Impact of Recycled Fiber on Total Carbon Dioxide Output During Linerboard Production

by

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Abstract

Papermaking is a highly energy intensive process. A paper mill utilizes biomass and fossil fuel energy to provide steam and electricity for plant operations. Biomass is a renewable energy source that is derived from wood waste during the production of virgin fiber. Fossil fuels are non-renewable resources used to meet the remaining energy demand at the mill. A mill may produce a paper product that contains a certain percentage of recycled fiber and virgin fiber. The type of fiber and paper grade directly impacts the amount and source of energy consumed in a paper mill. There is a correlation between the increase in recycled fiber and the increase in fossil fuel use which contributes to the total carbon dioxide output at the mill.

A model was developed to calculate the energy balance in a paper mill producing unbleached kraft linerboard with a pulp yield of 52 percent. The total carbon dioxide output was determined for the production of 100 % virgin fiber and 100 % recycled fiber. It was then compared with actual data from an undisclosed linerboard mill. This helped determine the accuracy of the results.

This study determined that replacing virgin fiber with recycled fiber increases fossil fuel consumption during linerboard production; however, virgin fiber had the highest total carbon dioxide output for the paper mill. Using the available data from the model, replacing one ton of virgin fiber with one ton of recycled fiber will decrease carbon dioxide output by 1.5 tons.

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Chapter 1: Introduction

In the late 1960's and throughout the 1970's, as environmental issues became more prevalent and the federal and state governments began to create environmental protection agencies within their organizational structures, the concern for human health and the environment grew in the United States. The proponents of this environmental awakening pointed their fingers at industry since the smokestacks and drainage pipes at factories and mills made an easy, visible target. As history would unfold, this assumption turned out to be fairly accurate, and an immediate but tedious remedy to this situation would be the advent of strict environmental regulations enforced by the federal and state government.

During the United States' environmental awakening, Americans were faced with the depletion of natural resources, the increase in pollution, and the threat of losing landfill space. As the blame shifted from industry to consumers to the government, it is no wonder then how recycling came to the forefront under such concern for the natural environment. Recycling is essentially the reprocessing of discarded materials into new, useful products with environmental benefits and some economic incentives. Among the many environmental benefits, recycling prevents pollution, saves energy, conserves natural resources, and reduces landfilling.

Although recycling has many environmental benefits, some critics will contend that certain recycling processes pose negative environmental impacts, ultimately defeating the sole purpose of recycling. The question revolves around whether or not recycling paper into newer paper products is an efficient process that actually reduces pollution.

1.1 Statement of Hypothesis

The increase in recycled paper fiber entering a paper mill to be made into newer paper products can increase the mill's fossil fuel consumption and carbon dioxide (CO_2) output. The papermaking process is energy-intensive and requires energy sources from both fossil fuels (coal, oil, natural gas) and biomass (wood chips, sawdust, etc.). Biomass is generated during the production of virgin fiber and is a renewable resource when trees are harvested. Fossil fuels are non-renewable resources used in the absence of biomass as in the case of recycled fiber.

1.2 Background Information

According to the United States Environmental Protection Agency (US EPA), paper and paperboard products constitute the largest portion of Municipal Solid Waste (MSW) in the United States, and as the greatest portion of the waste stream, it also offers the greatest opportunity for recycling (2007, p. 4). Most of the paper products people use on a daily basis only has a life span of a few days (e.g. newspapers) or a few weeks (e.g. packaging). Therefore, it is no wonder why the thought of recycling has been a firm component of paper production since as early as the 13th century (Onusseit, 2006, 174). Although the reasons for recycling have changed over time (e.g. scarcity of resources vs. disposal issues), it is still widely viewed as a practical means to conserve natural resources and landfill space, save energy, and reduce pollution.

Ideally, recycling reduces our demand for raw resources, both renewable and non-renewable. For example, two million trees are cut down every year in the United States to produce newsprint and paper products. Recycling the print run of a single Sunday issue of the *New York Times* would spare 75,000 trees (Cunningham et al., 2003, p. 536). However, it becomes more difficult to determine the actual benefits of recycling paper when we are comparing renewable resources (e.g. biomass) to non-renewable resources (e.g. fossil fuels). This can be determined by looking at the energy consumption at a paper mill during the papermaking process.

There are various types of paper that a mill processes, and this has an impact on the total energy consumed. For the scope of this thesis, linerboard production will be analyzed. Linerboard is one of two basic components that makeup corrugated packaging materials (cardboard boxes). It is simply the flat cardboard piece that is glued on both sides of the medium – a grooved corrugated paper channel. The combination allows packaging containers to remain durable even under immense force and pliability.

Chapter 2: Literature Review

2.1 Energy Consumption: The Papermaking Process

Papermaking is an age old art that has been refined and modified over centuries into the modern process that the world is familiar with today. It is a complex process that has incorporated waste-to-energy recycling practices within the mill to fully utilize all of the waste resources generated. This process has a great impact on the energy consumed, and each part within the overall process is unique. Figure 1 displays a detailed flow chart of the papermaking process. For the practical purpose of this paper, the unbleached kraft papermaking process for linerboard will be outlined and described.

The first part of the process begins in the forest with the harvesting of trees to be used as a raw material to make paper. The wood used by the pulp mill can be in the form of either wood chips or logs. Logs are transported to a paper mill where they are washed, debarked, and then processed through a chipper. The small wood chips are then sorted through a screen which allows undesirable knots and fines to pass through before the wood chips are moved to the digester to undergo the pulping process.

The knots and fines that pass through the screen, along with the bark from the debarking process, are combined with saw mill waste being imported into the mill. The biomass is then burned in a hog fuel boiler to generate steam, which in turn produces electricity and more steam to be used by the plant in other processes such as the digester, evaporator, and papermachine. Steam and electricity are also generated by the power boiler which burns fossil fuels. The biomass and fossil fuels being burned contribute to the total carbon dioxide output of a mill.

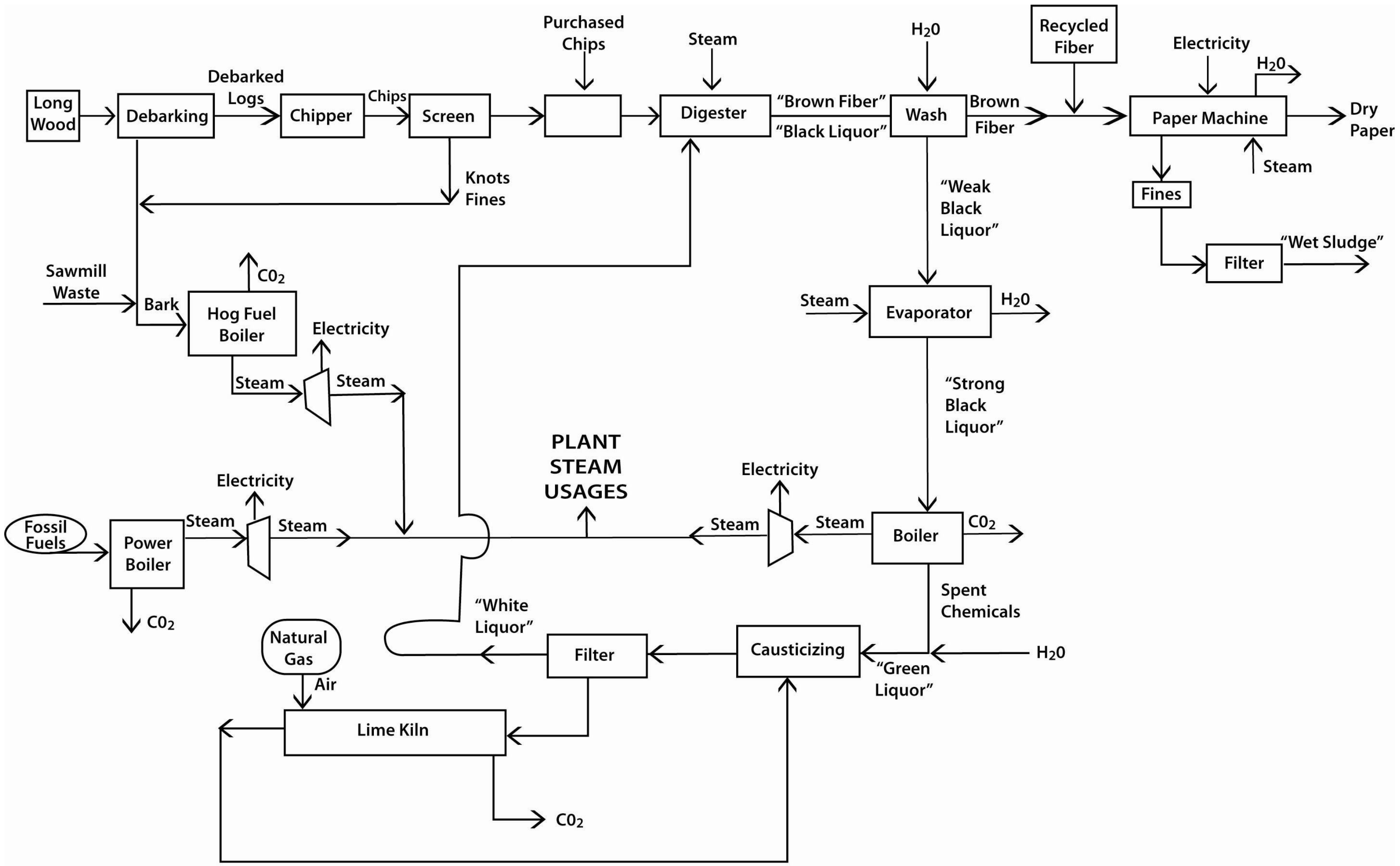


Figure 1. Flow chart of papermaking process.

