Techno-Economics of Retrofitting CCS in Pulp and Paper Industry

A Case for Demonstrating Industrial CCS and Bio-CCS

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Final Results Seminar
Helsinki, Finland

October 2016

Acknowledgement

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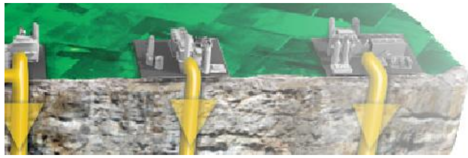
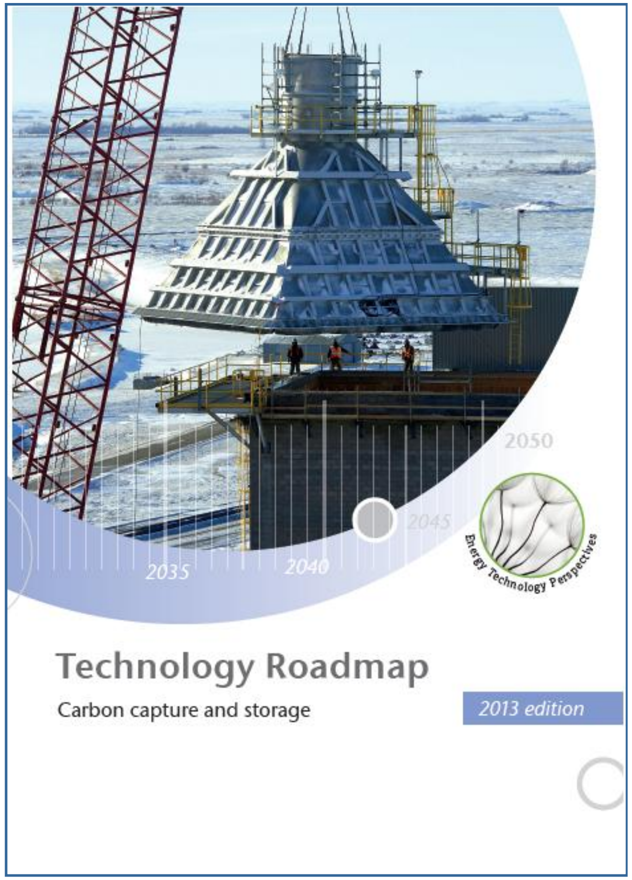
- This work was carried out under the Finnish Carbon Capture and Storage Program (CCSP) research program coordinated by CLIC Innovation Oy with funding from Tekes - the Finnish Funding Agency for Innovation and in collaboration with the IEA Greenhouse Gas R&D Programme.



International Energy Agency

2013 CCS Roadmap: Key Findings

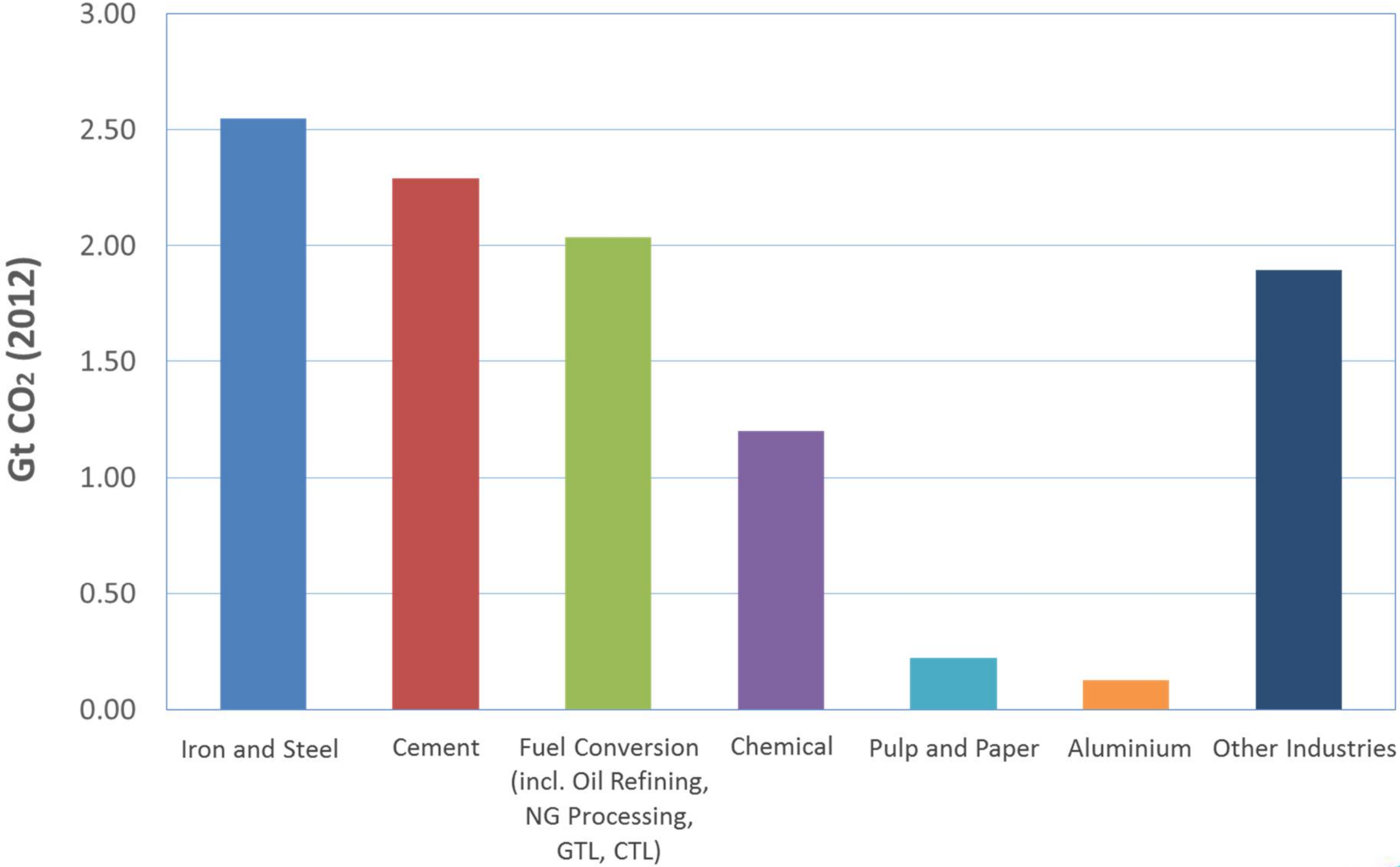


- CCS is a critical component in a portfolio of low-carbon energy technologies, contributing 14% of the cumulative emissions reductions between 2015 and 2050 compared with business as usual.
- The individual component technologies are generally well understood. The largest challenge is the integration of component technologies into large-scale demonstration projects.
- Incentive frameworks are urgently needed to deliver upwards of 30 operating CCS projects by 2020.
- CCS is not only about electricity generation: 45% of captured CO_2 comes from industrial applications between 2015 and 2050.
- The largest deployment of CCS will need to occur in non-OECD countries, 70% by 2050. China alone accounts for 1/3 of the global total of captured CO_2 between 2015 and 2050.
- The urgency of CCS deployment is only increasing. This decade is critical in developing favourable conditions for long-term CCS deployment.

Rationale for CCS:

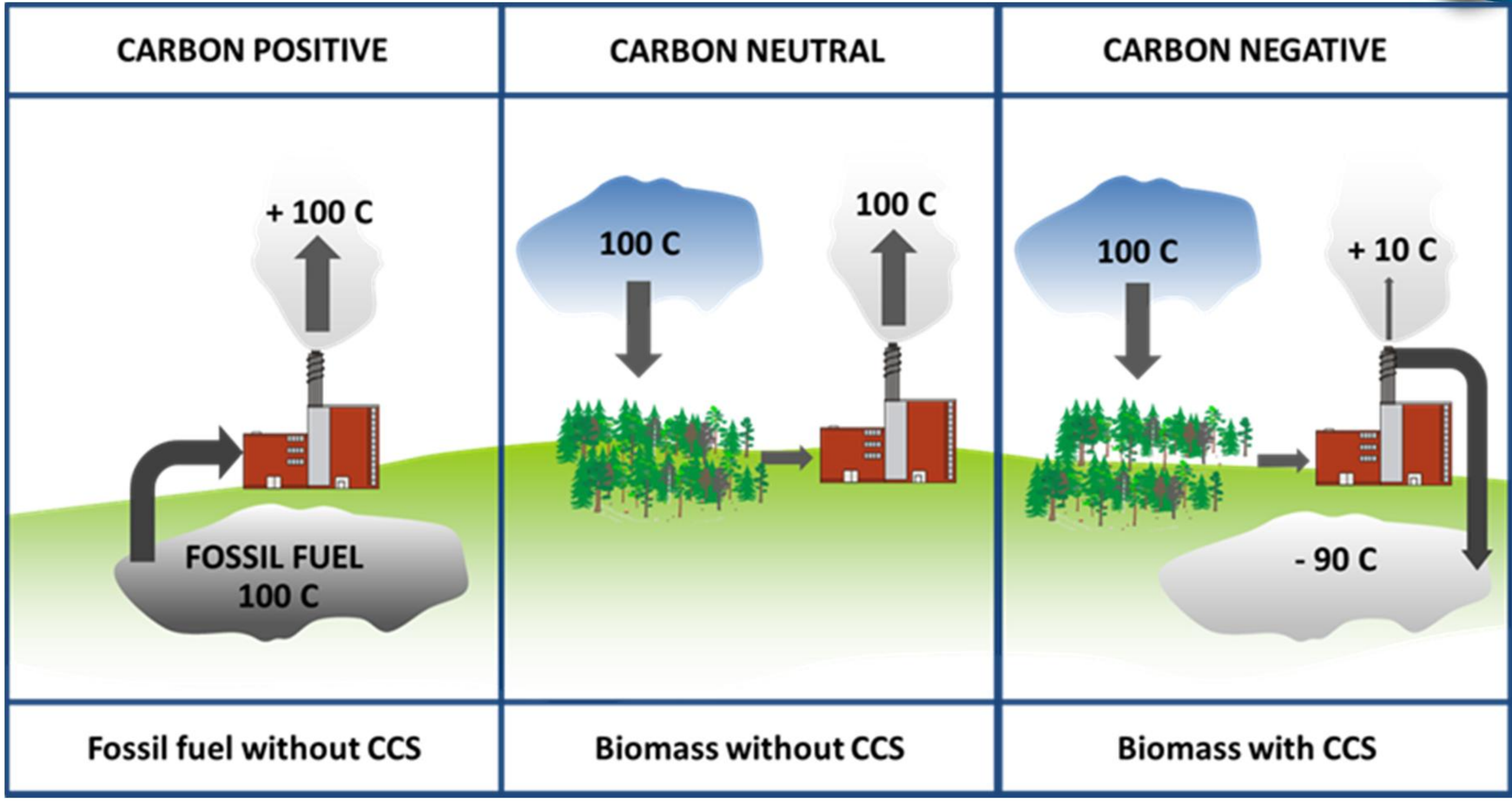
Only large-scale mitigation option for many industries

Updated from Tracking Clean energy Progress report 2013, industry-CCS annex (IEA)



Bio-CCS or BECCS

(Picture courtesy of K. Onarheim)



- Recent report of IPCC (2016) calls for solutions that can remove CO_2 from the atmosphere.
- ZEP Report (2012) emphasized that only Bio-CCS could realize large scale removal of CO2 from the atmosphere

