CAPCOM-NL

D3: Process design

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Contents

1 Introduction

In this document, the process design for production of CAPCOM pellets is described. First, the operation units required to the process are identified and disposed in a logical order (Chapter 2). Second, the mass and energy balances are prepared (Chapter 3). Then the equipment is sized (Chapter 4).

2 Starting points

From the results obtained in the studies performed in WP1 and WP2 the following processes must be implemented in the process to produce the CAPCOM pellets:

1) A shredder to reduce the biomass raw material to the required size for the CC SMB;
2) The CC SMB to leach out the problematic inorganics from the biomass raw material (mainly K and Cl). In WP2 it was concluded that the leaching should be done before the steam explosion (SE) process ([1]);
3) A screw press is needed to remove mechanically the maximum possible quantity of water (dewatering) from the biomass solids after the CC SMB. This is done to avoid large energy demands for the thermal heated drying;
4) A thermal heating dryer is needed to tune the moisture of the washed biomass to the required moisture content for the SE process;
5) A SE reactor to upgrade the biomass into a higher energy content commodity material;
6) A post dryer to reduce the moisture to the requirements of the pellets press;
7) A pellet press unit to increase the energy density of the upgraded biomass.

The disposing of the operation units is depicted in Figure 1.

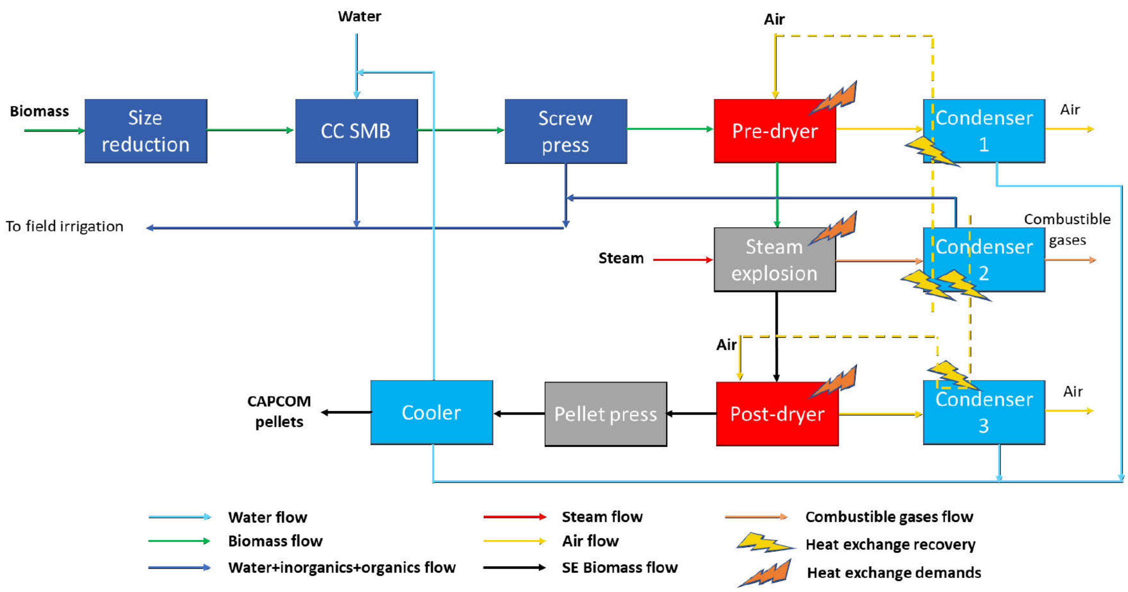

Figure 1 Identified operation units required for the CAPCOM process

From the chemical characterization of the biomasses, the sugar cane bagasse (SCB) is a relatively "clean" feedstock depleted of K and Cl, when compared to the SCT and EFB. Therefore the CC SMB and screw press are of no use and will be ignored in the upgrade of the SCB.
In the following paragraphs the known amounts of biomass materials per average plant mill size will be presented. However, for the process design work, a demo-size installation will be considered treating 9 000 kg/h of dry biomass material input. For the full chain analysis (WP4), involving a techno-economical assessment (TEA) and a life cycle analysis (LCA), the industrial size plant will be considered, upscaling from the demo-size plant case results.

It is assumed that CC SMB and pressing of Sugar cane trash (SCT) will be situated at the sugar mill.
It is assumed that CC SMB and pressing of Empty fruit bunch (EFB) will be situated at the palm oil mill.

For the mass and energy balances the following parameters were considered:

Biomass specific heat capacity	1.8	kJ/kg/K
Air specific heat capacity	1.01	kJ/kg/K
Water specific heat capacity	4.2	kJ/kg/K
Water heat of vaporization	2.4	MJ/kg
Methane higher heating value	55	MJ/kg
Reference temperature	20	°C
Electricity demand size reduction shredder	40	kWh/ton biomass
Electricity demand size reduction chopper	10	kWh/ton biomass
Electricity demand washing/extraction SCT	4.7	kWh/ton biomass
Electricity demand washing/extraction EFB	2.4	kWh/ton biomass
Electricity demand dewatering press	10	kWh/ton biomass
Electricity demand dryer	16	kWh/ton biomass
Electricity demand steam explosion	14	kWh/ton biomass
Electricity demand pellet press	100	kWh/ton biomass

3 Mass and energy balances

3.1 Feed

3.1.1 Sugar Cane Trash

A large sugar mill processes around 292 ton sugar cane per hour [2]. The amount of dry trash that grows is 14% of the amount of fresh cane [3]. It is assumed that 88% of the trash growing in the fields around a sugar mill is harvested and transported to the sugar mill [3]. It is assumed that the leaves are reasonably dry (brown fraction, 85% DM) [3]. All in all, 42 tons of trash per hour will be available at the mill. For the technoeconomic study it will be assumed that two lines of 20 ton trash per hour will be installed. For the process design a dry mass input of 9 000 kg/h will be assumed.

3.1.2 Sugar cane bagasse

Per ton of sugar cane, 140 kg of bagasse DM is produced [2]. Assuming the above mentioned 292 ton sugar cane per hour, this yields a 41 ton DM/hour sugar cane bagasse. Most of the bagasse is burnt to produce steam and electricity to run the process. Increasing boiler efficiencies and sugar mill efficiencies allow more and more bagasse to be sold on the market. Increased efficiencies may allow 30% less bagasse in the boiler[4]. This would yield 12.3 ton DM/hr to be used for pellet production. Another 30% of bagasse could be available if sugar cane trash is used as a boiler feed [4]. So, at a large scale sugar cane mill, up to 25 ton DM/hr could be available for pellet production.

3.1.3 Empty Fruit Bunch

Average oil palm factories process around 60 tonFFB/hr. The EFB yield is 0.215 tonEFB/tonFFB @35% DM. So the dry matter flow is 60*0.215*35% = 4.5 tonDM/hr ([5] and [6]). It is assumed that the empty fruit bunch is pressed and shredded in the palm oil mill for residual oil recovery. The expected dry matter content of pressed material is 45% available for the counter correct extraction.
For the process design a dry mass input of 9 000 kg/h will be assumed as the basis for the DEMO sized plant.

3.2 Unit operations

3.2.1 Size reduction

As verified in WP2, the EFB biomass will need to be shredded and subsequentially chopped in order to reduce the size of the biomass raw material to the required specifications (0.5 x 20 mm) for the CC SMB. The SCT will require just to be chopped (0.5 x 15 mm). The SCB is already delivered with a suitable particle size for the steam explosion reactor.

3.2.2 Counter Current Simulated Moving Bed (CC SMB) extraction

The CC SMB unit is a counter current simulated moving bed extraction. First, water is added to reach the biomass water holding capacity (from that moment, free flowing water is present). Then the extraction liquid flow is chosen to be 1.2 times the biomass water holding capacity. This way an extraction factor of 1.2 is reached. According to the work of Kremser, this should allow full extraction of K and Cl [7].
Based on the experiments and the modelling, it is assumed that 90% of the organic matter remains in the solid phase. It is assumed that 92% of KCl is extracted to the liquid phase in case of EFB and 84% in case of SCT . It is assumed that 50% of the other salts is extracted.

3.2.3 Screw Press

After the CC-SMB extraction, the biomass will contain a lot of water. This water is pressed from the biomass with a screw press. Based on experience, it is assumed that a dry matter (DM) content of 45% and 40% may be reached for the EFB and for the SCT respectively. It is assumed that 98% of the organic matter remains in the solid phase. It is assumed that 30% of KCl is extracted to the liquid phase. It is assumed that 10% of the other salts is extracted.

3.2.4 Pre-dryer

After the screw press, the biomass will have a DM content of 40-45%. However, the SE process requires a maximum moisture content of 50%. Therefore, a thermal dryer needs to be installed to assure that the moisture of the biomass at the inlet of the SE reactor is acceptable. The thermal dryer will be a belt-type and operating at a temperature below 130 °C. Preheated air will be required at 130 °C. In the case of the SCB, no pre-drying is required.

