for conservation. *Pulp and Paper Canada* 101(11):35-38.

Cherubini, F. 2010. GHG balances of bioenergy systems - Overview of key steps in the production chain and methodological concerns. *Renewable Energy* 35(7):1565-1573. doi:10.1016/j.renene.2009.11.035

Cherubini, F., N.D. Bird, A. Cowie, G. Jungmeier, B. Schlamadinger, and S. Woess-Gallasch. 2009. "Energy- and Greenhouse Gas-Based LCA of Biofuel and Bioenergy Systems: Key Issues, Ranges and Recommendations." *Resources, Conservation and Recycling* 53(8):434-447. doi:10.1016/j.resconrec.2009.03.013

Ekvall, T. and B.P. Weidema. 2004. "System Boundaries and Input Data in Consequential Life Cycle Inventory Analysis." *International Journal of Life Cycle Assessment* 9(3):161-171. doi:10.1007/BF02994190

Francis, D.W., M. T. Towers, and T.C. Browne. 2002. *Energy Cost Reduction in the Pulp and Paper Industry—An Energy Benchmarking Perspective*. Ottawa, ON: Natural Resources Canada. http://oee.nrcan.gc.ca/publications/infosource/pub/cipec/pulp-paper-industry/pdf/pulp-paper-industry.pdf.

Frischknecht, R., N. Jungbluth, J. Althaus, C. Bauer, G. Doka, R. Dones, R. Hischier, S. Hellweg, S. Humbert, T. Köllner, Y. Loerincik, M. Margnin, and T. Nemecek, eds. 2007. *Implementation of Life Cycle Impact Assessment Methods*. ecoinvent Report No. 3. Dübendorf, Switzerland: Swiss Centre for Life Cycle Inventories.

Froese, R.E., D.R. Shonnard, C.A. Miller, K.P. Koers, and D.M. Johnson. 2010. "An evaluation of Greenhouse Gas Mitigation Options for Coal-Fired Power Plants in the US Great Lakes States." *Biomass and Bioenergy* 34(3):251-262. doi:10.1016/j.biombioe.2009.10.013

Goedkoop, M., M. Oele, A. de Shriver, and M. Vieira. 2008. *SimaPro Database Manual - Methods Library*. Amersfoort, The Netherlands: PRé Consultants.

Heath, L.S., V. Maltby, R. Miner, K.E. Skog, J.E., Smith, J. Unwin, J. and B. Upton. 2010. "Greenhouse Gas and Carbon Profile of the U.S. Forest Products Industry Value Chain." *Environmental Science & Technology* 44(10):3999-4005. doi:10.1021/es902723x

Intergovernmental Panel on Climate Change (IPCC). 2006. *2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 1 General Guidance and Reporting*. Hayama, Japan: Institute for Global Environmental Strategies. http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol1.html.

International Organization for Standardization (ISO). 2000. *Environmental management—Life cycle assessment—Examples of application of ISO 14041 to goal and scope definition and inventory analysis*. ISO/TR 14049. Geneva: International Organization for Standardization.

———. 2002. *Environmental management—Life cycle assessment—Data documentation format*. ISO/TS 14048. Geneva: International Organization for Standardization.

———. 2003. *Environmental management—Life cycle impact assessment—Examples of application of ISO 14042*. ISO/TR 14047. Geneva: International Organization for Standardization.

———. 2006a. *Environmental management—Life cycle assessment—Principles and framework*. ISO 14040. Geneva: International Organization for Standardization.

———. 2006b. *Environmental management—Life cycle assessment—Requirements and guidelines*. ISO 14044. Geneva: International Organization for Standardization.

Larson, E.D. and L.J. Nilsson. 1991. "Electricity Use and Efficiency in Pumping and Air-Handling Systems." *ASHRAE Transactions* 97(2):363-377.

Lattimore, B., C.T. Smith, B.D. Titus, I. Stupak, and G. Egnell. 2009. "Environmental Factors in Woodfuel Production: Opportunities, Risks, and Criteria and Indicators for Sustainable Practices." *Biomass and Bioenergy* 33(10):1321-1342. doi:10.1016/j.biombioe.2009.06.005

Lee, J.M., J.J. Baker, D. Murray, R. Llerena, and J.G. Rolle. 1997. "Quality Analysis of Petroleum Cokes and Coals for Export Specifications Required in Use of Specialty Products and Utility Fuels." In *Preprints of Symposia from the 214th American Chemical Society National Meeting, Division of Fuel Chemistry in Las Vegas, NV*, pp. 844-853.

