DOCUMENTATION
FOR THE PAPER CALCULATOR
VERSION 3.2

Submitted to:

Environmental Paper Network

By:

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A Division of ERG

September 2012

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INTRODUCTION

The following documentation is for the final version of the new Full Paper Calculator Model (Version 3.2) submitted by Franklin Associates to Environmental Paper Network (EPN). Each section includes information on references used and assumptions made. In some cases, references are to documents and appendices from The Paper Task Force Report. While an attempt has been made to use public data whenever possible, data from the Franklin Associates database have been used in some cases. Additionally, some upstream transportation has been excluded either based on a lack of data, or an internal analysis that showed it not to have a significant impact on the final results.

FUELS

The Higher Heating Values (HHV), air emissions, water emissions, solid waste, and total energy (combustion plus pre-combustion energy) of all fuels in the model are taken from the Franklin Associates model. These data are outputs from the Franklin Associates model, and are provided on the basis of energy content (MMBtu), physical units (pounds, cubic feet or gallons), and transportation ton-miles where applicable. The fuels and energy data used by Franklin Associates is based on modules available in the US Life Cycle Inventory Database, with more recent updates from eGRID 2006 and GREET 1.8b. Global warming potentials are from the 2007 IPCC report.

The on-site fuel mix for pulp and paper has been devised from 2002 American Forest & Paper Association (AF&PA) data on fuels used for the entire pulp and paper industry, with the following assumptions:

- Only kraft pulp production uses black liquor as an energy source;
- Black liquor makes up 75 percent of the on-site[1] energy use for kraft pulp production, with the remaining 25 percent from hog and purchased fuels;
- Mechanical pulp production uses hog fuel and purchased fuels;
- Paper and board production uses entirely purchased fuels;
- With the exception of recycled boxboard, recycled pulp uses the same fuel mix as paper/board production; and
- When fuels are used in a process, they are in the same proportion to their use by the general industry.

Table 1. On-site Fuel Mix

	Kraft Pulp	Mechanical	Paper/Board	Mixed Rec pulp	Rec Board
Coal	6.1%	0.0%	35.2%	40.6%	24.3%
Distillate Oil	2.1%	0.0%	12.3%	13.5%	15.2%
Natural Gas	9.1%	20.0%	52.5%	46.0%	60.6%
Liquor/Hog	82.6%	80.0%	0.0%		

The assumption about the proportion of energy in kraft pulp production that comes from black liquor is based on confidential data collected by Franklin Associates and 2004 data provided to GreenBlue by the

[1] On-site energy refers to steam and electricity produced within the pulp mill, and does not include purchased electricity.
[2] The 2004 AF&PA data show 71 percent of energy from liquor and 17 percent of energy from wood chips (88 percent total). Our

AF&PA.[2] Based on data from Francis (2002), it is assumed that 80 percent of the on-site fuel for mechanical pulp is from hog fuel, with natural gas accounting for the remaining 20 percent.[3] Any electricity purchased by pulp or paper mills is assumed to be a national average for the United States.

TREE HARVESTING

Data on the harvesting of trees for use in pulp and paper are from the US LCI Database, which includes harvesting from the Pacific Northwest, Inland West, Northeastern North Central and the South-East of the US.[4] Energy use for the harvesting and transport of trees is included, as is replanting and the production of fertilizers. Wood use measures the amount of wood required to produce a given amount of paper. The number of typical trees assumes a mix of hardwoods and softwoods 6-8" in diameter and 40' tall. Calculated collaboratively by Conservatree, Environmental Defense Fund, and Environmental Paper Network based on data from Tom Soder, Pulp & Paper Technology Program, University of Maine, as reported in Recycled Papers: The Essential Guide, by Claudia G. Thompson, The MIT Press, 1992. Assumptions about the quantity of wood needed are used to determine the amount of fuel needed for harvest and transport.

Soil Carbon and Carbon Uptake

During the growth phase of a tree carbon is removed from the atmosphere and stored in the trunk and root system. When the tree is harvested the carbon in the trunk is removed, but the fate of the carbon in the soil is less certain. The Paper Calculator makes no assumptions about the possible gain or loss of carbon in the soil or in overall forest stock.

