Supplementary Material

Energy flows and carbon footprint in the forestry-pulp and paper industry

Qingjian Zhao [1,2,*], Sheng Ding [1], Zuomin Wen [1] and Anne Toppinen [3]

1 College of Economics and Management, Nanjing Forestry University, Nanjing 210037, China
2 Faculty of Forestry, University of Toronto, Toronto, ON M5S 3H7, Canada
3 Department of Forest Sciences, University of Helsinki, 00014 Helsinki, Finland
* Correspondence: zhao5190@126.com; Tel.: +86-138-5170-2610

Table S1. Energy consumption intensity table of major production processes

	Steam consumption intensity q_S^i	Power consumption intensity q_E^i	Direct fuel consumptiondensity q_F^i	energy efficiency improvement potential %	references
Forest cultivation and harvesting	\	\	0.07 GJ / m^3	\	[1,2,3,4]
Material transportation	\	\	0.01922 GJ / t • km	\	
Wood handling	0.1 MMBtu / adt	63 Kwh / adt	\	33	
digesting	1.5 MMBtu / adst	\	\	50%	
Screening and Washing	\	\	\	30	
Oxygen Delignification	0.6 GJ / adt	75 kWh / adt	\	28	
Bleaching	0.9 MMBtu / adt	287 Kwh / adt	\	\	
Evaporators	3.0 MMBtu / adt	67 Kwh / adt	\	41	
recovery boiler	0	0	\	27	
Lime Kilns	0.1 MMBtu / adt	27 Kwh / adt	1.4-1.6 MMBtu/adt	8-17	
Stock Preparation	0.4 MMBtu/mdt	195 Kwh / mdt	\	40-70	
Forming		9-11 kWh / adt	\	50-60%	
Pressing	1 MMBtu / mdt	100,195 Kwh / mdt	\	20-40 improvement in drying efficiency	
Drying	3.8 MMBtu / mdt	85,195 Kwh / mdt	\	4.9% improvement in drying efficiency	
Tissue Drying	6.0 MMBtu / ton tissue	\	\	20	
Surface Treatment	\	\	\	7% reducing water evaporated in the after drying section	
Calendering	\	80,195 Kwh / mdt	\	20	
Drives	\	\	\	more efficient high-pressure turbine-generators.	
Auxiliary Systems heat recovery systems	55 MJ / adt	30-70 kWh / adt	\	\	

Sludge and wastewater treatment	0.9 MMBtu / mdt	82,195 Kwh / mdt	\	35-50%

Note: mmBtu: million British Thermal Units; 1BTU≈1055 J≈252 cal; Mt: metric ton; ; adt: air dried tissue; admt: air dried metric ton; mdt: 1,000 air dried metric ton; Bone dry: Absolute dry; 1 GJ=1000 MJ=1,000,000 KJ=1,000,000,000 J; 1 Kwh=3600000 J.

Table S2. Energy supply and conversion parameters in the forestry pulp and paper industry

	Gross calorific value per unit	Main utilization	Utilized in hybrid boiler %	Boiler efficiency %	Fuel utilized in alkali recovery boiler %	Recovery boiler efficiency %	For boiler accessories, etc. %	Percent to generate electricity %	Direct fuel %	System and mechanical loss %	Percent utilized in process %	Recovery from process %	Percent utilized in non-process %	References
Off--site electricity	3596kJ/KWh	Machine driving	\	\	\	\	\	\	\	\	90	\	10	[1,2,3,4]
wood	21.25 GJ/t (IPCC 1996)	Raw material	\	\	\	\	\	\	\	\	\	\	\	
Coal (anthracite)	27300kJ / kg (anthracite)	Fossil fuel	100	86	\	\	\	\	\	\	\	\	\	
Bark and wood waste fuel	4GJ/admt	Biomass fuel	100	69	\	\	\	\	\	\	\	\	\	
Black liquor	14 GJ / t DS	Biomass fuel	\	\	100	64	\	\	\	\	\	\	\	
Steam	2,744 kJ/kg, 0.45 MPa 2,781 kJ/kg, 1.1MPa	Power generation and heating	\	\	\	\	6	\	\	\	\	\	\	
Steam	2,744 kJ / kg, 0.45MPa 2,781 kJ / kg, 1.1MPa	Power generation and heating	\	\	\	\	\	19.3	\	20	60.7	1.7	\	
On--site electricity	3,596 kJ KWh	Machine driving	\	\	\	\	\	\	\	\	90	\	10	
Residual fuel oil	40000 kJ/kg	Auxiliary fuel	\	\	100	86	\	\	\	\	100	\	\	
Diesel oil	0.038 GJ/l	Vehicle /Machine driven	\	\	\	\	\	\	\	\	\	\	100	
Natural gas	3,893 kJ/m^3	Direct fuel	\	86	\	\	\	\	100	\	100	\	\	

