Yale School of Forestry and Environmental Studies

Final Report

Life Cycle Assessment:

Environmental Impacts of Virgin vs. Recycled Toilet Paper

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Executive Summary

This report discusses the results and methodology used for a life cycle analysis, commissioned by aquaTECH, comparing the environmental impacts of virgin and recycled toilet paper. AquaTECH was founded in Geneva, Switzerland in 1997, by David Hunkeler. The company specializes in developing water-soluble polymers for wastewater treatment applications in various sectors, including the production of cosmetics, pharmaceuticals, and tissue paper. AquaTECH is interested in understanding and evaluating two types of toilet paper production, with respect to water use and efficiency of water recycling within a paper mill. The results of the study will be used to inform AquaTECH's technology development in wastewater treatment technologies.

Use of waste paper in recycled content toilet paper production has the potential to offset deforestation impacts of virgin forest harvesting; however, production of recycled pulp and paper has significant environmental burdens. The first goal of this comparative life cycle assessment is to assess and compare the environmental impacts of producing two types of toilet paper at Cellox Bangkok Plant (Cellox)[1], a non-integrated mill in Thailand: 100% virgin pulp and 70% recycled pulp. The second goal is to identify key processes and inputs within pulp and paper production that are linked to the largest environmental impacts.

Five impact categories were considered, according to ReCiPe Midpoint H V1.10 assessment method: climate change (CC), freshwater eutrophication (FE), photochemical oxidant formation (POF), terrestrial acidification (TA), and agricultural land occupation (ALO). The results of this cradle-to-gate LCA showed that virgin paper production has a larger impact on all five impact categories: CC by 56% TA by 32%, FE by 12%, POF by 24%, and ALO by 70%. As a result, recycled toilet paper is the environmentally preferable option across the five key impact categories. The inputs with the largest overall impact are:pulp, heat fuel, and electricity. Furthermore, pulp production for both virgin and recycled toilet paper is responsible for approximately 50% of overall environmental impact.

The use of rosin as a de-inking agent in the recycled paper production process has a substantial impact on the agricultural land occupation impact category; however, its effects on the other categories are minimal. Transport of virgin pulp by oceanic freight had greatest impacts on TA and POF for virgin paper production, while the effects on recycled paper were minor considering no transregional pulp transport. We have conducted sensitivity analyses to understand how the LCA results change when the inputs vary. These analyses revealed that substituting heavy fuel oil for natural gas alters the TA impact by 19% and POF impact by 13%. Similarly, electricity grids that are supported not by coal can significantly reduce the environmental burden on all impact categories except ALO.

[1] Henceforth, Cellox Bangkok Plant will be referred to as Cellox.

The findings of this study show that the environmental impacts of pulp and paper production are highly dependent on individual fuel choices of paper mills and/or location of the facility. Similarly, the disparities between virgin and recycled paper across all impact categories are not proportional. These results should not be used to make general conclusions regarding precise environmental impacts of virgin and recycled toilet paper production worldwide.

Though the results of this study indicate that 70% recycled toilet paper has a lesser environmental impact than 100% virgin, other environmental impact categories should be considered in future research, such as: human, freshwater and marine toxicity.

Technical Summary

David Hunkeler, AquaTECH Director, commissioned this life cycle assessment. The purpose of the report is to compare the environmental impacts of 100% virgin fiber toilet paper and 70% recycled fiber toilet paper. AquaTECH intends to use the results of this study for further research and to inform the development of wastewater treatment technology.

System boundaries were set so that this life cycle analysis is limited to a cradle to gate study. The foreground system includes the pulp and paper manufacturing processes, processes for which we have modeled directly. The background system includes the impacts associated with forest harvesting, waste paper collection and sorting, sludge disposal, energy, and transportation processes and were not measured directly. Since aquaTECH is primarily interested in understanding the water recycling system efficiencies, the scope of this study excludes final processing steps, which are identical for both virgin and recycled paper, such as: creping, rolling, cutting, and packaging. However, the following processes are included within the system boundary: pulp hydration, pressing, drying, and wastewater treatment. For the purposes of this study, the functional unit is 1000 kg toilet paper with a density of 15 g/m^2. The process flow diagram shown in Figure 1 highlights the differences between virgin and recycled toilet paper production.

Our findings show that for all the five impact categories- climate change (CC), freshwater eutrophication (FE), photochemical oxidant formation (POF), terrestrial acidification (TA), and agricultural land occupation (ALO)- virgin paper production has a larger impact: CC by 56% TA by 32%, FE by 12%, POF by 24%, and ALO by 70% (shown in summary table below).

Table 1: Comparison of virgin versus recycled toilet tissue environmental impacts

Impact Category	Unit	100% Virgin	70% Recycled	Change from Virgin to Recycled
Climate change	kg CO_2 eq/kg	2361.9	2111.7	-11%
Terrestrial acidification	kg SO_2 eq/kg	8	5	-32%
Freshwater eutrophication	kg P eq/kg	0.4	0.3	-12%
Photochemical oxidant formation	kg NMVOC	6	5	-24%
Agricultural land occupation	m^2/yr	989	296	-70%

1. Goal and Scope of the Study

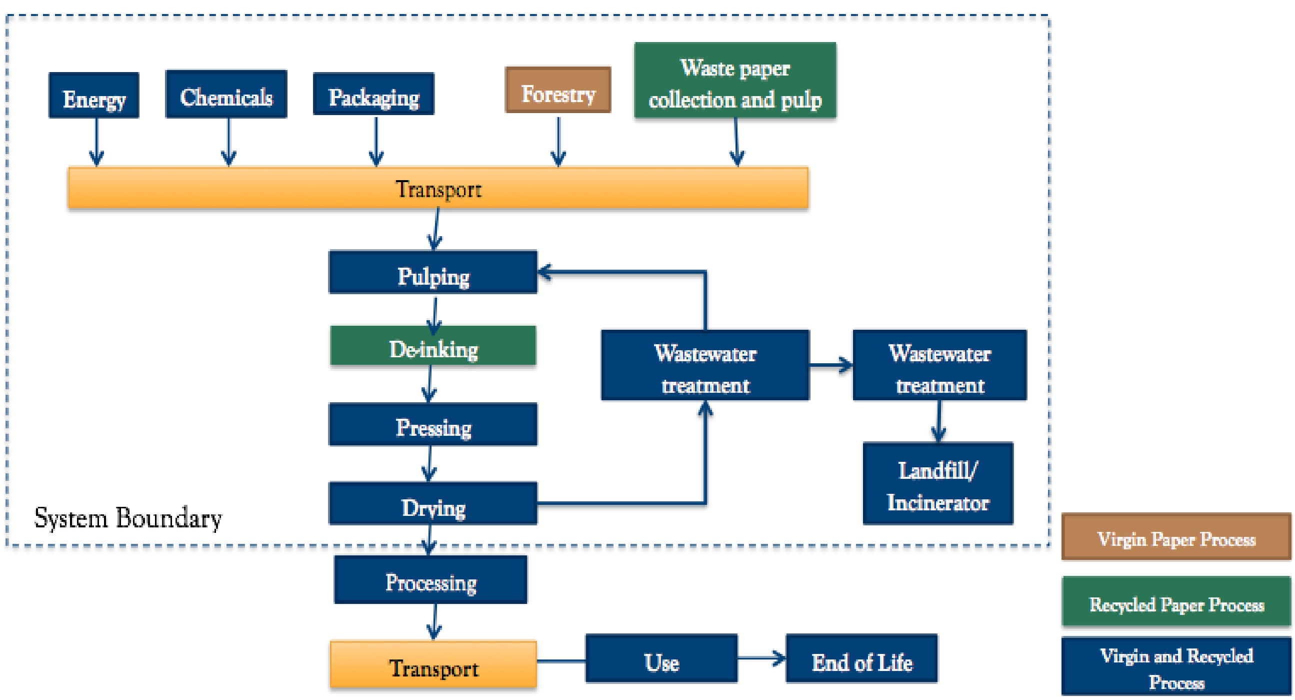
1.1 Goal

The first goal of the study is to conduct a comparative life cycle assessment to compare and assess the environmental impacts associated with the production of 100% virgin paper and 70% recycled content paper, across five key impact categories. The second goal of this study is to identify specific inputs and processes within virgin and recycled toilet paper production that contribute most to the overall environmental impact. Ultimately, the study will inform AquaTECH's strategy for technology development in wastewater treatment technologies.

1.2 Scope

This cradle-to-gate study considers forestry harvesting, energy generation, chemical production, transportation, and packaging as inputs to the 100% virgin toilet paper production system. The recycled paper production system accounts for waste paper collection and recycled paper inputs instead of forestry harvesting. Within the mill, virgin and recycled paper undergo almost identical processing steps, including pulp hydration, pressing, drying, whitewater treatment, wastewater treatment, and sludge disposal though the material and energy inputs may vary. Recycled paper has an additional step of de-inking waste paper, to remove ink from the pulp. The key process differences between virgin and recycled paper production are illustrated in Figure 1—recycled paper production includes the processes represented by blue and green boxes and virgin paper production includes the processes represented by blue and brown boxes.