———. 1999. "Comparison of Fuel Properties of Petroleum Cokes and Coals Used in Power Generation." In *Preprints of Symposia from the 217th American Chemical Society National Meeting, Division of Fuel Chemistry in Anaheim, CA*, pp. 80-89.

Mann, M. and P. Spath. 2001. "A life cycle assessment of biomass cofiring in a coal-fired power plant. *Clean Technologies and Environmental Policy* 3(2):81-91. doi:10.1007/s100980100109

National Council for Air and Stream Improvement, Inc. (NCASI). 2005. *Combustion Source Database*. Research Triangle Park, NC: National Council for Air and Steam Improvement, Inc.

———. 2010. *Life Cycle Assessment of North American Printing and Writing Paper Products*. Report prepared for American Forest & Paper Association and Forest Products Association of Canada. Research Triangle Park, NC: National Council for Air and Steam Improvement, Inc.

Nygaard, J. 1992. *The Energy Efficient Modern Mill for Bleached Kraft Pulp, a Net Supplier of Electrical Power*. Strasbourg, France.

Pehnt, M. 2006. Dynamic life cycle assessment (LCA) of renewable energy technologies. *Renewable Energy* 31(1):55-71. doi:10.1016/j.renene.2005.03.002

Petersen Raymer, A.K. 2006. A comparison of avoided greenhouse gas emissions when using different kinds of wood energy. *Biomass and Bioenergy* 30(7):605-617. doi:10.1016/j.biombioe.2006.01.009

Robinson, A.L., J.S. Rhodes, and D.W. Keith. 2003. "Assessment of Potential Carbon Dioxide Reductions Due to Biomass−Coal Cofiring in the United States." *Environmental Science & Technology* 37(22):5081-5089. doi:10.1021/es034367q

Schlamadinger, B., M. Apps, F. Bohlin, L. Gustavsson, G. Jungmeier, G. Marland, K. Pingoud, and I. Savolainen, I. 1997. "Towards a Standard Methodology for Greenhouse Gas Balances of Bioenergy Systems in Comparison with Fossil Energy Systems." *Biomass and Bioenergy* 13(6):359-375. doi:10.1016/S0961-9534(97)10032-0

Todd, J.A. and M.A. Curran, eds. 1999. *Streamlined Life-Cycle Assessment: A Final Report from the SETAC North America Streamlined LCA Workgroup*. Pensacola, FL: Society of Environmental Toxicology and Chemistry (SETAC).

U.S. Department of Transportation and U.S. Department of Commerce. 2004. *2002 Economic Census—Transportation—Commodity Flow Survey*. EC02TCF-US. Washington, DC: U.S. Department of Transportation and U.S. Department of Commerce.

U.S. Energy Information Agency. 2010. *Annual Energy Review 2009*. DOE/EIA-0384(2009). Washington, DC: U.S. Department of Energy, U.S. Energy Information Agency.

APPENDIX A

SCHEMATIC OF THE FULL MILL SIMULATION

APPENDIX B

SODIUM, POTASSIUM, SULFUR, AND CHLORIDE BALANCE FOR THE KRAFT PULPING, OXYGEN DELIGNIFICATION AND RECOVERY AREA

Material	Production (1500 admt/day)			
	Na	K	S	Cl
	kg/admt	kg/admt	kg/admt	kg/admt
Input				
Raw material	0.11	1.17	0.19	0.69
Caustic make-up	7.73	-	-	-
$Na_3H(SO_4)_2$ from R8/R10	4.89	-	4.55	-
Kiln Oil	-	-	2.68	-
O_2 $MgSO_4$	-	-	0.95	-
Total	12.73	1.174	8.38	0.69
Output				
Wash losses to bleach plant	2.10	0.41	0.68	0.00
Accidental black liquor losses	2.79	0.18	0.62	0.11
Accidental white liquor losses	2.14	0.13	0.52	0.08
Dregs and grits	0.51	0.03	0.12	0.02
Purged ESP dust	3.60	0.36	2.22	0.42
Recovery boiler flue gas	0.43	0.04	0.26	0.05
Purged lime dust	0.35	0.00	0.24	0.00
Knotter rejects	0.21	0.02	0.06	0.01
Sewered neutralized spent acid	0.62	0.00	0.58	0.00
Evaporator foul condensates	-	-	0.43	-
Evaporator NCG	-	-	0.38	-
Digester flash steam scrubber	-	-	0.87	-
Kiln flue gas	-	-	1.42	-
Total	12.73	1.175	8.40	0.69