Table S3. Boiler performance parameters

	Rated evaporation	Rated steam pressure	Rated steam temperature	Rated feed water temperature
Alkali recovery boiler	635t / h	9.4MPa	490^{o}C	215 ^{o}C
Fluidized bed boiler A	260t / h	9.4MPa	490^{o}C	215 ^{o}C
Fluidized bed boiler B	330t / h	9.81MPa	540 ^{o}C	215 ^{o}C
Fluidized bed boiler C	330t / h	9.81MPa	540 ^{o}C	215 ^{o}C

Table S4. Turbine generator set performance parameters

	Rated power	Rated inlet	Rated inlet steam	Steam intake	Steam extraction	Extraction pressure	Extraction temperature	Exhaust volume	Exhaust pressure	Exhaust steam

		pressure	temperature							temperature
Turbine generator set A	100MW	8.83MPa	535 °C	835t/h	370t/h	1.27MPa	300 °C	208t/h	0.785MPa	300 °C
Turbine generator set B	50MW	8.83MPa	535 °C	320t/h	132t/h	0.785MPa	300 °C	/	/	/
Turbine generator set C	50MW	8.83MPa	535 °C	330t/h	142t/h	0.785MPa	300 °C	/	/	/

Table S5. Main production workshop heat load parameters

Project name		Hourly steam (t/h)	Annual steam consumption (t/a)	Steam pressure (MPa)	Thermal energy (GJ)
Subtotal	900,000 tons of chemical pulp project	354.86	3,015,000	≥1.0	8,384,715
		188.27	1,480,590	0.45	4,062,739
Sub option	Pulping workshop	68.86	585,000	1.1	1,626,885
		47.67	405,000	0.45	1,111,320
	Alkali recovery workshop	286	2,430,000	1.0	6,757,830
	900,000 tons of pulp board workshop	116.6	891,990	0.45	2,447,621
	Paper machine hot air system	24	183,600	0.45	503,798
Subtotal	450,000 tons of high-grade packaging cardboard project	33.2	253,800	1.0	705,818
		119.8	916,200	0.45	2,514,053
	Paper machine hot air system	12	91,800	0.45	251,899
Subtotal	450,000 tons of high-grade cultural paper project	14	107,000	1.08	297,567
		142.72	109,1800	0.45	2,995,899
Sub option	200,000 tons of high-grade cultural paper project	4.183	32,000	1.08	88,992
		52.287	400,000	0.45	1,097,600
	250,000 tons of copper paper project	9.8	75,000	1.08	208,575
		78.43	600,000	0.45	1,646,400
	Paper machine hot air system	12	91,800	0.45	251,899
Total		402.06	337,5800	≥1.0	9,388,100
		462.79	3,580,390	≥0.45，≤1.0	9,824,590

Note: The energy value of steam of 1.1MPa per kg is 2781kJ; the heat value of steam of 0.45MPa per kg is 2,744 kJ.

Table S6. Energy value and boiler combustion efficiency

Energy	Energy value	boiler combustion efficiency	**References**
Coal	6500Kcal / kg	0.86	[5]
Bark	4GJ / admt	0.69	
Black liquor	14GJ / t DS	0.64	
Natural gas	3893kJ / m^3	0.86	
Heavy oil	40000 kJ / kg	0.86	
Steam of 1.1MPa	2781kJ / kg	\	
Steam of 0.45MPa	2744kJ / kg	\	