2.2 The Digester

The next phase for the wood chips is the pulping process, which is necessary for separating the individual wood fibers from one another. Prominent pulp and paper researchers, Malcolm et al. (1989), explain the detailed process in their overview (pp. 3-14). To produce unbleached kraft pulp, wood chips are reacted with aqueous cooking liquors - primarily sodium hydroxide and sodium sulfide. The sulfide is used to accelerate the delignification process. This exposes the wood chips to hot alkali for a shorter period of time, increasing the strength of the pulp. The cooking liquor is mixed with the wood chips and heated in a large pressurized vessel called a digester as shown in Figure 2. There are two types of digesters that can be used for this process: a batch digester and a continuous digester.

The only significant difference between the batch and continuous process is the way that the chips are cooked. In either case, the outcome is similar: spent liquor is washed and removed and any undigested knots are screened and removed. The batch process includes an individual digester where the chips are cooked. All loading, cooking, and dumping are done in sequence, and washing takes place after the pulp is blown from the bottom of the digester.

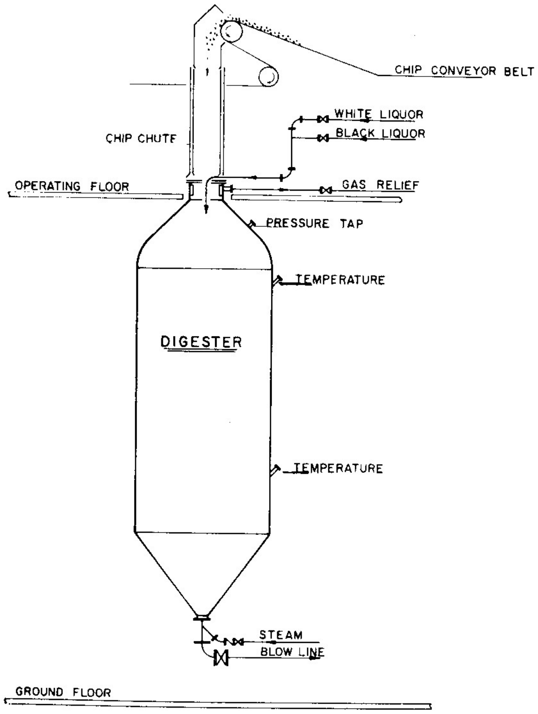


Figure 2. Kraft pulp digester (Malcolm et al., 1989, p. 9).

During the continuous process, however, chips and liquor are fed at a constant rate into the top of the digester until they are discharged under pressure from the bottom. Washing occurs inside the digester, allowing liquor to be removed and pulp to cool. The spent liquor is reintroduced, through heat exchangers, into the moving chip column to provide the proper heat for cooking.

In both processes, the individual wood fibers are separated as the cooked chips exit the digester, leaving a mixture of spent cooking liquor and fiber. As the fiber is further processed to be sent to the papermachine to produce linerboard, the liquor is sent through stages of a recovery process that consist of an evaporator, recovery boiler, causticizer, clarifier, and lime kiln.

2.3 The Evaporator

After the spent cooking liquor leaves the digester, it is now dark in color and referred to as black liquor. This liquor is comprised of dissolved organic substances from the wood used and inorganic compounds derived from the white cooking liquor. According to Thomas M. Grace (1989a), a well-published researcher in the field of chemical recovery in alkaline pulping, the black liquor collected from the pulp washing is considered weak black liquor because it contains 13-17% solids (p. 486). This liquor is sent to an evaporator where it is concentrated through evaporation to roughly 60 percent solids for proper firing in the recovery boiler (Malcolm et al., 1989, p. 9). The evaporator is basically a heat transfer device that requires steam energy from the plant to operate.

According to researchers Venkatesh and Nguyen, evaporator capacity (evaporation rate) and steam economy are the twin performance variables of major concern in evaporator operations (1992, p. 21). The steam economy is simply the amount of water evaporated per unit of live steam consumed. Multiple effect evaporators raise the steam economy by incorporating several units (effects) that are connected in series by vapor piping. In one effect, the water vapor evaporated acts as heating steam in the steam chest of the following effect, conserving heat in the vapor by condensing at a lower pressure and temperature in another effect. The principle behind the multiple effect evaporators is to raise black liquor concentration in stages. The number of effects in an evaporator train is normally established based on steam and capital cost considerations.

Although there are different types of evaporators, each provide the necessary heat transfer and separate the vapor from the concentrated liquor. The most common type of evaporator used for black liquor service is the long-tube-vertical (LTV) evaporator as show in Figure 3. The LTV evaporator typically has five to seven effects consisting of a vapor head, a steam chest, and a main liquor box (Venkatesh & Ngyuen, 1992, p. 15). LTV evaporators increase steam economy through variations of backward flow sequences by first introducing feed liquor into high vacuum effects and then pumping the liquor in a straight backward flow to the first effect. The feed liquor is preferably introduced at the effect nearest the liquor temperature to minimize liquor preheating or flashing (p. 21).

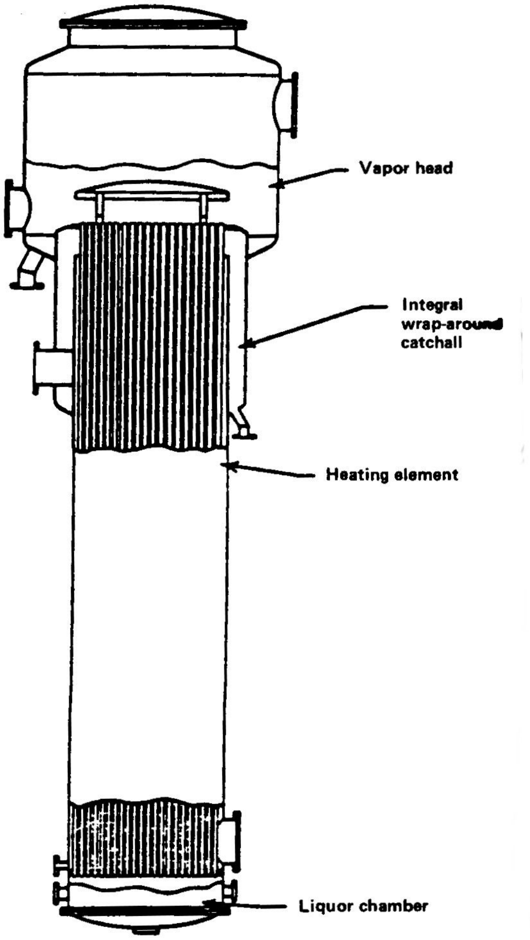


Figure 3. LTV evaporator (Grace, 1989a, p. 488).

2.4 The Recovery Boiler

The highly concentrated liquor from the evaporator is sent to a chemical recovery boiler, outlined in Figure 4, to reclaim the inorganic chemicals present. Any dissolved organics from the evaporation process are burned to generate steam and electricity. Carbon dioxide is produced during this combustion process as the organic components of wood burn to generate heat. The biomass carbon in the wood is dissolved and either captured in sodium carbonate or emitted as biomass carbon dioxide, contributing to the mill's total carbon dioxide output.

Many reactions occur during the combustion process. Among them, the sulfur contained in the inorganic chemicals is converted to sulfate. After a series of reactions, sodium sulfate is reduced to sodium sulfide. Sodium carbonate is also present in the form of ash and is recovered as well. The ash is dissolved in water to form green liquor.

The green liquor then undergoes a causticizing process, outlined in Figure 5, treating it with lime to convert the sodium carbonate to sodium hydroxide before it is filtered into white liquor. The white liquor is recycled back into the digester to heat incoming chips along with steam during the pulping process. During the conversion of green liquor to white liquor, a calcium carbonate precipitate is formed, filtered out, and sent to a lime kiln.