WATER USE AND CONSUMPTION

Water results are displayed on a consumptive basis. When water is withdrawn from one water source and returned to another source, this is considered consumption, as there is a net removal (depletion) of water from the original water source. Consumption also includes water that is withdrawn and evaporated or incorporated into the product. Finally, water that is returned to the source in a degraded condition is considered part of consumptive use. Water consumption is only included as an inventory category in this study, and does not attempt to assess water-related damage factors. For instance, there is no differentiation between water consumption that occurs in water-scarce or water-abundant regions of the world. Additionally, some types of water consumption (e.g. evaporated cooling water) would not have the same potential impact on water quality as would direct contact in industrial processes or use in agriculture.

Water consumption values for upstream electricity processes have been taken from literature. For power production, water consumption of 6.19 m^3/MWh is modeled for the US electrical grid (Pfister 2011). In addition to water consumption associated with thermal generation of electricity from fossil and nuclear fuels, the water consumption for power generation includes evaporative losses due to establishment of dams for hydropower. In the study from which the power production water

[2] The 2004 AF&PA data show 71 percent of energy from liquor and 17 percent of energy from wood chips (88 percent total). Our method arrives at 7.6 percent hog fuel (82.6 percent total).
[3] TMP is the only type of mechanical pulp that requires on-site fuel.
[4] LCI data were submitted by CORRIM. Weight factors for the various types of wood are from Table 17 of the AF&PA 2008 Statistical Summary. Weight factors for regional sources are from the USITC Industry & Trade Summary: Wood Pulp and Waste Paper.

consumption is derived, a climate-dependent scheme was developed to determine the evaporative losses from establishment of dams in different countries. For calculating consumptive use in hydroelectric facilities, water flowing through the turbine into the river is not considered consumptive; however, converting a free flowing stream to a reservoir controlled by a dam increases the water surface area, resulting in an increased evaporative loss. This increased evaporative loss is included as consumptive use, with the evaporative losses allocated over the total MWh produced (NREL 2003).

Due to data limitations, water consumption in the Paper Calculator is generally limited to measured effluent from pulp and paper mills, and water consumed during electricity generation.[5] The sources for effluent measurement are described in the Appendices to the Paper Task Force White Papers 10 through 12. Comparing these effluent measurements with data compiled in an ecoinvent report, however, highlighted a discrepancy in the water use for virgin unbleached kraft fiber (Hischier 2007). While it seems unreasonable that the water use for unbleached kraft pulp should be higher than bleached kraft pulp,[6] the value of 17.5 liters/kg of pulp previously used in the calculator does not appear to include cooling water. Because every other type of pulp and paper – both virgin and recycled – fell within the range of values shown in the ecoinvent report, cooling water was added to the total amount for unbleached kraft pulp.[7]

A review of water consumption for several paper types in ecoinvent showed that these two sources – the pulp/paper mills, and the electricity they purchase – account for more than 90 percent of the life cycle water consumption.

END OF LIFE CARBON CALCULATIONS

Paper products contain cellulose, hemicellulose, and lignin, with the ratio of the fiber types varying based on the pulping method employed. Chemical pulping removes most of the lignin fraction, whereas mechanical pulping leaves it intact. If a paper product is sent to a landfill the cellulose and hemicellulose are able to decompose more easily than the lignin. Additionally, there is evidence that the presence of lignin can help to lower the potential decomposition rate of the cellulose and hemicellulose (Barlaz 1997). Because conditions such as moisture content vary at each landfill, the actual decomposition rates may differ from those used in the model. The ratio of cellulose/hemicellulose/lignin fibers in kraft pulp are based on factors from the Papermaking Science & Technology series. It is assumed that mechanical pulp has the same composition as wood, and the semi-chemical pulp is an average of the two. Decomposition rates used in the Paper Calculator are provided by NCASI.

In this study, estimates of the end results of landfilling and Waste to Energy (WTE) combustion are limited to global warming potential effects. There are GWP contributions from fugitive emissions of landfill methane from decomposition of paper products. There are also GWP credits for grid electricity displaced by the generation of electricity from WTE combustion of post-consumer paper and from WTE combustion of methane recovered from decomposition of landfilled paper.