APPENDIX C

KEY INPUT PARAMETERS AND OUTPUT RESULTS FOR THE SIMULATION CASES

Key Output Values	Co-generation cases			Non co-generation cases			Units
	Kiln fired with…			Kiln fired with…			
	Fuel oil[2]	Natural Gas[5]	Petcoke[7]	Fuel oil[2]	Natural Gas[5]	Petcoke[7]	
Bleached Pulp							
Production rate	1500	1500	1500	1500	1500	1500	admt/day (10% moisture)
Production rate	1425	1425	1425	1425	1425	1425	machine dried mt/day (5% water)
Unbleached Pulp							
Production rate	1562	1562	1562	1562	1562	1562	admt/day
Fresh shower water to O_2 wash press	475	475	475	475	475	475	mt/hr
O_2 wash press dilution factor	5.8	5.8	5.8	5.8	5.8	5.8	-
O_2 wash press wash liquor ratio	3.5	3.5	3.5	3.5	3.5	3.5	-
Sodium losses from brown stock	2.2	2.2	2.2	2.2	2.2	2.2	kg Na/admt pulp
White Liquor							
Flow rate	175	171	175	175	171	175	mt/hr
Temperature	101	101	101	101	101	101	°C
EA	130	131	130	130	131	130	g/L as NaOH
Sulfidity	32.0	30.3	32.0	32.0	30.3	32.0	%
Carbonate (as Na_2CO_3)	26	27	26	26	27	26	g/L
Caustic make-up (50% NaOH solution)	1.7	1.5	1.7	1.7	1.5	1.7	mt/hr
Mass flow of hydroxide in white liquor	20.8	20.5	20.8	20.8	20.5	20.8	mt/hr as (100% NaOH)
Mass flow of hydrosulfide in white liquor	7.7	7.1	7.7	7.7	7.1	7.7	mt/hr as (100% Na_2S)

Key Output Values	Co-generation cases			Non co-generation cases			Units
	Kiln fired with…			Kiln fired with…			
	Fuel oil[2]	Natural Gas[5]	Petcoke[7]	Fuel oil[2]	Natural Gas[5]	Petcoke[7]	
Oxidized White Liquor							
Flow rate	9.4	9.3	9.4	9.4	9.3	9.4	mt/hr
EA	119	121	119	119	121	119	g/L as NaOH
Mass flow of hydroxide in oxidized white liquor	1.02	1.02	1.02	1.02	1.02	1.02	mt/hr as (100% NaOH)
Digester							
Circulation heaters steam flow	63	63	63	63	63	63	mt/hr
Wash liquor heater steam flow	35	35	35	35	35	35	mt/hr
Evaporators/Concentrators							
Weak black liquor flow	734	730	734	735	730	735	mt/hr
Weak black liquor total dissolved solid content	13.1	13.0	13.1	13.1	13.0	13.1	mass %
Weak black liquor total inorganic load (% of TDS)	28.3	27.7	28.4	28.3	27.7	28.4	mass %
Strong black liquor total dissolved solids	67.4	67.4	67.4	67.4	67.4	67.4	mass %
Steam flow	120	119	120	120	120	120	mt/hr
Steam economy	4.9	4.9	4.9	4.9	4.9	4.9	
Boiling point rise of strong black liquor	13	13	13	13	13	13	Δ°C
Tall oil	2.4	2.4	2.4	2.4	2.4	2.4	mt/hr
Recovery Boiler							
Superheated steam flow leaving boiler	308	309	308	308	309	308	mt/hr
Temperature of superheated steam	450	450	450	450	450	450	°C
Pressure of superheated steam	85	85	85	85	85	85	bars
Enthalpy of superheat steam	3264	3264	3264	3264	3264	3264	kJ/kg