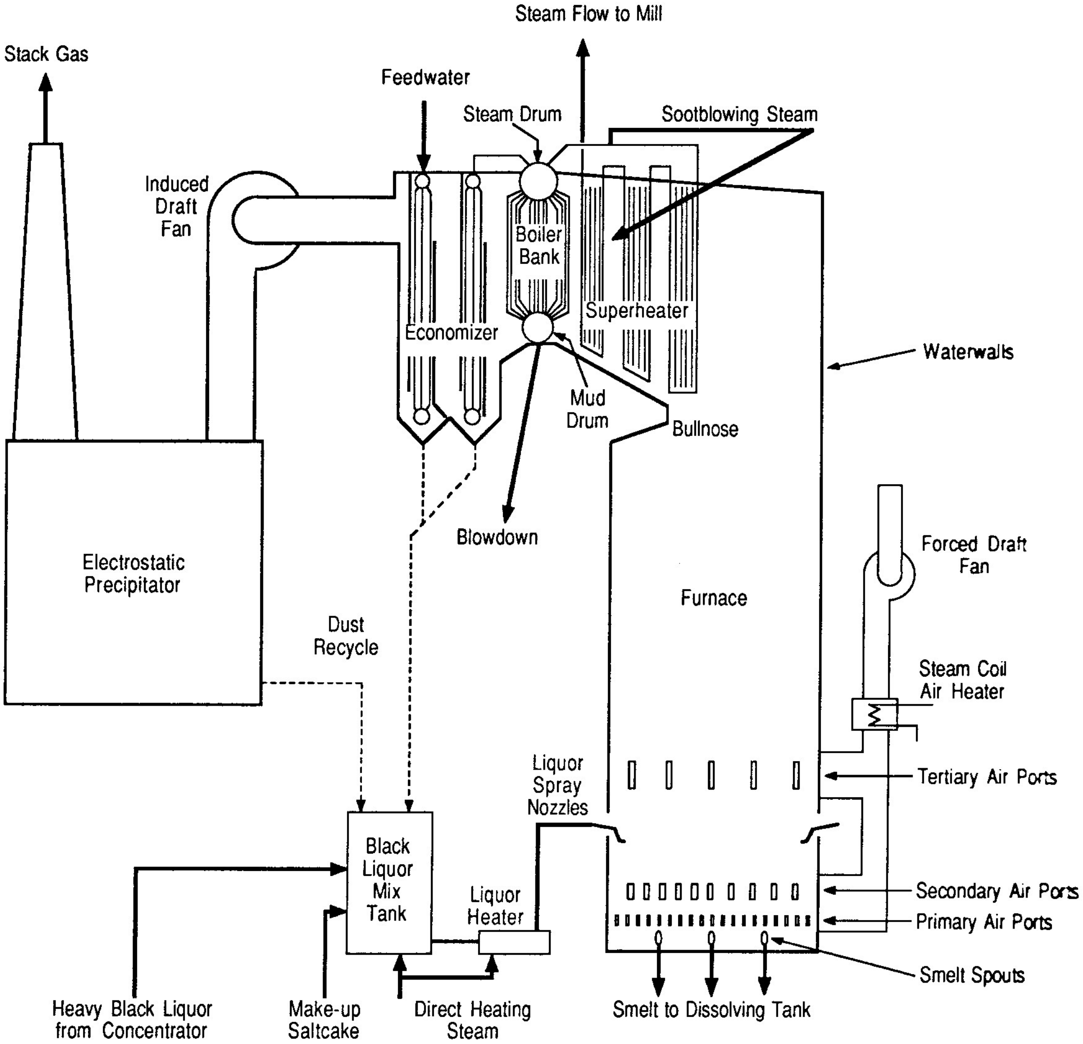


Figure 4. Schematic diagram of kraft recovery boiler (Adams, 1989a, p. 533).

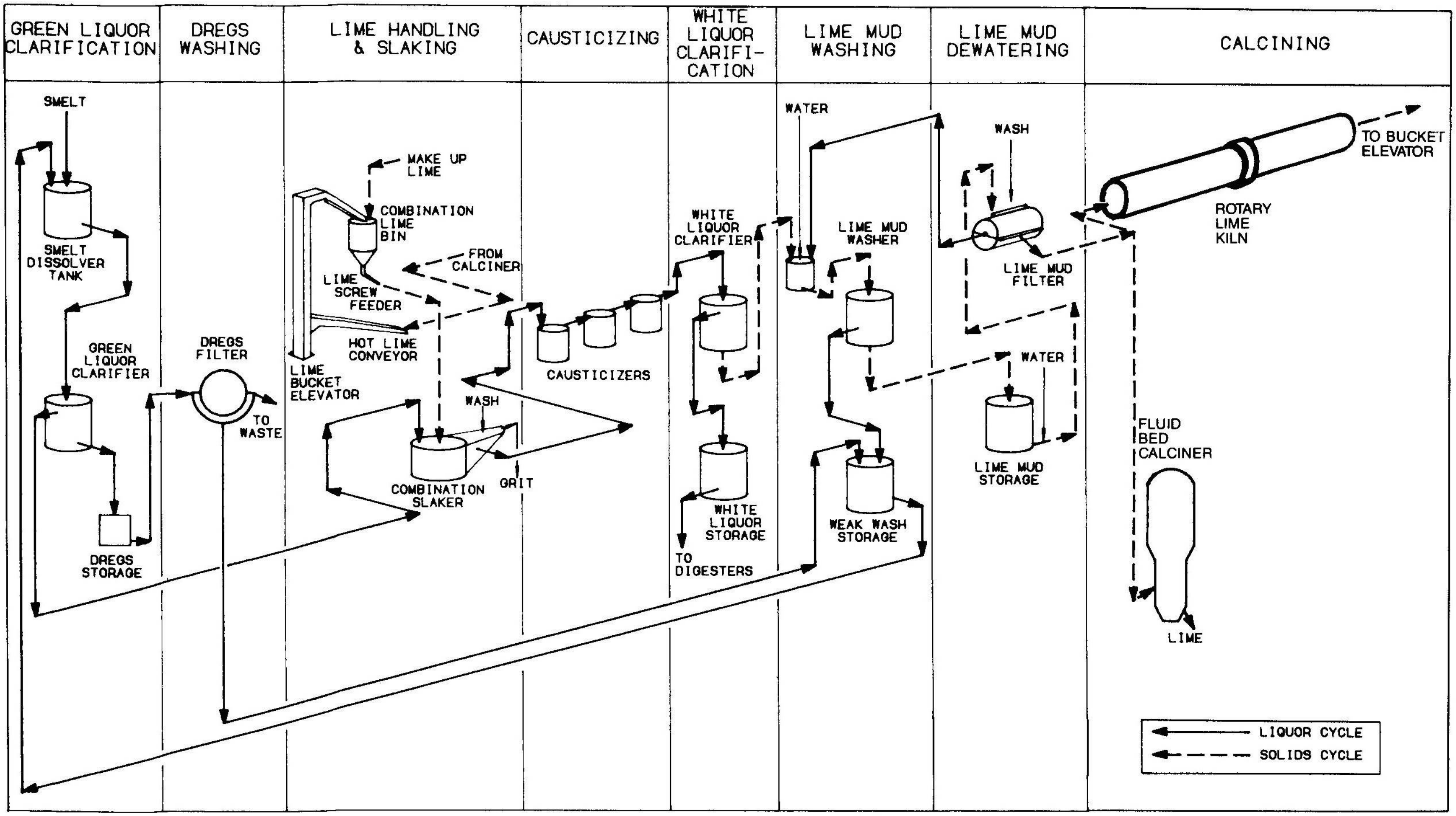


Figure 5. Recausticizing process flowsheet (Grace, 1989b, page565).

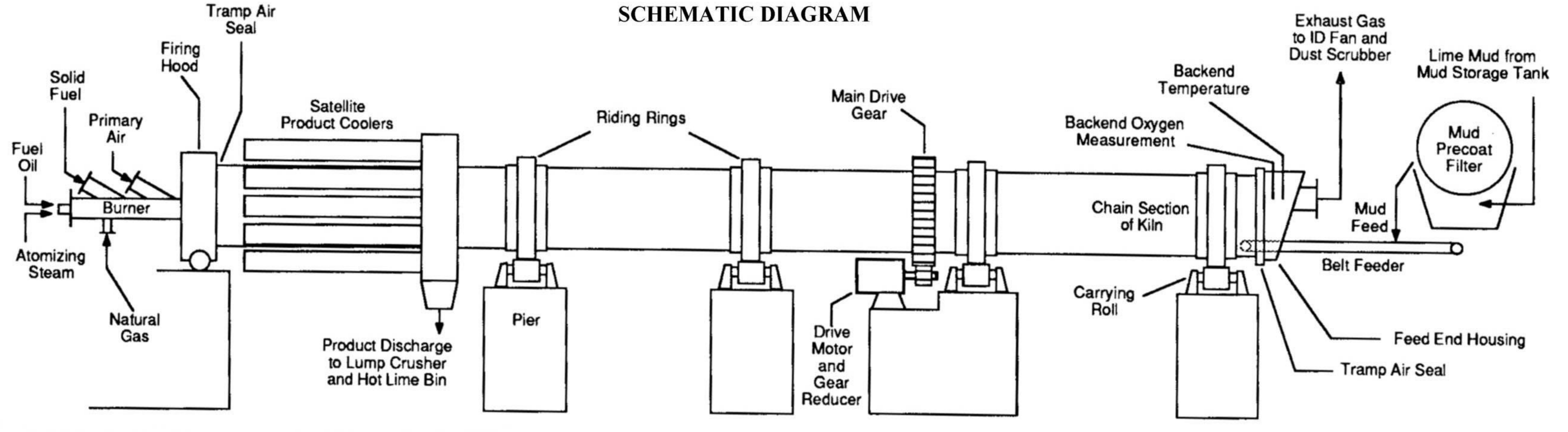
2.5 The Lime Kiln

In his article, “Lime Reburning,” Terry Adams (1989b) offers a detailed description of the processes contained within a lime kiln (pp. 590-608). A schematic and internal diagram of the lime kiln is outlined in Figure 6. The main purpose of the lime kiln is to convert the calcium carbonate back into calcium oxide. The calcium carbonate must be heated at a high temperature, without overheating, to drive off the carbon dioxide in order to form the calcium oxide. The calcium oxide formed is then reused during the causticizing process.

The high energy required to operate the lime kiln is produced by natural gas, a fossil fuel that emits carbon dioxide during the lime reburning process. However, according to a study done by R. Miner and B. Upton (2002), the carbon dioxide emissions from kraft mill lime kilns can be difficult to properly characterize because they contain a combination of fuel- and process-derived carbon of both fossil and biomass origin (p. 729). The authors contend that the carbon dioxide emitted from kraft mill lime kilns originates from two sources—fossil fuels burned in the kiln and the conversion of calcium carbonate to calcium oxide (p. 736).