Figure 1 Process flow diagram for virgin and recycled paper



1.2.1 Functional Unit

Cellox produces several types of tissue paper with varied composition of virgin fiber and recycled fiber. This study focuses on the comparison between two Cellox products:

- T1033: 100% virgin fiber which is composed of 60% sulphate pulp and 40% chemi-thermomechanical (CTM) pulp; and
- T1043[2]: 70% recycled fiber, 20% virgin fiber (with the same composition as T1033 above), and 10% broke (waste fiber).

The functional unit for the purposes of this study is 1000 kg (1 ton) of toilet paper with an absorbency of 15 g/m^2, which is an industry standard specification. Comparing T1033 and T1043 with the same density values will ensure consistency across both products' performance and functionality.

1.2.2 Impact Category Methodology

In this study, five key impact categories were analyzed:

- Climate change (kg CO_2-eq)
- Terrestrial acidification (kg SO_2-e)
- Freshwater eutrophication (kg P-e)
- Photochemical oxidant formation (kg NMVOC)
- Agricultural land occupation (m^2/yr)

The first four impact categories are required for all Environmental Product Declarations (EPD) for tissue paper products (EPD, 2013). The Product Category Rules (PCR) require monitoring and measurement of emissions that contribute to ground level ozone formation, and in this study, photochemical oxidant formation (POF) serves as an indicator. Since we suspect significant differences between the amount of land directly required for virgin and recycled paper production, agricultural land occupation (ALO) was also included for analysis.

[2] For the purposes of this study, T1043 was modeled with a composition of 77.8% recycled pulp, 13.8% sulphate pulp, and 8.9% chemi-thermomechanical (CTM) pulp, distributing the 10% broke fiber across the three pulp inputs proportionally.

2. Life Cycle Inventory

2.1 Introduction

The following section presents the inputs and outputs of the pulp and paper making processes. It is divided into the three unit processes developed for the three types of pulp inputs followed by unit processes developed for the two types of paper production. Whenever available, inventory data from Cellox provided via aquaTECH were used in our analysis. We verified or supplemented these data with Ecoinvent proxy models and the Energy and Environmental Profile of the U.S. Pulp and Paper Industry report (DOE, 2005).

Electricity consumption for all modeled unit processes is allocated by the three primary electricity sources in Thailand- natural gas (71%), coal (21%), and hydro (5) (U.S. EIA, 2013). Since no Ecoinvent databases existed for the environmental impacts electricity production in Thailand, UCTE (Union for Coordination of Transmission of Electricity) was determined to be an appropriate proxy. Remaining data were taken from comprehensive literature reviews and the paper and board chapter in Ecoinvent v.2.2. All inputs and outputs have been normalized for the production of 1 kg of toilet paper with similar functionality.

2.2 Pulp Production

Chemi-thermomechanical (CTM) Pulp Production

The Chemi-thermomechanical pulp, at plant/RER U was used as the basis for CTM pulp in Thailand. It was modified to reflect the electricity grid composition of Thailand and to include transportation distance from Vancouver to Bangkok.

Table 2 Pulp production- CTM pulp inputs

SimaPro Inputs	Input Descriptions	Input Amounts
Industrial residue wood, softwood, forest-debarked, u=70%, at plant/RER U	Ecoinvent v 2.2 unit processes	0.000967 m3
Chips, Scandinavian softwood (plant-debarked), u=70%, at plant/NORDEL U		0.00212 m3
EDTA, ethylenediaminetetraacetic acid, at plant/RER U		0.002 kg
Hydrogen peroxide, 50% in H2O, at plant/RER U		0.025 kg
Sodium silicate, spray powder 80%, at plant/RER U		0.019 kg
Sulphite, at plant/RER U		0.025 kg
Chemicals inorganic, at plant/GLO U		0.001 kg
Heavy fuel oil, burned in industrial furnace 1MW, non-modulating/RER U		0.675 MJ
Wood chips, from industry, softwood, burned in furnace 300kW/CH U		0.723 MJ
Natural gas, burned in industrial furnace >100kW/RER U		0.225 MJ
Transport, lorry >16t, fleet average/RER U		0.216 tkm
Transport, freight, rail/RER U		0.126 tkm
Electricity, natural gas, at power plant/UCTE U	Ecoinvent v 2.2 unit processes allocated by Thai electricity grid	1.37314 kWh
Electricity, hydropower, at power plant/GB U		0.15472 kWh
Electricity, hard coal, at power plant/UCTE U		0.40614 kWh

Table 3 CTM pulp emission to water

SimaPro Input	Input Description	Input Amounts
BOD5, Biological Oxygen Demand	BOD5 emitted to river	2.49 x 10^-3 kg
COD, Chemical Oxygen Demand	COD emitted to river	1.64 x 10^-2 kg
Nitrogen	Nitrogen emitted river	4.0 x 10^-4 kg
Phosphorus	Phosphorus emitted to river	1.0 x 10^-5 kg
Suspended solids, unspecified	Suspended solids emitted to river	9.6 x 10^-4 kg

Table 4 Pulp production: CTM pulp emission to air

SimaPro Input	Input Description	Input Amounts
Heat, waste	Heat emitted to air	6.95 MJ
Nitrogen oxides	Nitrogen oxide emitted to air	2.0 x 10^-4 kg
Sulfur dioxide	Sulfur dioxide emitted to air	1.0 x 10^-5 kg

Table 5 Pulp production: CTM pulp solid waste disposal

SimaPro Input	Input Description	Input Amounts
Disposal, wood ash mixture, pure, 0% water, to sanitary landfill/CHU	Disposal of wood ash mixture to sanitary landfill	4.03 x 10^-3 kg
Disposal, municipal solid waste, 22.9% water, to sanitary landfill/CH	Disposal of municipal solid waste to sanitary landfill	7.0 x 10^-4 kg
Disposal, plastics, mixture, 15.3% water, to municipal incineration/ CH U	Disposal of plastics to municipal incineration	4.54 x 10^-2 kg
Disposal, paper, 11.2% to municipal incineration/CH U	Disposal of paper to municipal incineration	1.44 x 10^-2 kg
Disposal, textiles, soiled, 25% water, to municipal incineration/ CH U	Disposal of textiles to municipal incineration	4.68 x 10^-3 kg
Disposal, wood untreated, 20% water, to municipal incineration/ CH	Disposal of untreated wood to municipal incineration	2.52 x 10^-3 kg
Disposal, steel, 0% water, to municipal incineration/CH U	Disposal of steel to sanitary landfill	5.04 x 10^-3

Sulphate Pulp Production

"Sulphate pulp, from eucalytuss ssp. (SFM), unbleached, at pulpmill/TH U" was used as the basis for sulphate pulp in Thailand. This unit process adjusts the parent unit process, Sulphate pulp, unbleached, at plant/RER U, for Thailand by showing transportation and energy credits within the subunit process. The subunit process was adjusted to reflect more precise information we obtained regarding the electricity grid.

Table 6 Sulphate pulp inputs

SimaPro Inputs	Input Descriptions	Input Amounts
Industrial residue wood, softwood, forest-debarked, u=70%, at plant/RER U	Ecoinvent v 2.2 unit processes	-0.000314 m3
Sulphate pulp, unbleached, at plant/RER U		1 kg
Transport, freight, rail/RER U		-0.0746 tkm
Transport, lorry >16t, fleet average/RER U		-0.002725 tkm
Industrial wood, hardwood, under bark, u=80%, at forest road/RER U		-0.000505 m3
Industrial wood, softwood, under bark, u=140%, at forest road/RER U		-0.000731 m3
Chips, Scandinavian softwood (plant-debarked), u=70%, at plant/NORDEL U		-0.000421 m3
Industrial wood, Scandinavian hardwood, under bark, u=80%, at forest road/NORDEL U		-0.000678 m3
Industrial wood, Scandinavian softwood, under bark, u=140%, at forest road/NORDEL U		-0.000981 m3
Roundwood, eucalyptus ssp. (SFM), under bark, u=50%, at forest road/TH U		0.0022667 m3
Electricity, hydropower, at power plant/GB U	Ecoinvent v 2.2 unit processes allocated by Thai electricity grid	0.03328 kWh
Electricity, natural gas, at power plant/UCTE U		0.29536 kWh
Electricity, hard coal, at power plant/UCTE U		0.08736 kWh
Electricity, medium voltage, production UCTE, at grid/UCTE U		-0.178 kWh
Electricity, medium voltage, production NORDEL, at grid/NORDEL U		-0.238 kWh

Table 7 Pulp production: Sulphate pulp emission to air

SimaPro Input	Input Description	Input Amounts
Carbon dioxide, biogenic	Carbon dioxide emitted to air	1.60 kg

Table 8 Pulp production: Sulphate pulp solid waste disposal

SimaPro Input	Input Description	Input Amounts
Disposal, municipal solid waste, 22.9% water, to sanitary landfill/CH U	Disposal of municipal solid waste to sanitary landfill	1.16 x 10^-3 kg
Disposal, plastics, mixture, 15.3% water, to municipal incineration/ CH U	Disposal of plastic mixture to sanitary landfill	-7.31 x 10^-4 kg
Disposal, paper, 11.2% to municipal incineration/CH U	Disposal of paper to sanitary landfill	-2.32 x 10^-4 kg
Disposal, textiles, soiled, 25% water, to municipal incineration/ CH U	Disposal of textiles to municipal incineration	-7.54 x 10^-5 kg
Disposal, wood untreated, 20% water, to municipal incineration/ CH U	Disposal of untreated wood to municipal incineration	-4.06 x 10^-5 kg
Disposal, steel, 0% water, to municipal incineration/CH U	Disposal of steel mixture to sanitary landfill	-8.12 x 10^-5 kg

Recycled Pulp Production

The recycled pulp unit process was modeled by subtracting proportional inputs associated with the "Kraft paper, bleached, at plant RER U" from the "Paper, recycling, with deinking, at plant RER U" unit process. Since the unit process for the Kraft paper is non-integrated and the recycled paper is an integrated process the difference should yield an approximation of pulp inputs. We then reviewed the inputs and removed any that were associated with packaging.

