

Supplementary material to “Impact of Structural Changes on Energy Efficiency of Finnish Pulp and Paper Industry”

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Contents

Appendix A	Productions and products of Finnish pulp and paper industry	1
Appendix B	Energy consumption of Finnish pulp and paper industry	3
Appendix C	Specific energy consumption of Finnish pulp and paper industry	6
Appendix D	Mechanical forest industry in Finland.....	9
Appendix E	Bioproducts in Finland	9
Appendix F	Electricity consumption of Finnish forest industry	10
References	10

Abbreviations

BCTMP	Bleached chemi-thermomechanical pulp
CTMP	Chemi-thermomechanical pulp
SEC	Specific energy consumption
TMP	Thermomechanical pulp

Appendix A Productions and products of Finnish pulp and paper industry

Production rates and products are gathered for every mill included in this study. They are presented in Table S1. Most of the production rates have been found from Finnish Forest Industries’ environmental reports [1]. Production rates in years with inadequate data were estimated utilizing available data.

Table S1. Products and production rates of Finnish pulp and paper mills [1–23].

Mill	Product	2010	2011	2012	2013	2014	2015	2016	2017
Mill A	Other paper	68	75	73	72	68	68	63	63
Mill A	Recycled pulp	32	32	34	36	38	38	36	36
Mill B	Other paper	70	61	60	71	69	73	73	73
Mill C	Other paper	71	61	55	60	51	0	0	0
Mill D	Chemical pulp	594	603	606	604	595	595	619	619
Mill E	Paperboard	356	341	343	373	368	368	411	411
Mill E	Chemical pulp	534	532	539	564	552	552	604	604
Mill F	BCTMP	259	246	273	287	303	303	311	311
Mill G	BCTMP	247	212	251	296	305	305	327	327
Mill H	Paperboard	240	207	261	228	249	249	227	227
Mill H	Groundwood	77	74	55	34	32	32	20	0
Mill I	Other paper (tissue)	125	124	116	113	113	113	111	111
Mill I	Recycled pulp	47	47	45	30	25	25	28	28
Mill J	Chemical pulp	544	567	573	612	607	607	585	585
Mill K	Paperboard	267	193	227	251	260	260	266	266

Mill K	Groundwood	86	77	81	85	97	97	100	100
Mill L	Paperboard	189	183	192	184	195	195	208	208
Mill M	Chemical pulp	502	503	519	516	504	504	510	0
Mill M	Paperboard	218	205	202	221	227	227	219	219
Mill M	Fine paper	175	136	0	0	0	0	0	0
Mill N	Magazine paper	465	424	0	0	0	0	0	0
Mill N	Groundwood	213	198	0	0	0	0	0	0
Mill O	Paperboard	77	86	83	88	85	85	78	78