IEAGHG's CCS Activities in Process Industries

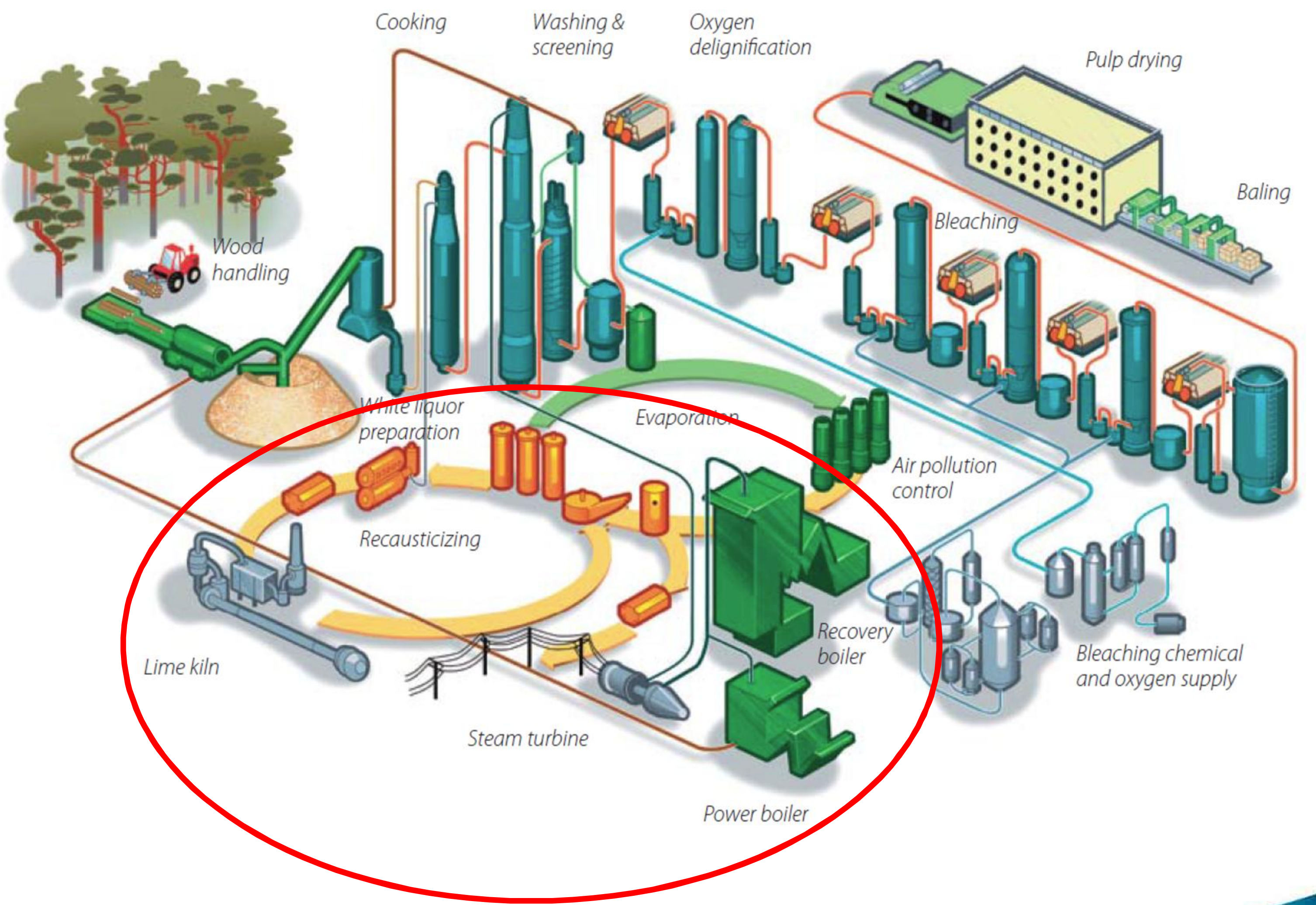
- **Iron and Steel Industry**
  - Techno-economic evaluation of CCS deployment in steel mill – completed 2013
  - Overview of the current state and future development of CO_2 capture technologies in the Iron Making Process – completed 2013
  - 1st Steel industry CCS workshop with VDEH and Swerea MEFOS in Germany in November 2011
  - 2nd Steel industry CCS workshop in Japan November 2013 – collaboration with World Steel and IETS
- **Cement Industry**
  - Techno- economic assessment completed in 2008
  - Studies on barriers to implementation completed in 2013 (with GCCSI)
- **Hydrogen Production for Industrial Applications**
  - State of the art review completed
  - Techno-economic evaluation for SMR in Merchant Market Scenario now completed – Final Report due Q4 of 2016
  - Techno-economic evaluation for SMR in Captive Market Scenario (Methanol, Ammonia/Urea) is Final Report due Q4 of 2016.
- **Oil Refining Industry**
  - Techno-economic evaluation is now underway – due Q3 of 2017
- **Pulp and Paper Industry**
  - Techno-economic evaluation now underway – due Q4 of 2016

Industrial CCS

- Deploying Industrial CCS is very site specific.
  - This makes it more complicated to gather general conclusions on how CCS in industry could impact its performance and cost.

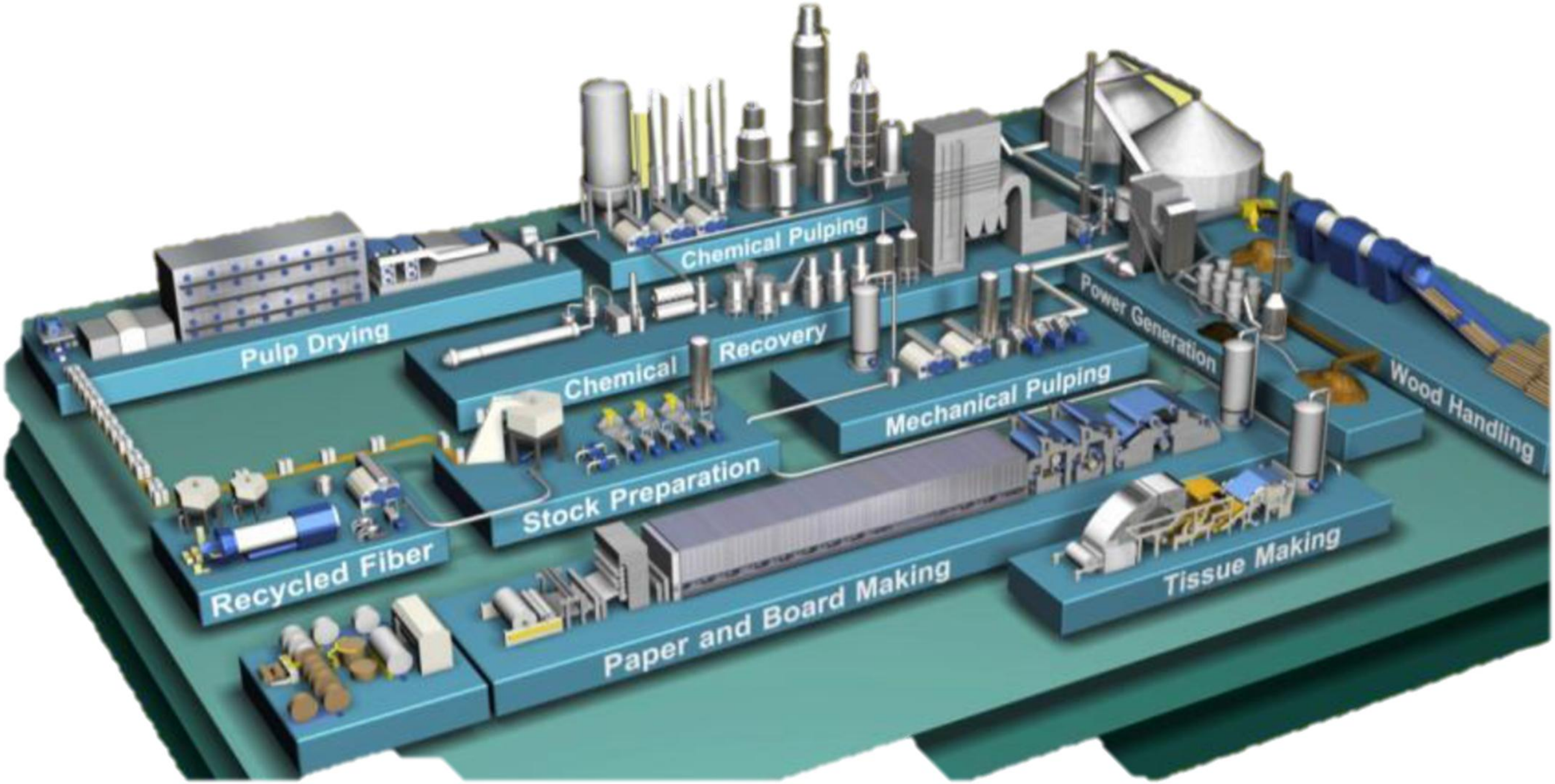
- Like any industry – retrofitting CCS in the pulp and paper industry is also site specific.
- Work done in this study presents a good baseline information in understanding the performance and cost of retrofitting CCS in the pulp and paper industry.

Kraft Pulp Mill
(Picture Courtesy of Metso)



Integrated Pulp and Paper Mill

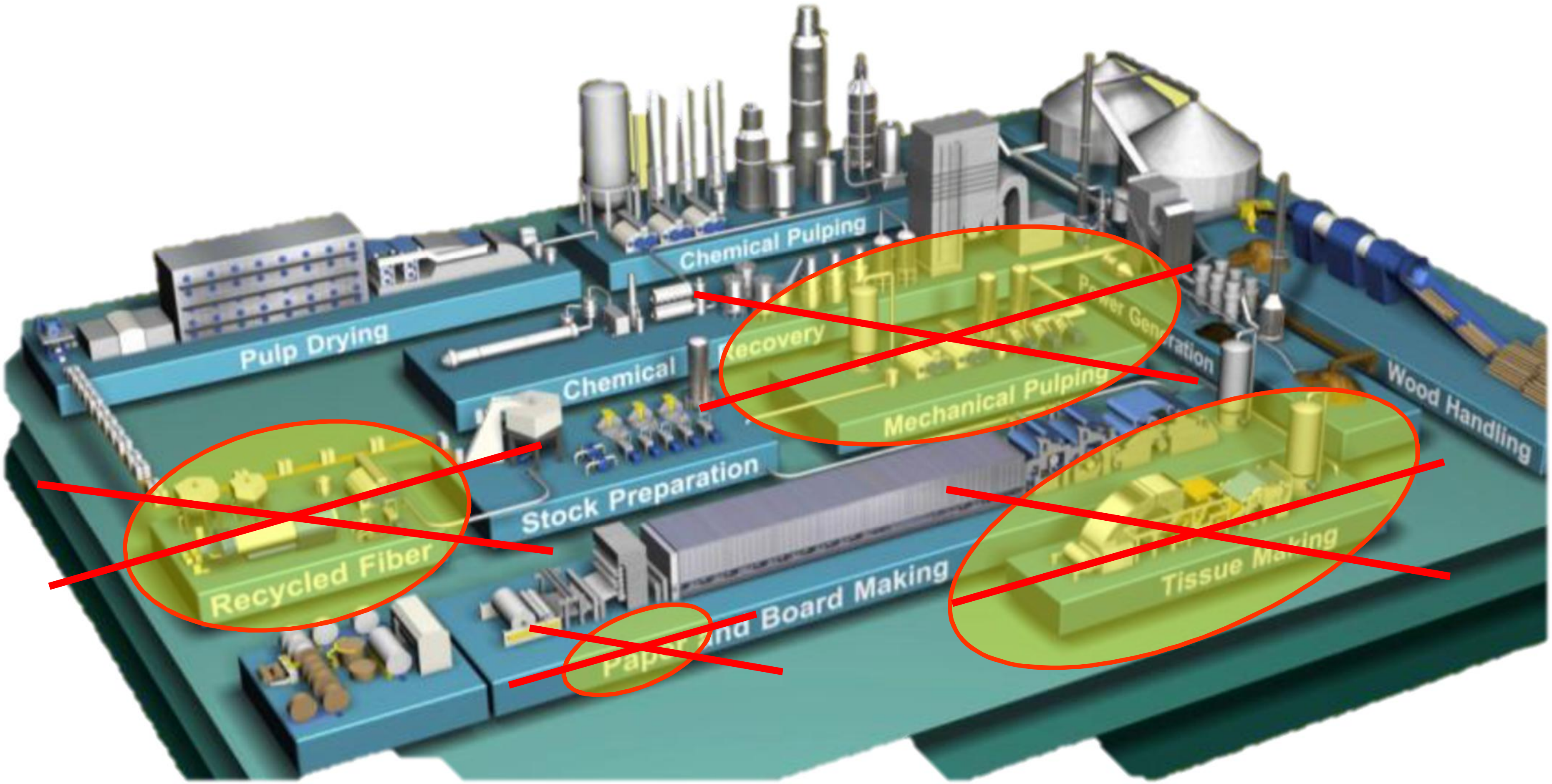
(Fully Integrated Plant)
Picture Courtesy of Metso



Integrated Pulp and Board Mill

(Partial Integration)

Picture Courtesy of Metso



Scope of Work
(Defining the Specification of the Reference Mills)

Reference mill
- A typical modern Nordic pulp mill
- Production 800 000 of pulp annually
- Excess heat / electricity available

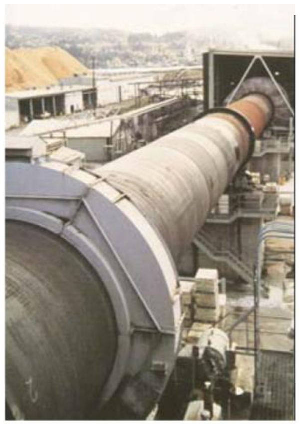
Fibre line
- delignification (cooking plant, brown stock handling and oxygen delignification)
- bleaching (D_0-EOP-D_1-P)
- pulp drying

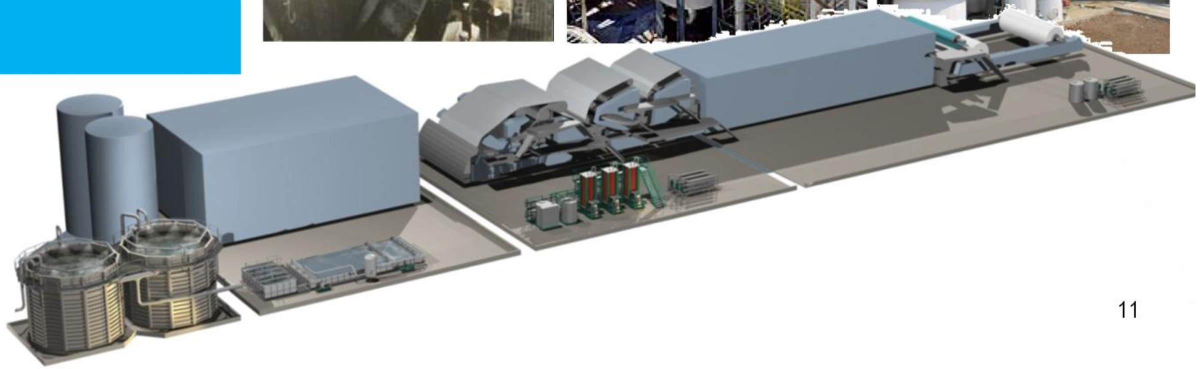
Recovery island
- evaporators
- kraft recovery boiler,
- recausticizing
- lime kiln