Table 9 Pulp Production: Recycled pulp inputs

SimaPro Input	Input Description	Input Amounts
Waste paper, mixed, from public collection, for further treatment/RER U	Deduction of two Ecoinvent 2.2. unit processes allocated by Thai elec grid. (see above)	0.587 kg
Waste paper, sorted, for further treatment/RER U		0.587 kg
Aluminium sulphate, powder, at plant/RER U		0.0159 kg
Hydrogen peroxide, 50% in H2O, at plant/RER U		0.0211 kg
Sodium silicate, spray powder 80%, at plant/RER U		0.0125 kg
Sodium hydroxide, 50% in H2O, production mix, at plant/RER U		0.0157 kg
Chemicals inorganic, at plant/GLO U		0.0074 kg
Rosin size, in paper production, at plant/RER U		0.0245 kg
Electricity, natural gas, at power plant/UCTE U	Deduction of two Ecoinvent 2.2. unit processes allocated by Thai elec grid. (see above)	0.2221164 kWh
Electricity, hard coal, at power plant/UCTE U		0.0656964 kWh
Electricity, hydropower, at power plant/GB U		0.0250272 kWh
Heavy fuel oil, burned in industrial furnace 1MW, non-modulating/RER U	Deduction of two Ecoinvent 2.2. unit processes	0.07216 MJ
Light fuel oil, burned in industrial furnace 1MW, non-modulating/RER U		0.07216 MJ
Natural gas, burned in industrial furnace >100kW/RER U		0.7458 MJ
Hard coal, burned in industrial furnace 1-10MW/RER U		0.1705 MJ
Transport, lorry >16t, fleet average/RER U		0.0248 tkm
Transport, freight, rail/RER U		0 tkm
Electricity, nuclear, at power plant boiling water reactor/UCTE U		0 kWh

Table 10 Recycled pulp emission to air

SimaPro Input	Input Description	Input Amounts
Heat, waste	Ecoinvent v 2.2 unit process	2.84 MJ

Table 11 Recycled pulp emission to water

SimaPro Input	Input Description	Input Amounts
BOD5, Biological Oxygen Demand	Ecoinvent v 2.2 unit process	4.10 x 10^-4 kg
COD, Chemical Oxygen Demand		1.74 x 10^-3 kg
TOC, Total organic carbon		1.05 x 10^02 kg
Nitrogen		2.10 x 10^-4 kg
Phosphorus		3.06 x 10^-6 kg
Suspended solids, unspecified		7.95 x 10^- kg

Table 12 Recycled pulp solid waste disposal

SimaPro Input	Input Description	Input Amounts
Disposal, wood ash mixture, pure, 0% water, to sanitary landfill/CHU	Ecoinvent v 2.2 unit process	6.28 x 10^-1 kg
Disposal, municipal solid waste, 22.9% water, to sanitary landfill/CH U		1.39 x 10^-3 kg
Disposal, ash from deinking sludge, 0% water, to residual material landfill/ CH U		7.78 x 10^-2 kg
Disposal, plastics, mixture, 15.3% water, to municipal incineration/ CH U		4.50 x 10^-3 kg
Disposal, paper, 11.2% water, to municipal incineration/CH U		1.43 x 10^-3 kg
Disposal, textiles, soiled, 25% water, to municipal incineration/ CH U		4.64 x 10^-4 kg
Disposal, wood untreated, 20% water, to municipal incineration/ CH U		2.50 x 10^-4 kg
Disposal, steel, 0% water, to municipal incineration/CH U		5.00 x 10^-4 kg
Disposal, hazardous waste, 0% water, to underground deposit/DE U		1.20 x 10^-4 kg

2.3 Toilet Paper Production

The following tables reflect the inputs for 100% virgin toilet paper production and 70% recycled toilet paper production. All inputs have been normalized for the amount required for 1 kg output. Each type of toilet paper was modeled according to a specific pulp composition (see Section 1.2.1). 1.2 kg of pulp is required for virgin tissue production and 1.3 kg of pulp is required for recycled paper production (aquaTECH).

Table 13 Paper production: pulp inputs

SimaPro Input	Input Description	Input Amount for virgin paper	Input amount for recycled paper
_Chemi-thermochemical pulp, at plant/RER U; adjusted transport	From modeled pulp (see above)	1.2 x 0.4=0.48 kg	1.3 x 0.222*0.4 =1.15 x 10^-1 kg
Sulphate pulp, from eucalyptus ssp, (SFM), unbleached, at pulp-mill/ TH U		1.2 x 0.6 = 0.72 kg	1.3 x 0.222*0.6=1.73 x 10^-1 kg
_Recycled pulp with deinking at plant; based on paper, recycling, with deinking, at plant/RER		NA	1.3 x 0.778*=1.01 kg

Table 14 Paper production: Transport of pulp to paper mill[3]

CTM Pulp used at Cellox comes from Vancouver Canada. The distance from Vancouver to Bangkok is 13071 km. Sulphate and recycled pulp travel approximately 140 km from the pulp mill to the paper mill (aquaTECH).

SimaPro Input	Input Description	Input Amount for virgin paper	Input amount for recycled paper
Transport, transoceanic freight ship/OCE U	*Distance x kg pulp Ecoinvent v2.2 unit process*	*13,071 x 0.4 = 5.23 x 10^3 kgkm*	*13,071 x 0.222*.4 = 1.16 x 10^3 kgkm*
Transport, lorry > 16 ft, fleet average/RER U	*Distance x kg pulp Ecoinvent v2.2 unit process*	*140 x 0.6 =84 kgkm*	*(140 x 0.778) +(140*.222*.6) =128 kgkm*

[3] Transportation inputs for the Canadian chemi-thermochemical pulp were calculated using the distance from Vancouver to Bangkok (13071 km) by ship and the distance from the eucalyptus plantation to the pulp mill (50 km) by transport lorry for the Thai sulphate pulp.

Table 15 Paper production: water use

In both the virgin and recycled paper production, water is used to hydrate the pulp and to produce steam to dry the paper. The water inputs were based on data provided by aquaTECH.

SimaPro Input	Input Description	Input Amount for virgin paper	Input amount for recycled paper
Water, unspecified natural origin/m3	Ecoinvent v2.2 unit process	6.0 x 10^-3 m^3	7.25 x 10^-3 m^3

Table 16 Paper production: electricity use

Electricity is used to pump the pulp and water and to operate the machines. Electricity consumption data (measured in kWh) was provided by Cellox through aquaTECH. The consumption is then allocated by the three primary electricity sources in Thailand- natural gas (71%), coal (21%), and hydro (5) **(U.S. EIA, 2013)**. Since no Ecoinvent databases exist for the environmental impacts of electricity production in Thailand, the Union for Coordination of Transmission of Electricity (UCTE) standards based on average European data were determined to be an appropriate proxy. Figure 2 shows the electricity and thermal inputs based on data from separated virgin and recycled tissue paper production trials within Cellox.

SimaPro Input	Input Description	Input Amount for virgin paper	Input amount for recycled paper
Electricity, hydropower, at power plant/UCTE U	kWh x percentage Thai electricity grid % Ecoinvent v2.2 unit process	0.9246*0.08 = 7.54 x 10^-2 kWh	0.997*0.08 = 7.98 x 10^-2 kWh
Electricity, natural gas, at power plant/UCTE U		0.9246*0.71 = 6.99 x 10^-1 kWh	0.997*0.71 = 7.08 x 10^-1 kWh
Electricity, hard coal, at power plant/UCTE U		0.9246*0.21 = 1.98 x 10^-1 kWh	0.997*0.21 = 2.09 x 10^-1 kWh

Figure 2 Comparing energy inputs for virgin and recycled paper making process

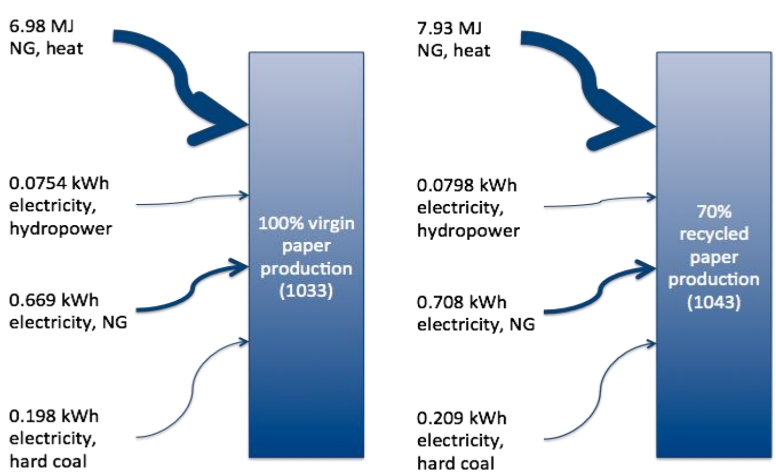


Table 17 Paper production: maintenance

During paper making process, tissue machines form paper web between wire and felt. When pulp leaves the headbox, it is distributed on a wire mesh screen. The screen allows water to be filtered out while retaining the fiber. We assumed that the felt weighs 8 kg (64 ft^3) with a density of ⅛ lb/ft^3), and that the felt is composed of polyester resin and weighs 593 kg (436 ft^3) with a density of 3 lbs/ft^3) based on dimension observed from an Massachusetts-based paper mill (Erving Paper Mill). The amount of felt and wire required for 1 kg of paper was determined by manipulating the mass by the replacement frequency and the amount of paper produced before being changed.