Mill O	Groundwood	40	46	41	43	42	42	38	38
Mill P	Paperboard	120	118	115	116	117	117	118	118
Mill Q	Recycled pulp	113	118	113	113	114	114	116	116
Mill R	Paperboard	238	248	234	259	257	257	266	266
Mill R	Semi-chemical pulp	238	248	234	259	257	257	255	255
Mill S	Magazine paper	629	678	685	648	594	650	598	598
Mill S	Groundwood, refiner	209	228	237	198	195	195	199	199
Mill T	Paperboard	75	73	75	74	76	76	80	80
Mill U	Magazine paper	555	566	561	604	606	606	645	645
Mill U	Groundwood, refiner	429	440	444	456	461	461	488	488
Mill V	Chemical pulp	457	464	419	448	428	428	460	460
Mill W	Paperboard	258	244	256	264	258	258	255	255
Mill W	Semi-chemical pulp	259	244	250	257	250	250	246	246
Mill X	Paperboard	946	914	933	972	999	999	1029	1029
Mill X	Chemical pulp	884	858	911	983	1001	1001	1026	1026
Mill X	CTMP	100	100	100	100	100	100	100	100
Mill Y	Other paper	150	150	156	153	136	141	125	125
Mill Y	Chemical pulp	150	136	152	153	155	155	110	110
Mill Y	Magazine paper	116	141	150	143	138	143	143	143
Mill Y	Refiner (TMP)	82	77	90	91	94	94	90	90
Mill Z	Fine paper	982	969	968	925	917	917	907	907
Mill Z	Chemical pulp	341	341	326	331	335	335	349	349
Mill AA	Magazine paper, fine paper	418	253	257	262	259	262	267	267
Mill AA	Chemical pulp	261	197	209	227	222	227	305	305
Mill AA	Groundwood	100	0	0	0	0	0	0	0
Mill AB	Magazine paper	446	446	444	332	304	307	307	307
Mill AB	Chemical pulp, groundwood	451	453	435	451	405	375	375	375
Mill AB	Fine paper	404	400	400	400	400	400	400	400
Mill AC	Chemical pulp	336	339	350	350	350	350	371	371
Mill AD	Other paper	92	112	113	112	108	108	105	105
Mill AE	Magazine paper	723	723	685	699	677	677	556	556
Mill AE	Refiner, groundwood	266	166	138	258	252	252	192	192
Mill AF	Magazine paper	621	619	606	642	626	626	657	657
Mill AF	Refiner, groundwood	430	430	417	448	433	433	451	451
Mill AG	Magazine paper	500	480	494	425	421	305	305	305
Mill AG	Chemical pulp	629	834	867	885	810	810	98	98
Mill AH	Fine paper	725	675	708	692	715	715	700	700
Mill AH	Chemical pulp	505	487	573	541	588	588	775	775
Mill AI	Other paper	196	178	196	200	200	200	200	200
Mill AI	Chemical pulp	732	691	682	745	739	739	782	782
Mill AJ	Magazine paper	1024	992	995	884	792	792	816	816
Mill AJ	Refiner, groundwood, fluff	535	500	482	439	405	405	436	436
Mill AK	Other paper	350	300	300	300	300	300	300	300