Key Output Values	Co-generation cases			Non co-generation cases			Units
	Kiln fired with…			Kiln fired with…			
	Fuel oil²	Natural Gas⁵	Petcoke⁷	Fuel oil²	Natural Gas⁵	Petcoke⁷	
Energy content of superheated steam leaving boiler	16.1	16.1	16.1	16.1	16.1	16.1	GJ/admt
High pressure steam used for sootblowing	7.9	7.9	7.9	7.9	7.9	7.9	mt/hr
High pressure steam used for sootblowing	2.50	2.50	2.50	2.50	2.50	2.50	% of total recovery boiler steam
Calculated black liquor HHV	12.97	13.07	12.97	12.97	13.07	12.97	MJ/kg solids
As-fired black liquor flow rate	100.6	99.1	100.7	100.6	99.1	100.7	mt solids/hr
As-fired liquor dry solids	1.61	1.59	1.61	1.61	1.59	1.61	kg dry solids/admt pulp
Black liquor fuel energy	20.9	20.7	20.9	20.9	20.7	20.9	GJ/admt
Black liquor elemental composition							
C	34.8	35.3	34.8	34.8	35.3	34.8	wt % solids
H	4.0	4.0	4.0	4.0	4.0	4.0	wt % solids
S	5.5	5.2	5.6	5.5	5.2	5.6	wt % solids
Na	19.8	19.5	19.8	19.8	19.5	19.8	wt % solids
O	33.6	33.7	33.6	33.6	33.7	33.6	wt % solids
K	1.3	1.3	1.3	1.3	1.3	1.3	wt % solids
Cl	0.9	1.0	0.9	0.9	1.0	0.9	wt % solids
$Na_3H(SO_4)_2$ addition from R8/R10 plant	1.02	1.16	1.02	1.02	1.16	1.01	mt/hr
Auxiliary Fuel¹	0.00	0.00	0.00	0.00	0.00	0.00	mt/hr
Power Boiler							
Hogged fuel flow (including hogged fuel water content)³	38.96	38.96	38.96	36.95	36.36	36.96	mt/hr
Moisture content of hogged fuel	0.50	0.50	0.50	0.50	0.50	0.50	mass fraction
Hogged fuel energy	6.39	6.39	6.39	6.06	5.96	6.06	GJ/admt
Steam production from hogged fuel boiler	102.1	102.1	102.1	96.8	95.3	96.8	mt/hr

Key Output Values	Co-generation cases Kiln fired with…			Non co-generation cases Kiln fired with…			Units
	Fuel oil[2]	Natural Gas[5]	Petcoke[7]	Fuel oil[2]	Natural Gas[5]	Petcoke[7]	
Steam production from hogged fuel boiler	21.3	21.3	21.3	23.9	23.6	23.9	% of total steam production
Coal flow to power boiler[4]	7.4	7.4	7.4	0.0	0.0	0.0	mt/hr
Coal fuel energy	3.64	3.64	3.64	0.00	0.00	0.00	GJ/admt
Steam production from coal power boiler	68.1	68.1	68.1	0.0	0.0	0.0	mt/hr
Steam production from coal power boiler	14.2	14.2	14.2	0.0	0.0	0.0	% of total steam production
Natural gas flow to power boiler[5]	0.0	0.0	0.0	0.0	0.0	0.0	mt/hr
Natural gas fuel energy	0.0	0.0	0.0	0.0	0.0	0.0	GJ/admt
Steam production from natural gas power boiler	0.0	0.0	0.0	0.0	0.0	0.0	mt/hr
Steam production from natural gas power boiler	0.0	0.0	0.0	0.0	0.0	0.0	% of total steam production
Smelt Dissolving Tank							
Smelt flow rate	39	38	39	39	38	39	mt/hr
Steam flow rate	4.9	4.8	4.9	4.9	4.8	4.9	mt/hr
(2*EA - AA)/(TTA + 2EA - 2AA)*100	18.9	19.3	19.0	18.9	19.3	19.0	%
Clarified Green Liquor							
Flow rate	249	245	249	249	245	249	mt/hr
Temperature	100	100	100	100	100	100	°C
Green liquor $CO_3^=$ concentration	66.1	67.3	66.0	66.1	67.3	66.0	g/L
Green liquor OH^- concentration	19.1	18.9	19.1	19.1	18.9	19.1	g/L
Slaking/Causticizing							
Steam flow rate	8.8	8.8	8.8	8.8	8.8	8.8	mt/hr
(2*EA - AA)/(TTA + 2EA - 2AA)*100	82.4	82.5	82.4	82.4	82.5	82.4	%
Fresh water to liquor preparation	190	187	190	190	187	190	mt/hr