Table S7. Carbon content of materiala

Material	Main raw material component	Carbon content %
Bone dry wood	\	0.5
Bone dry branches and roots	\	0.5
Bone dry bark	\	0.5
Bone dry chip	\	0.5
Bone dry pulp	\	0.5
Bone dry black liquor	\	0.5
Heavy oil	\	0.8
Paper and cardboard	\	0.5
Wood-based panel	\	0.468
Sawmilling	\	0.5
High-grade writing and printing paper	Softwood pulp, eucalyptus chemical pulp, calcium carbonate	0.454
High-grade writing paper filler	calcium carbonate	0.072
High-grade packaging card board	Eucalyptus chemical pulp, softwood pulp, chemical pulp, calcium carbonate	0.51
High-grade packaging cardboard filler	Calcium carbonate, alkaline yellow, polyethylene	0.144
Copper sheet	Softwood pulp, eucalyptus chemical pulp, china clay, talcum powder, calcium carbonate	0.283
Copper paper filler	Porcelain clay, talcum powder, calcium carbonate	0.028
Sludge	\	0.523
Coal	\	0.7

Table S8. Carbon emissions parameters of raw materials

	Total emission equivalent	CO2 emission equivalent	CH_4 emission equivalent	N_2O emission equivalent	**References**
Electricity	7.14t CO_2/10,000 kWh	7.14t CO_2/10,000 kWh	77.58g/10,000kWh	107.79g/10,000 kWh	[3,6]
Steam	0.11t CO_2 /GJ	0.11t CO_2 / GJ	1.22g / million kJ	1.65g/million kJ	
Residual oil	77,555 kg CO2-equiv./TJ	77,400 kg CO_2-equiv./TJ	62 kg CO_2-equiv./TJ	93 kg CO_2-equiv./TJ	
Coal	95244 kg CO2-equiv./TJ	94,600 kg CO_2-equiv./TJ	210 kg CO_2-equiv./TJ	434 kg CO_2-equiv./TJ	
Natural gas（Boilers）	56,160 kg CO_2-equiv./TJ	56,100 kg CO_2-equiv./TJ	29.4 kg CO_2-equiv./TJ	31 kg CO_2-equiv./TJ	
Bark and wood waste fuel	1,282 kg CO_2-equiv./TJ	N/A	42-630 kg CO_2-equiv./TJ	1,240 kg CO_2-equiv./TJ	
Black liquor	197 kg CO2-equiv./TJ	N/A	42-630 kg CO_2-equiv./TJ	155-29800 kg CO2-equiv./TJ	
Lime kilns	Based on fuel	Based on fuel	21-57 kg CO_2-equiv./TJ	0	
Lime calciners	Based on fuel	Based on fuel	21-57 kg CO_2-equiv./TJ	1,550 kg CO_2-equiv./TJ	
Pulp mill make-up $CaCO_3$	440 kg CO2-equiv./TJ	440 kg CO_2/t	0	0	
Pulp mill make-up	415 kg CO2-equiv./TJ	415 kg CO_2/t	0	0	

$Na2CO_3$				
Diesel fuel used in vehicles	79.3 t CO_2-equiv./TJ	78.6 t CO_2/TJ	82-231 kg CO_2-equiv./TJ	620-9770 kg CO2-equiv./TJ
Forestry – diesel Non-Road Mobile Sources and Machinery	66.8 t CO_2-equiv./TJ	66.8 t CO_2/TJ	0.004 g CH_4/MJ	0.03 g N_2O/MJ
Diesel Non-Highway Vehicles	66.8 t CO_2-equiv./TJ	66.8 tonne CO_2/TJ	0.006g CH_4/MJ	0.002 g N_2O/MJ
Anaerobic wastewater treatment	5.25 kg CO_2-equiv./kg COD treated	N/A	5.25 kg CO_2-equiv./kg COD treated	0
Mill solid waste landfills	3,500 kg CO_2-equiv. / dry ton solid waste	N/A	3,500 kg CO_2-equiv./dry ton solid waste	0

Table S9. Global warming potential of greenhouse gases for 100 years (IPCC 2001)