Auxiliary units
- steam turbine island
- air separation unit
- bleach chemical preparation
- waste water treatment plant

Board machine
- (only for reference mill B).
- Capacity of 400 000 adt/a





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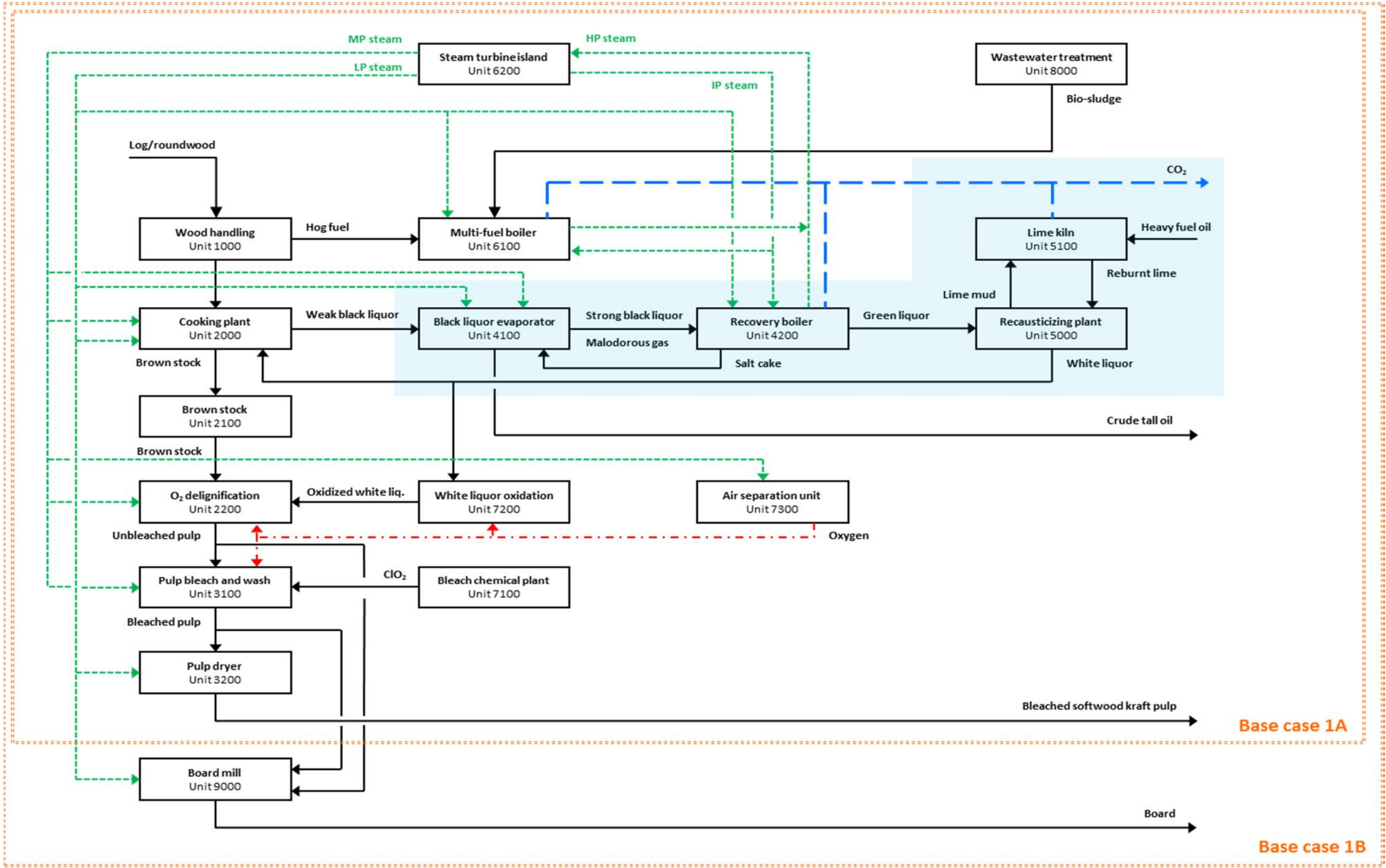


Mass Balance

Raw Materials	Units*	Base Case 1A	Base Case 1B
Log (round wood)	[m^3/adt]	5.8	5.8
Bleached hardwood kraft pulp (BHKP)	[kg/adt]	-	106.1
Chemi-thermo mechanical pulp (CTMP)	[kg/adt]	-	290.6
Filler	[kg/adt]	-	24.0
Coating	[kg/adt]	-	40.0
Chemicals			
NaOH	[kg/adt]	37.2	36.2
H_2O_2	[kg/adt]	7.4	7.0
$MgSO_4$	[kg/adt]	3.5	3.5
CaO	[kg/adt]	5.2	5.2
H_2SO_4	[kg/adt]	20.0	19.3
$NaClO_3$	[kg/adt]	24.5	23.3
Methanol	[kg/adt]	2.5	2.4
Talc	[kg/adt]	4.0	3.8
Products			
Market Pulp	[kg/adt]	1000.0	923.0
Board	[kg/adt]	-	500.0
Crude Tall Oil (CTO)	[kg/adt]	39.0	39.0
Energy			
HFO	[kg/adt]	35.0	35.0
Electricity Exported to Grid	[MWh/adt]	1127.2	666.0

* Basis of calculation – annual pulp production of 800,000 adt/y

Products of the reference mills

A. Kraft pulp mill

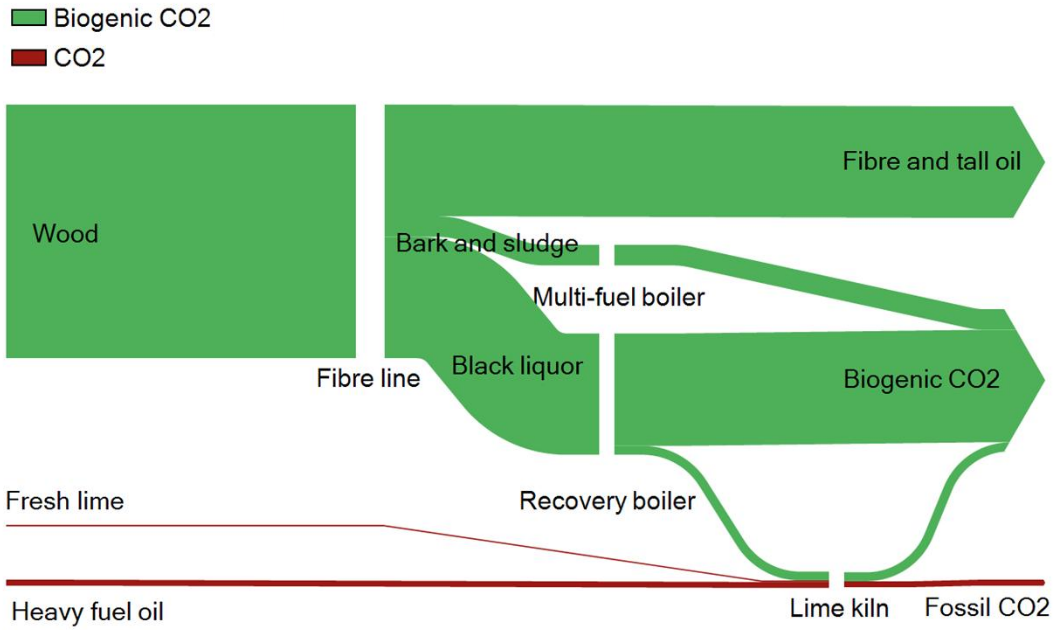
- Pulp production 800 000 adt/a
  - Bleached Softwood Kraft Pulp
- Electricity: 902 GWh/a
- Crude tall-oil: 31200 t/a
- CO_2 emissions:
  - Recovery boiler: 1.6 Mt/a
  - Multi-fuel boiler: 0.3 Mt/a
  - Lime kiln: 0.2 Mt/a

B. Integrated pulp and board mill

- Pulp production 740 000 adt/a
  - Bleached Softwood Kraft Pulp
- Board production 400 000 adt/a
  - 3-ply folding box board
- Electricity: 533 GWh/a
- Crude tall-oil: 31200 t/a
- CO_2 emissions:
  - Recovery boiler: 1.6 Mt/a
  - Multi-fuel boiler: 0.3 Mt/a
  - Lime kiln: 0.2 Mt/a

Energy and CO_2 balance of the reference mills*

REFERENCE MILLS	Steam Consumption[1]			Fuel Consumption[2]	Electricity Consumption	Electricity Production (Gross)	Electricity Export
	IP	MP	LP				
	[GJ/adt]			[GJ/adt]	[kWh/adt]		
Base Case 1A - Market Pulp Mill	0.384	3.537	5.701	42.37	640.0	1767.2	1127.2
Base Case 1B - Pulp & Board Mill	0.384	3.464	7.861	42.37	990.0	1656.0	666.0



* Energy figures comperable with Berglin et al.2011, *TAPPI PEERS Conference* (Portland, Oregon, US, 2011), pp. 273–279; 1.; European IPPC Bureau 2015, "Best Available Techniques (BAT) Production of Pulp , Paper and Board".

Biogenic Nature of the CO_2 Emissions from the Lime Kiln within the Pulp Mill

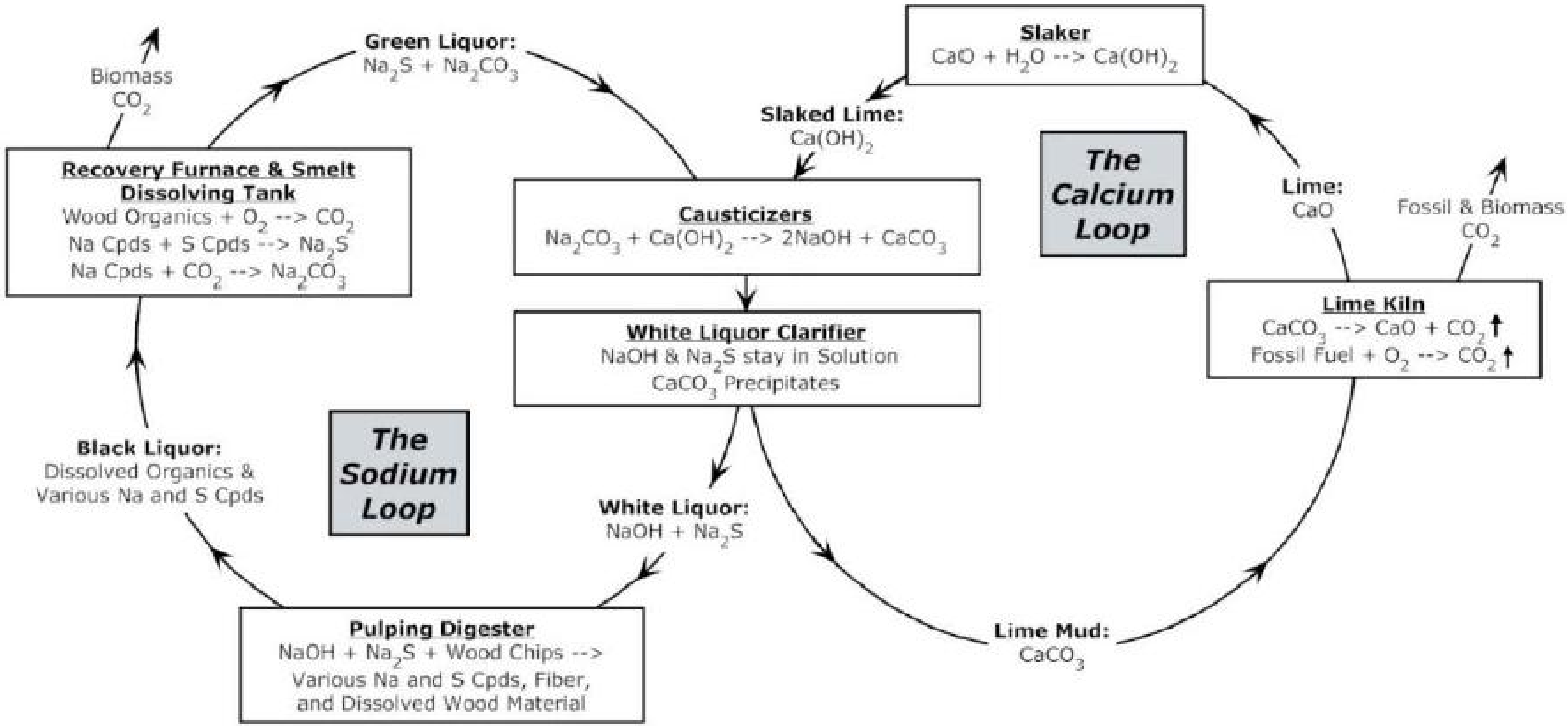


Figure 8. Calcium and sodium loops in a typical kraft pulp mill (National Council for Air and Stream Improvement, Inc. (NCASI). 2011. Greenhouse gas and non-renewable energy benefits of black liquor recovery. Technical Bulletin No. 984. Research Triangle Park, N.C.: National Council for Air and Stream Improvement, Inc.).