3.2.5 Steam Explosion reactor

The SE reactor is the core of the CAPCOM process. The SE will be done at 210 °C, for a residence time of 15min. A continues system is used at industrial scale. A screw feed the biomass to a horizontal reactor. Pressure is increased to 20 bar. The sudden release of pressure at the end of the reactor creates the explosion effect on the biomass structure. The biomass moisture content at the outlet of the SE reactor was determined to be 55%.

3.2.6 Post-dryer

After the SE reactor the biomass moisture will have to be reduced from 55% to about 10% before pelletization is possible. Therefore, a thermal dryer needs to be installed to assure that the moisture of the biomass at the inlet of the pellet mill is acceptable. The thermal dryer will be a belt-type and preheated air will be required at 130 °C. In the case of the SCB, the post-dryer temperature will be limited to 60 °C, to avoid the destruction of the sugars. The air inlet temperature will be 100 °C.

3.2.7 Pellet mill

A pellet mill will be located after the post-dryer and will work at a temperature around 100 °C with some water addition to optimize the pelletization process. At the outlet of the pellet mill a cooler needs to be installed to bring the pellets to a close environment temperature.

3.3 Mass and energy flows

3.3.1 Size reduction

A shredder will be needed to handle the EFB biomass flow of 9 000 kg/h on dry basis, or 20 000 kg/h wet basis, and to reduce the material size. However, to get a particle size below 20 mm, a chopper will also be needed. For the SCT a chopper will be enough to assure the required particle size. The chopper will handle about 10 588 kg/h wet basis of SCT.
No mass balance is done and presented for size reduction since it is assumed that there are no mass losses in this unit. An energy balance is also not required since there are no thermal needs.
The electricity consumption to chop one ton of the SCT is estimated to be 10 kWh x 10.59 ton/h = 105.9 kW, or 0.11 MW.
The EFB is a more wet and tough material and more difficult to reduce size and a shredder will be needed before chopping. The specific electricity consumption to reduce the EFB size is estimated to be higher than for other types of biomass: 50 kWh x 20.0 ton/h = 1000 kW, or 1.0 MW.
The SCB is already available with the required size for direct feed to the SE reactor and therefore no milling is required.

3.3.2 CC SMB extraction

3.3.2.1 Sugar cane trash

The mass balance for the CCE and dewatering units is presented in Figure 2. After the CCE a press is placed to separate the maximum moisture possible out the washed biomass. As the operations are performed at ambient temperature, no thermal energy is required.

The electricity demand to drive the water pumps and the press is estimated to be about 0.31 MW.

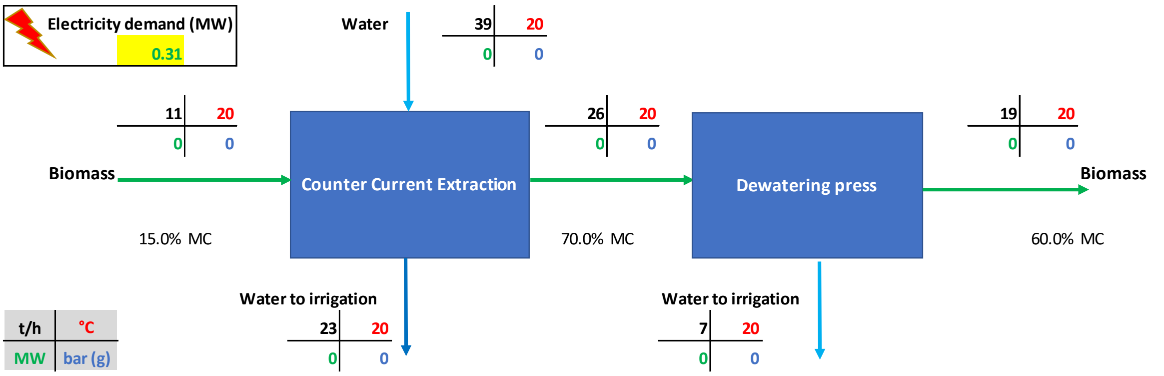

Figure 2 ***Counter-current extraction and dewatering press units process flows for the SCT***

The mass balance of the counter-current extraction and press is presented in Table 1, for the Sugar Cane Trash. The washing is performed with a liquid to dry solids ratio of 4.5 and the biomass mass yield remaining is about 87%. However, the biomass ash yield is just 45% and more important the KCl yield is even more reduced to 16%. The pressing brings extra benefits apart from the moisture reduction after washing from 70 to 60% since the ash and KCl yields are further reduced to 40 and 11% of the initial contents before washing. Consequentially, the dry matter yield is also reduced to 85%.

Table 1 ***Mass balance of Sugar Cane Trash CC SMB extraction and pressing***

Counter Current Extraction				
P-101			L/S	4.49
EF		1.2	EF	1.2
Total	10.588	38.79		
DM	85%		DM	30%
OM	94%		Y_OM	90%
KCleq	0.9%		Y_KCleq	16%
OtherSalts	4.8%		Y_OtherSalts	50%

ton/hr	In			ton/hr	Out		
	S-101	S-102			S-103	S-104	
	Biomass	Water	Total		Residue CCX	Extract	Total
Water	1.59	38.79	*40.38*	Water	18.35	22.03	*40.38*
OM	8.48		*8.48*	OM	7.64	0.85	*8.48*
KCl	0.08		*0.08*	KCl	0.01	0.07	*0.08*
OtherSalts	0.44		*0.44*	OtherSalts	0.22	0.22	*0.44*
Total	10.59	38.79	*49.38*	Total	26.22	23.16	*49.38*
DM	9.00	0.00	*9.00*	DM	7.87	1.13	*9.00*
Ash	0.52	0.00	*0.52*	Ash	0.23	0.29	*0.52*

Press		
P-102	MY_DM	0.85
	MY_Ash	0.40
	MY_KCl	0.11
	sf_Water	62.83%
	DM	40%
	sf_OM	98%
	sf_KCl	70%
	sf_OtherSalts	90%

ton/hr	In		ton/hr	Out		
	S-103			S-105	S-106	
	Residue CCX	Total		Press residue	Press water	Total
Water	18.35	*18.35*	Water	11.53	6.82	*18.35*
OM	7.64	*7.64*	OM	7.48	0.15	*7.64*
KCl	0.01	*0.01*	KCl	0.01	0.00	*0.01*
OtherSalts	0.22	*0.22*	OtherSalts	0.20	0.02	*0.22*
Total	26.22	*26.22*	Total	19.22	7.00	*26.22*
DM	7.87	*7.87*	DM	7.69	0.18	*7.87*
Ash	0.23	*0.23*	Ash	0.21	0.03	*0.23*

3.3.2.2 Empty Fruit Bunch

The mass balance for the CCE and dewatering units is presented in Figure 3. Again, after the CCE a press is placed to separate the maximum moisture possible out the washed EFB. As the operations are performed at ambient temperature, no thermal energy is required.

The electricity demand to drive the water pumps and the press is estimated to be about 0.31 MW.

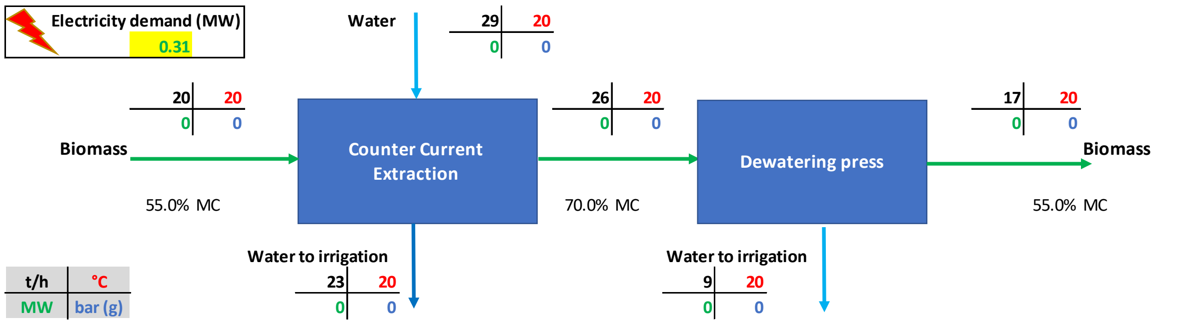

Figure 3 ***Counter-current extraction and dewatering press units process flows for the EFB***

The mass balance of the counter-current extraction and press is presented in Table 2, for the Empty Fruit Branches case. The washing is performed with a liquid to dry solids ratio of 4.4 and the biomass mass yield remaining is about 86%. The EFB ash yield is 26% and the KCl yield is even more reduced to 8% after washing. The pressing brings extra benefits apart from the moisture reduction after washing from 70 to 55% since the ash and KCl yields are further reduced to 22 and 6% of the initial contents before washing. Consequentially, the dry matter yields is also reduced to 84%.
One observation was that the washing was even more efficient for the EFB than for the SCT.