Miner and Upton (2002) go on to state that since the origin of the carbon in kraft mill calcium carbonate is wood, the carbon dioxide released from this calcium carbonate is biomass carbon dioxide and should not be included in estimates of emissions contributing to increased atmospheric levels of greenhouse gases (p. 737). However, there is no difference between the carbon dioxide emitted from both sources.

SCHEMATIC DIAGRAM



INTERNAL FEATURES

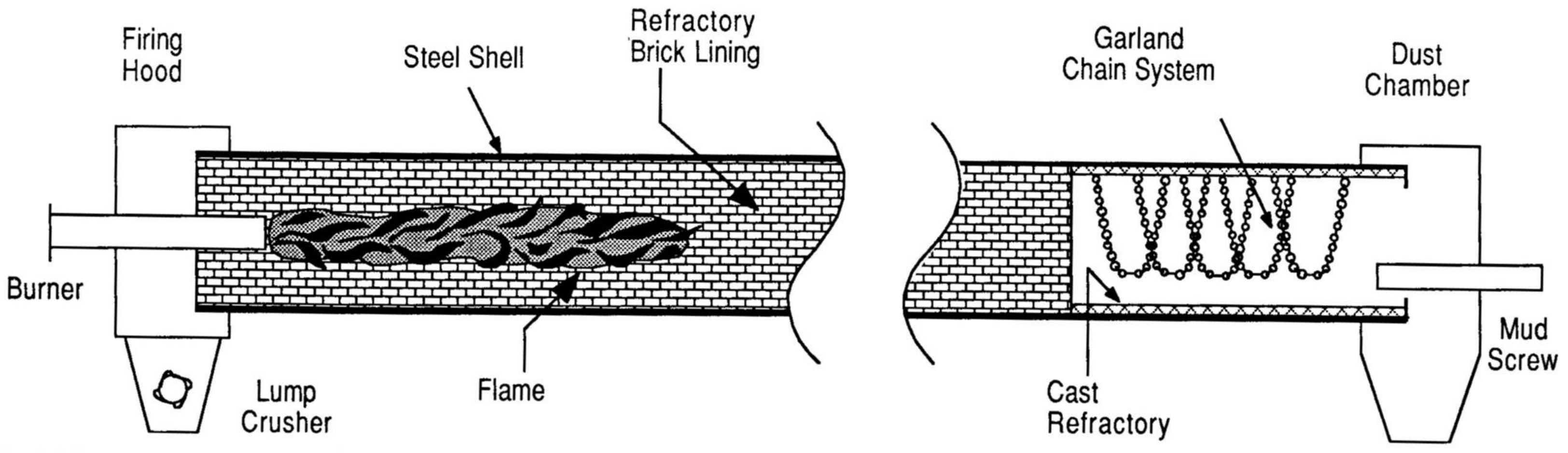


Figure 6. Lime kiln - schematic and internal diagram.

2.6 The Papermachine

After the wet pulp has been blown from the digester and the cooking chemicals have been recovered, it is then transported to the papermachine. (Note: the bleaching process is not used for the production of kraft linerboard because the desired appearance is brown, not white as with office paper). At this point in time, pre- or post-consumer recycled fiber - repulped by adding water, sodium hydroxide, and heat - can be mixed with the virgin pulp to obtain a certain percentage of recycled-content fiber. The fist step of this process is to make a pulp mat on a screen. This allows water to be removed from the sheet through a combination of heat, vacuum, and pressure applied through rollers. The water is then further treated on- or off-site. Any fines fall through the screen and pass through a filter where they are treated as a wet sludge. The finished product leaving the papermachine is then shipped to other processing plants as large rolls. The papermachine requires a significant amount of steam and electricity to operate.

According to Paul Tucker from International Paper, the papermachine steam consumption is impacted by heat integration with the pulp mill. Hot stock provides a heat source as does hot water for the showers. Tucker states that in the case of recycled fiber, all water heating must be supplied via steam and can be as much as 1000 lb steam/ton. Papermachine steam consumption is also impacted by once-dried fiber because it drains better; specific steam consumption would then be less for recycle-only case (personal communication, November 15, 2007).

2.7 Sources of Carbon Dioxide

A paper mill generates steam and electricity by burning two fuel sources that contribute to the mill's total carbon dioxide output: renewable biomass and fossil fuels. Renewable biomass - wood chips, bark, knots and fines, and black liquor – are common by-products of virgin fiber production. Some biomass is purchased from saw mills producing other wood products, but much of it is readily available on-site through the debarking and chipping processes. These materials are then burned in a hog fuel boiler to generate steam and electricity. There are a couple environmental impacts directly related to biomass energy production and consumption.

By incorporating a renewable biomass to produce energy in a paper mill, the mill eliminates the use of a non-renewable fossil fuel. This reduces any adverse environmental impact associated with fossil fuel consumption, and it helps conserve valuable natural resources. However, because wood waste is utilized by a paper mill, a more complex environmental impact concerns the growth and harvesting of trees for virgin fiber production.

Forests play a key role in the carbon cycle because the living organisms that make up the ecosystem capture atmospheric carbon dioxide through the process of photosynthesis. Carbon dioxide is then returned to the atmosphere through the process of respiration by soil microorganisms as organic matter decays. Trees, as do other plants, have the ability to store carbon throughout a lifetime. The forest age and species, carbon dioxide storage in the forest soils, carbon dioxide release rates from decaying organic matter, and climatological impacts on growth/decay, etc. must all be looked at to quantify the variability of carbon dioxide uptake (Gilbreath, 1995, p. 5).

Generally, old-growth forests, hundreds of years old, are thought to be the most beneficial at capturing carbon dioxide because they act as a carbon sink with their size and maturity. Large amounts of carbon are sequestered for years in old-growth forests in the trees and in the soil. The soils are rich with carbon as fallen leaves and other organic matter bind to soil particles and remain in place for many years until the forest is disturbed. When old-growth forests are cut or burned, the roots of the trees decay and carbon dioxide is released into the atmosphere. If new trees are replanted in place of the old-growth forest, the new forest would not be nearly as efficient at storing carbon because of the growth-rate and respiration of the younger trees.

A study by Janisch and Harmon (2002) found that young trees shift from being a carbon source to a sink between 0 and 57 years; thus, the transition between a forest acting as a carbon source or sink occurs near the 20 - 30 year period (pp. 77 – 89). Although old-growth forests are rarely harvested to make paper in the United States, most paper comes from privately owned tree farms that are harvested on cycles of 25-30 years (Gilbreath, 1995, p. 49). Selective harvesting is mainly practiced on a plot of land in which only a small percentage of the mature trees, 10 or 20 years old, are harvested in rotation (Cunningham et al., 2003, p. 312). Sustainable forestry practices require that an equal or greater amount of trees be replanted for those that are harvested to make paper and wood products to insure a sustained forest over future harvest cycles. Although the harvesting of a renewable resource in a sustained forest may be objectionable to some individuals, the benefits of the wood (and wood waste) should be compared to the excavation of land for non-renewable resources.

Aside from renewable biomass generated through forest harvesting, the remaining energy used in a paper mill is compensated through burning fossil fuels – coal, oil and natural gas – and must be burned on-site or purchased from a grid supplied by an electric utility. The environmental impacts associated with fossil fuel production and consumption are well-known. Fossil fuel consumption contributes to global climate change, air quality degradation, and acid rain, while mining and excavating these resources can harm human health (ex. asbestosis), destroy vast acres of land, and contaminate surface and ground water (ex. acid mine drainage). The type of energy used in a paper mill and its overall environmental impact is dependent upon two main feedstocks: virgin fiber and recycled fiber.

2.8 Virgin Fiber versus Recycled Fiber

As discussed earlier, a certain percentage of recycled fiber is mixed in with virgin fiber to produce unbleached kraft linerboard. The percentage of recycled fiber is dependent upon the type and quality of linerboard a mill is looking to achieve as an end product. The incorporation of recycled fiber has a direct impact on the amount of virgin fiber used and the type of energy a mill consumes. There is a correlation between recycled fiber and an increase in fossil fuel carbon dioxide output at a paper mill.

As recycled fiber is increased in the production of linerboard, less virgin fiber is needed during the process. As less virgin fiber is needed, fewer trees are harvested, and in return less biomass is available for fuel usage. To compensate for this energy loss, more fossil fuels are burned to provide steam and electricity. While recycled fiber conserves the renewable forest resource, it consumes over thirty times the non-renewable fossil fuel energy (Gilbreath, 1995, p. 17). However, an increase in recycled fiber does decrease the amount of energy consumed during the recovery process.

There have been many studies since the early 1990's regarding the environmental impacts (positive and negative) of recycled fiber. This can be attributed to stricter environmental regulations directed at paper companies to produce a higher percentage of recycled content paper products. Regardless, the type of paper being produced certainly has a profound impact on the total carbon output of a mill as each paper grade is made differently – either through mechanical or chemical pulping processes. It is beneficial to first understand the life cycle of paper once it ends up in the waste stream.

2.9 Life Cycle Assessment (LCA) of Paper in the Waste Stream

According to the United States Environmental Protection Agency (U.S. EPA), paper and paperboard products constitute the largest portion of the Municipal Solid Waste (MSW) stream at about 34 percent (2007, p. 4). The standard waste management options for discarding paper consist of: landfilling, recycling, composting, or incineration (waste-to-energy). Each waste management alternative has an impact on its total energy use and contribution to global climate change. Landfilling is the most recognized form of waste management options in the United States.