The composition of landfill gas as generated is approximately 50 percent by volume methane and 50 percent by volume CO_2. Currently, about 53 percent of methane generated from solid waste landfills is converted to CO_2 before it is released to the environment. 23 percent is flared, 25 percent is burned with energy recovery, and about 5 percent is oxidized as it travels through the landfill cover (USEPA 2008). The

[5] Water consumed during the production of pulping chemicals, coatings/fillers, and other upstream sources not directly related to the mills or purchased electricity is not included in the Paper Calculator.
[6] Bleached pulp requires additional wash water after the brownstock wash.
[7] The amount of cooling water added is 36 liters/kg of pulp, the same amount used by bleached kraft pulp.

Paper Calculator makes the assumption that biomass CO_2 released from decomposition of paper products or from oxidation of biomass-derived methane to CO_2 is considered carbon neutral, as the CO_2 released represents a return to the environment of the carbon taken up as CO_2 during the plant's growth cycle and does not result in a net increase in atmospheric CO_2. Thus, biomass-derived CO_2 is not included in the GHG results shown in this analysis. Methane releases to the environment from anaerobic decomposition of biomass are *not* considered carbon neutral, however, since these releases resulting from human intervention have a higher global warming potential (GWP) than the CO_2 taken up or released during the natural carbon cycle.

The U.S. EPA's Landfill Methane Outreach Program (LMOP) Landfill Database[8] indicates that the majority of landfill gas burned with energy recovery is used to produce electricity. The gross energy recovered from combustion of landfill gas from each material is converted to displaced quantities of grid electricity using an efficiency factor of 1 kWh generated per 11,700 Btu of landfill gas burned.[9] Each paper type is credited with avoiding the GWP associated with production of the offset quantity of grid electricity.

Waste-to-energy combustion of post-consumer material is modeled using a similar approach to the landfill gas combustion credit. The gross heat produced from waste to energy combustion is calculated based on the pounds of material burned and the higher heating value of the material. The heat is converted to kWh of electricity using a conversion efficiency of 1 kWh per 19,120 Btu for mass burn facilities[10], and a credit is given for avoiding the greenhouse gas (GHG) emissions associated with producing the equivalent amount of grid electricity (USEPA 2008).

The net end-of-life global warming potential (GWP) for each paper type is calculated by summing the individual impacts and credits described above, based on 80 percent landfill and 20 percent WTE combustion.

Limitations of End-of-Life Modeling Approach**.** As noted, the landfill methane calculations in this analysis are based on the aggregated emissions of methane that may result from decomposition of the degradable carbon content of the landfilled material. The long time frame over which those emissions occur has implications that result in additional uncertainties for the landfill methane GWP estimates.

- In this analysis, the management of the aggregated landfill methane emissions is modeled based on current percentages of flaring, WTE combustion, and uncaptured releases. Over time, it is likely that efforts to mitigate global warming will result in increased efforts to capture and combust landfill methane. Combustion of biomass-derived methane converts the carbon back to CO_2, neutralizing the net global warming impact. In addition, if the combustion energy is recovered and used to produce electricity, there would be GHG credits for displacing grid electricity. With increased future capture and combustion of landfill methane, the future net effect of landfill methane could gradually shift from a negative impact to a net credit.
- Although the landfill methane releases occur gradually over many years, the modeling approach used here models the impacts of the aggregated emissions using 100-year global warming potentials. This is consistent with the use of 100-year global warming potentials used for all other life cycle greenhouse gas emissions. Future refinements to end-of-life modeling may include time-scale modeling of landfill methane emissions; however, this is not part of the current study.

[8] Operational LFG energy projects spreadsheet, sorted by LFGE utilization type and project type. Accessible at http://www.epa.gov/lmop/proj/#1.
[9] LMOP Benefits Calculator. Calculations and References tab. Accessible at http://www.epa.gov/lmop/res/lfge_benefitscalc.xls
[10] Calculation is based on 550 kWh produced per ton of MSW burned, with a heat value of 5,000 Btu per pound of MSW. For mass burn facilities, 523 kWh of electricity are delivered per 550 kWh generated.