Table 2 ***Mass balance of Empty Fruit Bunch CC SMB extraction and pressing***

Counter Current Extraction				
P-101			L/S	4.40
EF		1.2	EF	1.2
Total	20.00	28.64		
DM	45%		DM	30%
OM	93%		Y_OM	90%
KCleq	4%		Y_KCleq	8%
OtherSalts	3%		Y_OtherSalts	50%

ton/hr	In			ton/hr	Out		
	S-101	S-102			S-103	S-104	
	Biomass	Water	Total		Residue CCX	Extract	Total
Water	11.00	28.64	*39.64*	Water	18.02	21.62	*39.64*
OM	8.41		*8.41*	OM	7.57	0.84	*8.41*
KCl	0.34		*0.34*	KCl	0.03	0.32	*0.34*
OtherSalts	0.25		*0.25*	OtherSalts	0.12	0.12	*0.25*
Total	**20.00**	**28.64**	***48.64***	Total	**25.74**	**22.90**	***48.64***
DM	**9.00**	**0.00**	***9.00***	DM	**7.72**	**1.28**	***9.00***
Ash	**0.59**	**0.00**	***0.59***	Ash	**0.15**	**0.44**	***0.59***

Press		
P-102	MY_DM	0.84
	MY_Ash	0.22
	MY_KCl	0.06
	sf_Water	51.21%
	DM	45%
	sf_OM	98%
	sf_KCl	70%
	sf_OtherSalts	90%

ton/hr	In		ton/hr	Out		
	S-103			S-105	S-106	
	Residue CCX	Total		Press residue	Press watei	Total
Water	18.02	*18.02*	Water	9.23	8.79	*18.02*
OM	7.57	*7.57*	OM	7.42	0.15	*7.57*
KCl	0.03	*0.03*	KCl	0.02	0.01	*0.03*
OtherSalts	0.12	*0.12*	OtherSalts	0.11	0.01	*0.12*
Total	**25.74**	***25.74***	Total	**16.78**	**8.96**	***25.74***
DM	**7.72**	***7.72***	DM	**7.55**	**0.17**	***7.72***
Ash	**0.15**	***0.15***	Ash	**0.13**	**0.02**	***0.15***

3.3.2.3 Sugar cane bagasse

During the sugar mill processing the sugar cane is submitted to a washing step and therefore the SCB is most free of K and Cl and a sequent washing step is not required for the CAPCOM process. Instead, the SCB can go directly for the steam explosion process unit after moisture conditioning (no pre-drying is needed).

3.3.3 Pre-dryer

3.3.3.1 Sugar cane trash

The mass and energy balance for the pre-dryer unit is presented in Figure 4. The biomass water content is reduced from 60 to 50%. At an air inlet temperature of 130 °C about 9.7 ton of air is needed per ton of wet biomass to dry. After the pre-dryer a condenser is placed to separate the excess moisture of the drying air and recover the energy content of the air stream. The energy demand to maintain the drying process is about 2.84 MW, after implementing energy recovery in the condenser 1 and use about 40% of the recovered energy in condenser 2. This represents about 0.75 MW/ton of evaporated water.
In these calculations it is assumed a radiant energy loss of 2% of the inlet energy in the pre-dryer. Furthermore, a 10% energy loss is assumed in each one of the condensers.

The electricity demand to drive the belt and air fans is estimated to be about 0.30 MW.

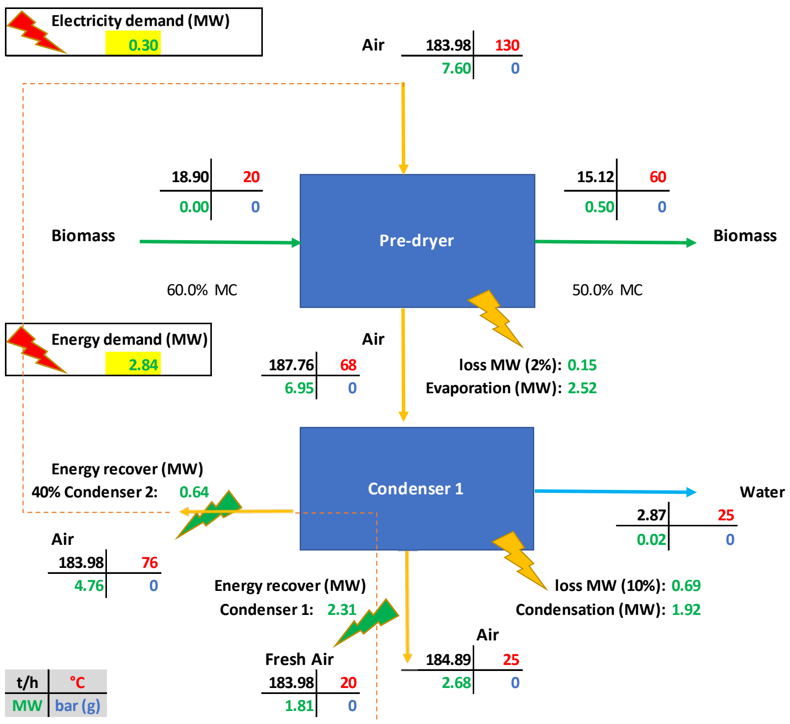

Figure 4 ***Pre-dryer unit process flows for the SCT***

The mass and energy balances of the pre-dryer and for the condenser 1 are presented in Table 3 and Table 4, respectively.

Table 3 ***Mass and energy balance of the pre-dryer for the Sugar Cane Trash case***

Pre-Dryer	**SC Trash**	
units: ton/h	**in**	**out**
Dry SE biomass	7.56	7.56
Moisture	11.34	7.56
Total	18.90	15.12
Dry air	181.26	181.26
Moisture	2.72	6.50
Total	183.98	187.76
units: MW		
Biomass	0.00	0.50
Air	7.60	6.95
Evaporation	0.00	2.52
Loss	-	0.15

Table 4 **Mass and energy balance of the condenser 1 for the Sugar Cane Trash case**

Condenser 1	**SC Trash**	
units: ton/h	**in**	**out**
Dry Air	181.26	181.26
Moisture	6.50	3.63
Water	-	2.87
Total	187.76	187.76
units: MW		
Dry Air	2.45	0.25
Moisture	4.49	2.43
Water	-	0.02
Loss	-	0.69
Energy recovery	-	3.56

3.3.3.2 Empty Fruit Bunch

The mass and energy balance for the pre-dryer unit is presented in Figure 5. The biomass water content is reduced from 55 to 50%. At an air inlet temperature of 130 °C about 5.8 ton of air is needed per ton of wet biomass to dry. After the pre-dryer a condenser is placed to separate the excess moisture of the drying air and recover the energy content of the air stream. The energy demand to maintain the drying process is about 1.50 MW, after implementing energy recovery in the condenser 1 and using 25% of the available energy recovered from condenser 2. This represents about 0.86 MW/ton of evaporated water. In this case most part of the energy recovered from the condenser 2 is also available for the post dryer.

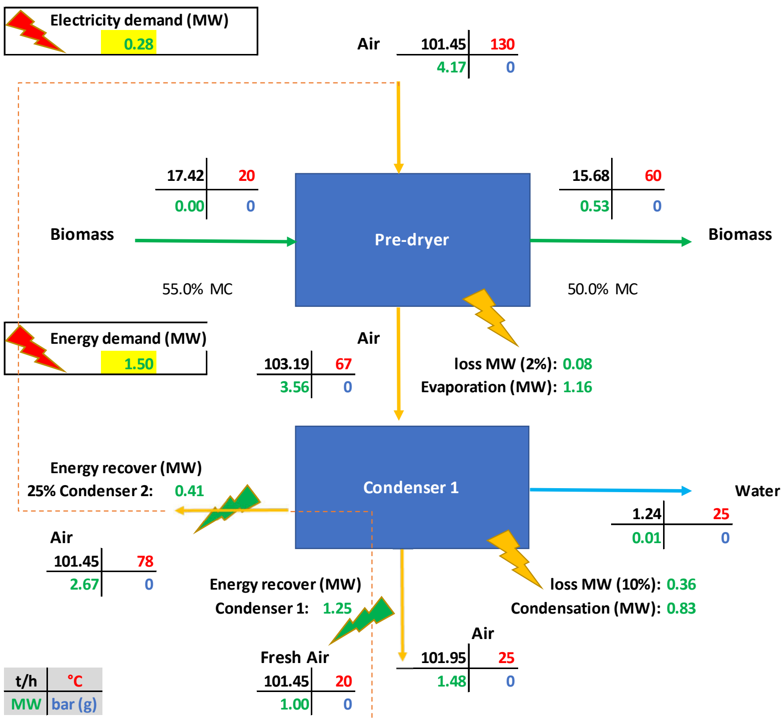

Figure 5 ***Pre-dryer unit process flows for the EFB***

In these calculations it is assumed a radiant energy loss of 2% of the inlet energy in the pre-dryer. Furthermore, a 10% energy loss is assumed in each one of the condensers.
The electricity demand is estimated to be about 0.28 MW.

The mass and energy balances of the pre-dryer and for the condenser 1 are presented in Table 5 and Table 6, respectively.