Mill R	Annual consumption [GWh/a]	179	168	186	185	185	192	192
Mill S	SEC [MWh/t]	1.60	1.60	1.60	1.60	1.60	1.60	1.60
Mill S	Annual consumption [GWh/a]	1085	1096	1037	950	1040	957	957
Mill T	SEC [MWh/t]	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Mill T	Annual consumption [GWh/a]	15	15	15	15	15	16	16
Mill U	SEC [MWh/t]	1.77	1.77	1.77	1.77	1.77	1.77	1.77
Mill U	Annual consumption [GWh/a]	1002	993	1069	1073	1073	1142	1142
Mill V	SEC [MWh/t]	0.73	0.73	0.73	0.73	0.73	0.73	0.73
Mill V	Annual consumption [GWh/a]	339	306	327	312	312	336	336
Mill W	SEC [MWh/t]	0.72	0.72	0.72	0.72	0.72	0.72	0.72
Mill W	Annual consumption [GWh/a]	176	184	190	186	186	184	184
Mill X	SEC [MWh/t]	1.29	1.29	1.29	1.29	1.29	1.29	1.29
Mill X	Annual consumption [GWh/a]	1179	1204	1254	1289	1289	1327	1327
Mill X	SEC [MWh/t]	0.62	0.62	0.62	0.62	0.62	0.62	0.62
Mill X	Annual consumption [GWh/a]	62	62	62	62	62	62	62
Mill Y	SEC [MWh/t]	1.72	1.72	1.72	1.72	1.72	1.72	1.72
Mill Y	Annual consumption [GWh/a]	258	268	263	234	243	215	215
Mill Y	SEC [MWh/t]	1.34	1.34	1.34	1.34	1.32	1.32	1.32
Mill Y	Annual consumption [GWh/a]	189	201	192	185	189	189	189
Mill Z	SEC [MWh/t]	0.96	0.96	0.96	0.96	0.96	0.96	0.96
Mill Z	Annual consumption [GWh/a]	929	928	887	879	879	870	870
Mill AA	SEC [MWh/t]	1.27	1.27	1.27	1.27	1.27	1.27	1.27
Mill AA	Annual consumption [GWh/a]	321	326	333	329	333	366	366
Mill AA	SEC [MWh/t]	2.49	2.49	2.49	2.49	2.49	2.49	2.49
Mill AA	Annual consumption [GWh/a]	0	0	0	0	0	0	0
Mill AB	SEC [MWh/t]	1.22	1.22	1.22	1.22	1.22	1.22	1.22
Mill AB	Annual consumption [GWh/a]	544	542	405	371	375	375	375
Mill AB	SEC [MWh/t]	2.34	2.34	2.34	2.34	2.34	2.34	2.34
Mill AB	Annual consumption [GWh/a]	936	936	936	936	936	936	936
Mill AC	SEC [MWh/t]	0.84	0.84	0.84	0.84	0.84	0.84	0.84
Mill AC	Annual consumption [GWh/a]	285	294	294	294	294	312	312
Mill AD	SEC [MWh/t]	1.25	1.25	1.25	1.25	1.25	1.25	1.25
Mill AD	Annual consumption [GWh/a]	140	141	140	135	135	131	131
Mill AE	SEC [MWh/t]	2.15	2.15	2.15	2.15	2.15	2.15	2.15
Mill AE	Annual consumption [GWh/a]	1554	1473	1503	1456	1456	1195	1195
Mill AF	SEC [MWh/t]	2.18	2.18	2.18	2.18	2.18	2.18	2.18
Mill AF	Annual consumption [GWh/a]	1349	1321	1400	1365	1365	1432	1432
Mill AG	SEC [MWh/t]	1.77	1.77	1.77	1.77	1.77	1.77	1.77
Mill AG	Annual consumption [GWh/a]	1097	1135	1074	1017	893	395	395
Mill AH	SEC [MWh/t]	1.35	1.35	1.35	1.35	1.35	1.35	1.35
Mill AH	Annual consumption [GWh/a]	911	956	934	965	965	945	945
Mill AI	SEC [MWh/t]	0.96	0.96	0.96	0.96	0.96	0.96	0.96
Mill AI	Annual consumption [GWh/a]	530	528	574	569	569	599	599
Mill AJ	SEC [MWh/t]	0.81	0.81	0.81	0.81	0.81	0.81	0.81
Mill AJ	Annual consumption [GWh/a]	804	806	716	642	642	661	661
Mill AJ	SEC [MWh/t]	3.26	3.26	3.26	3.26	3.26	3.26	3.26
Mill AJ	Annual consumption [GWh/a]	1630	1571	1431	1320	1320	1421	1421
Mill AK	SEC [MWh/t]	1.44	1.44	1.44	1.44	1.44	1.44	1.44
Mill AK	Annual consumption [GWh/a]	432	432	432	432	432	432	432
Mill AL	SEC [MWh/t]	0.58	0.58	0.58	0.58	0.58	0.58	0.58
Mill AL	Annual consumption [GWh/a]	0	0	0	0	0	0	563