With flat-rate, inexpensive disposal fees, individuals and companies may be less inclined to consider recycling paper in communities where a fee is applied to recycling. Obviously, in communities where no such recycling programs exist, it is not even a consideration. When recycling is available and easily accessible, individuals and companies may be more inclined to recycle wastepaper over landfilling.

According to the U.S. EPA, about 52 percent of all paper and paperboard products discarded in MSW were recovered and recycled (2007, p. 3). That means that less wastepaper is being landfilled, and newer paper products are being made using the waste paper. Although some of the low-grade paper products may eventually end up in the landfill, there are still other disposal options. If the wastepaper is not being landfilled or recycled, it may either be composted or incinerated.

Composting is simply the natural degradation of organic materials into a nutrient rich fertilizer. It requires a balance of carbon-and nitrogen-rich materials in order to effectively decompose at a steady rate. Paper, which contains organic wood fiber, is a decent source of carbon to add to the composting process; although, it is usually found in the form of absorbable paper products such as napkins. However, waste paper and paperboard can be composted in small- or large-scale operations as an alternative to the other waste management practices.

The last option for wastepaper disposal is incineration as a waste-to-energy practice. This type of incineration does not refer to the “burn barrel” incineration of garbage that some households still practice today. Instead, the wastepaper is incinerated in a controlled manner by energy-intensive industries, not households or small businesses. Any energy recovered is then converted into steam or electricity, often offsetting emissions derived from a fossil fuel source.

Numerous studies have attempted to compare life cycle analyses of paper from “the cradle to the grave” to determine which is the best method of recovery, and the results must be taken into consideration to better understand the discussion related to recycled fiber and total carbon dioxide output. In one study, researchers Pickin et al.

(2002) conducted a comprehensive investigation of total greenhouse gas emissions (GGE) from the paper cycle – from forest through to landfill. The researchers were able to assess the effectiveness of various waste management options to reduce GGEs from wastepaper (p. 741). The study focused on fossil fuel use during the harvesting, manufacturing, and transporting of wood from the forest. The researchers also considered the uptake and emission of carbon-bearing gases during growth and decay of organic material used in paper production (the organic material cycle) (2002, p. 742). The results of this study indicate that the most uncertainty exists within the fate of organics in landfills due to the oxygen-depraved environment.

According to archaeological research conducted by Rathje and Murphy (1992), biodegradation is not occurring at a rapid rate as was once thought, allowing organics such as paper to exist for decades in the landfill (pp. 1-250). The landfill essentially is a carbon sink, and it delays the biodegradation and emission of GGEs from paper as confirmed by research conducted by the pulp and paper industry (Pickin et al., 2002, p. 748). The carbon-bearing gases will eventually be released into the atmosphere; however, with the advent of technology to increase the decay process, its release may be much sooner. Therefore, Pickin et al. (2002) concludes that waste management options keeping paper out of landfills significantly reduces greenhouse gas emissions (741 - 752).

Recycling was determined to be a better alternative to landfilling, but it was not deemed the best method of waste management. Generally, producing materials from recycled sources usually results in less energy consumption and greenhouse gas emissions. However, according to a study by Anna Bjorklund and Goran Finnveden (2005), the savings of recycling paper products are much smaller compared to other recyclable materials, prompting a more in depth look at paper recycling (p. 309). The type of paper and energy source used at the mill must be taken into consideration to determine the impacts of recycling versus incineration.

2.10 Environmental Impacts of Recycling Versus Incineration

According to researchers Finnveden and Ekvall (1998), more energy may be saved when recycling mechanical pulp, typically used in newsprint, than when recycling chemical pulp, typically used in cardboard (pp. 235 - 256). To make newsprint, a substantial amount of mechanical and thermochemical energy is required to refine the wood chips into a fibrous pulp. Unlike the kraft process, the lignin and hemicellulose contained in these fibers is retained in the sheet because the end product use is only for a short time.

According to a study by pulp and paper expert Ken Gilbreath (1995), newsprint high yield fiber can be recycled into a recycled newsprint product using about the same amount of energy as producing courrugating medium (p. 21). The main energy resource to make high yield virgin fiber is derived from fossil fuels, so total carbon output is significantly reduced. Therefore recycling newsprint is a better alternative compared to waste-to-energy incineration because it reduces the need for fossil fuel derived energy at a mill. The case is not the same for some types of paper produced from kraft pulp.

Gilbreath (1995) contends that recycling other types of wastepaper into newer paper products in turn creates a negative environmental impact when the initial intent was to help protect the environment. He states that virgin kraft fiber combined with recycling wastepaper as a waste-to-energy resource can not only eliminate the use of fossil fuel at the virgin fiber mill, but it can also shut down the equivalent use of 13.07 x 10^6 Btu/ADT of fossil fuel at an Electric Utility (p. 17). In his LCA approach, Gilbreath compares numerous environmental impacts concerning 100% virgin kraft fiber production, 100% recycled fiber production, virgin kraft fiber production with wastepaper incineration, and recycled fiber with wastepaper incineration.

The study looked at total mill energy through carbon dioxide output but excluded collection and transportation to the mill from both virgin kraft fiber and recycled fiber in the balance. Bjorklund and Finnveden (2005) agree that none of the key factors associated with transportation and collection are significant enough to alter the ranking between recycling and incineration (p. 316). Gilbreath also took into account a detailed carbon tracking method incorporating forest carbon dioxide uptake which is necessary when comparing recycling versus incineration as the former reduces the consumption of forest resources while the latter increases consumption.

In a brief overview, Gilbreath found that the recycled fiber alternative contributes to the highest total combined carbon dioxide emissions with the virgin kraft fiber/wastepaper incinerator alternative generating the least combined carbon dioxide emissions. The reason the recycled fiber emissions are higher is because of the incremental fossil fuel energy introducing new carbon into the atmosphere. The virgin fiber alternative consumes more total energy and has higher total carbon dioxide emissions than the recycled fiber alternative, but the energy and carbon dioxide emissions are mostly from biomass, which can be offset by the forest carbon dioxide uptake according to Gilbreath (1995, p. 7). Carbon dioxide emissions were reduced the greatest in the virgin kraft fiber/wastepaper incinerator because no energy derived from fossil fuels was used (except in the lime kiln), and there was a net reduction in the electric utility incremental fossil fuel usage due to the exported power from the incinerator.

The research does not seem to imply that recycling paper fiber is unnecessary. However, the arguments seem to focus on the application of the recycled fiber as either a feedstock for newer paper products or as an energy resource to eliminate or reduce fossil fuel usage in the mill. Also, the incorporation of other alternative fuels to replace fossil fuels at certain mills has already been implemented over the years. This makes it even more difficult to deliver a verdict on the benefits of waste-to-energy incineration of recycled fiber as fossil fuel carbon dioxide emissions have been eliminated. Regardless, there is a trend concerning the increase in recycled fiber in linerboard production and the total output of carbon dioxide emissions from both biomass and fossil fuel energy resources.

Chapter 3: Method and Procedure

In order to determine the total carbon output for both recycled fiber and virgin fiber produced at a linerboard mill, it is necessary to look at the energy processes for production of each fiber. Recycled fiber spends less time in a mill compared to virgin fiber as it is incorporated into the papermaking process during the last stage of production. However, harvesting virgin fiber generates wood waste that is used as an energy source in the mill, whereas recycled fiber contributes no such by-product. The type of energy being used by a mill is important regarding total carbon output. Therefore, it is necessary to determine what fraction is biomass-derived versus fossil fuel-derived energy.

A model was created to help determine the connection between the types of fiber, energy processes, and fuel sources used at a linerboard mill. To develop the model, equations were derived from multiple sources and adapted to fit the scope of this research. The equations and data for each process are outlined in detail and pertain to three specific areas regarding the digester, chemical recovery process, and the papermachine. Actual data from an undisclosed linerboard mill, operated by International Paper (IP), are used to compare results. This data was provided courtesy of Paul Tucker, an engineer at IP.

3.1 Pulp Yield

Pulp yield is essentially a function of the pulping process in which recovery from pulping wood is often expressed as a percentage of pulp from the original wood weight. The yield is dependent on the type of pulp grades being produced. Linerboard is made from an unbleached pulp grade, and it is cooked to a higher yield to retain more lignin. Highest yield pulps are characterized by a kappa number between 80 and 110 (Perkins, 1989, p. 248). The kappa number provides the pulp lignin content, and it is determined by the amount of standard potassium permanganate solution absorbed in a specific pulp grade considered. The kraft pulp yield is determined by the kappa number in Figure 7.

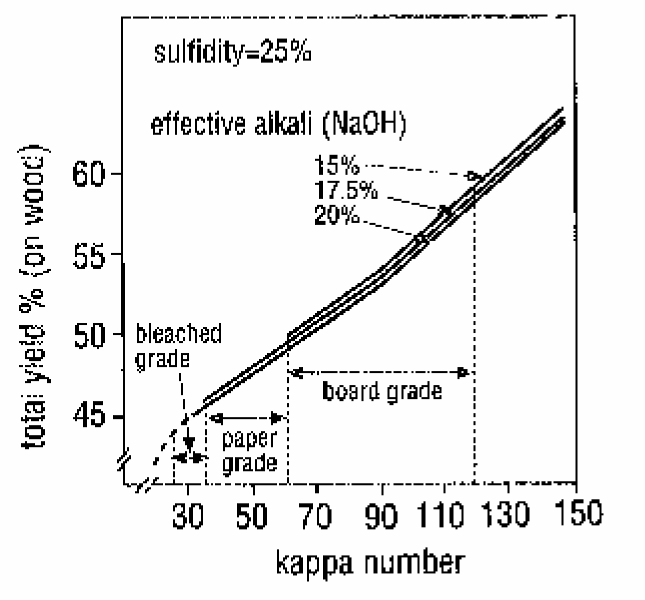


Figure 7. Kraft pulp yield vs. kappa and effective alkali charge (Smook, 1992).