Key Output Values	Co-generation cases			Non co-generation cases			Units
	Kiln fired with…			Kiln fired with…			
	Fuel oil[2]	Natural Gas[5]	Petcoke[7]	Fuel oil[2]	Natural Gas[5]	Petcoke[7]	
Lime make-up	0.001	0.001	0.001	0.001	0.001	0.001	mt/hr
Lime Mud							
Flow rate	74	75	75	74	75	75	mt/hr
Lime Kiln							
Fuel usage	2.70	2.11	3.00	2.70	2.11	3.00	mt/hr
Energy consumption per weight of product	6.80	7.24	6.42	6.80	7.24	6.42	GJ/mt
Energy consumption per weight of lime	8.09	8.62	7.72	8.09	8.62	7.72	GJ/mt
Energy consumption per admt of bleached pulp	1.78	1.90	1.70	1.78	1.90	1.70	GJ/admt
Energy Summary							
Medium pressure steam flow from turbines	100	99	100	0	0	0	mt/hr
Temperature	223.6	223.6	223.6	0.0	0.0	0.0	°C
Pressure	12.0	12.0	12.0	0.0	0.0	0.0	bar
Enthalpy	2871.9	2871.9	2871.9	2872.6	2872.6	2872.6	kJ/kg
Low pressure steam flow from turbines	213	214	213	0	0	0	mt/hr
Temperature	147.9	147.9	147.9	0.0	0.0	0.0	°C
Pressure	4.5	4.5	4.5	0.0	0.0	0.0	bar
Enthalpy	2741.0	2741.0	2741.0	2786.7	2786.7	2786.7	kJ/kg
Medium pressure steam requirements							
Digester	63	63	63	63	63	63	mt/hr
Oxygen delignification	36	36	36	37	37	37	mt/hr
Low pressure steam requirements							
Pulp dryer	95	95	95	95	95	95	mt/hr
Evaporators	120	119	120	120	120	120	mt/hr

C6

| Key Output Values | Co-generation cases | | | Non co-generation cases | | | Units |
| | Kiln fired with… | | | Kiln fired with… | | | |
	Fuel oil[2]	Natural Gas[5]	Petcoke[7]	Fuel oil[2]	Natural Gas[5]	Petcoke[7]	
Steam stripper	35	35	35	35	35	35	mt/hr
Other[6]	55	55	55	55	55	55	mt/hr
Bleach plant	28	28	28	28	28	28	mt/hr
Digester	35	35	35	35	35	35	mt/hr
ClO$_2$ plant	3.9	3.9	3.9	3.9	3.9	3.9	mt/hr
Total steam consumption	20.9	20.9	20.9	21.2	21.2	21.2	GJ/admt
Turbine condensate	2.9	2.9	2.9	0.0	0.0	0.0	mt/hr
Power Production							
1st turbine stage	34.4	34.4	34.4	0.0	0.0	0.0	MW
MP steam extraction	99.5	99.2	99.5	0.0	0.0	0.0	mt/hr
2nd turbine stage	9.6	9.6	9.6	0.0	0.0	0.0	MW
MP steam extraction	213.4	214.0	213.4	0.0	0.0	0.0	mt/hr
Total	44.0	44.0	44.0	0.0	0.0	0.0	MW
Fraction of high pressure steam not passing through turbine	0.34	0.34	0.34	1.00	1.00	1.00	
High pressure turbine steam from recovery boiler	203.5	203.8	203.5	0.0	0.0	0.0	mt/hr
High pressure turbine steam from hogged fuel boiler	67.4	67.4	67.4	0.0	0.0	0.0	mt/hr
High pressure turbine steam from coal power boiler	45.0	45.0	45.0	0.0	0.0	0.0	mt/hr
High pressure turbine steam from natural gas power boiler	0.0	0.0	0.0	0.0	0.0	0.0	mt/hr
Produced electricity-to-heat ratio	33.6	33.8	33.6	0.0	0.0	0.0	KWh of power produced/GJ steam produced