Table 5 ***Mass and energy balance of the pre-dryer for the empty fruit branches case***

Pre-Dryer	**EFB**	
units: ton/h	**in**	**out**
Dry SE biomass	7.84	7.84
Moisture	9.58	7.84
Total	17.42	15.68
Dry air	99.95	99.95
Moisture	1.50	3.24
Total	101.45	103.19
units: MW		
Biomass	0.00	0.53
Air	4.17	3.56
Evaporation	0.00	1.16
Loss	-	0.08

Table 6 ***Mass and energy balance of the condenser 1 for the empty fruit branches case***

Condenser 1	**EFB**	
units: ton/h	**in**	**out**
Dry Air	99.95	99.95
Moisture	3.24	2.00
Water	-	1.24
Total	103.19	103.19
units: MW		
Dry Air	1.32	0.14
Moisture	2.24	1.34
Water	-	0.01
Loss	-	0.36
Energy recovery	-	1.72

3.3.3.3 Sugar cane bagasse

It is assumed that, after the sugar mill processing, the sugar cane do not require pre-drying and the moisture content is appropriate for the SE reactor feed (max. 50% moisture content).

3.3.4 SE reactor

3.3.4.1 Sugar cane trash

The mass and energy balance for the SE reactor unit is presented in Figure 6. About 3.1 ton/h of dry saturated steam at 220 °C is needed for the SE process. After the SE reactor a condenser is placed to separate the excess moisture of the combustible gases and recover the energy content of the air stream going to pre/post-drying. The energy demand to maintain the SE process is about 2.41 MW. This represents about 0.16 MW/ton of wet biomass.
After the condenser 2, about 1.6 MW are available for heat recovery to be used in the pre/post-dryer.

The electricity demand is estimated to be about 0.21 MW.

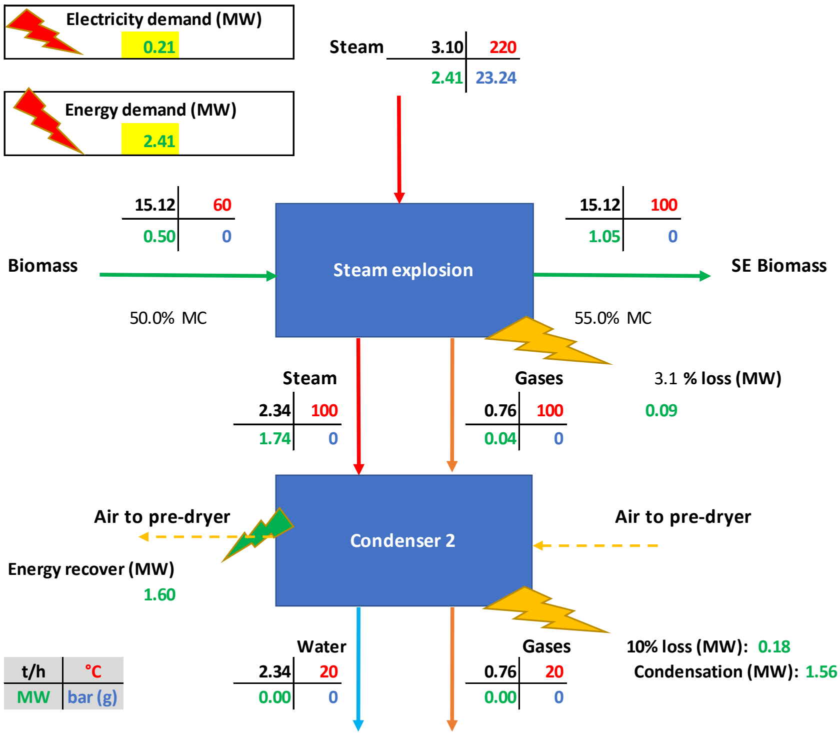

Figure 6 ***SE reactor unit process flows for the SCT***

The mass and energy balances of the SE reactor and for the condenser 2 are presented in Table 7 and Table 8, respectively.

Table 7 ***Mass and energy balance of the SE reactor for the Sugar Cane Trash case***

SE reactor	**SC Trash**	
units: ton/h	**in**	**out**
Dry biomass	7.56	6.80
Water	7.56	8.32
Total	15.12	15.12
Steam	3.10	2.34
Gases	0.00	0.76
Total	3.10	3.10
units: MW		
Biomass	0.50	1.05
Steam	2.41	1.74
Gases	-	0.04
Loss	-	0.09

Table 8 **Mass and energy balance of the condenser 2 for the Sugar Cane Trash case**

Condenser 2	**SC Trash**	
units: ton/h	**in**	**out**
Steam	2.34	2.34
Gases	0.76	0.76
Total	3.10	3.10
units: MW		
Steam/water	1.74	0.00
Gases	0.04	0.00
Loss	-	0.18
Energy recovery	-	1.60

3.3.4.2 Empty Fruit Bunch

The mass and energy balance for the SE reactor unit is presented in Figure 7. About 3.2 ton/h of dry saturated steam at 220 °C is needed for the SE process. After the SE reactor a condenser is placed to separate the excess moisture of the combustible gases and recover the energy content of the air stream going to the pre and post-drying. The energy demand to maintain the SE process is about 2.50 MW. This represents about 0.16 MW/ton of wet biomass.
After the condenser 2, about 1.66 MW are available for heat recovery to be used divided between the pre and post-dryer.

The electricity demand is estimated to be about 0.22 MW.

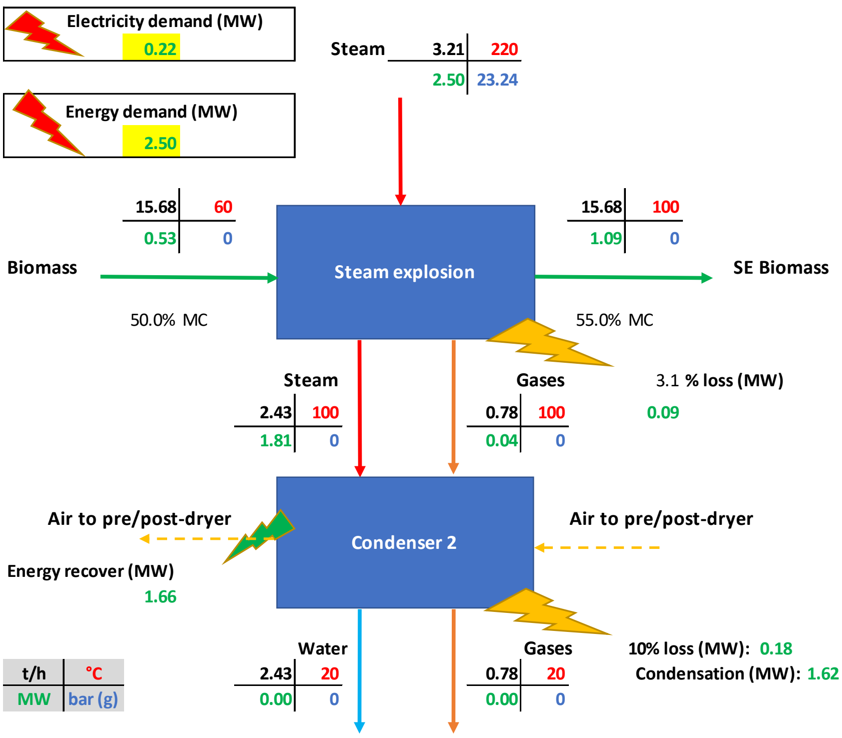

Figure 7 ***SE reactor unit process flows for the EFB***

The mass and energy balances of the SE reactor and for the condenser 2 are presented in Table 9 and Table 10, respectively.

Table 9 ***Mass and energy balance of the SE reactor for the empty fruit branches case***

SE reactor	**EFB**	
units: ton/h	**in**	**out**
Dry biomass	7.84	7.06
Water	7.84	8.62
Total	15.68	15.68
Steam	3.21	2.43
Gases	0.00	0.78
Total	3.21	3.21
units: MW		
Biomass	0.53	1.09
Steam	2.50	1.81
Gases	-	0.04
Loss	-	0.09

Table 10 ***Mass and energy balance of the condenser 2 for the empty fruit branches case***

Condenser 2	**EFB**	
units: ton/h	**in**	**out**
Steam	2.43	2.43
Gases	0.78	0.78
Total	3.21	3.21
units: MW		
Steam/water	1.81	0.00
Gases	0.04	0.00
Loss	-	0.18
Energy recovery	-	1.66

3.3.4.3 Sugar cane bagasse

The mass and energy balance for the SE reactor unit is presented in Figure 8. About 3.7 ton/h of dry saturated steam at 200 °C is needed for the SE process. It is assumed that the SE occurs at milder conditions for the SCB, compared to the SCT and EFB, to minimize the degradation of the residual sugars content. In the case of SCB more energy is required to heat up the wet biomass inflow, when compared to SCT and EFB. Therefore, after SE the biomass leaves at a lower temperature 90 °C and the steam leaves at 100 °C with a dryness of 75%. After the SE reactor a condenser is placed to separate the excess moisture of the combustible gases and recover the energy content of the air stream going to post-drying. The energy demand to maintain the SE process is about 2.86 MW. This represents about 0.16 MW/ton of wet biomass.
After the condenser 2, about 1.5 MW are available for heat recovery to be used in the post-dryer.