Mill V	Annual consumption [GWh/a]	1638	1479	1581	1511	1511	1624	1624
Mill W	SEC [MWh/t]	2.64	2.64	2.64	2.64	2.64	2.64	2.64
Mill W	Annual consumption [GWh/a]	644	676	697	681	681	673	673
Mill X	SEC [MWh/t]	4.74	4.74	4.74	4.74	4.74	4.74	4.74
Mill X	Annual consumption [GWh/a]	4332	4422	4607	4735	4735	4877	4877
Mill X	SEC [MWh/t]	-0.57	-0.57	-0.57	-0.57	-0.57	-0.57	-0.57
Mill X	Annual consumption [GWh/a]	-57	-57	-57	-57	-57	-57	-57
Mill Y	SEC [MWh/t]	5.12	5.12	5.12	5.12	5.12	5.12	5.12
Mill Y	Annual consumption [GWh/a]	768	799	783	696	722	640	640
Mill Y	SEC [MWh/t]	1.89	1.89	1.89	1.89	1.89	1.89	1.89
Mill Y	Annual consumption [GWh/a]	266	284	270	261	270	270	270
Mill Z	SEC [MWh/t]	2.12	2.12	2.12	2.12	2.12	2.12	2.12
Mill Z	Annual consumption [GWh/a]	2054	2052	1961	1944	1944	1923	1923
Mill AA	SEC [MWh/t]	4.35	4.35	4.35	4.35	4.35	4.35	4.35
Mill AA	Annual consumption [GWh/a]	1101	1118	1140	1127	1140	1161	1161
Mill AA	SEC [MWh/t]	-0.67	-0.67	-0.67	-0.67	-0.67	-0.67	-0.67
Mill AA	Annual consumption [GWh/a]	0	0	0	0	0	0	0
Mill AB	SEC [MWh/t]	6.21	6.21	6.21	6.21	6.21	6.21	6.21
Mill AB	Annual consumption [GWh/a]	2770	2757	2062	1888	1906	1906	1906
Mill AB	SEC [MWh/t]	1.15	1.15	1.15	1.15	1.15	1.15	1.15
Mill AB	Annual consumption [GWh/a]	460	460	460	460	460	460	460
Mill AC	SEC [MWh/t]	3.23	3.23	3.23	3.23	3.23	3.23	3.23
Mill AC	Annual consumption [GWh/a]	1095	1131	1131	1131	1131	1198	1198
Mill AD	SEC [MWh/t]	2.76	2.76	2.76	2.76	2.76	2.76	2.76
Mill AD	Annual consumption [GWh/a]	309	312	309	298	298	290	290
Mill AE	SEC [MWh/t]	0.34	0.34	0.34	0.34	0.34	0.34	0.34
Mill AE	Annual consumption [GWh/a]	958	932	801	773	773	654	654
Mill AF	SEC [MWh/t]	1.15	1.15	1.15	1.15	1.15	1.15	1.15
Mill AF	Annual consumption [GWh/a]	712	697	738	720	720	756	756
Mill AG	SEC [MWh/t]	5	5	5	5	5	5	5
Mill AG	Annual consumption [GWh/a]	2400	2470	2125	2105	883	883	1525
Mill AH	SEC [MWh/t]	4.24	4.24	4.24	4.24	4.24	4.24	4.24
Mill AH	Annual consumption [GWh/a]	2862	3002	2934	3032	2648	2593	3108
Mill AI	SEC [MWh/t]	4.01	4.01	4.01	4.01	4.01	4.01	4.01
Mill AI	Annual consumption [GWh/a]	2253	2244	2437	2419	2419	2548	2548
Mill AJ	SEC [MWh/t]	1.36	1.36	1.36	1.36	1.36	1.36	1.36
Mill AJ	Annual consumption [GWh/a]	1349	1353	1202	1077	1077	1110	1110
Mill AJ	SEC [MWh/t]	0.69	0.69	0.69	0.69	0.69	0.69	0.69
Mill AJ	Annual consumption [GWh/a]	345	333	303	279	279	301	301
Mill AK	SEC [MWh/t]	1.81	1.81	1.81	1.81	1.81	1.81	1.81
Mill AK	Annual consumption [GWh/a]	543	543	543	543	543	543	543
Mill AL	SEC [MWh/t]	2.8	2.8	2.8	2.8	2.8	2.8	2.8
Mill AL	Annual consumption [GWh/a]	0	0	0	0	0	0	2730