The blade used for creping paper after it leaves the Yankee Dryer, is assumed to be composed of stainless steel and estimated to be replaced every 8 hours. Xylene, a chemical in tissue processing, is used for maintenance purpose. We calculated the amount of xylene used per kg of paper based on the amount of xylene consumed and the amount of paper produced per day. The materials used for maintenance were reflected using the following proxy unit processes.

SimaPro Input	Input Description	Input Amounts for virgin paper	Input Amounts for recycled paper
Xylene, at plant/RER U	Ecoinvent v2.2 unit process	8.62 x 10^-4 kg	1.05 x 10^-3 kg
Polyamide 6.6 fibres (PA 6.6), from adipic avid and hexmethylene diamine (HMDA)		2.26 x 10^-5 kg	3.56 x 10^-5 kg
Polyester resin, unsaturated, at plant/RER U		1.20 x 10^-4 kg	2.01 x 10^-4 kg
Stainless steel hot rolled coil, annealed & pickled, elec. Arc furnace rout, prod. Mix, grade 3		1.74 x 10^-6 kg	2.68 x 10^-6 kg
Dummy_Lube oil, at plant/US		4.3 x 10^-5 kg	4.41 x 10^-5 kg

AquaTECH explained the following chemicals being used in the papermaking process:

- PAC (Polyaluminium Chloride): coagulant agent to filter water for re-use
- Sodium hydroxide: used in the separation of cellulose fibers from lignin
- Volatile amines: used for corrosion control in the boiler
- Antiscalant: prevents the buildup of calcium carbonate
- Sodium meta bisulfide: used for bleaching

The only chemical with an associated unit process in the Ecoinvent databases was sodium hydroxide. As such the other chemicals are characterized using the "Chemicals, inorganic" Ecoinvent unit process as a proxy. The concentrations of chemicals used per kg of toiler paper were calculated based on the amount of chemicals used per day and the amount of paper produced per day at Cellox (aquaTECH).

Table 18 Paper production: chemical additives

SimaPro Input	Input Description	Input Amounts for virgin paper	Input Amounts for recycled paper
Sodium hydroxide, 50% in H20, production mix, at plant/ RER U	Ecoinvent v2.2 unit process	0.075 g	0.075 g
Chemicals inorganic, at plant/GLO U		0.0031 kg	0.0031 kg

Whitewater that is not reused for the papermaking process is then treated at an internal wastewater treatment facility, prior to being discharged. The Ecoinvent unit process for the treatment of soft fibreboard at a class 3 plant was used to represent the environmental impacts of the treatment process. This type of treatment facility and the waste material proxies are representative of the level of wastewater treatment that would occur at Cellox. The quantity of water discharged per kg of paper produced comes from aquaTECH.

Table 19 Paper production: solid waste disposal

SimaPro Input	Input Description	Input Amounts for virgin paper	Input Amounts for recycled paper
Treatment, soft fibreboard production effluent, to wastewater treatment, class 3/CHU	Ecoinvent v2.2 database	4.5/1000=4.5 x 10^-3 m^3	5.5/1000=5.5 x 10^-3 m^3

3. Interpretation of Impact Assessment Results

This study analyzed the impacts of five key impact categories according to ReCiPe Midpoint (H) V1.10. ReCiPe was selected over other impact assessments since it contains all impact categories required by the PCR and allows for normalization of results using worldwide, versus European or North American. Impacts were calculated at the midpoints, or the point where disparate flows can be characterized using a standard unit and grouped into environmental impact category. Since aquaTECH is most interested in understanding the tradeoffs between different types of tissue and environmental processes, instead of the downstream effects on humans, the ReCiPe midpoint method was selected over the endpoint method. Finally, the normalization, or the relative comparison of impacts among each other, was based using the hierarchic perspective. This perspective accounts for impacts over a 100-year period instead of a 20 or 500-year timeframe, which has less consensus (Goedkoop, et al., 2013).

The first part of this impact assessment assesses the impacts for 100% virgin when compared 70% recycled toilet tissue for the five impact categories. Impacts for both tissue types are summarized in Table 20.

Table 20 Comparison of virgin versus recycled toilet tissue environmental impacts

Impact Category	Unit	100% Virgin	70% Recycled	Change from Virgin to Recycled
Climate change	kg CO_2 eq/kg	2361.9	2111.7	-11%
Terrestrial acidification	kg SO_2 eq/kg	8	5	-32%
Freshwater eutrophication	kg P eq/kg	0.4	0.3	-12%
Photochemical oxidant formation	kg NMVOC	6	5	-24%
Agricultural land occupation	m^2/yr	989	296	-70%

3.1 Climate Change

Virgin toilet paper has a slightly higher global warming potential (GWP) than recycled toilet paper. The largest subunit emission variance between the two types of paper comes from the "Natural gas, burned in power plant/UCTE U" unit process. Though the amount of energy consumed during paper production (post-pulping process) is slightly higher for recycled tissue than virgin, the amount of electricity required during the pulping stages is higher for the sulphate pupl and chemi-thermal mechanical (CMP) pulp, which comprise virgin toilet paper.

3.2 Terrestrial Acidification

Terrestrial acidification impacts the acidity of soils, which can hinder plant growth or change the biotic composition of an ecosystem. The emissions contributing to acidification are sulfur dioxide, nitrogen oxides and ammonia; these emissions are more prevalent within virgin tissue production. Sulphate pulping accounts for less than half of all SO_2-e emissions. Ecoinvent reports show sulphuric acid, sodium sulphate, and liquid sulphur dioxide inputs associated with sulphate pulp production; these inputs are not found in the recycled pulp model used in this study.

3.3 Freshwater Eutrophication

Eutrophication is a process that results from excessive phosphorus and increased algal growth, which decreases levels of dissolved oxygen in in freshwater bodies. Virgin tissue has a slightly higher eutrophication potential than recycled paper. The largest contribution to eutrophication comes from the disposal of spoils from coal mining, which contain phosphorus. Since coal comprises 21% of the Thai electricity grid (EIA, 2013), coal mining would be found in the background of both tissue paper processes. Similar to the rationale for virgin having a higher climate change potential, virgin paper has a higher eutrophication potential given the positive net energy consumption of virgin paper.

3.4 Photochemical Oxidant Formation (ground level ozone creation)

Ground level ozone is created in the presence of non-methane volatile organic compounds (NMVOCs). Virgin paper has a higher photochemical oxidant formation potential from increased sulphate pulp composition and the shipment of pulp via ocean freight. Sulphate pulp production and fuel oil consumed during transoceanic shipping results in emissions of nitrogen oxides, sulfur dioxide and carbon dioxide.

3.5 Agricultural Land Occupation

Virgin toilet paper production requires approximately 989 m^2 of land per year for the production of one tonnage of toilet paper compared to 296 m^2/yr for recycled toilet paper production. The land for virgin toilet paper production is occupied by trees, which will be used for fiber production.

3.6 Normalization of Results across Impact Categories

Independent comparison of the two papers does not however, indicate what categories have the highest impacts. Normalizing results can merely provide a comparison. The ReCiPe impact assessment normalizes impact category results by dividing the emissions from the product by the total worldwide emissions for the base year 2000 and then scales the results so they are comparable (Goedkoop, et al., 2013). Figure 3 normalizes the five impact categories using the ReCiPe midpoint (H) worldwide perspective.

Normalization is based on a number of assumptions and should not be used for making policy or sensitive management issues without further exploration. However, normalized results show that eutrophication has a relatively higher level of impact than does agricultural land transformation. This suggests that more effort to transition from coal or reduce phosphorus loadings in coal mining tailings would have a greater environmental benefit than would occupying less land for timber production.

When evaluating the merits of virgin versus recycled toilet paper based on the five established impact categories, virgin toilet paper is preferable. However, it should be noted that virgin is not least preferable for all environmental parameters. Figure 4 shows normalized and comparative results for virgin and recycled toilet paper for 18 impact categories. Recycled paper is preferable when comparing impacts associated with toxicity (marine, freshwater and human). Emissions of heavy metals to water and air result in high toxicity to these impact categories. Ash from incineration of sludge and other byproducts at pulp mills for energy is the primary pathway through which toxins are emitted to water and air. The Ecoinvent databases used for pulp inputs and outputs show higher amounts of fiber feedstock and fiber, waste byproduct (non-fiber material in sorted paper bales) and sludge for recycled paper resulting in higher toxicity levels (Hischier, 2007).