The electricity demand is estimated to be about 0.25 MW.

The mass and energy balances of the SE reactor and for the condenser 2 are presented in Table 11 and Table 12, respectively.

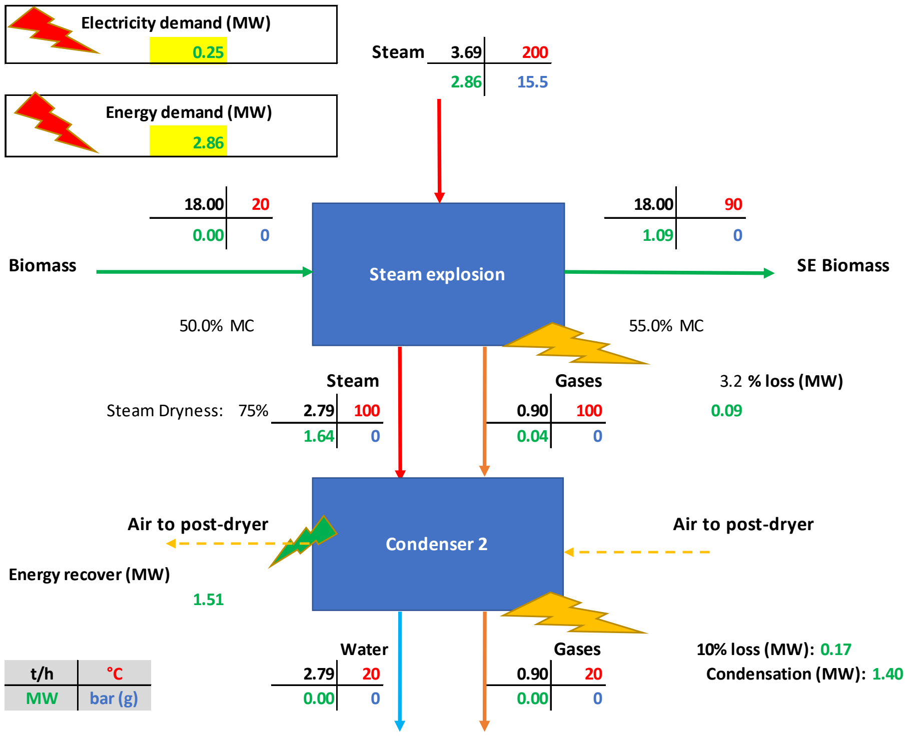

Figure 8 ***SE reactor unit process flows for the SCB***

Table 11 ***Mass and energy balance of the SE reactor for the sugar cane bagasse case***

SE reactor	**SCB**	
units: ton/h	**in**	**out**
Dry biomass	9.00	8.10
Water	9.00	9.90
Total	18.00	18.00
Steam	3.69	2.79
Gases	0.00	0.90
Total	3.69	3.69
units: MW		
Biomass	0.00	1.09
Steam	2.86	1.64
Gases	-	0.04
Loss	-	0.09

Table 12 ***Mass and energy balance of the condenser 2 for the sugar cane bagasse case***

Condenser 2	**SCB**	
units: ton/h	**in**	**out**
Steam	2.79	2.79
Gases	0.90	0.90
Total	3.69	3.69
units: MW		
Steam/water	1.64	0.00
Gases	0.04	0.00
Loss	-	0.17
Energy recovery	-	1.51

3.3.5 Post-dryer

3.3.5.1 Sugar cane trash

The mass and energy balance for the post-dryer unit is presented in Figure 9. The biomass is dried from 55% to 15%, which is a suitable moisture for the inlet of the pelletizer. At an air inlet temperature of 130 °C about 15.8 ton of air is needed per ton of wet biomass to dry. After the post-dryer a condenser is placed to separate the excess moisture of the drying air and recover the energy content of the air stream. The energy demand to maintain the drying process is about 3.36 MW, after implementing energy recovery in the condenser 3 and harvesting about 60% of the energy recovered in condenser 2. This represents about 0.47 MW per ton of evaporated water.
In these calculations it is assumed a radiant energy loss of 2% of the inlet energy in the post-dryer. Furthermore, a 10% energy loss is assumed in each one of the condensers.

The electricity demand is estimated to be about 0.24 MW.

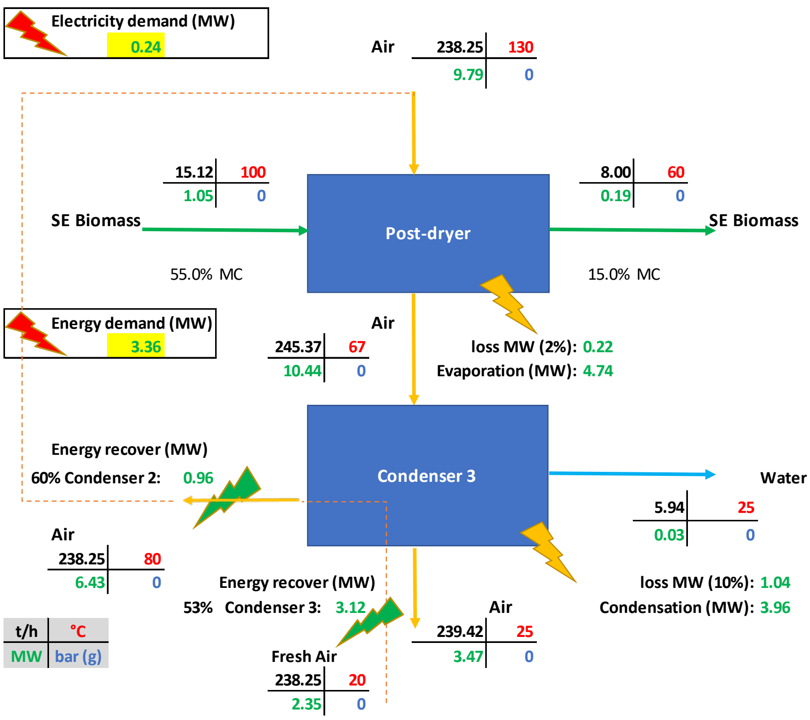

Figure 9 ***Post-dryer unit process flows for the SCT***

The mass and energy balances of the post-dryer and for the condenser 3 are presented in Table 13 and Table 14, respectively.

Table 13 Mass and energy balance of the post-dryer for the Sugar Cane Trash case

Post-Dryer	**SC Trash**	
units: ton/h	**in**	**out**
Dry biomass	6.80	6.80
Moisture	8.32	1.20
Total	15.12	8.00
Dry air	234.73	234.73
Moisture	3.52	10.64
Total	238.25	245.37
units: MW		
Biomass	1.05	0.19
Air	9.79	10.44
Evaporation	-	4.74
Loss	-	0.22

Table 14 Mass and energy balance of the condenser 3 for the Sugar Cane Trash case

Condenser 3	**SC Trash**	
units: ton/h	**in**	**out**
Dry Air	234.73	234.73
Moisture	10.64	4.69
Water	-	5.94
Total	245.37	245.37
units: MW		
Dry Air	3.10	0.33
Moisture	7.35	3.14
Water	-	0.03
Loss	-	1.04
Energy recovery	-	5.89

3.3.5.2 Empty Fruit Bunch

The mass and energy balance for the post-dryer unit is presented in Figure 10. The biomass is dried from 55% to 15%, which is a suitable moisture for the inlet of the pelletizer. At an air inlet temperature of 130 °C about 15.8 ton of air is needed per ton of wet biomass to dry. After the post-dryer a condenser is placed to separate the excess moisture of the drying air and recover the energy content of the air stream. The energy demand to maintain the drying process is about 3.44 MW, after implementing energy recovery in the condenser 3 and use 75% of the energy recovered in condenser 2. This represents about 0.47 MW per ton of evaporated water.

In these calculations it is assumed a radiant energy loss of 2% of the inlet energy in the post-dryer. Furthermore, a 10% energy loss is assumed in each one of the condensers.

The electricity demand is estimated to be about 0.25 MW.