Appendix C Specific energy consumption of Finnish pulp and paper industry

Specific electricity and heat consumption values of different products in Table S4 and Table S5 are calculated utilizing values in previous tables (Tables S1–3) and coefficients from [36]. Mills are divided into categories based on their products.

Table S4. Specific electricity consumption of Finnish pulp and paper production.

Mill	Electricity consumption [MWh/t]	Mill	Electricity consumption [MWh/t]
Chemical pulp		Paperboard	
Mill D	0.62	Mill E	0.56
Mill E	0.71	Mill H	0.80
Mill J	0.70	Mill K	0.46*
Mill M	0.59	Mill L	0.74
Mill V	0.73	Mill M	0.80
Mill X	0.58*	Mill O	0.60
Mill Y	0.66	Mill P	0.37
Mill Z	0.59	Mill R	0.31
Mill AA	0.59	Mill T	0.20
Mill AB	0.53	Mill W	0.31
Mill AC	0.84	Mill X	0.67
Mill AG	0.77	Mill Y	0.60*
Mill AH	0.58*	Mill AA	0.48*
Mill AI	0.60		
Mill AL	0.63		
		Magazine paper	
		Mill N	0.78
		Mill S	0.89
Semi-chemical pulp		Mill U	0.61
Mill R	0.41	Mill AB	0.68
Mill W	0.41	Mill AE	1.19
		Mill AF	1.02
Groundwood		Mill AG	0.80
Mill H	1.50	Mill AJ	0.81
Mill N	2.02		
Mill O	1.63		
Mill K	1.11	Fine paper	
Mill S	2.14	Mill M	1.00
		Mill Z	0.76
Refiner		Mill AH	0.66
Mill U	1.53		
Mill Y	1.79	Other paper	
Mill AE	2.61	Mill A	1.53
Mill AF	1.68	Mill B	1.11
		Mill C	1.72
Chemi-mechanical pulp		Mill I	2.42
Mill F	2.81	Mill Y	0.69
Mill G	2.71	Mill AD	1.25
Mill X	0.62	Mill AI	0.63
		Mill AK	1.44
Recycled pulp			
Mill A	0.86		
Mill I	1.36		
Mill Q	0.53		

*Mills have gone through significant modifications and consequently SEC values have changed during reviewed period. Electricity consumptions before modifications in mills K, Y, AA, AH and X were 0.47 MWh/t, 0.67 MWh/t, 0.60 MWh/t, 0.69 MWh/t and 0.67 MWh/t, respectively.

Table S5. Specific heat consumption of Finnish pulp and paper production.

Mill	Heat consumption [MWh/t]	Mill	Heat consumption [MWh/t]
Chemical pulp		Paperboard	
Mill D	4.20	Mill E	1.37
Mill E	3.01	Mill H	1.30
Mill J	3.10	Mill K	1.50*
Mill M	3.14	Mill L	1.51
Mill V	3.53	Mill M	1.56
Mill X	3.41	Mill O	1.76
Mill Y	3.79	Mill R	1.53
Mill Z	2.70	Mill T	0.06
Mill AA	4.03	Mill W	1.53
Mill AB	4.29	Mill X	1.55
Mill AC	3.23	Mill Y	1.45*
Mill AG	3.00	Mill AA	1.54*
Mill AH	2.26*		
Mill AI	2.92	Magazine paper	
Mill AL	2.80	Mill N	1.50
		Mill S	1.20
Semi-chemical pulp		Mill U	1.31
Mill R	1.11	Mill AB	1.88
Mill W	1.10	Mill AE	1.42
		Mill AF	1.70
Groundwood		Mill AG	1.23
Mill H	0.00	Mill AJ	1.36
Mill N	0.00		
Mill O	0.00	Fine paper	
Mill K	0.00	Mill M	1.33
Mill S	0.00	Mill Z	1.18
Mill U	0.00	Mill AH	1.44
Refiner		Other paper	
Mill Y	-0.81	Mill A	2.31
Mill AE	-0.74	Mill B	2.41
Mill AF	-0.80	Mill C	2.74
		Mill I	5.73
Chemi-mechanical pulp		Mill Y	2.38
Mill F	0.44	Mill AD	2.76
Mill G	0.45	Mill AI	1.33
Mill X	-0.57	Mill AK	1.81
Recycled pulp			
Mill A	0.06		
Mill I	0.15		
Mill Q	1.27		

*Mills have gone through significant modifications and consequently SEC values have changed during reviewed period. Heat consumptions before modifications in mills K, Y, AA and AH were 1.50 MWh/t, 1.53 MWh/t, 1.63 MWh/t and 2.8 MWh/t, respectively.

Appendix D Mechanical forest industry in Finland

Production rates of mechanical forest industry products are presented in Table S6.

Table S6. Production rates of mechanical forest industry products [37].

Product [1000 m ³]	2010	2011	2012	2013	2014	2015	2016	2017
Sawnwood	9600	9700	9440	10440	10920	10640	11410	11900
Panels	1250	1255	1267	1339	1358	1314	1304	1300
Total	10850	10955	10707	11779	12278	11954	12714	13200

There is no data available about electricity consumption of mechanical forest industry. Specific electricity consumption values were estimated, and the total consumptions were calculated utilizing production rates. Estimated SEC values for sawnwood, chipboards, plywoods and fiberboards were 0.075 MWh/1000 m³, 0.160 MWh/1000 m³, 0.175 kWh/1000 m³ and 0.500 kWh/1000 m³, respectively. [36] It was assumed that 80% of produced panels were plywoods, 15% fiberboards and 5% chipboards. Estimations based on previous project [38]. Table S7 presents the calculated electricity consumptions of mechanical forest industry products.