RECYCLING & DISPOSAL

The model calculates the total energy and emissions associated with both the collection of fiber for use in recycled paper, and the disposal of paper at the end of life. It is assumed that recycled paper is collected via curb-side bins, and all paper products are assumed to be recycled at national rates (USEPA 2010).

Landfill and incineration are assumed to occur at an 80/20 split.[11] How much of each paper and board type is generated in the waste stream, and the percent recovered in recycling programs is from the 2009 EPA Municipal Solid Waste (MSW) report. Finally, the energy use and emissions for the landfill and incineration of one ton paper are calculated.

The current Paper Calculator methodology assumes that the paper or board type picked by the user will fall into the largest appropriate category defined in the MSW recycling table; uncoated freesheet could be used in a book and have a recycling rate of 33 percent, but the model puts all uncoated freesheet in the category of "office-type papers" with a recycling rate of 74 percent. If the recycling rate of a paper product is different from what is present in the model, the results may not be accurate.

An open loop recycling methodology is used in the Paper Calculator to account for the diversion of waste from landfills when it is incorporated into paper as recycled fiber content. Limitations in the structure of the Paper Calculator do not allow the methodology to be applied consistently over all aspects of the life cycle; the method is used only for solid waste and the associated energy recovery and greenhouse gas emissions from decomposition. As part of the method, it assumed that recycled fiber has, on average, two previous lives. Over these three lives, a single ton of fiber will displace two tons of fiber from the solid waste stream, or 2/3 of a ton for each ton of recycled fiber used.

When paper fiber is diverted from a landfill, it reduces the amount of methane released during the decomposition process. The detailed fate of methane is covered in the End of Life section, but the net greenhouse gas emissions that would have come from the 2/3 tons of fiber for each ton of recycled fiber content are treated as a credit. This means, however, that the system energy is also increased by the amount that would have been recovered through direct incineration of the fiber, and burning recovered methane that would have been released during decomposition.

FILLERS & COATINGS

While some earlier versions of the Paper Calculator model did not include burdens from the production of coatings and fillers, they are included in the current version of the model. A number of materials can be used as coating and fillers in paper and board, but an assumption that these will always be approximately the same has been made. The coating is a mixture of clay, titanium dioxide and latex, and was previously modeled by Franklin Associates with data provided by a proprietary source. Fillers are usually clay or some form of calcium carbonate; a lack of production data on either ground or precipitated calcium carbonate precluded their use, so Franklin Associates data on kaolin clay production were used.

CHEMICALS

As with previous versions, the current model includes data on the production and use of chemicals in both the pulping and bleaching stages of pulp production. The amount of each chemical used in different pulping/bleaching techniques was verified with several different sources, but primarily comes from *Energy*

[11] Approximately equal to the ratio supplied in the 2009 EPA Municipal Solid Waste report.

Cost Reduction in the Pulp and Paper Industry.[12] It is assumed that chlorine dioxide is produced on-site in kraft mills; the mix of fuels for the final production step is the same as for kraft pulp, but with all electricity purchased from the grid.[13] No public data were available on chemical usage in semi-chemical pulping, so Franklin Associates data were used.

The data on energy use for the production of chemicals is primarily from Franklin Associates, with the exceptions of chlorine dioxide production (mentioned above) and oxygen (Williamson 1999).[14] Process emissions for the production of chemicals and their precursors are also from Franklin Associates data.

Total energy and emissions are compiled based on the fuels used in each pulping and bleaching process. A 60/40 split of bleaching technologies in kraft pulp (40 percent using oxygen delignification, 60 percent without) is based on a search of Lockwood-Post data. The actual ratio is 36 percent with oxygen delignification, 64 percent without. Because data in Lockwood-Post is self-reported and are often incomplete, the rounded approximation is used. The ratio is similar to that used in the last update to the Paper Calculator, but without chlorine bleaching.

Transportation of chemicals and upstream precursors has not been included due to a lack of data. The mass of chemicals used is small in comparison to the paper produced, and excluding this step should not influence the final results.