CAPEX for the reference mills

800 000 adt/y BSKP @ 2005*

Unit	Description	Nominal Capacity	Total CAPEX (MEUR 2005)	
			Base Case 1A	Base Case 1B
0000	Mill infrastructure	800000 adt/y	67	82
1000	Wood handling	943 m^3/h	53	53
2000	Cooking plant	2795 adt/d	107	107
2100	Brown stock handling		Included in Unit 2000	Included in Unit 2000
2200	Oxygen delignification		Included in Unit 2000	Included in Unit 2000
3100	Pulp bleaching and washing	2667 adt/d	49	48
3200	Pulp dryer	2824 adt/d	112	107
4100	Black Liquor evaporation	804 t_{H2O}/h	48	48
4200	Kraft recovery boiler	4985 t_{ds}/d	160	160
5000	Recausticizing plant	11120 $m3_{WL}$/d	49	49
5100	Lime Kiln	t_{CaO}/d	Included in Unit 5000	Included in Unit 5000
6100	Multi-fuel boiler	82MW_{th}	56	56
6200	Steam turbine Island	187 MW_e	51	49
7100	Bleach chemical plant	34 t ClO_2/d	14	13
7200	White liquor oxidation		Included in Unit 7100	Included in Unit 7100
7300	Air separation unit	64 t/d	8	8
8000	Waste water treatment	49000 m^3/d	25	27
9000	Board Mill	400,000 adt/y	-	136
		Total	**€ 799 million**	**€ 943 million**

- Total Plant Cost
  - Kraft pulp mill 799 MEUR
  - Integrated pulp and board mill 943 MEUR
- Other Investment Cost
  - Project Contingencies 10%;
  - Start-up costs ~10%;
  - Working capital equivalent to 30 days inventories (raw materials) and 15 days inventories of products

* More information in Kangas et al. 2014, *Nord. Pulp Pap. Res. J.* **29**, 620–634;

Assumption for the economic evaluation of the mills without CO_2 capture

OPEX*
- Raw materials and chemicals
- Utilities and Waste
- Maintenance 4%
- Labour: 120 total
- Logistics: 50 €/adt

CAPEX*
- Green-field investment costs at year 2005
- 10% contingency
- Start-up costs 10%
- Working capital 1 month

Revenues*
- Pulp
- Board
- Crude tall-oil
- Electricity

DCF analysis
- Construction 3 years (20%-40%-35%-5%)
- EBITDA basis
- Lifetime 25 years
- IRR 8%

LCOP
- Estimate Levelised Cost of Production of pulp and board
- NPV after 25 years is 0€.

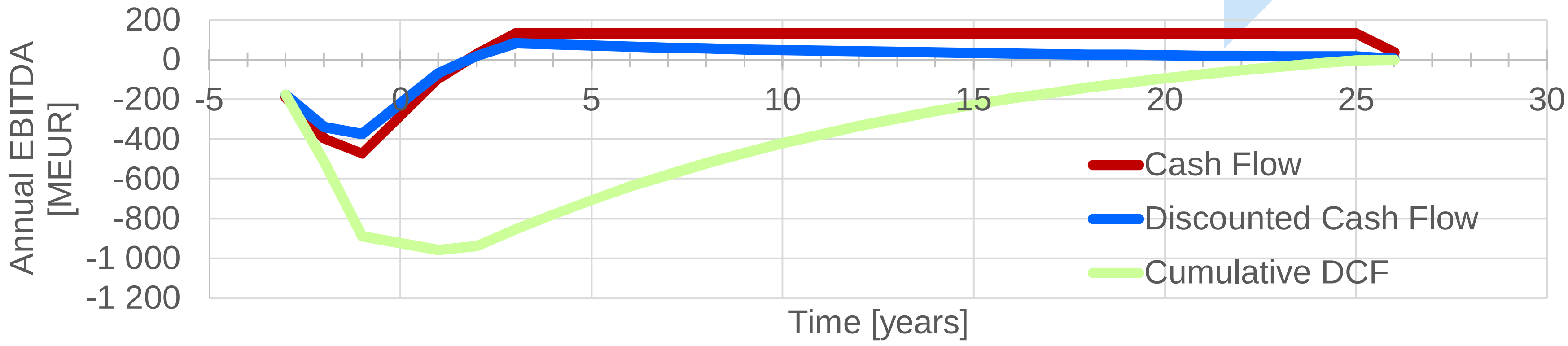


Figure 8. Discounted Cash Flow (DCF) analysis conducted for estimating the Levelised Cost of Production (LCOP) for Pulp and Board.

* Costs of raw materials, chemicals, utilities etc are obtained from Kangas et al. 2014, *Nord. Pulp Pap. Res. J.* **29**, 620–634 and adjusted as needed. The investment costs are mainly from the same source.

Effects of CO_2 Emission Costs for LCOP of Pulp in the Reference Mill

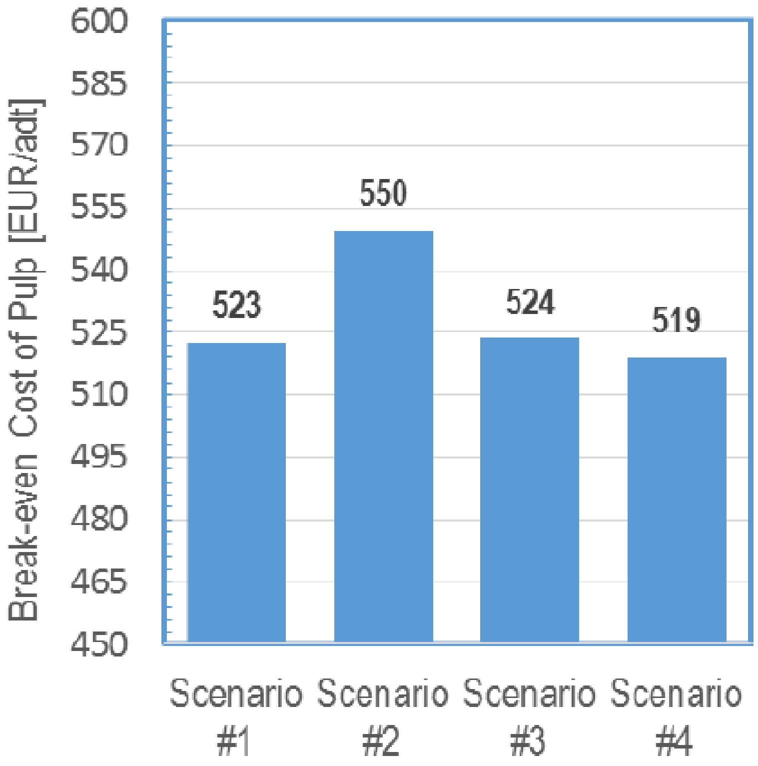


Figure 12. Impact to the breakeven cost of pulp (for kraft pulp mill) vs CO_2 emissions cost as defined by the 4 different scenarios.

Scenario #1

- No CO_2 emissions tax nor any incentives to the biogenic CO_2 emissions

Scenario #2

- CO_2 emissions tax at €10/t and the biogenic CO_2 emitted by the mills is not recognized as CO_2 neutral (i.e. biogenic CO_2 is not exempted to the tax).

Scenario #3

- CO_2 emissions tax at €10/t and the biogenic CO_2 is recognized as CO_2 neutral – therefore exempting these emissions from the tax.

Scenario #4

- CO_2 emissions tax at €10/t, the biogenic CO_2 is exempted from the tax and an additional incentive is credited to the Renewable Electricity exported to the grid at 10% of the electricity selling price (at € 4 / MWh for the Base Number).

Summary of reference mills

Production

- 800,000 adt/y of BSKP pulp
- 5.8 m3/adt of round wood
- LCOP is 523 EUR / adt
- 400 000 adt/y of 3-ply board
- LCOB is 637 €/adt

Energy demand

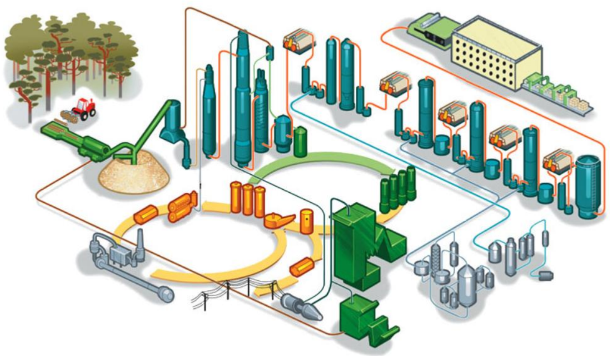
- 9.6 GJ/adt of steam
- 640 kWh/adt of electricity.
- Lime kiln 1.4 GJ/adt of imported HFO (fossil)

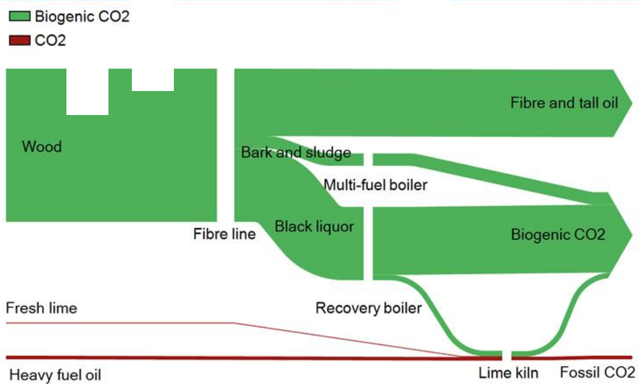
Energy available

- Excess Electricity sent to the grid
- 1.13 MWh/adt (~107 MWe) for Base Case 1A
- 0.67 MWh/adt (~63 Mwe) for Base Case 1B

CO_2 emissions

- 2.1 million MTPY of CO_2 total
- Only 0.1 million MTPY is fossil based CO_2 emissions





Study Cases

(Recovery Boiler, Multi-fuel Boiler and Lime Kiln)

Table 2: Properties and composition of the flue gas from the recovery boiler, multi-fuel boiler and lime kiln.

	Unit	Recovery boiler	Multi-fuel boiler	Lime kiln
Temperature	[°C]	184.0	189.0	250.0
Mass flow	[MTPY]	8 151 000	1 508 000	684 000
CO_2	[wt-%]	20.0	20.0	32.0
N_2	[wt-%]	66.0	56.0	47.0
O_2	[wt-%]	3.0	2.0	1.0
H_2O	[wt-%]	11.0	22.0	20.0
SO_X	[ppm]	60.0	40.0	50.0
NO_X	[ppm]	125.0	150.0	175.0
TRS	[ppm]	15.0	15.0	15.0
Particulates	[ppm]	30.0*	15.0**	30.0***

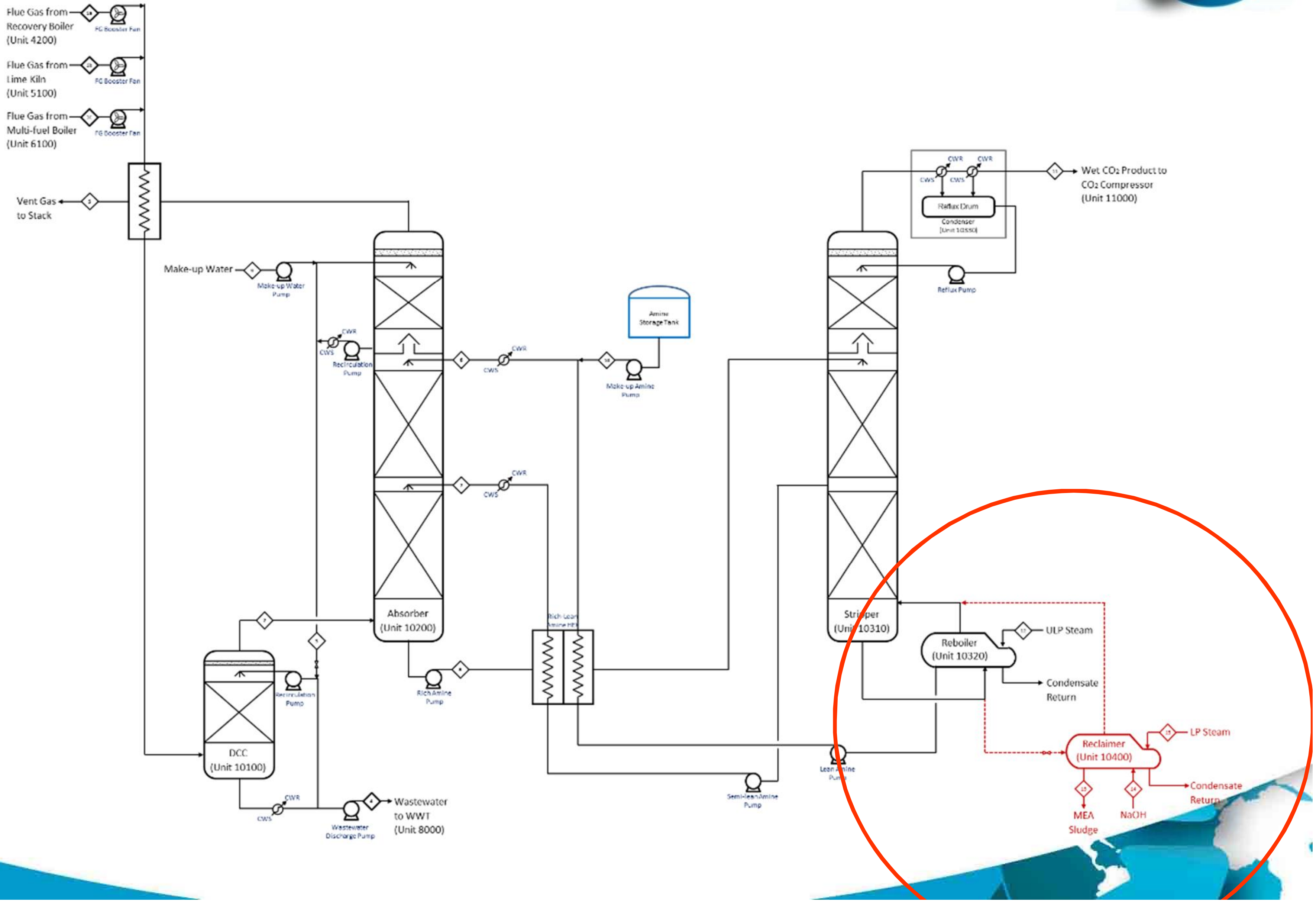
*Fly ash mainly Na_2SO_4. **Contains components of Al, Ca and Si. ***Fly ash mainly $CaCO_3$.