Figure 3 Normalized comparison of virgin and recycled toilet paper for five impact categories

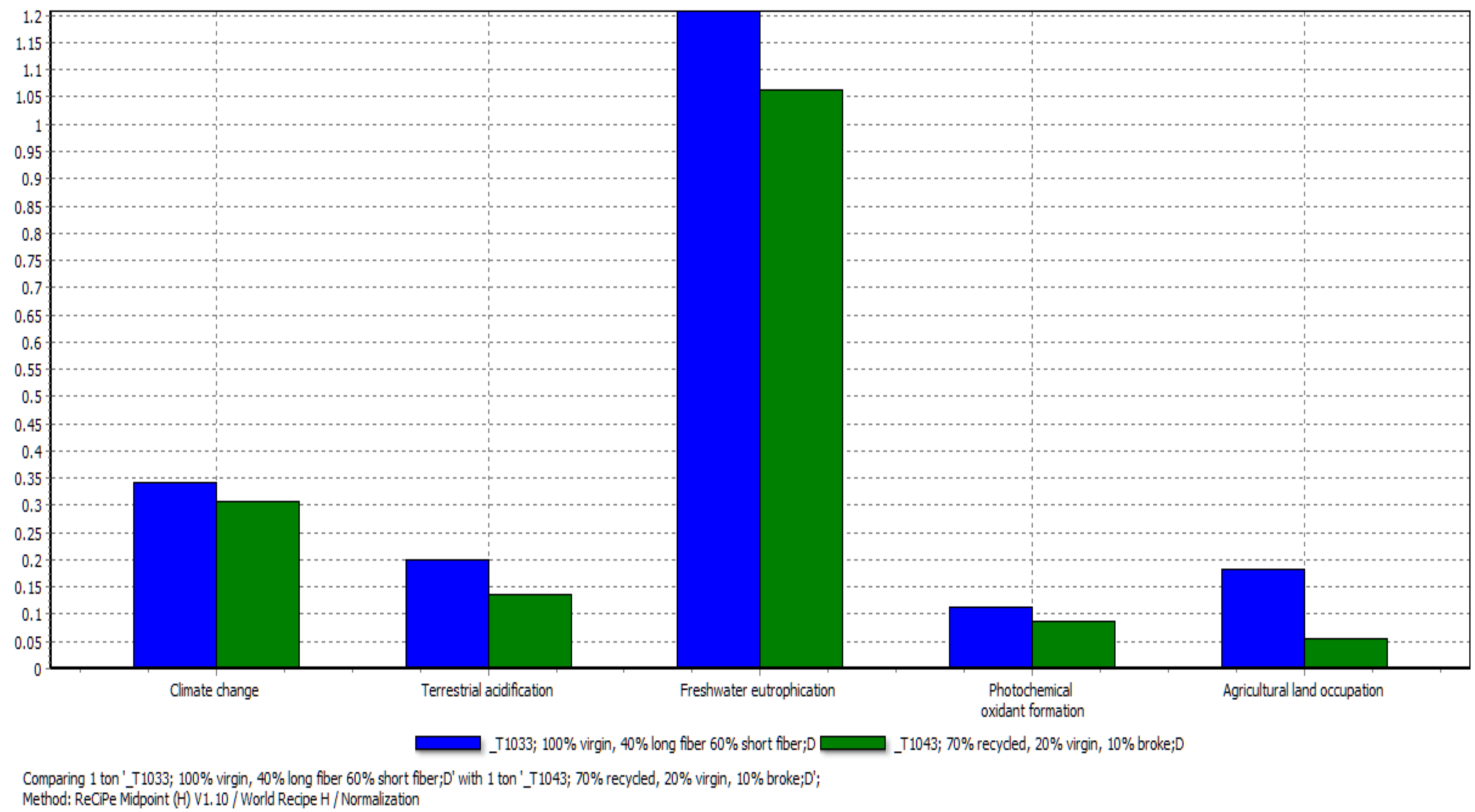
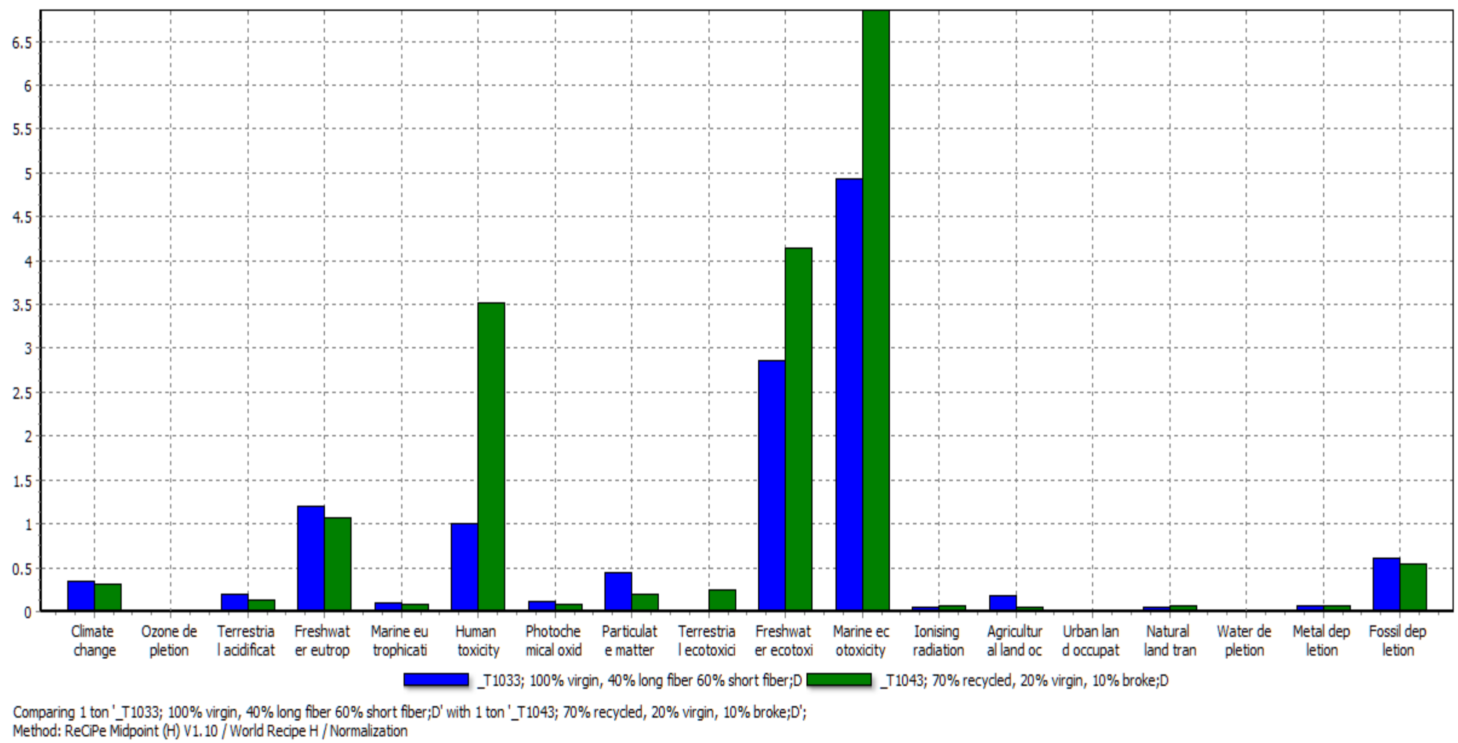
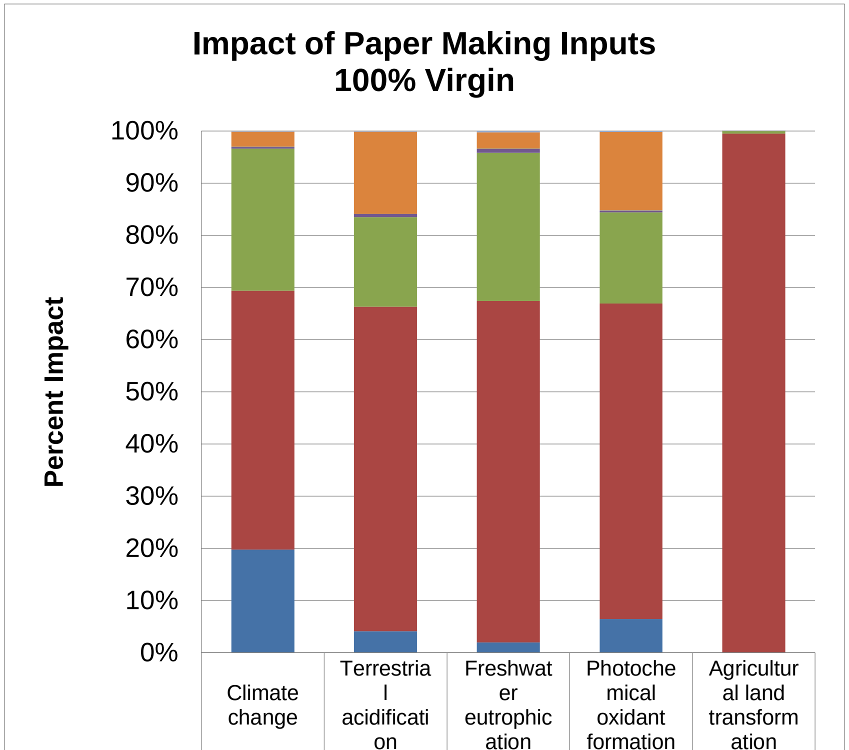