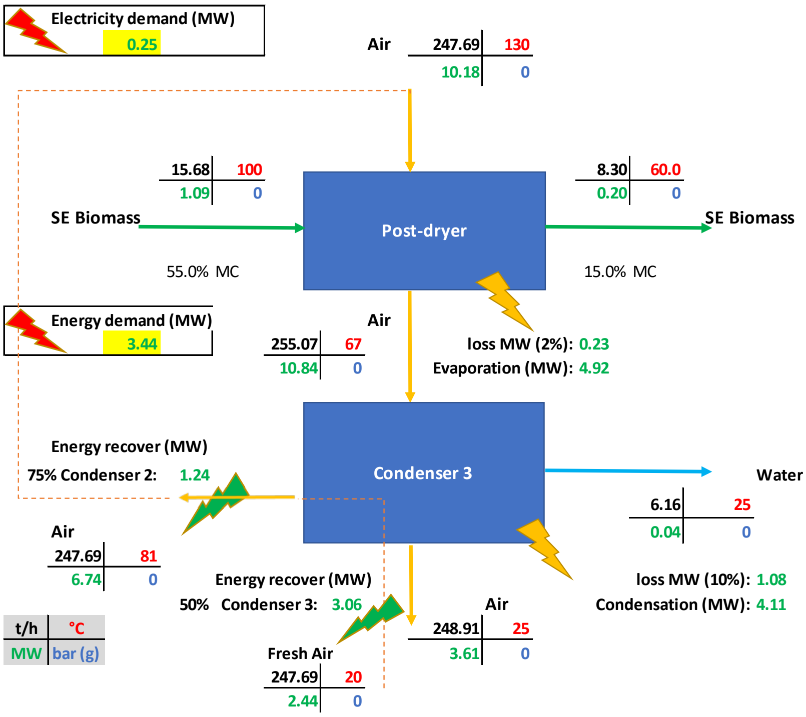

Figure 10 Post-dryer unit process flows for the EFB

The mass and energy balances of the post-dryer and for the condenser 3 are presented in Table 15 and Table 16, respectively.

Table 15 Mass and energy balance of the post-dryer for the empty fruit branches case

Post-Dryer	**EFB**	
units: ton/h	**in**	**out**
Dry biomass	7.06	7.06
Moisture	8.62	1.25
Total	15.68	8.30
Dry air	244.03	244.03
Moisture	3.66	11.04
Total	247.69	255.07
units: MW		
Biomass	1.09	0.20
Air	10.18	10.84
Evaporation	-	4.92
Loss	-	0.23

Table 16 ***Mass and energy balance of the condenser 3 for the empty fruit branches case***

Condenser 3	**EFB**	
units: ton/h	**in**	**out**
Dry Air	244.03	244.03
Moisture	11.04	4.88
Water	-	6.16
Total	255.07	255.07
units: MW		
Dry Air	3.22	0.34
Moisture	7.63	3.27
Water	-	0.04
Loss	-	1.08
Energy recovery	-	6.12

3.3.5.3 Sugar cane bagasse

The mass and energy balance for the post-dryer unit is presented in Figure 11. Compared to the SCT and EFB the post-drying in done at a lower temperature to prevent the decomposition of the sugars still contained in the biomass. The biomass is dried from 55% to 15%, which is a suitable moisture for the inlet of the pelletizer. At an air inlet temperature of 130 °C about 13.7 ton of air is needed per ton of wet biomass to dry. After the post-dryer a condenser is placed to separate the excess moisture of the drying air and recover the energy content of the air stream. The energy demand to maintain the drying process is about 3.75 MW, after implementing energy recovery in the condenser 3 and condenser 2. This represents about 0.44 MW per ton of evaporated water.
In these calculations it is assumed a radiant energy loss of 2% of the inlet energy in the post-dryer. Furthermore, a 10% energy loss is assumed in each one of the condensers.

The electricity demand is estimated to be about 0.29 MW.

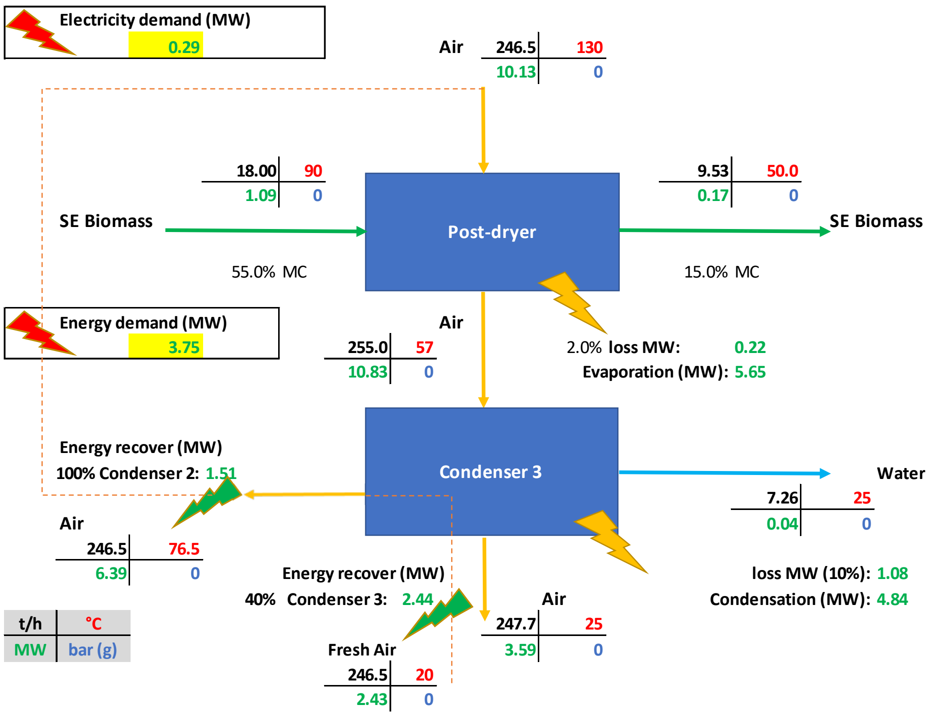

Figure 11 ***Post-dryer unit process flows for the SCB***

The mass and energy balances of the post-dryer and for the condenser 3 are presented in Table 17 and Table 18, respectively.

Table 17 Mass and energy balance of the post-dryer for the sugar cane bagasse case

Post-Dryer	**SCB**	
units: ton/h	**in**	**out**
Dry biomass	8.10	8.10
Moisture	9.90	1.43
Total	18.00	9.53
Dry air	242.88	242.88
Moisture	3.64	12.11
Total	246.52	254.99
units: MW		
Biomass	1.09	0.17
Air	10.13	10.83
Evaporation	-	5.65
Loss	-	0.22

Table 18 Mass and energy balance of the condenser 3 for the sugar cane bagasse case

Condenser 3	**SCB**	
units: ton/h	**in**	**out**
Dry Air	242.88	242.88
Moisture	12.11	4.86
Water	-	7.26
Total	254.99	254.99
units: MW		
Dry Air	2.52	0.34
Moisture	8.31	3.25
Water	-	0.04
Loss	-	1.08
Energy recovery	-	6.11

3.3.6 Pellet press

3.3.6.1 Sugar cane trash

The mass and energy balance for the pellet press unit is presented in Figure 12. The pellet press will need some water (1% of the SE biomass mass) to compensate the losses due to heat generated by friction, which are estimated to be close to 50% of the total electric energy required. After the pellet press a cooler is placed to reduce the pellets temperature close to ambient temperature to allow a safe storage. No thermal requirements are needed in this process, apart from the cooling of the pellets. This can be done with the water coming out from condensers 1 and 3.

The electricity demand is estimated to be about 0.80 MW.

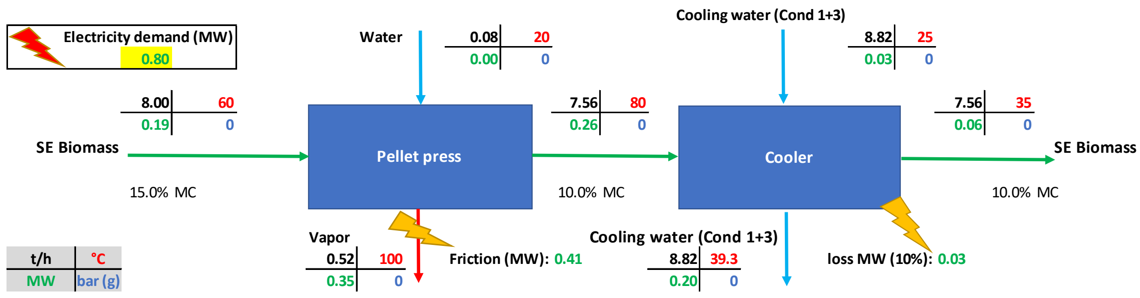

Figure 12 Pellet press unit process flows

The mass and energy balances of the pre-dryer and for the condenser 1 are presented in Table 19 and Table 20, respectively.

Table 19 Mass and energy balance of the pellet press for the Sugar Cane Trash case

Pellet press	**SC Trash**	
units: ton/h	**in**	**out**
Dry biomass	6.80	6.80
Moisture	1.20	0.76
Total	8.00	7.56
Water	0.08	0.00
Vapor	0.00	0.52
Total	0.08	0.52
units: MW		
Biomass	0.19	0.26
Water	0.00	-
Friction	0.41	-
Vapor	-	0.35

Table 20 Mass and energy balance of the cooler for the Sugar Cane Trash case

Cooler	**SC Trash**	
units: ton/h	**in**	**out**
Dry biomass	6.80	6.80
Moisture	0.76	0.76
Cool water	8.82	8.82
Total	16.38	16.38
units: MW		
Dry biomass	0.26	0.06
Cool water	0.03	0.20
Loss	-	0.03

3.3.6.2 Empty Fruit Bunch

The mass and energy balance for the pellet press unit is presented in Figure 13. The pellet press will need some water (1% of the SE biomass mass) to compensate the losses due to heat generated by friction, which are estimated to be close to 50% of the total energy required. After the pellet press a cooler is placed to reduce the pellets temperature close to ambient temperature to allow a safe storage. No thermal requirements are needed I this process, apart from the cooling of the pellets. This can be done with the water coming out from condensers 1 and 3.
The electricity demand is estimated to be about 0.83 MW.