To find a pulp yield that closely represents actual linerboard production, a kappa number of 85 is used for this model. The pulp yield is approximately 52 %, which means that for every oven-dry ton (ODT) of pulp produced, 3846 oven-dry pounds of wood is processed. This helps determine how much energy is required for the cooking phase of the digester.

3.2 Digester Energy Requirements

To produce 1 ODT of pulp with a 52 % yield, approximately 3,846 lb of dry wood are needed in the form of chips. One ton equals 2,000 lb:

$$\frac{1\,ton}{0.52} \times \frac{2{,}000\,lb}{ton} = 3{,}846\,lb\ dry\ wood \tag{1}$$

The wood is approximately 40 % moisture and 60 % solids, leaving 6,410 lb of "wet wood" shown in Equation (2). The weight of the dry wood is divided by the percent solids to determine this amount. In Equation (3), the amount of water is calculated by subtracting the weight of "wet wood" by the weight of dry wood:

$$\frac{3{,}846\,lb\ dry\ wood}{0.60} = 6{,}410\,lb\ wet\ wood \tag{2}$$

$$6{,}410\ lb\ wet\ wood - 3{,}846\ lb\ dry\ wood = 2{,}564\ lb\ water \tag{3}$$

In a model continuous digester, wood chips are first steamed at 212°F to increase yield. This process provides energy savings by reducing cooking time and temperature. Wood chips (containing dry wood and wood moisture) are brought in at 70°F and brought up to 212°F with a relatively small heat loss to the environment. The amount of energy consumed is shown in Equations (4) and (5). The total amount of steam energy consumed in Equation (6) is then divided by the delta differential (enthalpy 150 psig saturated steam minus enthalpy feedwater at 212°F) in Equation (7). The following equations are adapted from Van Fleet (1989, p. 224).

$$3846\ lb\ dry\ wood \times \frac{0.33\ BTU}{lb\,°\mathrm{F}} \times (212°\mathrm{F} - 70°\mathrm{F}) = 180{,}231\ BTU\ \ steam \tag{4}$$

$$2{,}564\ lb\ water \times \frac{1\ BTU}{lb°\text{F}} \times (212°\text{F} - 70°\text{F}) = 364{,}103\ BTU\ \ steam \tag{5}$$

$$180{,}231\ BTU\ \ steam + 364{,}103\ BTU\ \ steam = 544{,}333\ BTU\ \ steam \tag{6}$$

$$\frac{544{,}333\ BTU\ \ steam}{(1{,}195\ BTU / lb - 180\ BTU / lb} = 536\ lb\ steam \tag{7}$$

After steaming, the chips are subjected to a low pressure heating at 257°F to bring the batch up to cooking temperature from 212°F. No cooking liquor is needed at this stage since the temperature is already hot enough from the previous steaming.

$$3{,}846\ lb\ dry\ wood \times \frac{0.33\ BTU}{lb°\text{F}} \times (257°\text{F} - 212°\text{F}) = 57{,}115\ BTU\ \ steam \tag{8}$$

$$2{,}564\ lb\ water \times \frac{1\ BTU}{lb°\text{F}} \times (257°\text{F} - 212°\text{F}) = 115{,}385\ BTU\ \ steam \tag{9}$$

$$\frac{(57{,}115\ BTU\ \ steam + 115{,}385\ BTU\ \ steam)}{(1{,}195\ BTU / lb - 216\ BTU / lb)} = 176\ lb\ steam \tag{10}$$

Finally, the chips undergo a high pressure heating at 357°F using hot black liquor charging in Equation (13) and preheated white liquor charging in Equation (14).

$$3{,}846\ lb\ dry\ wood \times \frac{0.33\ BTU}{lb°\text{F}} \times (356°\text{F} - 257°\text{F}) = 125{,}654\ BTU\ \ steam \tag{11}$$

$$2{,}564\ lb\ water \times \frac{1\ BTU}{lb°\mathrm{F}} \times (356°\mathrm{F} - 257°\mathrm{F}) = 253{,}846\ BTU\ \ steam \tag{12}$$

$$6{,}922\ lb\ black\ liq. \times \frac{0.9\ BTU}{lb°\mathrm{F}} \times (356°\mathrm{F} - 329°\mathrm{F}) = 168{,}205\ BTU\ \ steam \tag{13}$$

$$5{,}335\ lb\ white\ liq. \times \frac{0.91\ BTU}{lb°\mathrm{F}} \times (356°\mathrm{F} - 310°\mathrm{F}) = 223{,}323\ BTU\ \ steam \tag{14}$$

$$\frac{(Sum : Equations\ 11 - 14)}{(1{,}195\ BTU / lb - 288\ BTU / lb)} = 850\ lb\ steam \tag{15}$$

The total amount of energy required for the cooking phase in the digester is the sum of Equations (7), (10), and (15).

$$536\ lb\ steam + 176\ lb\ steam + 850\ lb\ steam = 1{,}563\ lb\ steam \tag{16}$$

3.3 Lime Kiln Energy Requirements

For this model, the values for active alkali (AA), lime required, and lime mud produced are given and adapted from an article written by Conrad Cornell (1992, p. 125):

Active Alkali:	250 kg/ODT
Lime:	200 kg/ODT
Lime mud:	330 kg/ODT

The heat rate of the lime kiln with product coolers is estimated to be $\frac{6.4\ mmBTU}{ton\ CaO}$ (Adams, 1989b, p. 598). The amount of lime must first be converted from kilograms to pounds (1 kg = 2.204 lb) and then from pounds to tons (1 ton = 2,000 lb).

$$200\ kg\ CaO \times \frac{2.204\ lb}{kg} \times \frac{1\ ton}{2{,}000\ lb} = \frac{0.2\ ton\ CaO}{ton\ \ fiber} \tag{17}$$

By knowing the energy requirement for the lime kiln and the amount of CaO/ton fiber, the amount of BTU per ton of fiber can be determined.

$$\frac{6.4\ mmBTU}{ton\ CaO} \times \frac{0.2\ CaO}{ton\ \ fiber} = \frac{1.4\ mmBTU}{ton\ \ fiber} \tag{18}$$

To calculate the next step of the energy balance equation, given the heating value at 60°F = 1,050 BTU/cubic feet (cf), liters per mole must first be calculated using a standard temperature conversion to convert degree Fahrenheit to Kelvin (K):

$$\frac{100\ mol \times \frac{22.4\ L}{mol} \times \frac{(60\text{°F} - 32)}{1.8 + 273}}{273} = \frac{2{,}367.6\ L}{100\ mol\ natural\ \ gas} = \frac{23.6\ L}{mol\ natural\ \ gas} \tag{19}$$

The next step is to determine the energy content (BTU/mole) of natural gas (NG) by using the result found in Equation (19). Standard conversions for cubic feet (1 cf = 28.3 L) are applied in Equation (20).

$$\frac{1{,}050\ BTU}{cf} \times \frac{1\ cf}{28.3\ L} \times \frac{23.6\ L}{mol\ NG} = \frac{878.4\ BTU}{mol\ NG}$$

(20)

By producing 330 kg lime mud ($CaCO_3$) per ODT, the amount of CO_2 released can be calculated. The molecular weight of $CaCO_3$ is 100. When $CaCO_3$ is heated, it forms CaO (56) and CO_2 (44).

$$330\ kg\ CaCO_3 \times \frac{44}{100} = 145\ kg\ \mathrm{CO_2}$$

(21)

By multiplying the total amount of $\frac{BTU}{mol\ NG}$ from Equation (20), the amount of $\frac{BTU}{mol\ CO_2}$ can be calculated by using the standard natural gas composition of $\frac{100\ mol\ NG}{104.2\ mol\ CO_2}$ in this energy balance equation.

$$\frac{878.4\ BTU}{mol\ NG} \times \frac{100\ mol\ NG}{1} \times \frac{1}{104.2\ mol\ CO_2} = \frac{843\ BTU}{mol\ CO_2}$$

(22)

Finally, the amount of CO_2 per ton of pulp can be calculated by converting MMBTU into BTU (multiply by one million). That number is then divided by the total from Equation (22), and it is then multiplied by 44 kg CO_2 over 1000 moles. On a gram-per-mole ratio, using the molecular weight of CO_2, there are 44 g CO_2 per 1 mole. The standard conversion from grams to kilograms is 1000 g = 1 kg.

$$\frac{1{,}400{,}000\ BTU}{ton\ pulp} \times \frac{1\ mol}{\frac{843\ BTU}{mol\ CO_2}} \times \frac{44\ kg\ CO_2}{1000\ mol} = \frac{74\ kg\ \mathrm{CO}_2}{\text{ton pulp}} \tag{23}$$

The total amount of CO_2 released is calculated adding the total in Equation (21) with the total from Equation (23).