Capture Cases:
CO_2 Emissions / Overall Capture Rate

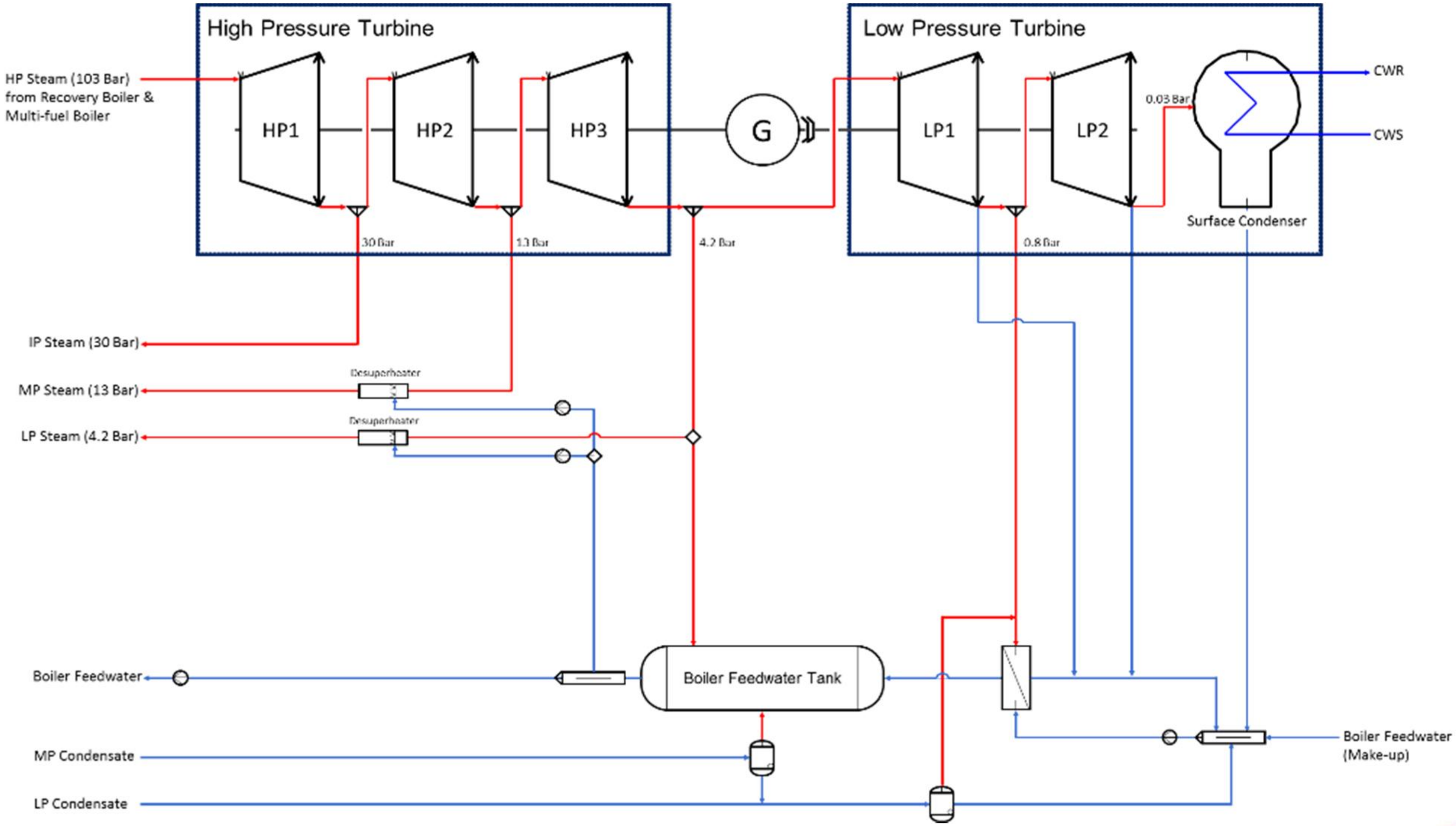
Case	Case description	Total emissions (whole Site)	Biogenic based CO_2 emissions	Fossil based CO_2 emissions[1]	Total Biogenic CO_2 captured	Overall CO_2 capture rate[2]
		[MTPY]	[MTPY]	[MTPY]	[MTPY]	%
Market pulp mill with CCS						
Case 2A-1	Recovery Boiler (REC) only	683,636	597,054	86,582	1,477,526	68.4%
Case 2A-2	Multi-fuel Boiler (MFB) only	1,891,678	1,805,097	86,582	270,696	12.5%
Case 2A-3	Lime Kiln (LK) only	1,974,532	1,974,532	-	101,209	4.9%
Case 2A-4	REC + MFB	412,736	326,155	86,582	1,749,596	80.9%
Case 2A-5	REC + LK	495,628	495,628	-	1,580,126	76.1%
Case 2A-6[MP]	All 3 (REC + MFB + LK)	224,728	224,728	-	1,851,025	89.2%
Integrated pulp & board mill with CCS						
Case 2B-1[CO2MP]	Recovery Boiler (REC) only	833,005	746,423	86,582	1,477,526	63.9%
Case 2B-2	Multi-fuel Boiler (MFB) only	1,891,678	1,805,097	86,582	270,696	12.5%
Case 2B-3	Lime Kiln (LK) only	1,974,532	1,974,532	-	101,209	4.9%
Case 2B-4[CO2MP]	REC + MFB	644,832	558,251	86,582	1,749,596	73.1%
Case 2B-5[CO2MP]	REC + LK	715,085	715,085	-	1,580,126	68.8%
Case 2B-6[CO2MP]	All 3 (REC + MFB + LK)	574,021	574,021	-	1,851,025	76.3%

[1] Emissions from the mill with CO_2 capture from the lime kiln has been calculated assuming that all fossil CO_2 is captured first before any biogenic CO_2 is captured.
[2] Overall CO_2 capture rate is calculated as total CO_2 captured / total CO_2 Emissions (without capture) of the recovery boiler, multi-fuel boiler, lime kiln and auxiliary boiler

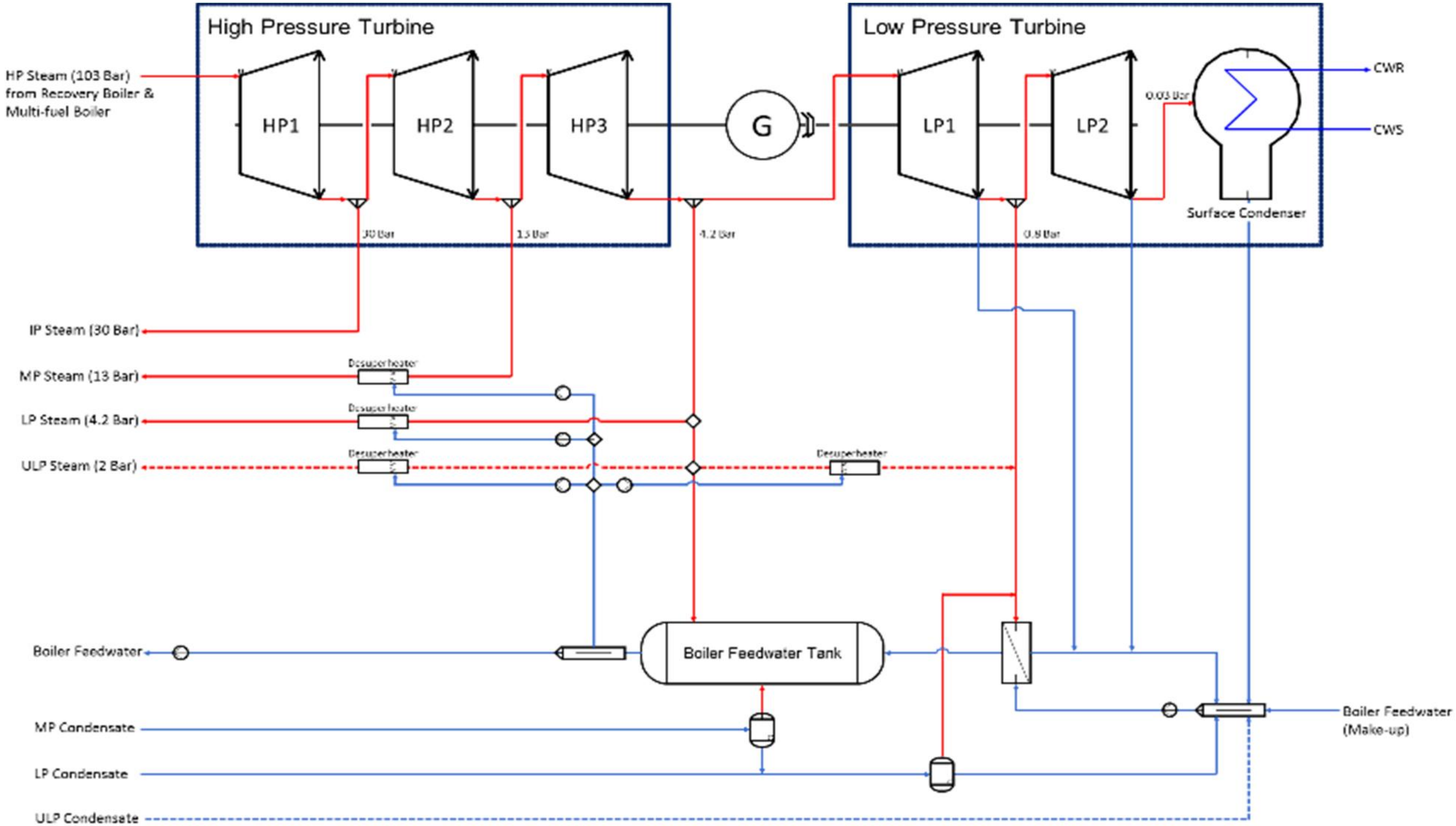
Capture of CO_2 from the Pulp Mill



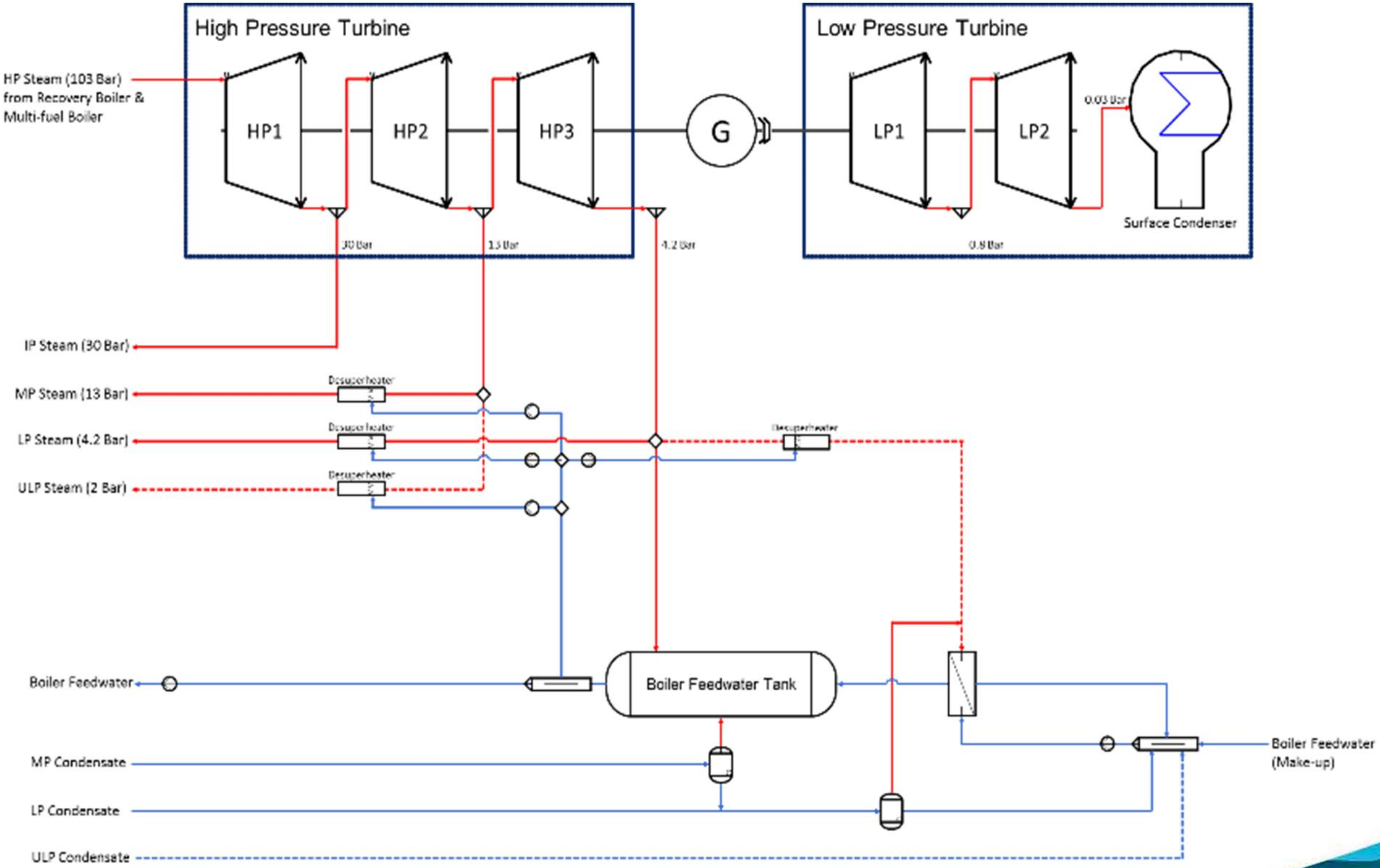
Modification to the Steam Turbine (Reference Cases)