Greenhouse gases	GWP
CO_2	1
CH_4	21
N_2O	310

Table S10. Emission Factors

	CO2	**CH_4**	**N_2O**	**References**
Electricity	7.14t CO_2 / 10,000 kWh	77.58g / 10,000 kWh	107.79g / 10,000 kWh	[6,7,8,9]
Steam	0.11t CO_2 / million kJ	1.22g/million kJ	1.65g / million kJ	
Residual oil	76,600 kg CO_2-equiv. / TJ	62 kg CO_2-equiv./TJ	93 kg CO_2-equiv. / TJ	
Coal	96,300 kg CO_2-equiv. / TJ	210 kg CO_2-equiv./TJ	434 kg CO_2-equiv ./ TJ	
Natural gas（Boilers）	55,900 kg CO_2-equiv. / TJ	29.4 kg CO_2-equiv./TJ	31 kg CO_2-equiv. / TJ	
Bark and wood waste fuel	N/A	42-630 kg CO_2-equiv./TJ	1,240 kg CO_2-equiv. / TJ	
Black liquor	N/A	42-630 kg CO_2-equiv ./ TJ	155-29,800 kg CO_2-equiv. / TJ	
Lime kilns	Based on fuel	21-57 kg CO_2-equiv ./ TJ	0	
Lime calciners	Based on fuel	21-57 kg CO_2-equiv. / TJ	1,550 kg CO_2-equiv. / TJ	
Pulp mill make-up CaCO3	440 kg CO_2 / t	0	0	
Pulp mill make-up Na2CO3	415 kg CO_2 / t	0	0	
Diesel fuel used in vehicles	78.6 t CO_2 / TJ	82-231 kg CO_2-equiv. / TJ	620-9,770 kg CO2-equiv. / TJ	
Forestry – diesel Non-Road Mobile Sources and Machinery	66.8 t CO_2/ TJ	0.004g CH_4 / MJ	0.03g N_2O / MJ	
Diesel Non-Highway Vehicles	66.8 tonne CO_2/TJ	0.006g CH_4 / MJ	0.002g N_2O / MJ	
Anaerobic wastewater treatment	N / A	5.25 kg CO_2-equiv. / kg COD treated	0	
Mill solid waste landfills	N / A	3,500 kg CO_2-equiv. / dry ton solid waste	0	

N/A – Not Applicable - carbon dioxide emissions from biomass are not included in GHG totals because this carbon is considered part of the natural cycle; i.e., it is recycled between the atmosphere and plant tissue

Table S11. Conversion ratio parameters of materials in the supply chain

	Harvesting%	Wood preparation %	Slice %	Pulping%	Net recover %	Bleached stock%	Paper making%	Recycle paper %	Bark %	Black liquor%	Loss in Sludge effluent %	Waste and landfilled %	References

Log	70												[6,10]
Wood preparation		94							6				
Chips			95						5				
Yield Bone dry pulp				49.8						50.2			
Bone dry washed pulp					88.9						11.1		
Bleaching						96.2					3.8		
Paper products							95				5		
Waste paper								46.8				53.2	

Table S12. Proportions of raw materials for high-grade packaging cardboard

Material	Unit	Consumption per ton of paper
Eucalyptus chemical pulp	kg	349.31
Softwood pulp	kg	241.62
Chemical mechanical pulp	kg	292.245
Sizing agent	kg	2.687
Alum	kg	2.196
Starch for wet end	kg	5.762
Spray starch	kg	8.062
Surface sizing starch	kg	9.067
Latex	kg	10.438
Calcium carbonate	kg	54.664
china clay	kg	7.678
Pigment	kg	43.587
PE (Polyethylene)	kg	84.6
Aluminum foil	kg	6.533

Table S13. Main raw materials of high-grade writing paper

Material	Unit	Consumption per ton of paper
Softwood pulp board	kg	147.29
Eucalyptus chemical pulp	kg	834.64
Calcium carbonate	kg	103
Cationic starch	kg	12
AKD	kg	14
Polymer	kg	0.15
Dye	kg	0.1

Oxidized starch	kg	43.26

Table S14. Main raw materials of coated paper

Material	Unit	Consumption per ton of paper
Softwood pulp board	kg	118.4
Eucalyptus chemical pulp	kg	473.6
china clay	kg	208
Calcium carbonate	kg	136
Talcum powder	kg	118
Latex	kg	76.7
Cationic starch	kg	10.3
Stearate	kg	5.25
Oxidized starch	kg	21

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