$$145\ kg\ CO_2 + 74\ kg\ CO_2 = \frac{219\ kg\ CO_2}{ton\ pulp} \times \frac{2.204\ lb}{kg} = \frac{483\ lb\ CO_2}{ton\ pulp} \tag{24}$$

3.4 Black Liquor Solids (BLS) Recovery

Spent cooking liquor from the digester is sent through the recovery process for recycling. The spent cooking liquor contains a certain amount of active alkali, dissolved cellulose, and lignin from the pulping process in the form of black liquor. The amount of dissolved cellulose and lignin is determined by the amount of dry wood needed by the digester multiplied by the percentage of pulp yield remaining after wash.

$$1 - 0.52 \times 3{,}846\ lb\ dry\ wood = 1{,}846\ lb\ lignin \tag{25}$$

The active alkali (AA) is calculated by multiplying the amount of dry wood (3,846 lb) by the percentage of AA on an oven dried ton of wood (Cornell, 1992, p. 150). The active alkali is then divided by the percentage of white liquor activity to determine the total alkali content (p. 150).

$$\frac{2{,}000\ lb}{0.52} \times 0.165\ AA = 635\ lb\ AA \tag{26}$$

$$\frac{635\ lb}{0.85\ CaO} = 747\ lb\ total\ alkali \tag{27}$$

The concentration of black liquor is comprised mostly of total active alkali and lignin. The amount of lignin contained in the black liquor is determined by the undissolved solids left after pulping with a sulfide solution. This number is then multiplied by the amount of dry wood needed for digestion and added together with the total active alkali content to determine the amount of black liquor solids in Equation (28). The total black liquor solids are then divided by percent solids to determine the amount of weak black liquor (WBL) available for evaporation in Equation (29) (Grace, 1989a, p. 486). In Equation (30), the amount of water is then determined by multiplying the amount of weak black liquor by the percentage of liquid.

$$747\ lb\ total\ alkali + 1846\ lb\ lignin = 2{,}593\ lb\ BLS \tag{28}$$

$$\frac{2{,}593\ lb\ BLS}{0.139} = 18{,}653\ lb\ WBL \tag{29}$$

$$18{,}653\ lb\ WBL \times 0.861 = 16{,}060\ lb\ water \tag{30}$$

The weak black liquor is sent to an evaporator to be concentrated to about 65 % solids for firing in the recovery boiler (Grace, 1989a, p. 486). To calculate the amount of strong black liquor (SBL), the total black liquor solids from the digester are divided by 65 %. In Equation (32), the amount of water available is the difference between the strong black liquor and the black liquor solids. The amount of evaporation is calculated in Equation (33) by subtracting the amount of water in weak black liquor from the amount of water in strong black liquor. The total amount of steam consumed for the evaporator is the amount of evaporation divided by the steam economy (pounds evaporation per pound of steam) derived for the six effect evaporator train (p. 511).

$$\frac{2{,}593\ lb\ BLS}{0.65} = 3{,}989\ lb\ SBL \tag{31}$$

$$3{,}989\ lb\ SBL - 2{,}593\ lb\ BLS = 1{,}396\ lb\ water \tag{32}$$

$$16{,}060\ lb\ water - 1396\ lb\ water = 14{,}664\ lb\ evaporation \tag{33}$$

$$14{,}664\ lb\ evaporation \times \frac{1\ lb\ steam}{4.75\ lb\ evaporation} = 3{,}087\ lb\ steam \tag{34}$$

The strong black liquor, containing 65 % solids, is prepared for the next stage of the recovery process: the recovery boiler (RB). The total amount of black liquor solids must first be converted into kilograms before it is multiplied by the amount of steam flow to the mill per 100 kg of black liquor solids (Adams, 1989a, p. 536). The total amount of steam available to the mill is then converted back to pounds. The total amount of steam available for the papermachine after consumption by the digester and evaporator is calculated in Equation (38).

$$2{,}593\ lb\ BLS \times \frac{1\ kg}{2.204\ lb} = 1{,}176\ kg\ total\ BLS \tag{35}$$

$$1{,}176\ kg\ BLS \times \frac{323.4\ kg\ steam}{100\ kg\ BLS} = 3{,}804\ kg\ steam \tag{36}$$

$$3804\ kg\ steam \times \frac{2.204\ lb}{kg} = 8{,}385\ lb\ steam \tag{37}$$

$$8{,}385\ lb\ RB\ steam - 4{,}650\ lb\ steam\ used = 3{,}735\ lb\ available\ steam \tag{38}$$

The total amount of biomass carbon dioxide emitted from the recovery boiler can be calculated by using the weight percentage of black liquor solids for carbon (Adams, 1989a, p. 537). The percentage is multiplied by the total amount of black liquor solids (kg) and then multiplied by a conversion of carbon into carbon dioxide outlined in a report by the United States Department of Energy (2000, p. 1) and converted into pounds of CO_2 derived from biomass.

$$0.39 \times \frac{1176\ kg\ BLS}{1} \times \frac{44}{12} \times \frac{2.204\ lb}{kg} = 3{,}707\ lb\ CO_2\ (biomass) \tag{39}$$

According to Paul Tucker, the pulp entering the drying section of the papermachine consists of approximately 60.2 % moisture and 38.8 % solids. The total flow to the papermachine, amount of water, and steam use can be calculated using specific heat, which is the amount of steam needed to evaporate one pound of water.

$$2{,}000\ lb \times 0.38 = 5{,}155\ lb\ total\ \ flow \tag{40}$$

$$5{,}155\ lb\ total\ \ flow - 2{,}000\ lb = 3{,}155\ lb\ water \tag{41}$$

$$1.3\ specific\ heat \times 3{,}155\ lb\ water = 4{,}101\ lb\ steam\ needed \tag{42}$$

3.5 Carbon Dioxide Emissions Calculations

The following conversions established by Thomas Grace (1989a, p. 502) and the United States Department of Energy (DOE) (1994), are used to help estimate the amount of carbon dioxide emissions from a power boiler to supply the steam required by the papermachine:

- 1 lb coal (anthracite) = 14,500 BTUs. (source: US DOE)
- 1 lb coal (anthracite) is 80 % carbon or 0.8 lb carbon.
- 1,000 BTU = 1 lb steam (source: Grace)
- 1 lb coal = 14.5 lbs steam. ($14{,}500\ BTU \times 1\ lb\ steam / 1{,}000\ BTU$)
- 3 lb CO_2 released per pound coal. See Equation (43).

$$1\ lb\ coal \times \frac{0.8\ lb\ carbon}{lb\ coal} \times \frac{1\ lb\ mol}{12\ lb\ carbon} \times \frac{44\ lb\ CO_2}{1\ lb\ mol\ carbon} = 3\ lb\ CO_2 \tag{43}$$

The papermachine requires 4,101 pounds worth of steam to operate. Equation (43) converts steam into amount of coal use to provide steam. Equation (44) converts the pounds of coal needed to supply energy to the papermachine into BTU, with a coal boiler low-load heating efficiency of 75 % as estimated by the Council of Industrial Boiler Owners (2003).

$$4{,}101\ lb\ steam \times \frac{1\ lb\ coal}{14.5\ lb\ steam} = 283\ lb\ coal \tag{44}$$

$$283\ lb\ coal \times \frac{14{,}500\ BTU}{lb\ coal} \times 0.75\ efficiency = 3{,}077{,}625\ BTU \tag{45}$$

To calculate the carbon dioxide emissions for 100 % recycled fiber to supply the steam needed by the papermachine, assuming complete combustion of 283 lb of coal is needed to operate, Equation (45) calculates the amount of carbon dioxide released into the atmosphere.

$$283\ lb\ coal \times \frac{3\ lb\ CO_2}{1\ lb\ coal} = 849\ lb\ CO_2 \tag{46}$$

The impact from 100 % virgin fiber production is calculated using excess steam available from the recovery boiler to power the papermachine. Since the papermachine requires 4,101 lb steam to operate and 3,735 lb steam is available from the recovery boiler through biomass incineration, only 366 lb steam has to be made up from coal.

Equation (46) converts 366 lb steam to lb coal, and Equation (47) calculates the pounds of carbon dioxide released into the atmosphere.

$$366\ lb\ steam \times \frac{1\ lb\ coal}{14.5\ lb\ steam} = 25\ lb\ coal \tag{47}$$

$$25\ lb\ coal \times \frac{3\ lb\ CO_2}{1\ lb\ coal} = 75\ lb\ CO_2 \tag{48}$$

Chapter 4: Discussion and Results

4.1 Linerboard Model Results

The total amount of carbon dioxide emitted during the production of kraft linerboard is dependent upon the source of fiber used for production. The model outlined in Chapter 3 uses a comparison of 100 % virgin fiber and 100 % recycled fiber. The results in Table 1 are based on only energy intensive processes in a linerboard mill that produces carbon dioxide. Steam production is affected by the incorporation of recycled fiber, but this has an effect on the amount of steam available for digester consumption.

Table 1. Total Carbon Dioxide Output – Virgin versus Recycled.

Mill Area	Virgin Fiber CO_2 Output, lb/ton fiber	Recycled CO_2 Output, lb/ton fiber
Lime Kiln	483	0
Papermachine*	75	849
Biomass	3,707	0
Total	4,265	849

*The carbon dioxide output from the papermachine is attributed to the steam demand which cannot be satisfied by the recovery boiler and must be produced via the power boiler.