Table S7. Electricity consumption of mechanical forest industry products [36–38].

Electricity consumption, [GWh]	2010	2011	2012	2013	2014	2015	2016	2017
Sawnwood	720	728	708	783	819	798	856	893
Panels	236	237	239	253	256	248	246	246
Total	956	965	947	1036	1075	1046	1102	1138

Appendix E Bioproducts in Finland

Estimated production rates of bioproducts are presented in Table S8.

Table S8. Production rates of bioproducts [37,39–41].

Product	2010	2011	2012	2013	2014	2015	2016	2017
Wood fuels (s) [1000 m ³]	6705	7252	7695	7660	7832	7964	7107	7964
Wood fuels (l) [1000 t]	0	0	0	50	150	150	150	160

There is no data available about electricity consumption of bioproducts manufacturing. Specific electricity consumption values were estimated, and the total consumptions were calculated utilizing production rates. Estimated SEC values for solid wood fuels and liquid wood fuels were 0.25 MWh/1000 m³ and 1.33 MWh/t, respectively [38]. It was estimated that 58% of solid biofuels were chips, 39% residues and 3% pellets [38]. Used densities for chips, residues and pellets were 228 kg/m³, 196 kg/m³ and 600 kg/m³, respectively [42]. Calculated energy consumption values are presented in Table S9.

Table S9. Electricity consumption of bioproducts [38,43]

Electricity consumption [GWh]	2010	2011	2012	2013	2014	2015	2016	2017
Bioproducts	382	413	439	503	646	653	605	667

Appendix F Electricity consumption of Finnish forest industry

Electricity consumption of Finnish forest industry is presented in Figure S1. It is assumed that the total consumption includes pulp and paper industry, mechanical forest industry and bioproducts manufacturing. Pulp and paper industry consume the major share of the total consumed electricity due to high production rate and energy intensity. Electricity consumption statistics including only pulp and paper industry are not available. Therefore, the consumption must be calculated. The most accurate way for defining electricity consumption of pulp and paper industry is to subtract electricity consumptions of mechanical forest industry and bioproducts manufacturing from the total consumption.

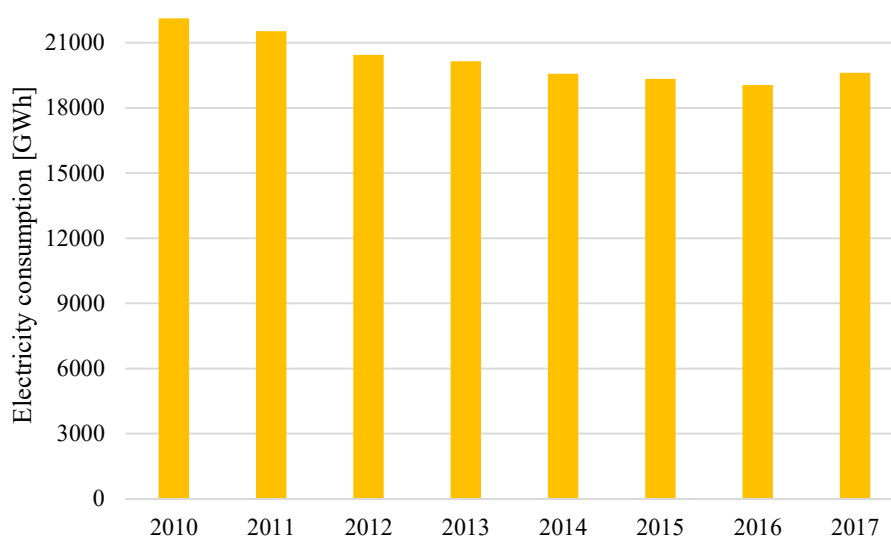


Figure S1. Electricity consumption of Finnish forest industry in 2010s. Data from [43].

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