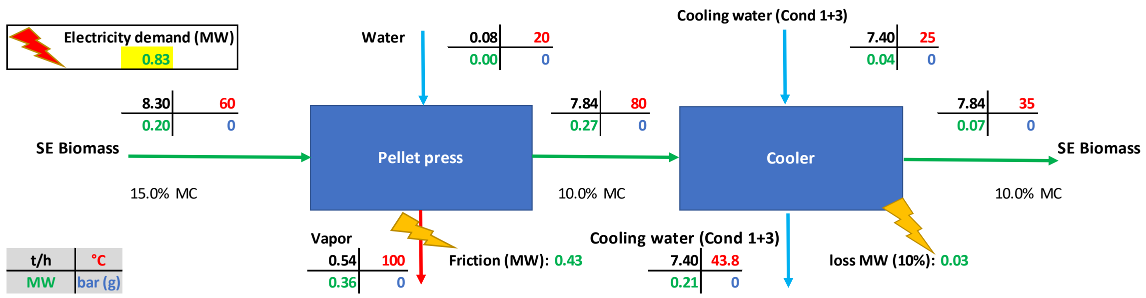

Figure 13 Pellet press unit process flows for EFB

The mass and energy balances of the pre-dryer and for the condenser 1 are presented in Table 21 and Table 22, respectively.

Table 21 Mass and energy balance of the pellet press for the empty fruit branches case

Pellet press	**EFB**	
units: ton/h	**in**	**out**
Dry biomass	7.06	7.06
Moisture	1.25	0.78
Total	8.30	7.84
Water	0.08	0.00
Vapor	0.00	0.54
Total	0.08	0.54
units: MW		
Biomass	0.20	0.27
Water	0.00	-
Friction	0.43	-
Vapor	-	0.36

Table 22 Mass and energy balance of the cooler for the empty fruit branches case

Cooler	**EFB**	
units: ton/h	**in**	**out**
Dry biomass	7.06	7.06
Moisture	0.78	0.78
Cool water	7.40	7.40
Total	15.24	15.24
units: MW		
Dry biomass	0.27	0.07
Cool water	0.04	0.21
Loss	-	0.03

3.3.6.3 Sugar cane bagasse

The mass and energy balance for the pellet press unit is presented in Figure 14. The pellet press will need some water (1% of the SE biomass mass) to compensate the losses due to heat generated by friction, which are estimated to be close to 50% of the total energy required. After the pellet press a cooler is placed to reduce the pellets temperature close to ambient temperature to allow a safe storage. No thermal requirements are needed in this process, apart from the cooling of the pellets. This can be done with the water coming out from condenser 3.
The electricity demand is estimated to be about 0.95 MW.

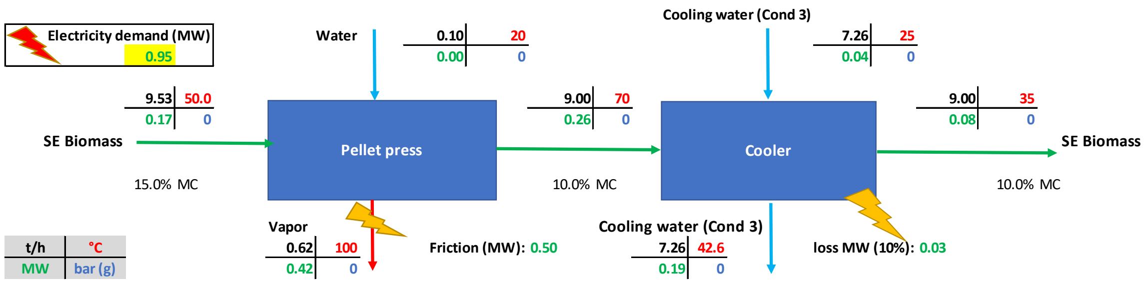

Figure 14 ***Pellet press unit process flows for SCB***

The mass and energy balances of the pre-dryer and for the condenser 1 are presented in Table 23 and Table 24, respectively.

Table 23 ***Mass and energy balance of the pellet press for the sugar cane bagasse case***

Pellet press	**SCB**	
units: ton/h	**in**	**out**
Dry biomass	8.10	8.10
Moisture	1.43	0.90
Total	9.53	9.00
Water	0.10	0.00
Vapor	0.00	0.62
Total	0.10	0.62
units: MW		
Biomass	0.17	0.26
Water	0.00	-
Friction	0.50	-
Vapor	-	0.42

Table 24 ***Mass and energy balance of the cooler for the sugar cane bagasse case***

Cooler	**SCB**	
units: ton/h	**in**	**out**
Dry biomass	8.10	8.10
Moisture	0.90	0.90
Cool water	7.26	7.26
Total	16.26	16.26
units: MW		
Dry biomass	0.26	0.08
Cool water	0.04	0.19
Loss	-	0.03

3.4 Resume of the mass and energy requirements

In the following Table (Table 25) the resume of the mass and energy requirements is presented for each biomass feedstock per process unit. The total needs are referred in the end of the table for each feedstock. This information will be useful for the technoeconomic and life cycle assessments.
The overall mass and energy yield is highest for bagasse because bagasse was already extracted in the sugar cane mill and therefore no further extraction (and consequential losses) was needed. The energy yield of sugar cane trash is lower than for EFB due to a higher loss of soluble organic matter in the extraction phase.

Table 25 ***Resume of the Mass and energy balance per operation unit for the three feedstocks***

	Biomass feedstock					
	SCT		EFB		SCB	
Operation unit	in	out	in	out	in	out
Size reduction						
dry biomass (ton/h)	9.00	9.00	9.00	9.00	n.a.	n.a.
moisture biomass (ton/h)	1.59	1.59	11.00	11.00	n.a.	n.a.
electricity (kW)	106	n.a.	1000	n.a.	n.a.	n.a.
chemical energy biomass_HHV (MW)	47.40	47.40	46.65	46.65	n.a.	n.a.
CC SMB + press						
dry biomass (ton/h)	9.00	7.56	9.00	7.84	n.a.	n.a.
moisture biomass (ton/h)	1.59	11.34	11.00	9.58	n.a.	n.a.
water (ton/h)	38.11	n.a.	30.09	n.a.	n.a.	n.a.
waste water (ton/h)	n.a.	29.79	n.a.	32.66	n.a.	n.a.
electricity (kW)	308	n.a.	315	n.a.	n.a.	n.a.
chemical energy biomass_HHV (MW)	47.40	38.68	46.65	41.85	n.a.	n.a.
chemical energy loss_HHV (MW)	n.a.	8.72	n.a.	4.80	n.a.	n.a.
Mass yield	*0.84*		*0.87*		*n.a.*	
Energy yield	*0.82*		*0.90*		*n.a.*	
Pre-dryer + condenser					n.a.	n.a.
dry biomass (ton/h)	7.56	7.56	7.84	7.84	n.a.	n.a.
moisture biomass (ton/h)	11.34	7.56	9.58	7.84	n.a.	n.a.
dry air (ton/h)	181.3	181.3	99.9	99.9	n.a.	n.a.
moisture air (ton/h)	2.72	3.63	1.50	2.00	n.a.	n.a.
waste water (ton/h)	n.a.	2.87	n.a.	1.24	n.a.	n.a.
electricity (kW)	302	n.a.	279	n.a.	n.a.	n.a.
Heat (MW)	2.80	n.a.	1.50	n.a.	n.a.	n.a.
chemical energy biomass_HHV (MW)	38.68	38.68	41.85	41.85	n.a.	n.a.
SE-reactor + condenser						
dry biomass (ton/h)	7.56	6.80	7.84	7.06	9.00	8.10
moisture biomass (ton/h)	7.56	8.32	7.84	8.62	9.00	9.90
steam (ton/h)	3.10	n.a.	3.21	n.a.	3.69	n.a.
biogas (ton/h)	n.a.	0.76	n.a.	0.78	n.a.	0.90
waste water (ton/h)	n.a.	2.34	n.a.	2.43	n.a.	2.79
electricity (kW)	212	n.a.	219	n.a.	252	n.a.
Heat (MW)	2.41	n.a.	2.50	n.a.	2.86	n.a.
chemical energy biomass_HHV (MW)	38.68	37.06	41.85	39.74	47.93	45.97
chemical energy biogas_HHV (MW)	n.a.	1.62	n.a.	2.11	n.a.	1.96
Mass yield	*0.90*		*0.90*		*0.90*	