Key Output Values	Co-generation cases			Non co-generation cases			Units
	Kiln fired with…			Kiln fired with…			
	Fuel oil[2]	Natural Gas[5]	Petcoke[7]	Fuel oil[2]	Natural Gas[5]	Petcoke[7]	
Turbine electricity-to-heat ratio	51.0	51.2	51.0	0.0	0.0	0.0	kWh of power produced/GJ HP steam to turbine
Electricity production	703	704	703	0.0	0.0	0.0	kWh of power produced/admt

[1] No. 2 Fuel Oil: C - 87.3%, H - 12.6%, S - 0.22%, O - 0.04 %, Ash - < 0.01%, HHV - 44.7 MJ/kg; [2] No. 6 High Sulfur Fuel Oil: C - 85.5%, H - 11%, S - 3%, O - 0.45 %, Ash - 0.05%, HHV - 40.6 MJ/kg; [3] Dry Hogged fuel: C - 51.5%, H - 6.1%, S - 0.1%, O - 41.1 %, Ash - 1.1%, N - 0.1 %, HHV - 20.5 MJ/kg; [4] Coal: C - 76.2%, H - 5.1%, S - 1.5%, O - 6.7%, Ash - 8.9%, N - 1.6 %, HHV - 32.2 MJ/kg; [5] Natural gas: C - 74.8%, H - 25.2%, HHV - 55.6 MJ/kg; [6] Other includes steam to deaerator, chiller, and other misc. steam uses; [7] Petcoke: C: 86.3%, H 3.5%, S 5.5%, O 0.5%, Ash 0.3%, HHV 34.9 MJ/kg

APPENDIX D

GHG MITIGATION BENEFITS—FULL RESULTS

Scenario	Black Liquor System	Fossil Fuel System	Difference		Chemical Contribution	
	(kg CO$_2$ eq./GJ, %)					
1.1, AI	19.1	201	-182	-90.5%	-90.4	49.8%
1.1, AII	15.7	169	-154	-90.7%	-86.1	56.1%
1.1, BI	15.7	207	-191	-92.4%	-86.1	45.0%
1.1, BII	15.7	180	-164	-91.3%	-86.1	52.4%
1.1, CI	15.7	183	-167	-91.4%	-86.1	51.6%
1.1, CII	15.7	156	-140	-89.9%	-86.1	61.6%
1.2, AI	15.7	196	-181	-92.0%	-86.1	47.7%
1.2, AII	19.1	174	-155	-89.0%	-90.4	58.5%
1.2, BI	19.1	211	-192	-91.0%	-90.4	47.0%
1.2, BII	19.1	184	-165	-89.7%	-90.4	54.7%
1.2, CI	19.1	187	-168	-89.8%	-90.4	53.9%
1.2, CII	19.1	160	-141	-88.1%	-90.4	64.2%
1.3, AI	19.3	187	-168	-89.7%	-78.2	46.6%
1.3, AII	19.3	160	-140	-87.9%	-78.2	55.7%
1.3, BI	19.3	196	-177	-90.2%	-78.2	44.2%
1.3, BII	19.3	169	-150	-88.6%	-78.2	52.3%
1.3, CI	19.3	175	-156	-89.0%	-78.2	50.2%
1.3, CII	19.3	148	-128	-86.9%	-78.2	60.9%
2.1, AI	33.2	170	-137	-80.5%	-70.2	51.3%
2.1, AII	27.9	141	-113	-80.2%	-71.0	62.8%
2.1, BI	36.8	171	-134	-78.5%	-71.0	53.0%
2.1, BII	36.8	141	-104	-73.9%	-71.0	68.1%
2.1, CI	16.6	171	-154	-90.3%	-71.0	46.0%
2.1, CII	16.6	141	-124	-88.3%	-71.0	57.1%
2.2, AI	27.9	171	-143	-83.7%	-71.0	49.7%
2.2, AII	33.2	140	-107	-76.3%	-70.2	65.6%
2.2, BI	42.3	170	-128	-75.1%	-70.2	55.0%
2.2, BII	42.3	140	-98	-69.8%	-70.2	71.7%
2.2, CI	21.5	170	-149	-87.3%	-70.2	47.3%
2.2, CII	21.5	140	-119	-84.7%	-70.2	59.2%
2.3, AI	35.6	175	-139	-79.6%	-74.8	53.8%
2.3, AII	35.6	145	-109	-75.4%	-74.8	68.5%
2.3, BI	44.9	175	-130	-74.3%	-74.8	57.7%
2.3, BII	44.9	145	-100	-69.0%	-74.8	74.9%
2.3, CI	23.7	175	-151	-86.5%	-74.8	49.5%
2.3, CII	23.7	145	-121	-83.7%	-74.8	61.7%