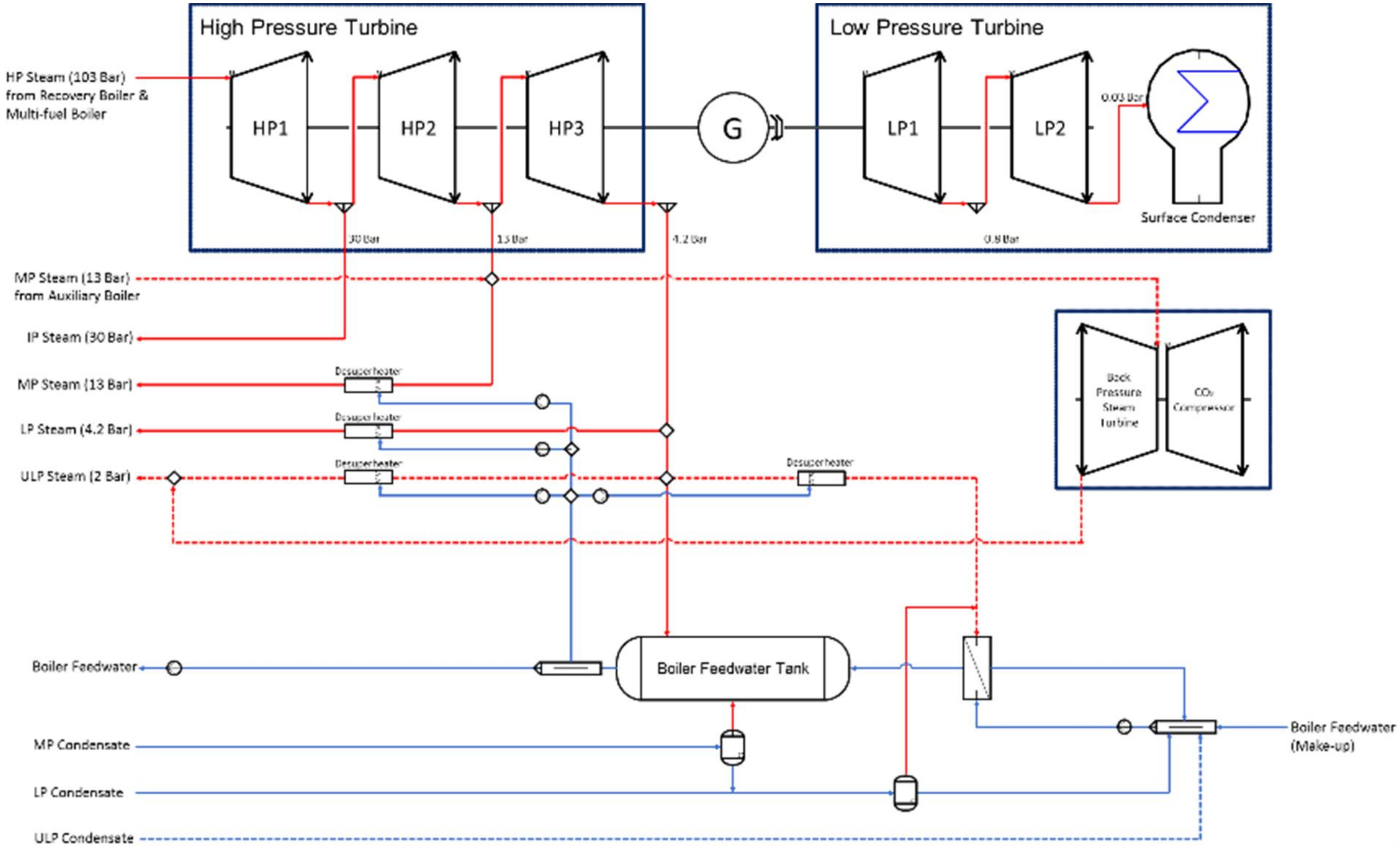
Modification to the Steam Turbine (Configuration I)



Modification to the Steam Turbine (Configuration II)



Modification to the Steam Turbine (Configuration III)



Energy Performance of Pulp Mill with CCS

	Base Case	Pulp Mill w/CCS					
	1A	2A-1	2A-2	2-A3	2A-4	2A-5	2A-6[MP]
Steam Demand							
Pulp Mill							
Steam 30 bar [t/h]	20.4	20.4	20.4	20.4	20.4	20.4	20.4
Steam 13 bar [t/h]	171.0	171.0	171.0	171.0	171.0	171.0	171.0
Steam 4.2 bar [t/h]	255.2	255.2	255.2	255.2	255.2	255.2	255.2
CCS Plant							
Steam 13 bar [t/h]	-	-	-	-	-	-	-
Steam 4.2 bar [t/h]	-	0.9	0.1	0.1	1.1	1.0	1.3
Steam 2.0 bar [t/h]	-	256.0	45.4	30.0	290.6	285.1	336.4
Auxiliary Boiler							
Steam 30 bar [t/h]	-	-	-	-	-	-	-
Steam 4.2 bar [t/h]	-	-	-	-	-	-	-
Steam Supply							
Ex: Steam Turbine							
Steam 30 bar [t/h]	20.4	20.4	20.4	20.4	20.4	20.4	20.4
Steam 13 bar [t/h]	171.0	171.0	171.0	171.0	171.0	171.0	171.0
Steam 4.2 bar [t/h]	255.2	256.2	255.4	255.3	256.4	256.3	256.5
Steam 2 bar [t/h]	-	256.0	45.4	30.0	290.6	285.1	336.4
Ex: Auxiliary Boiler							
Steam 13 bar [t/h]	-	-	-	-	-	-	-
Electricity Demand							
Pulp Mill	61.0	61.0	61.0	61.0	61.0	61.0	61.0
CCS Plant	-	23.5	4.4	2.8	28.5	26.9	31.4
Auxiliary Boiler	-	-	-	-	-	-	-
Total [MWe]	61.0	84.5	65.4	63.8	89.5	87.9	92.4
Electricity Supply							
Ex: Steam Turbine							
HP Section [MWe]	130.4	130.4	130.4	130.4	130.4	130.4	113.7
LP Section [MWe]	37.9	7.7	33.0	34.7	-	4.3	-
Total [MWe]	168.3	138.1	163.4	165.1	130.4	134.7	113.7
Electricity Export to the Grid	107.3	53.6	98.0	101.3	40.9	46.8	21.3

Between 1 to 8 GJ/adt of heat is needed.

For this case, the amount of excess steam available within the pulp mill should be sufficient to cover the additional demand

As a result of retrofitting CCS:

- Increased demand of steam
- Increased demand of electricity.
- reduced electricity production
- **Reduced amount of renewable electricity sold to the grid**

Energy Performance of Pulp Mill with CCS

	Base Case	Integrated Pulp & Board Mill w/CCS					
	1B	2B- ^{CO2MP}	2B-2	2B-3	2B-4^{CO2MP}	2B-5^{CO2MP}	2B-6^{CO2MP}
Steam Demand							
Pulp & Board Mill							
Steam 30 bar [t/h]	20.4	20.4	20.4	20.4	20.4	20.4	20.4
Steam 13 bar [t/h]	167.3	167.3	167.3	167.3	167.3	167.3	167.3
Steam 4.2 bar [t/h]	351.8	351.8	351.8	351.8	351.8	351.8	351.8
CCS plant							
Steam 13 bar [t/h]	-	184.1	-	-	218.6	207.8	241.2
Steam 4.2 bar [t/h]	-	0.9	0.1	0.1	1.1	1.0	1.3
Steam 2.0 bar [t/h]	-	255.7	45.3	31.1	289.3	284.2	335.4
Auxiliary boiler							
Steam 30 bar [t/h]	-	1.3	-	-	2.1	2.0	3.1
Steam 4.2 bar [t/h]	-	2.7	-	-	4.2	4.0	6.3
Steam Supply							
Ex: Steam Turbine							
Steam 30 bar [t/h]	20.4	21.7	20.4	20.4	22.5	22.4	23.5
Steam 13 bar [t/h]	167.3	286.4	167.3	167.3	284.9	279.6	256.5
Steam 4.2 bar [t/h]	351.8	355.4	351.9	351.9	357.1	356.8	359.4
Steam 2 bar [t/h]	-	66.3	45.3	31.1	65.3	71.0	87.8
Ex: Auxiliary Boiler							
Steam 13 bar [t/h]	-	65.0	-	-	101.0	95.5	152.0
Electricity Demand							
Pulp Mill	94.3	94.3	94.3	94.3	94.3	94.3	94.3
CCS Plant	-	7.8	4.4	2.8	9.9	9.2	10.9
Auxiliary Boiler	-	1.6	-	-	2.4	2.3	3.7
Total [MWe]	94.3	103.6	98.7	97.1	106.6	105.8	108.9
Electricity Supply							
Ex: Steam Turbine							
HP Section [MWe]	130.6	124.2	130.6	130.6	124.5	124.5	127.3
LP Section [MWe]	27.1	-	21.8	23.5	-	-	-
Total [MWe]	157.7	124.2	152.4	154.1	124.5	124.5	127.3
Electricity Export to the Grid	63.4	20.6	53.7	57.0	17.9	18.7	18.4

Between 1 to 8 GJ/adt of heat is needed.
For this case, due to the board mill, the excess steam available within the pulp mill is not sufficient to cover this demand in 4 out of 6 cases

- To optimise the energy balance – an auxiliary boiler is added and steam turbine driven CO_2 compressor is used.

As results of retrofitting CCS:

- Increased demand of steam and electricity.
- Lost of electricity production
- **Reduced amount of renewable electricity sold to the grid**

CAPEX due to the Retrofit of CCS

	Total Plant Cost - Pulp Mill / Changes to Mill (for CCS Cases)	Total Plant Cost - CO_2 Capture Plant	Total Plant Cost CO_2 Compression	Project Contingency	Total Plant Cost - TPC	Total Capital Requirement - TCR
	(million €)	(million €)	(million €)	(million €)	(million €)	(million €)
Base Case 1A	798.5	-	-	79.9	878.4	1,341.5
Case 2A-1	9.4	227.9	14.5	25.2	277.0	353.9
Case 2A-2	8.7	61.7	3.9	7.4	81.7	104.0
Case 2A-3	8.4	36.1	2.3	4.7	51.5	65.6
Case 2A-4	9.8	253.1	16.1	27.9	306.9	393.6
Case 2A-5	10.6	239.3	15.2	26.5	291.7	372.8
Case 2A-6[MP]	11.1	264.0	16.8	29.2	321.0	410.8

	Total Plant Cost - Pulp Mill / Changes to Mill (for CCS Cases)	Total Plant Cost - CO_2 Capture Plant	Total Plant Cost CO_2 Compression	Project Contingency	Total Plant Cost - TPC	Total Capital Requirement - TCR
	(million €)	(million €)	(million €)	(million €)	(million €)	(million €)
Base Case 1B	942.6	-	-	94.3	1036.9	1,556.0
Case 2B-1[CO2MP]	33.9	227.9	29.0	29.1	319.9	410.1
Case 2B-2	8.7	61.7	3.9	7.4	81.7	103.9
Case 2B-3	8.4	36.1	2.3	4.7	51.5	65.5
Case 2B-4 [CO2MP]	46.3	253.1	32.2	33.2	364.7	468.0
Case 2B-5 [CO2MP]	45.1	239.3	30.4	31.5	346.3	444.4
Case 2B-6[CO2MP]	51.6	264.0	33.5	34.9	384.0	493.6