Figure 4 Normalized comparison of virgin and recycled toilet paper for all ReCiPe impact categories



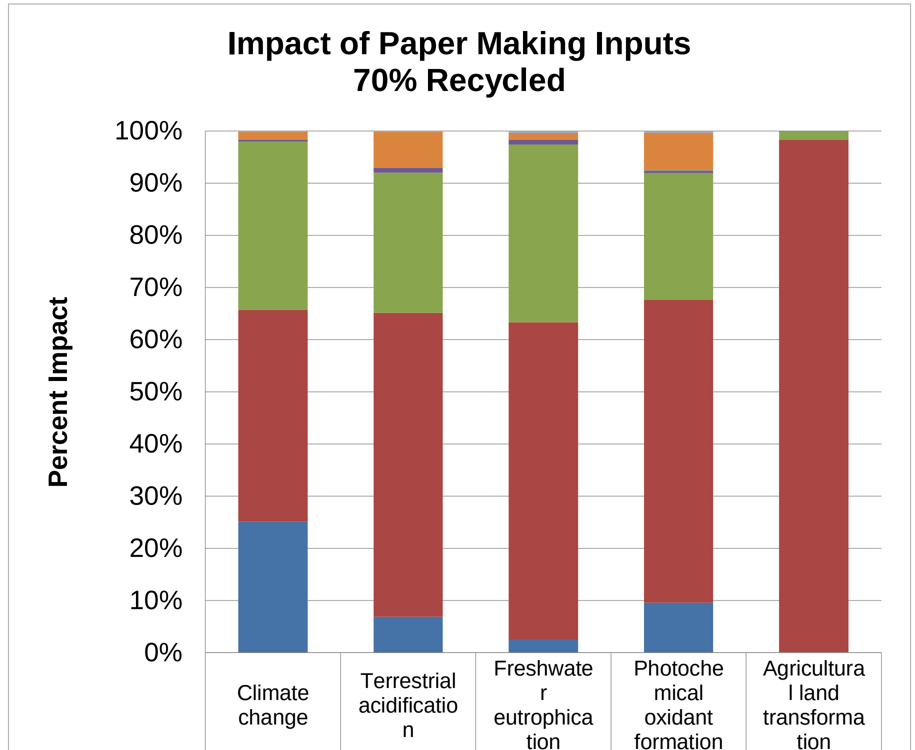
Exclusive of the comparative impacts of virgin and waste papers in general, specific unit processes for each paper type may have more of an impact on overall environmental impact of the production process. Table 21 and Figures 5 and 6 (see below) illustrate the principle input categories for the production of toilet paper. Each input reflects environmental impacts from sub-unit unit processes. For example, pulp would include impacts from electricity, heat fuel and harvesting of timber/collection of waste paper that goes into its production. Electricity, heat fuel and the other categories listed explicitly here reflect the inputs exclusively during the paper making stage.

Figure 5 Impact of virgin paper making inputs



	Climate change	Terrestrial acidification	Freshwater eutrophication	Photochemical oxidant formation	Agricultural land transformation
Treatment	0%	0%	0%	0%	0%
Transport	3%	16%	3%	15%	0%
Maintenance	0%	0%	0%	0%	0%
Chemicals	0%	1%	1%	0%	0%
Electricity	27%	17%	28%	17%	0%
Pulp	50%	62%	65%	61%	99%
Heat Fuel	20%	4%	2%	6%	0%

Figure 6 Impact of recycled paper inputs



	Climate change	Terrestrial acidification	Freshwater eutrophication	Photochemical oxidant formation	Agricultural land transformation
Treatment	0%	0%	0%	0%	0%
Transport	1%	7%	1%	7%	0%
Maintenance	0%	0%	0%	0%	0%
Chemicals	0%	1%	1%	0%	0%
Electricity	32%	27%	34%	24%	2%
Pulp	41%	58%	61%	58%	98%
Heat Fuel	25%	7%	3%	10%	0%

Table 21 Recycled and virgin toilet paper environmental impacts by paper making input

Input	Climate change		Terrestrial acidification		Freshwater eutrophication		Photochemical oxidant formation		Agricultural land transformation	
	kg CO_2 eq/kg		kg SO_2 eq/kg		kg P eq/kg		kg NMVOC		m^2/yr	
	Virgin	Recycled	Virgin	Recycled	Virgin	Recycled	Virgin	Recycled	Virgin	Recycled
Heat Fuel	467.14	530.72	0.31	0.36	0.01	0.01	0.42	0.48	0.16	0.18
Pulp	1171.75	856.36	4.76	3.01	0.23	0.19	3.93	2.87	984.26	290.65
Electricity	643.65	681.13	1.31	1.39	0.10	0.11	1.14	1.20	4.66	4.93
Chemicals	7.25	7.47	0.05	0.05	0.00	0.00	0.02	0.02	0.11	0.11
Maintenance	1.15	1.90	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01
Transport	67.21	29.42	1.20	0.35	0.01	0.00	0.98	0.36	0.20	0.10
Treatment	3.81	4.65	0.01	0.01	0.00	0.00	0.01	0.02	0.03	0.04
Total	2361.95	2111.65	7.64	5.17	0.35	0.31	6.50	4.94	989.43	296.02

3.6.1 Pulp

Figures 5 and 6 illustrated above show that the upstream pulping process accounts for at least 50% of the impacts for most impact categories. Though the tissue paper PCR does not require separation of processes upstream of the core processes (PCR Section 11.3.1) we have disaggregated the key processes in Table 22 considering the significant impacts of pulp for the climate change impact category.

Table 22 Greenhouse gas contributions by upstream pulping inputs by pulp type[4]

Input	Recycled Pulp	CTM Pulp	Sulphate Pulp
Electricity at pulp mill	38%	79%	41%
Heat at pulp mill	13%	4%	4%
Waste paper sorting	6%	NA.	NA.
Waste paper collection	14%	NA.	NA.
Rosin sizing production	7%	NA.	NA.
NaOH Production	6%	NA.	NA.
Chemicals inorganic	NA.	NA.	7%
Wood harvesting	NA.	NA.	9%
Transport	NA.	NA.	6%
Other	17%	17%	33%
Total	100%	100%	100%

The greenhouse gases from the primary upstream processes for recycled and sulphate pulp are comparable. Twenty percent of greenhouse gases from in the recycled pulping process originate from the waste paper collecting for recycled paper and 15% are associated with wood harvesting and transportation to the pulp mill for sulphate pulp. As the fiber for CTM pulp in the Ecoinvent reports come from industrial byproducts and CTM Pulp consumes more energy than other types of pulps there are few GHGs attributed to wood harvesting for CTM pulp.

Pulping makes up approximately 100% of the impact for ALO for both virgin and recycled paper. The impacts for virgin are associated with timber production. Furthermore, 84% of ALO for the 70% recycled paper is associated with timber production. The remaining 16% (50 m^2/year) balance however is attributed to space needed to harvest palm oil that is used to make rosin, or soap, which can be used as a de-inker in the recycled pulping process.

3.6.2 Electricity and Heat Fuel (Energy)

Electricity used for pumping the pulp and operating the machines in Cellox and fuel used to generate steam to dry the toilet paper are the second and third highest impact categories for both virgin and recycled paper and will be discussed in more detail in the sensitivity analysis.

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[4] This is according to a 3-5% cutoff when allocating contributions.

4. Sensitivity Analysis

Sensitivity analyses were conducted to assess the importance of select data, uncertainties within data, and to determine how local inputs reduce environmental impact. The parameters were varied based on likely substitutes to model conditions at a different mill.

4.1 Chemicals: Doubling of Inputs

As explained in 2.4.4, we were most uncertain on the composition and mass of chemical inputs in addition to the frequency of maintenance and material replacement. We were uncertain of the chemical inputs for bleaching and delignification as well as the composition and mass of felt and wire. To understand the impact of these uncertainties, we doubled the estimated quantities for each of the above inputs. The results show no significant change if chemical and maintenance inputs are doubled.

Table 23 Sensitivity analysis for chemical inputs

Impact Category	Unit	Recycled		Virgin		Change to Doubling of Chemicals	
		Forecasted	2x	Forecasted	2x	Forecasted	2x
Climate change	kg CO_2 eq/kg	2111.7	2119.5	2361.9	2368.9	0%	0%
Terrestrial acidification	kg SO_2 eq/kg	5	5	8	8	1%	1%
Freshwater eutrophication	kg P eq/kg	0.3	0.3	0.4	0.4	1%	1%
Photochemical oxidant formation	kg NMVOC	5	5	6	7	0%	0%
Agricultural land occupation	m^2/yr	296	296	989	990	0%	0%

4.2 Pulping Agent: Rosin vs. no-Rosin

The pulping process has a significant impact on all five key impact categories, and has an especially large impact on AOL for both virgin and recycled toilet paper. Though there is some virgin pulp in the 70% recycled pulp product, which would account for a large portion of the ALO, recycled pulp accounts for 50 m^2/yr. The Ecoinvent database reveals that rosin, a de-inking agent, can be palm oil-based, which contributes to a large impact on AOL. It is unclear whether Cellox uses rosin as a principle de-inking agent, or the extent to which other palm oil products are used in the de-inking process. This clarification requires further investigation. We have chosen to model whether there would be any changes in the impact categories if rosin were not used as a de-inking agent in recycled pulp production. When rosin is removed as a de-inking agent the ALO potential decreases by 17%. A simulation of just virgin pulp would show a 100% decrease in this impact category when rosin is removed.