The lime kiln is part of the chemical recovery process that recycles spent cooking liquor from the digester. The kiln requires a fossil fuel source, natural gas, to convert calcium carbonate into calcium oxide so that it can be used in the causticizing process. The entire chemical recovery process is only necessary when pulp is derived from virgin fiber and cooked in the digester to remove lignin from the wood. Since recycled fiber consists of pre- and post-consumer paper fiber, there is no lignin to be removed.

Therefore, the lime kiln is a direct source of carbon dioxide output for virgin fiber and not for recycled fiber.

The papermachine requires both steam and electricity to operate, and both virgin and recycled fibers have an impact on this process. The electricity can be purchased on a grid or provided through on-site boilers burning fossil fuels or biomass. The wood waste generated through virgin fiber production provides ample amount of biomass derived energy, whereas recycled fiber requires only fossil fuel derived energy. That is because, in the case of recycled fiber, all water heating must be supplied via steam and can be as much as 1,000 lb steam/ton (Tucker, 2007). Papermachine steam consumption is also impacted by once-dried fiber because it drains better, and specific steam consumption would be less for the recycle-only case.

In the model, however, there was not enough steam energy produced through the recovery process to meet the steam requirement for the papermachine for virgin fiber production. The papermachine requires 4,101 lb of steam for evaporation, and only 3,735 lb of steam was available for usage. Therefore, 366 lb of steam is needed from a fossil fuel source to make up for the deficit. In this case, recycled fiber does contribute to the increase of fossil fuel derived carbon dioxide emitted during the linerboard production process. However, because the steam produced by the recovery boiler is biomass derived, carbon dioxide output must be included in the calculations.

Since there is no biomass waste energy associated with recycled fiber, it does not have an impact on carbon dioxide output. Even though biomass is a renewable energy source compared to fossil fuels, the carbon dioxide output still has the same negative impact when released into the atmosphere. Although other greenhouse gases may be reduced through burning biomass over fossil fuels, the net carbon dioxide output is of most importance in this research.

Using the available data from the model, replacing one ton of virgin fiber with one ton of recycled fiber will decrease carbon dioxide output by 1.5 tons. For example, if a mill is producing 100 tons of virgin fiber per day and wants to incorporate 50 % recycled fiber into the production, 50 tons of virgin fiber will be replaced by 50 tons of recycled fiber. That will amount to a reduction of 75 tons of carbon dioxide output per day from the mill. The amount of energy has been greatly reduced even though more fossil fuels are being used to produce recycled fiber

4.2 Model Results Compared to Actual Data

The results from the model indicate that recycled fiber has a low total carbon dioxide output. The only increase in carbon dioxide emissions is from the papermachine energy demand. This is because no other areas that produce carbon dioxide in the mill during linerboard production are affected by recycled fiber. Virgin fiber production, however, has a higher overall impact on total carbon dioxide output. In order to strengthen the results, it is necessary to compare data derived from the model with actual data from a linerboard mill with a similar pulp yield. With the help of Paul Tucker from International Paper (IP), the results for virgin fiber production are compared in Table 2.

Since recycled fiber has less CO_2 levels compared to virgin fiber, it is not necessary to compare actual data regarding recycled fiber. As for virgin fiber production, the results are quite similar when including data from IP into the model. The numbers suggest that the only significant deviation between the model and the actual data is regarding the amount of steam available to the papermachine. In the model, the digester and evaporator energy balances are much higher than the data provided by IP.

Table 2. Virgin Fiber Production Total CO_2: Comparison of Actual Data and Model Data.

Mill Area	Actual (IP) CO_2 Output, lb/ton fiber	Model CO_2 Output, lb/ton fiber
Lime Kiln	469	483
Papermachine	0	75
Biomass	3,707*	3,707
Total	4,176	4,265

*The amount of biomass calculated in the model was deemed an appropriate estimation by Tucker. Since the amount of biomass is generated through virgin fiber production, it is not tracked in the same way as purchased fuel. Therefore, with no data provided, the model data is sufficient for the scope of this project.

This results in the extra energy required to produce steam for the papermachine in the model. Thus, the energy is derived from fossil fuels in the model and contributes to carbon dioxide emissions. The 75 lbs of CO_2 output, though, is only the difference between the production of virgin fiber and recycled fiber. Table 3 contains more information on steam production and consumption broken down by each individual process.

The data shows significant differences in the amount of steam consumed by the digester and evaporator which would affect the amount of steam available to the papermachine for evaporation. It must be noted that the power boiler data is not representative of the total mill output and only accounts for the steam necessary to operate the papermachine. Using the data provided by IP in the model, there are approximately 7,800 lb of steam produced by the recovery boiler, and only 3,604 lb of steam is consumed by the digester and evaporator combined. This leaves an excess of 4,196 lb of steam available for the papermachine which only requires 4,100 lb of steam to operate. Therefore, no fossil fuel energy is required to compensate for the absence of biomass derived energy.

Table 3. Energy Use Data Comparing Model Data and Actual Data For Virgin Fiber Production. *Note*: (Actual Data).

Mill Area	Fossil Fuel Usage BTU/ton fiber	Steam Usage, lb/ton fiber		CO_2 Output, lb/ton fiber	
		Produced	Consumed	Biomass	Fossil Fuel
Digester	0	0	1,563 (1,304)	0	0
Evaporator	0	0	3,087 (2,300)	0	0
Lime Kiln	1,410,560 (1,300,000)	0	0	0	483 (469)
Papermachine	0	0	4,101 (4,100)	0	0
Recovery Boiler	0	8,385 (~7,800)	0	3,707 (3,707)*	0
Power Boiler	247,370	366	0	0	75 (0)
Total	1,657,930 (1,300,000)	8,751 (7,800)	8,751 (7,704)	3,707 (3,707)	558 (469)

*The amount of biomass calculated in the model was deemed an appropriate estimation by Tucker. Since the amount of biomass is generated through virgin fiber production, it is not tracked in the same way as purchased fuel. Therefore, with no data provided, the model data is sufficient for the scope of this project.

4.3 Recycled Fiber Quality

The quality of recycled fiber is determined by 1) the number of times recycled and 2) the use as an end product. In the case of linerboard, strength is a determining factor for the percentage of recycled fiber used to make new corrugated packaging containers. The recycled fiber consists of mainly post-consumer corrugated cardboard packaging collected by local recycling programs. Each time the paper grade is recycled, the fibers become shorter compared to the longer fibers of virgin wood. As the paper fiber degrades due to recycling processes, it is no longer recyclable. The recycled fiber is then used to produce lower grade paper products that eventually end up in the landfill.

Certain paper products can be made from 100 % recycled fiber; although, the quality and appearance may not be acceptable for specific uses (ex. shipping packages). That is one reason why virgin fiber is usually mixed with recycled fiber to make newer products. The product will usually list the recycled content on the packaging as "post-consumer recycled content." Table 4 shows total carbon dioxide emissions given the recycled fiber content mixed with virgin fiber using modeled data (including actual data).

Table 4. Total CO_2 Output: Recycled Content Fiber

Recycled Fiber, %	CO_2 Output, lb/ton fiber
0	4,177
10	3,844
20	3,511
30	3,179
40	2,846
50	2,513
60	2,180
70	1,847
80	1,514
90	1,181
100	849

Table 4 represents a more realistic model of total carbon dioxide output with the incorporation of recycled content fiber compared to models comparing 100 % virgin fiber and 100 % recycled fiber production. A simple formula was developed in Equations (49) – (51) to determine the correlation between the percentage of recycled fiber content and the pounds of carbon dioxide output per ton of fiber.

$$\frac{\%\ recycled\ \ fiber}{100} \times \frac{Total\ CO_2}{ton\ recycled\ \ fiber\ (RF)} \tag{49}$$

$$\frac{1 - \%\ RF}{100} \times \frac{Total\ lb\ CO_2\ output}{ton\ virgin\ \ fiber\ (VF)} \tag{50}$$

$$RF + VF = \frac{Total\ CO_2\ output}{ton\ recycled\ content\ \ fiber} \tag{51}$$

Although the higher percentage of recycled content fiber may have the most reduction in carbon dioxide emissions, it may not be feasible or economical for a mill to produce such a product. Also, in the case of linerboard, it is only one part of the end product along with the corrugated medium. Therefore, the percentages of post-consumer recycled fiber for both products are calculated to give a total post-consumer fiber percentage for the corrugated packaging container.

Chapter 5: Conclusion

In this study, although recycled fiber does contribute to an increase in fossil fuel consumption during linerboard production, it has less of an impact on total carbon dioxide output from a mill compared to virgin fiber production. Using recycled fiber to produce newer linerboard products does save energy and forest resources; however, recycling mills may consume more fossil fuel than conventional paper mills that generate much of their energy from biomass. As indicated in this study, there is no difference in the carbon dioxide emissions from fossil fuels or biomass. On a level of resource conservation – saving trees or conserving fossil fuels – deeper investigation may be necessary when choosing between burning wood waste or coal, oil, and natural gas as an energy source. Also, the release of other pollutants or particles associated with energy combustion may also be addressed.

There are two things that are certain; paper mills require a lot of energy to make paper, and Americans purchase and discard a lot of paper products. To reduce the amount of carbon dioxide emissions, paper mills should seek out alternative renewable energy sources, ultimately eliminating fossil fuels. When coupled with wastepaper recycling, the energy savings and total carbon dioxide emissions reductions would be significant enough to participate in a carbon offsetting program. To increase paper recycling, communities should invest in efficient dual stream recycling collection programs to source separate clean paper fiber from other recyclables to provide to mills. In turn, consumers should support recycling efforts by buying recycled content products.

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