APPENDIX E

NON-RENEWABLE ENERGY BENEFITS—FULL RESULTS

Scenario	Black Liquor System	Fossil Fuel System	Difference		Chemical Contribution	
	(GJ$_{NR}$/GJ, %)					
1.1, AI	0.257	2.51	-2.25	-89.8%	-1.24	55.2%
1.1, AII	0.275	2.58	-2.31	-89.3%	-1.19	51.5%
1.1, BI	0.275	2.58	-2.30	-89.3%	-1.19	51.5%
1.1, BII	0.275	2.71	-2.43	-89.8%	-1.19	48.8%
1.1, CI	0.275	2.28	-2.01	-88.0%	-1.19	59.1%
1.1, CII	0.275	2.41	-2.14	-88.6%	-1.19	55.5%
1.2, AI	0.275	2.45	-2.18	-88.8%	-1.19	54.5%
1.2, AII	0.257	2.64	-2.38	-90.3%	-1.24	52.2%
1.2, BI	0.257	2.63	-2.38	-90.3%	-1.24	52.2%
1.2, BII	0.257	2.76	-2.51	-90.7%	-1.24	49.5%
1.2, CI	0.257	2.34	-2.08	-89.0%	-1.24	59.7%
1.2, CII	0.257	2.47	-2.21	-89.6%	-1.24	56.2%
1.3, AI	0.271	2.31	-2.04	-88.3%	-1.07	52.5%
1.3, AII	0.271	2.45	-2.18	-88.9%	-1.07	49.4%
1.3, BI	0.271	2.42	-2.15	-88.8%	-1.07	49.9%
1.3, BII	0.271	2.56	-2.29	-89.4%	-1.07	47.0%
1.3, CI	0.271	2.17	-1.90	-87.5%	-1.07	56.6%
1.3, CII	0.271	2.30	-2.03	-88.2%	-1.07	52.9%
2.1, AI	0.435	2.05	-1.62	-78.8%	-0.97	59.7%
2.1, AII	0.435	2.21	-1.77	-80.3%	-0.98	55.1%
2.1, BI	0.539	2.06	-1.52	-73.9%	-0.98	64.0%
2.1, BII	0.539	2.21	-1.67	-75.6%	-0.98	58.5%
2.1, CI	0.296	2.06	-1.77	-85.7%	-0.98	55.2%
2.1, CII	0.296	2.21	-1.91	-86.6%	-0.98	51.0%
2.2, AI	0.435	2.06	-1.63	-78.9%	-0.98	59.9%
2.2, AII	0.435	2.20	-1.76	-80.2%	-0.97	54.8%
2.2, BI	0.566	2.05	-1.49	-72.4%	-0.97	65.0%
2.2, BII	0.566	2.20	-1.63	-74.2%	-0.97	59.3%
2.2, CI	0.566	2.05	-1.49	-72.4%	-0.97	65.0%
2.2, CII	0.566	2.20	-1.63	-74.2%	-0.97	59.3%
2.3, AI	0.502	2.11	-1.61	-76.3%	-1.03	63.7%
2.3, AII	0.502	2.26	-1.76	-77.8%	-1.03	58.5%
2.3, BI	0.612	2.11	-1.50	-71.1%	-1.03	68.4%
2.3, BII	0.612	2.26	-1.65	-72.9%	-1.03	62.4%
2.3, CI	0.356	2.11	-1.76	-83.2%	-1.03	58.4%
2.3, CII	0.356	2.26	-1.90	-84.3%	-1.03	54.0%