PULPING & PAPER MAKING

Calculations of energy use in pulp and paper production are based on three sources:

- Energy Cost Reduction in the Pulp and Paper Industry (ECR);
- Pulp and Paper Industry Energy Bandwidth Study (Bandwidth); and
- Papermaking Science & Technology (PS&T) (various volumes).

The reported requirements of electricity and steam (and direct heat) were averaged among all reporting sources. Production amounts are calculated using an air dry basis, assuming 6 percent moisture content where sources provided data in bone dry weight. It is well known that the recovery boilers in chemical pulping mills provide the majority of steam used in operations, and in almost all cases also produce electricity through co-generation. Based on Williamson (1999) and Anderson (1991), it is estimated that 50 kWh of electricity are generated for 1 MMBtu of produced steam. This electricity is counted at 3,412 btu/kWh, rather than the 10,620 btu/kWh for electricity produced from the average US grid. In every case, some purchased power is still required for pulp production.

Because each source gives requirements in terms of steam (or direct heat), it is necessary to account for the average boiler efficiency. From the Energy Bandwidth study, the efficiencies of various boilers are: coal and distillate oil, 86 percent; natural gas, 87 percent; and black liquor or hog, 64 percent.

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[12] Other sources include proprietary Franklin Associates data, books from the *Papermaking Science and Technology* series, the Ecoinvent database and the IPPC *Reference Document on Best Available Techniques in the Pulp and Paper Industry*, published by the European Commission in 2001.
[13] The energy for this final step was verified by an expert from International Paper, who stated that most large plants have switched, or are switching, to R-10 technology. This process uses 5 tons of steam/ton ClO_2, but doesn't produce any by-products that require neutralization. Electricity usage was confirmed to be the same as that used in the previous Paper Calculator assumptions (272 kwh/metric ton).
[14] PSA/VSA technology.

While the production of both mechanical and recycled pulp requires some steam in addition to electricity, it is assumed that none of the steam and electricity is co-generated. This means that all electricity is purchased from the grid. Purchased electricity is modeled using the national average production. TMP is the only method of mechanical pulping that requires steam, and the energy for it is primarily generated with hog fuel. Integrated mills that use TMP are able to recover 4.5 MMBtu of clean steam per ton of pulp, which is used to dry the finished paper. Recycled pulp uses only purchased fuels.[15]

It is possible for integrated pulp and paper mills, or stand-alone paper mills, to use purchased fuels for cogeneration, but no data were available to support this practice. Discussions with Reid Miner, Vice-President of Sustainable Manufacturing at NCASI, yielded no knowledge of this occurring with any frequency.

Energy requirements for each pulp and paper type are used to calculate the fuel emissions. Each fuel emission is a sum of the emissions from the production of purchased electricity and emissions from the production and combustion of fuels used on-site. Process emissions, which are not from the combustion of fuels, are derived from two sources: the original Paper Task Force data (air emissions, solid waste and total effluent) and the EPA Cluster Rules (emissions to water). The emissions to water are the 30-day Best Practice Technology (BPT) published in the Cluster Rules, with a COD/BOD ratio of 2.8 (Hoa 2003). Estimates were made of what current releases might be based on AF&PA self-reported reductions across the industry, but these are not included because they were only for virgin sources. The Paper Calculator can be used to compare virgin and recycled sources of fiber, so one should not be updated without updating the other.

Most paper products in the calculator are produced in fully integrated mills, where the pulp is immediately incorporated into a paper product. Production in integrated mills uses less energy, because the pulp is not dried. Any paper products using bleached kraft pulp, however, are modeled with 10 percent dried market pulp. This assumption is made based on data provided by GreenBlue.

Recycled Boxboard

Data on the energy required to produce recycled boxboard were provided by the Recycled Paperboard Technical Association (RPTA) to EDF in 2006. The data provided by RPTA appears to take the direct energy value of purchased steam and electricity rather than accounting for losses; adjustments were made using 10,620 btu/kWh for purchased electricity and 86 percent boiler efficiency for purchased steam.

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[15] It is assumed that the proportion of fuels for recycled pulp is the same as that in paper production. The exception is for recycled boxboard, where a fuel mix was provided. This fuel mix is very close to the mix assumed for paper production.

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