OPEX – Market Pulp Mill with CCS

	Base Case 1A	Case 2A-1 (REC)	Case 2A-2 (MFB)	Case 2A-3 (LK)	Case 2A-4 (REC+MFB)	Case 2A-5 (REC+LK)	Case 2A-6[MP] (ALL 3)
1. Fixed Cost							
1a. Direct Labour	€ 7,200,000	€ 8,400,000	€ 8,100,000	€ 8,100,000	€ 8,400,000	€ 8,400,000	€ 8,400,000
1b. Indirect Labour Cost	€ 2,880,000	€ 3,360,000	€ 3,240,000	€ 3,240,000	€ 3,360,000	€ 3,360,000	€ 3,360,000
1c. Other Fixed Cost (incl. Insurance & Local Taxes)	€ 20,000,000	€ 22,769,870	€ 20,816,961	€ 20,514,744	€ 23,079,725	€ 22,916,627	€ 23,210,075
1d. Maintenance	€ 35,139,500	€ 43,469,714	€ 37,590,384	€ 36,689,671	€ 44,399,282	€ 43,909,988	€ 44,796,271
2. Variable Cost							
2a. Raw Materials / Feedstock	€ 185,600,000	€ 185,600,000	€ 185,600,000	€ 185,600,000	€ 185,600,000	€ 185,600,000	€ 185,600,000
2b. Chemicals	€ 27,250,400	€ 30,192,207	€ 27,789,593	€ 27,624,514	€ 30,732,453	€ 30,567,498	€ 31,106,523
2c. Fuel Cost	€ 11,200,000	€ 11,200,000	€ 11,200,000	€ 11,200,000	€ 11,200,000	€ 11,200,000	€ 11,200,000
2d. Other Utilities	€ 6,646,071	€ 12,056,841	€ 7,859,765	€ 7,327,160	€ 11,566,879	€ 11,920,696	€ 13,379,451
2e. Waste Processing & Disposal Charges	€ 1,521,925	€ 1,975,956	€ 1,618,132	€ 1,577,345	€ 2,068,834	€ 2,031,357	€ 2,126,974
3. Other Revenues							
3a. Crude Tall Oil (Sold to the Market)	-€ 15,600,000	-€ 15,600,000	-€ 15,600,000	-€ 15,600,000	-€ 15,600,000	-€ 15,600,000	-€ 15,600,000
3b. Electricity (Sold to the Grid)	-€ 36,068,800	-€ 18,025,600	-€ 32,928,000	-€ 34,036,800	-€ 13,758,400	-€ 15,724,800	-€ 7,156,800
4. Other Cost							
4a. Marketing, Logistics and Distribution	€ 40,000,000	€ 40,000,000	€ 40,000,000	€ 40,000,000	€ 40,000,000	€ 40,000,000	€ 40,000,000
4b. CO_2 Transport and Storage Cost	€ 0	€ 14,787,000	€ 2,706,577	€ 1,878,042	€ 17,495,997	€ 16,667,082	€ 19,376,079

OPEX – Integrated Mill with CCS

	Base Case 1B	Case 2B-1[CO2MP] (REC)	Case 2B-2 (MFB)	Case 2B-3 (LK)	Case 2B-4[CO2MP] (REC+MFB)	Case 2B-5[CO2MP] (REC+LK)	Case 2B-6[CO2MP] (ALL 3)
1. Fixed Cost							
1a. Direct Labour	€ 14,400,000	€ 16,200,000	€ 15,300,000	€ 15,300,000	€ 16,200,000	€ 16,200,000	€ 16,200,000
1b. Indirect Labour Cost	€ 5,760,000	€ 6,480,000	€ 6,120,000	€ 6,120,000	€ 6,480,000	€ 6,480,000	€ 6,480,000
1c. Other Fixed Cost (incl. Insurance & Local Taxes)	€ 28,460,000	€ 31,658,620	€ 29,276,961	€ 28,974,744	€ 32,107,056	€ 31,923,340	€ 32,300,030
1d. Maintenance	€ 41,478,800	€ 50,853,590	€ 43,929,684	€ 43,028,971	€ 52,077,898	€ 51,543,691	€ 52,607,759
2. Variable Cost							
2a. Raw Materials / Feedstock	€ 345,915,556	€ 345,915,556	€ 345,915,556	€ 345,915,556	€ 345,915,556	€ 345,915,556	€ 345,915,556
2b. Chemicals	€ 26,206,779	€ 29,148,586	€ 26,745,972	€ 26,580,893	€ 29,688,832	€ 29,523,877	€ 30,062,902
2c. Fuel Cost	€ 11,200,000	€ 18,750,940	€ 11,200,000	€ 11,200,000	€ 22,932,999	€ 22,294,073	€ 28,857,582
2d. Other Utilities	€ 5,583,751	€ 11,108,421	€ 6,823,652	€ 6,289,366	€ 11,911,663	€ 11,386,750	€ 13,733,341
2e. Waste Processing & Disposal Charges	€ 1,796,134	€ 2,272,759	€ 1,892,342	€ 1,851,555	€ 2,378,150	€ 2,338,762	€ 2,454,016
3. Other Revenues							
3a. Crude Tall Oil (Sold to the Market)	-€ 15,600,000	-€ 15,600,000	-€ 15,600,000	-€ 15,600,000	-€ 15,600,000	-€ 15,600,000	-€ 15,600,000
3b. Electricity (Sold to the Grid)	-€ 21,312,000	-€ 6,915,247	-€ 18,048,000	-€ 19,156,800	-€ 6,004,878	-€ 6,289,372	-€ 6,194,306
4. Other Cost							
4a. Marketing, Logistics and Distribution	€ 56,920,000	€ 56,920,000	€ 56,920,000	€ 56,920,000	€ 56,920,000	€ 56,920,000	€ 56,920,000
4b. CO_2 Transport and Storage Cost	€ 0	€ 14,787,000	€ 2,706,577	€ 1,878,042	€ 17,495,997	€ 16,667,082	€ 19,376,079

Assumption for the economic evaluation of the mill with CO_2 capture

OPEX*
- Operational costs of CO_2 capture plant.
- Effects to pulp mill
- Maintenance 3%
- Labour: 20 total
- Logistics: 10 €/adt
- Sales 25€/adt

CAPEX*
- Retro-fit investment after 10 years
- Pulp mill is running during installation
- 10% contingency
- Start-up costs 10%

Revenues*
- Pulp
- Board
- Crude tall-oil
- Electricity
- (Credits of negative CO_2 emissions or green electricity)

DCF analysis
- Construction 3 years (50%-50%)
- EBITDA basis
- Lifetime 10 years
- IRR 8%
- Pulp price fixed until 10 years.

LCOP
- Estimate the Levelized Cost of Production of pulp and board during last 15 years
- NPV after 25 years is 0€.

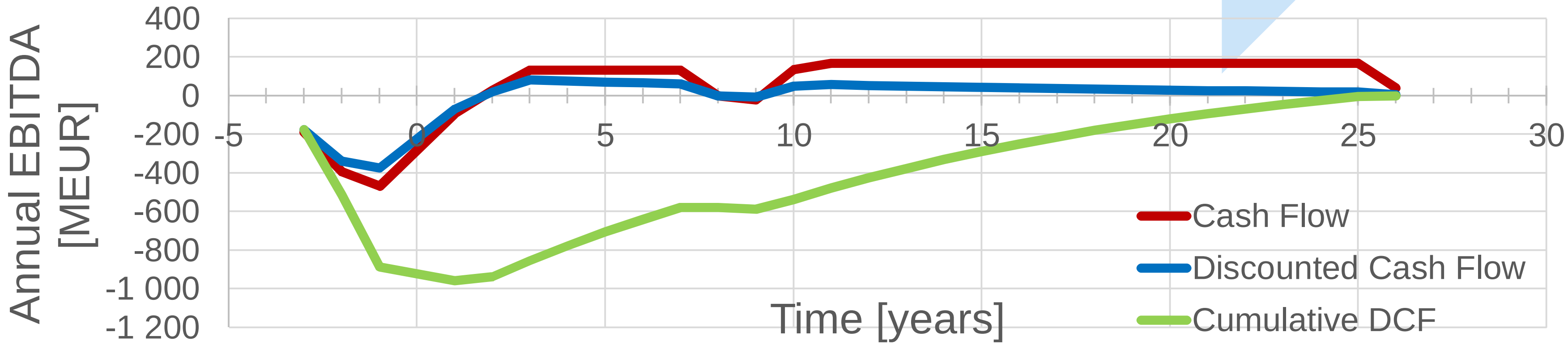


Figure X. Discounted Cash Flow (DCF) analysis conducted for estimating the Levelized Cost of Production (LCOP) for Pulp and Board.

* Costs of raw materials, chemicals, utilities etc are obtained from Kangas et al. 2014, *Nord. Pulp Pap. Res. J.* **29**, 620–634 and adjusted as needed. The investment costs are mainly from the same source.

% CO_2 Avoided

Accounting for the benefit of negative CO2 emissions

- Calculated %CO_2 Avoided if biogenic CO_2 is the same as fossil CO_2 emissions (i.e. no difference between the two types of emissions)

$$\%CO_2 \text{ Avoided} = 100\% \text{ x } \frac{CO_2\text{Emissions}_{\text{Ref.Mill}} - CO_2\text{Emissions}_{\text{Mill with CCS}}}{CO_2\text{Emissions}_{\text{Ref.Mill}}}$$

- Calculated %CO_2 Avoided if biogenic CO_2 emissions is recognised as CO_2 neutral and captured biogenic CO_2 is recognised as "negative CO_2 emissions"

$$\%CO_2 \text{ Avoided} = 100\% \text{ x } \frac{\text{Fossil } CO_2\text{Emissions}_{\text{Ref.Mill}} - (\text{Fossil } CO_2\text{Emissions} - \text{Captured Biogenic } CO_2)_{\text{Mill with CCS}}}{\text{Fossil } CO_2\text{Emissions}_{\text{Ref.Mill}}}$$

% CO_2 avoided - Results

Table 6: % CO_2 avoided for pulp mill with CCS with and without the consideration of "Negative CO_2 Emission"

	% CO_2 Avoided	
	Actual*	with considerations for captured biogenic CO_2 as negative emissions**
Case 2A-1	68%	1707%
Case 2A-2	13%	313%
Case 2A-3	9%	217%
Case 2A-4	81%	2021%
Case 2A-5	77%	1925%
Case 2A-6^{MP}	90%	2238%

* %CO_2 avoided calculated based on Eq. 9.
** %CO_2 avoided calculated based on Eq. 10.

Table 7: % CO_2 avoided for integrated pulp and board mill with CCS with and without the consideration of "Negative CO_2 Emission"

	% CO_2 Avoided	
	Actual*	with considerations for captured biogenic CO_2 as negative emissions**
Case 2B-1^{CO2MP}	61%	1707%
Case 2B-2	13%	313%
Case 2B-3	9%	217%
Case 2B-4^{CO2MP}	70%	2021%
Case 2B-5^{CO2MP}	67%	1925%
Case 2B-6^{CO2MP}	73%	2238%

* %CO_2 avoided calculated based on Eq. 9.
** %CO_2 avoided calculated based on Eq. 10.

Effects of CO_2 Emission Costs for LCOP of Mills with CCS

Scenario #1

- No CO_2 emissions tax nor any incentives to the biogenic CO_2 emissions

Scenario #2

- CO_2 emissions tax at €10/t and the biogenic CO_2 emitted by the mills is not recognized as CO_2 neutral (i.e. biogenic CO_2 is not exempted to the tax).

Scenario #3

- CO_2 emissions tax at €10/t and the biogenic CO_2 is recognized as CO_2 neutral – therefore exempting these emissions from the tax.

Scenario #4

- CO_2 emissions tax at €10/t, the biogenic CO_2 is exempted from the tax and an additional incentive is credited to the Renewable Electricity exported to the grid at 10% of the electricity selling price (at € 4 / MWh for the Base Number).

Scenario #5

- Same condition of Scenario 3 but with added credit to any negative emissions at €10/t.

Scenario #6

- Same condition of Scenario 4 but with added credit to any negative emissions at €10/t.

Levelised Cost of Pulp [€/adt] – Pulp Mill with CCS

	Base Case 1A	Case 2A-1 (REC)	Case 2A-2 (MFB)	Case 2A-3 (LK)	Case 2A-4 (REC+MFB)	Case 2A-5 (REC+LK)	Case 2A-6[MP] (ALL 3)[MP]
Scenario 1	€ 522.62	€ 642.48	€ 553.16	€ 542.68	€ 658.74	€ 651.57	€ 675.30
Scenario 2	€ 549.74	€ 651.05	€ 576.88	€ 567.44	€ 663.92	€ 657.79	€ 678.12
Scenario 3	€ 523.70	€ 643.56	€ 554.25	€ 542.67	€ 659.83	€ 651.56	€ 675.29
Scenario 4	€ 519.18	€ 641.30	€ 550.12	€ 538.40	€ 658.10	€ 649.59	€ 681.55
Scenario 5	€ 523.70	€ 625.02	€ 550.85	€ 541.41	€ 637.89	€ 631.76	€ 652.09
Scenario 6	€ 519.18	€ 622.76	€ 546.72	€ 537.14	€ 636.16	€ 629.78	€ 651.19

- Based on Scenario 1:
  The lowest possible CO_2 avoided cost that could be achieved by Case 2A-5. This is around 77% CO_2 avoided (actual) or a cumulative CO_2 capture of 1.7 million metric tonnes per annum at €62 / t CO_2.