Table 24 Sensitivity analysis for pulping agent

Impact Category	Unit	Recycled		Virgin	Change
		Rosin	No Rosin		Rosin --> No Rosin
Climate change	kg CO_2 eq/kg	2111.7	2073.9	2361.9	-2%
Terrestrial acidification	kg SO_2 eq/kg	5.2	5.0	7.6	-3%
Freshwater eutrophication	kg P eq/kg	0.3	0.3	0.4	-5%
Photochemical oxidant formation	kg NMVOC	4.9	4.8	6.5	-4%
Agricultural land occupation	m^2/yr	296.0	0.0	989.4	-100%

4.3 Heating Fuel: Natural gas vs. Fuel oil

The most common sources of fuel to generate heat in the papermaking process are natural gas and fuel oil. Cellox uses a natural gas boiler to generate heat for the paper drying process. The "Heat, natural gas, at boiler condensing modulating >100kW/RER/U" unit process was used to represent the heat input for the Cellox mill. Considering other mills may use fuel oil as a heat source we reran the paper making processes using "Heat, light fuel oil, at boiler 100Kw condensing, non-modulating/CH U" as an alternative.

Table 25 Sensitivity analysis for heating fuel

Impact Category	Unit	Recycled		Virgin		Change from Natural Gas and Fuel Oil	
		Natural Gas	Oil	Natural Gas	Oil	Recycled	Virgin
Climate change	kg CO_2 eq/kg	2111.7	2283.4	2361.9	2513.0	8%	6%
Terrestrial acidification	kg SO_2 eq/kg	5	6	8	9	19%	11%
Freshwater eutrophication	kg P eq/kg	0.3	0.3	0.4	0.4	4%	3%
Photochemical oxidant formation	kg NMVOC	5	6	6	7	13%	9%
Agricultural land occupation	m^2/yr	296	296	989	990	0%	0%

This analysis reveals that the heating fuel has a higher impact on four of the five key impact categories. Converting from natural gas to fuel oil most significantly increases terrestrial acidification and photochemical oxidant formation for both virgin and recycled materials and to a lesser extent freshwater eutrophication, climate change and agricultural land transformation.

4.4 Energy Source: Thai Grid vs. Massachusetts Grid

The second largest input into the papermaking process is electricity used to pump water and pulp throughout the mill and support machines. As we visited the Everett Paper Mill in Everett, MA which produces recycled toilet tissue, we modeled how impacts would vary the composition of the Thai electricity grid was replaced with the composition of the MA grid (EIA, 2014). The main differences between the Thai electricity grid and the Massachusetts grid is the use of coal in the former and nuclear power in the former. Figure 7 presents the comparative results for altering electricity grid.

Figure 7 Electricity Grid Composition Thailand vs. MA. USA

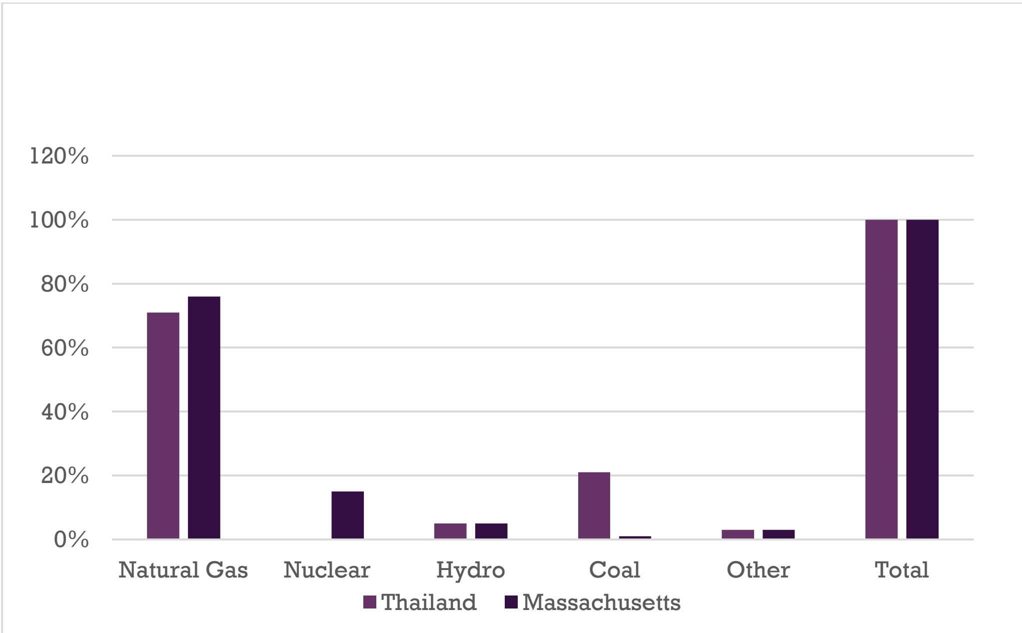


Table 26 Sensitivity analysis for electricity grid composition

Impact Category	Unit	Recycled		Virgin		Thailand to Massachusetts	
		Thailand	MA	Thailand	MA	Thailand	MA
Climate change	kg CO_2 eq/kg	2111.7	1818.1	2361.9	1965.8	-14%	-17%
Terrestrial acidification	kg SO_2 eq/kg	5	4	8	6	-27%	-25%
Freshwater eutrophication	kg P eq/kg	0.3	0.2	0.4	0.1	-51%	-60%
Photochemical oxidant formation	kg NMVOC	5	4	6	5	-15%	-16%
Agricultural land occupation	m^2/yr	296	289	989	980	-2%	-1%

The negative environmental impacts of electricity use can be mitigated with an electricity grid composition more similar to MA, specifically in substituting nuclear energy for coal. The most significant impact category decrease in freshwater eutrophication can be attributed to the disposal of coal ash and tailings. These substances as discussed in the impact assessment section contain phosphorus, which can lead to eutrophication.

4.5 Proximity of Inputs: Transcontinental vs. Continental Pulp

Much of the environmental discourse focuses on the proximity of inputs of a product to the place where that product is manufactured and consumed. Though transportation did not have a significant impact (see Table 32 below) in order to see whether or not the proximity of inputs would vary results, we varied the distance pulp would travel to Cellox. Similarly, though we were able to obtain reasonable distances between the pulp mills and the paper mill, these are not reflective of the distances for other factories. As such we have assessed the variance of the four impact categories when the distances are altered based on the two scenarios below:

Table 27 Sensitivity analysis for transportation distance

Impact Category	Unit	Existing Imported CTMP 13071KM; Local Recycled and Sulphate Pulp 140 KM		Modified Imported CTM Pulp 500 KM Local Recycled and Suplhate Pulp 50 KM		Change from Longer to Shorter	
		Recycled	Virgin	Recycled	Virgin	Recycled	Virgin
Climate change	kg CO_2 eq/kg	2,111.7	2,361.9	2,088.9	2,300.9	-1%	-3%
Terrestrial acidification	kg SO_2 eq/kg	5.2	7.6	4.9	6.5	-6%	-15%
Freshwater eutrophication	kg P eq/kg	0.3	0.4	0.3	0.3	-1%	-3%
Photochemical oxidant formation	kg NMVOC	4.9	6.5	4.7	5.6	-6%	-14%
Agricultural land occupation	m^2/yr	296.0	989.4	295.9	989.3	0%	0%

The varying distances have little effect on CC, FE, and ALO. However, there are larger impacts on TA and POF. We see the biggest impacts on virgin pulp, composed of a relatively higher contraction of CTM pulp. The CTM pulp travels from Vancouver to Thailand in virgin tissue (40%) versus recycled tissue (8%). As explained in the impact assessment section, the emissions of nitrogen and sulfur oxides from the consumption of heavy fuel oil in the "Operation, transoceanic freight ship/OCE U" unit process impact acidification and photochemical oxidant formation.

5. Conclusions and Recommendations

It has been long argued that use of waste paper in recycled content toilet paper production has the potential to offset deforestation impacts from virgin forest harvesting. The results of this study conclude that despite significant trade-offs between the production of virgin and recycled toilet paper, recycled toilet paper is still the environmentally preferable option. For all five the impact categories considered- climate change (CC), freshwater eutrophication (FE), photochemical oxidant formation (POF), terrestrial acidification (TA), and agricultural land occupation (ALO)- virgin paper production has a larger environmental impact: CC by 56% TA by 32%, FE by 12%, POF by 24%, and ALO by 70%. The inputs with the largest overall impact are: pulp, heat fuel, and electricity. Pulp production for both virgin and recycled toilet paper is responsible for approximately 50% of overall environmental impact.

An overarching finding across all five impact categories is the significance of the composition of electricity generation sources. Replacing coal power plants with other energy generation sources, such as nuclear, can reduce CC impacts for both recycled and virgin fibres by 14% and 17% respectively, reduce TA impact by 27% and 25%, reduce FE by 51% and 60%, reduce POF by 15% and 16%, and reduce ALO by 2% and 1%.