- Based on Scenario 2 or 5:
  With Case 2A-5, the CO2 avoided cost is at €52 / t CO_2.

Levelised Cost of Pulp [€/adt] – Integrated Mill with CCS

	Base Case 1B	Case 2B-1^{CO2MP} (REC)	Case 2B-2 (MFB)	Case 2B-3 (LK)	Case 2B-4^{CO2MP} (REC+MFB)	Case 2B-5^{CO2MP} (REC+LK)	Case 2A-6^{CO2MP} (ALL 3)^{MP}
Scenario 1	€ 522.62	€ 670.08	€ 555.91	€ 544.63	€ 694.04	€ 685.97	€ 712.43
Scenario 2	€ 549.74	€ 679.16	€ 579.35	€ 569.19	€ 700.58	€ 693.45	€ 718.02
Scenario 3	€ 523.70	€ 671.16	€ 557.00	€ 544.53	€ 695.13	€ 685.87	€ 712.33
Scenario 4	€ 519.18	€ 668.60	€ 552.92	€ 540.30	€ 692.69	€ 683.38	€ 709.86
Scenario 5	€ 523.70	€ 651.07	€ 553.32	€ 543.16	€ 671.36	€ 664.41	€ 687.20
Scenario 6	€ 519.18	€ 648.51	€ 549.24	€ 538.93	€ 668.92	€ 661.93	€ 684.73

- Based on Scenario 1:
  The lowest possible CO_2 avoided cost that could be achieved by Case 2B-1^{CO2MP}. This is around 61% CO_2 avoided (actual) or a cumulative CO_2 capture of 1.5 million metric tonnes per annum at €81 / t CO_2.

- Based on Scenario 5:
  With Case 2B-1^{CO2MP}, the CO2 avoided cost is at €71 / t CO_2.

Concluding remarks

Excess energy available for running carbon capture plant

- A standalone Kraft pulp mill should have excess steam and electricity that will be sufficient to cover the demand of the CO_2 capture plant. For integrated pulp mill, the excess steam is not enough to cover demand if 90% of the flue gas from recovery boiler is captured.
- As a consequence, most of the increase in the pulp price due to the cost of retrofitting CCS is mainly attributed to the CAPEX of the CCS and associated modification to the pulp mill.

A potential candidate for large scale demonstration

- The pulp and paper industry is a potential candidate for large-scale demonstration of bio-CCS that accounts for the negative CO_2 emissions. This could be considered as a low-hanging fruit and could lead to the first necessary business case for implementation of bio-CCS in the near future.

Feasibility of deploying CCS is dependent on applied policy framework

- It should be noted that the feasibility of retrofitting CCS will strongly depend on policy framework relevant to the CO_2 emission tax and incentives provided to the renewable electricity exported to the grid and to the negative CO_2 emission.

Negative CO_2 emission credits are most favourable

- Providing higher negative CO_2 emission credit may be the most favourable route to encourage the pulp mill to deploy CCS.

Future studies

Integration of warm water systems (Pulp mill, board mill, CCS)

- Large amount of heat is generated in carbon capture plant (condensers and possibly in compressor)
- How to effectively utilize large amount of low temperature heat?

Utilising excess heat by nearby industry or district heating

- Paper and board mills? Chemical industry? District heating?
- Seasonal variations?
- What if a fully integrate pulp mill is considered. (With deficit of steam available for CCS)
- How will it impact the CCS operation?

Integration of CO_2 capture plant and evaporation plant of pulp mill

- Temperature levels at CO_2 capture plant and evaporation plant are at same level
- Could deeper process integration provide additional benefits for the energy performance?
- Does it make the mill too sensitive for disturbances?

Utilisation of CO_2 within mill

- Not presented in this paper but worthwhile to consider that cases deploying lower capture rate could be favourable for CCU projects rather than CCS projects
- Lignin fractionation with CO_2 at pulp mill or production of precipitated calcium carbonate (PCC) are possible utilisation options.

Thank You, Any Questions?

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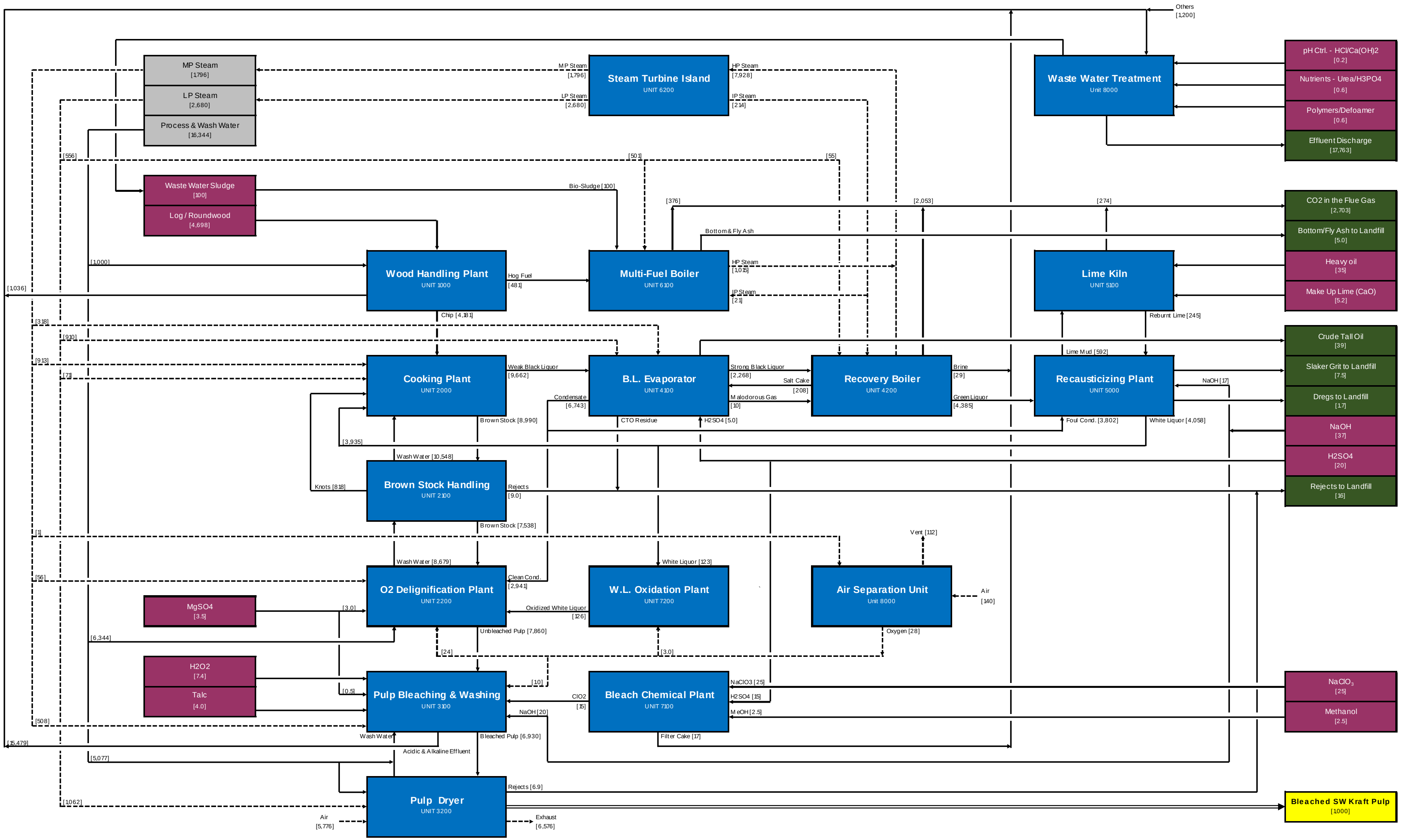
CUSTOMER REPORT: VTT-CR-01312-15

SCHEMATIC BLOCK FLOW DIAGRAM

Base Case 1A: Market Pulp Mill (800,000 adt/y)

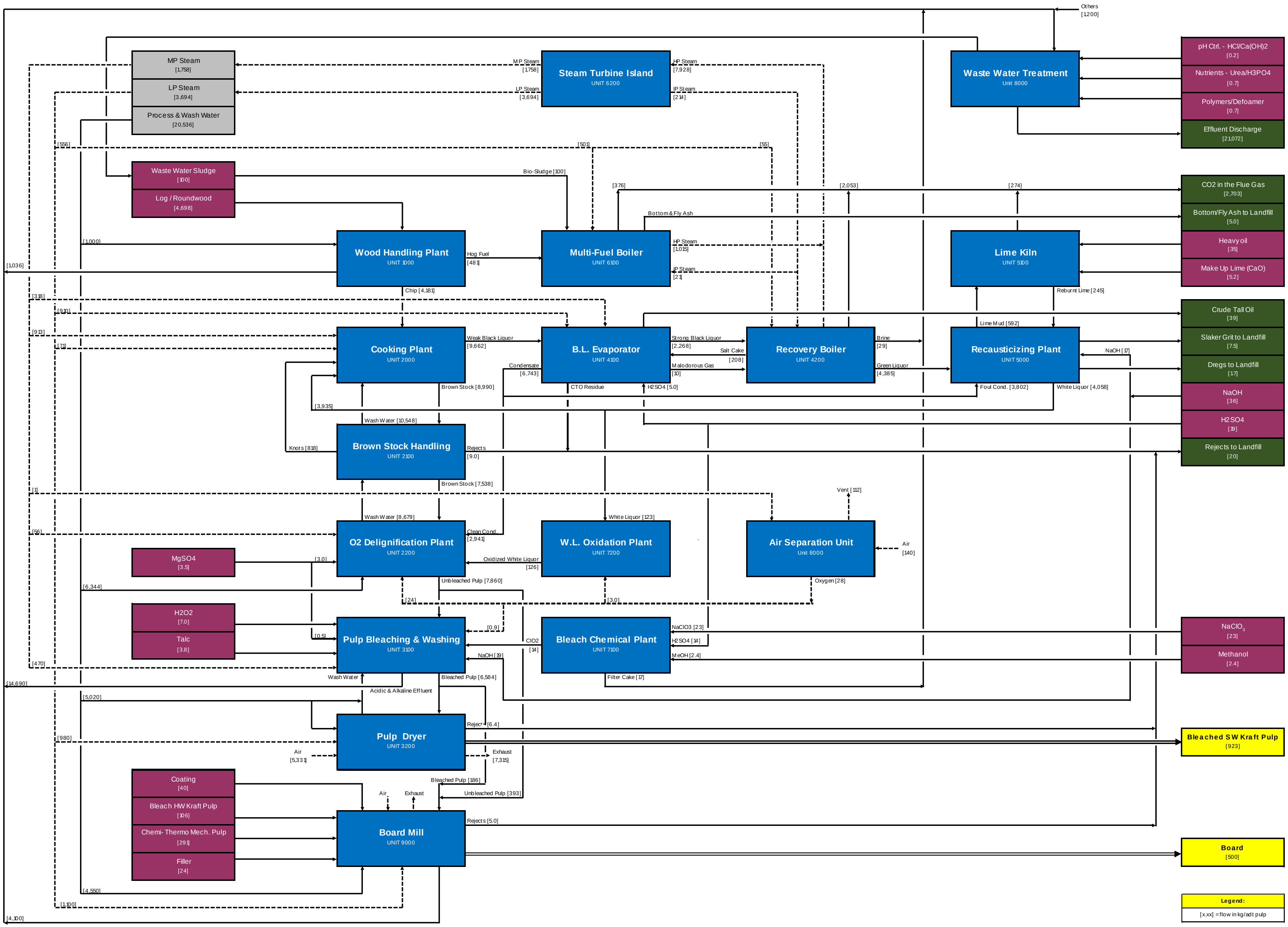
REVISION	DATE	BY	CHKD	APP.	SHEET
5.0	May. 16	SS	PK	PK	1 of 2



Legend:
[x.xx] = flow in kg/adt pulp

CUSTOMER REPORT: VTT-CR-01312-15

SCHEMATIC BLOCK FLOW DIAGRAM	REVISION	DATE	BY	CHKD	APP.	SHEET
Base Case 1B: Integrated Pulp (800,000 adt/y) & Board (400,000 adt/y) Mill	5.0	Oct. 16	SS	PK	PK	2 of 2



Assumptions – TPC & TCR

The TCR of the mills without CO_2 capture (Base Case) includes the following:

- 1% of TPC to cover the spare parts
- Start-up cost which includes:
  - 2% of TPC to cover the start-up CAPEX
  - 2.1% of annual fuel bill to cover additional fuel cost during start-up
  - 25% of annual operating expense (O&M, Fuel and Raw Materials)
  - 8.3% of chemicals cost
- 7% owner's cost
- 8% interest during construction
- Working capital which covers 30 days of feedstock, fuel and other raw materials; and 15 days of finished products.

The TCR for the retrofit of the Pulp Mill or Integrated Pulp and Board Mill with CO_2 Capture includes the following:

- 1% of TPC to cover the spare parts
- 3% of TPC to cover the start-up cost (including all the start-up CAPEX and OPEX)
- 7% owner's cost
- 8% interest during construction
- Additional working capital covering the inventories of the MEA and the make-up solvent