For each of the impact categories:

Virgin toilet paper has a slightly higher (11%) global warming potential (GWP) than recycled paper. Energy consumed during paper production is slightly higher for recycled fiber. Virgin fiber pulping process requires a much higher amount of electricity.

Virgin toilet paper has a higher (32%) TA impact than recycled paper. Emissions contributing to acidification mainly come from sulfur dioxide, nitrogen oxides, and ammonia, which are more relevant for virgin tissue production. Sulphate pulping, accounting for slightly less than half of all SO_2-e emissions, is the largest contributor to TA.

Virgin tissue has a slightly higher (12%) FE potential than recycled paper. The largest contribution to eutrophication comes from the disposal of spoils from coal mining, which contain phosphorus. Considering that coal comprises 21% of the Thai electricity grid (EIA, 2013), coal mining would be found in the background of both tissue paper processes. This again points towards the significance of electricity source composition to all impact categories.

Virgin paper has a higher (24%) POF potential from increased sulphate pulp composition and transportation of pulp via ocean freight. Our sensitivity analysis shows that transportation distance does not play a significant role for any of the five key impact categories (see 4.5 for detail). This conclusion confirms that emissions of nitrogen oxides, sulfur dioxide and carbon dioxide from sulphate pulp production and bunker fuel consumption contribute greatly to the POF impact category.

Virgin toilet paper production requires approximately 70% more ALO area than recycled paper. This is based on the assumption that land for virgin toilet paper production is occupied by trees, which will be used for fiber production. The much higher impact for virgin toilet paper results from the use of rosin- a palm oil-based soap. These results may change depending on whether rosin is used by Cellox and the extent to which palm oil products are used in the industry.

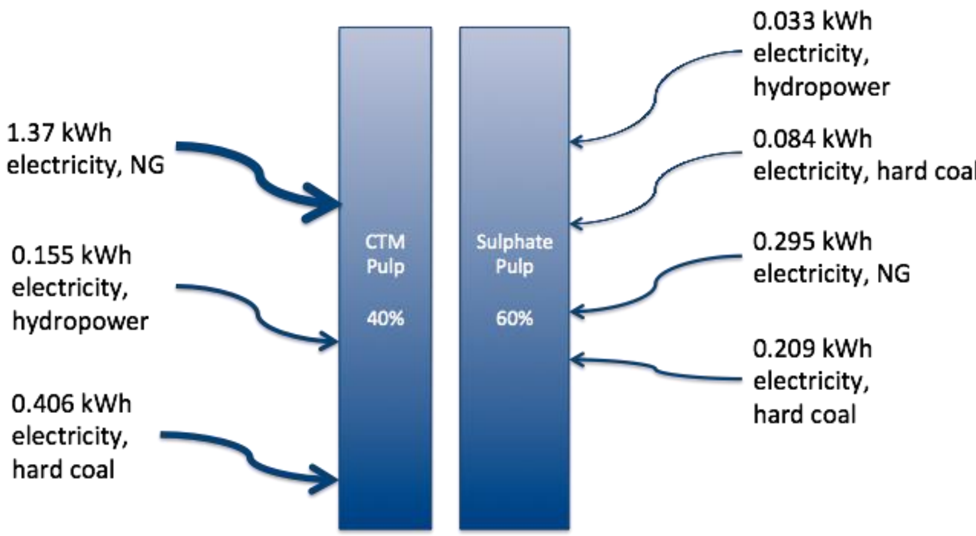
Though the study has been conducted with significant precision, there are a few limitations to acknowledge: this study is designed to model paper production for a specific case study—a non-integrated paper mill in Thailand (Cellox). Cellox data (provided via AquaTECH) were used for modeling; however, this study recognizes several assumptions were made regarding process efficiencies associated with electricity production, waste paper collection, pulp production, wastewater treatment, transportation, and several other main processes. Additionally, the energy data from Cellox excludes the processing steps (e.g. creping, rolling, cutting, packaging, distribution), which are similar for both types of papers. Though the downstream processes are expected to yield comparable results, a more comprehensive dataset may yield slightly different results. The team used proxies for chemical concentrations the papermaking process and estimated specifications of the paper machine clothing (e.g. synthetic felt, wire mesh). Lastly, there are no corresponding chemical additives in the Ecoinvent database to model in paper the production processes. Therefore, this study used proxies based on the chemical composition of the additives.

Based on the results we recommend that further research pursue a complete cradle-to-gate life cycle assessment of virgin and recycled toilet paper, including the final processing steps that were excluded from this study, using alternative impact assessment methods. To verify the robustness of this model, further research should explore the application of data from other paper mills (integrated and non-integrated) into this LCA for comparison.

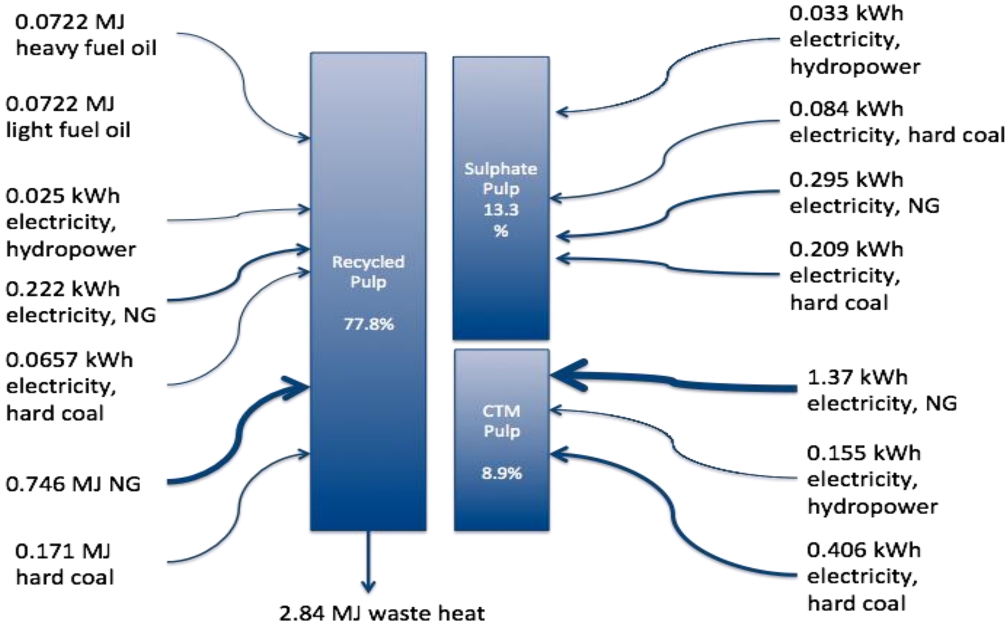
Appendices

Energy Inputs in Virgin vs. Recycled Pulp Production Processes

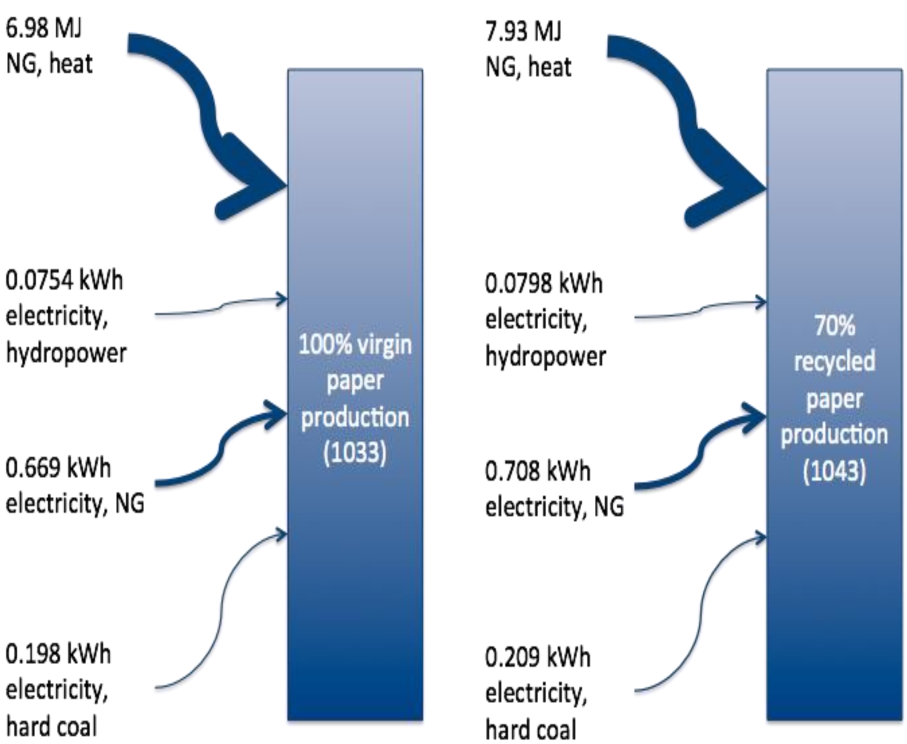
Appendix 1 Energy inputs in the virgin pulp production process.



Appendix 2 Energy inputs in the recycled pulp production process.



Appendix 3 Comparing energy inputs for virgin and recycled paper making processes.



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