Energy yield	*0.96*		*0.95*		*0.96*	
Post-dryer + condenser						
dry biomass (ton/h)	6.80	6.80	7.06	7.06	8.10	8.10
moisture biomass (ton/h)	8.32	1.20	8.62	1.25	9.90	1.43
dry air (ton/h)	234.7	234.7	244.0	244.0	242.9	242.9
moisture air (ton/h)	3.52	4.69	3.66	4.88	3.64	4.86
waste water (ton/h)	n.a.	5.94	n.a.	6.16	n.a.	7.26
electricity (kW)	242	n.a.	251	n.a.	288	n.a.
Heat (MW)	3.36	n.a.	3.44	n.a.	3.75	n.a.
chemical energy biomass_HHV (MW)	37.06	37.06	39.74	39.74	45.97	45.97
Pellet press						
dry biomass (ton/h)	6.80	6.80	7.06	7.06	8.10	8.10
moisture biomass (ton/h)	1.20	0.76	1.25	0.78	1.43	0.90
water (ton/h)	0.08	n.a.	0.08	n.a.	0.10	n.a.
vapor (ton/h)	n.a.	0.52	n.a.	0.54	n.a.	0.62
electricity (kW)	800	n.a.	830	n.a.	953	n.a.
chemical energy biomass_HHV (MW)	37.06	37.06	39.74	39.74	45.97	45.97
Total inputs						
Total dry biomass (ton/h)	9.00		9.00		9.00	
Total moisture biomass (ton/h)	1.59		11.00		9.00	
chemical energy biomass_HHV (MW)	47.40		46.65		47.93	
Total dry air (ton/h)	416.0		344.0		242.9	
Total water (ton/h)	38.19		30.17		0.10	
Total steam (ton/h)	3.10		3.21		3.69	
Total heat (MW)	8.57		7.44		6.61	
Total electricity (MW)	1.97		2.89		1.49	
Total outputs						
Total dry biomass (ton/h)		6.80		7.06		8.10
Total moisture biomass (ton/h)		0.76		0.78		0.90
chemical energy biomass_HHV (MW)		37.06		39.74		45.97
Total dry air (ton/h)		416.0		343.98		242.88
Total waste water (ton/h)		40.95		42.49		10.05
Total waste vapor (ton/h)		0.52		0.54		0.62
Total biogas (ton/h)		0.76		0.78		0.90
Heat content biogas_HHV (MW)*		1.16		1.20		1.38
Final mass yield	*0.76*		*0.78*		*0.90*	
Final energy yield	*0.78*		*0.85*		*0.96*	
required energy/input biomass energy	*0.20*		*0.20*		*0.14*	

n.a. - not applicable

* - The total heat content of the gases formed in the SE-reactor was calculated based on the assumption that the gases have about 10% m/m equivalent concentration in CH_4. The HHV of CH_4 was taken for the calculation. Comparing to the calculated chemical energy of the biogas from the mass and energy balance of the SE-reactor + condenser process it is a fair assumption.

4 Equipment sizing

4.1 CC SMB extraction (simulation)

The simulated moving bed was sized using a model in Mathcad (Appendix D3.1). Based on the experimental results, it is estimated that the characteristic time for mass transfer is around 0.5/hr. The simulation was performed with the following settings:

Extraction factor:	1.2
Number of heaps:	20
Number of switches:	40
Switch time:	2 hours

During start-up of a simulated moving bed, it will take some time for the concentration profile to develop. In Figure 15, this development is clearly seen. At the start of the run (nS = 0), the concentration in all heaps is 1. Heap 19 is fed with fresh biomass after each switch and therefore its concentration is highest. Heap 0 is always washed with fresh elution liquid and fed with biomass from heap 1 that was already washed before, therefore the concentration in heap 0 will quickly drop. In the end, a linear concentration profile will develop (as seen at nS = 40). After 20 switches, the profile is already well developed and a 90% reduction of salts is reached.

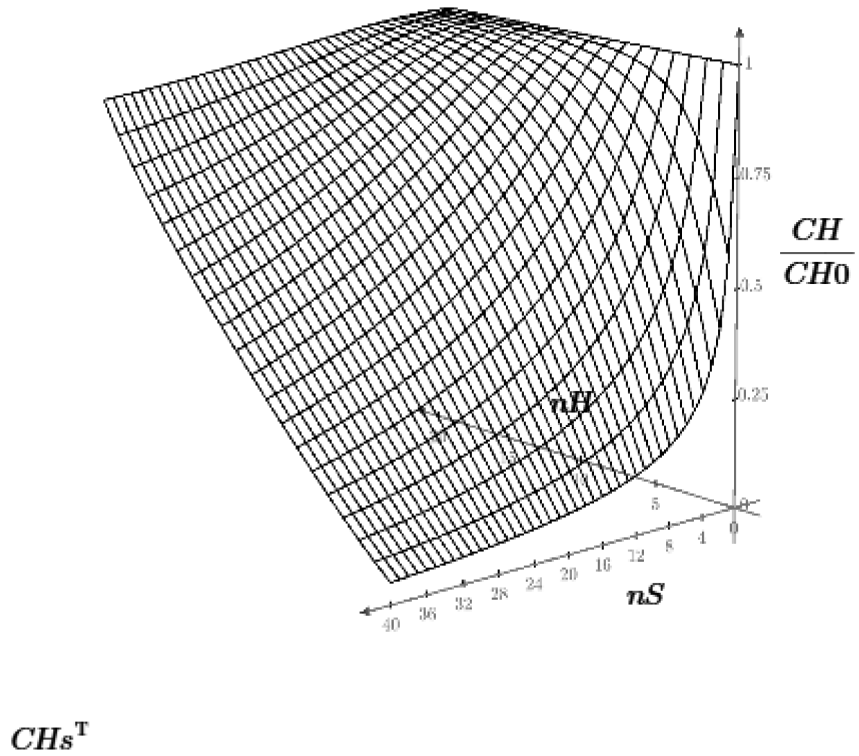

Figure 15 Development of heap concentration profiles over time (nS)

The same data are also presented inFigure 16.

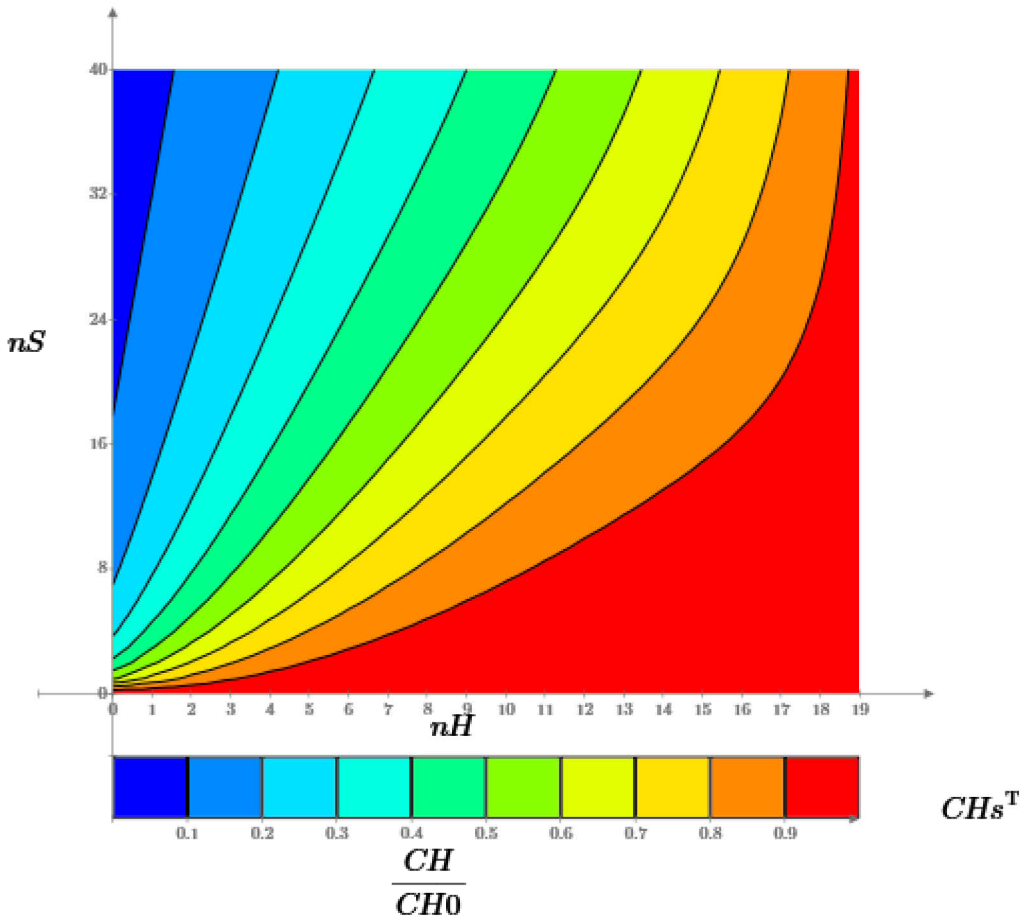

Figure 16 Development of heap concentration profile over time (nS)

From the simulation results we may conclude that it should be possible to reach sufficient (>90%) reduction of salts using a setup with 20 heaps and a 2 hour switch time. This means that in total 24 heaps will be needed (20 in operation, 2 fill/refill and 2 to drip dry). One heap is processed every 2 hours. So if 10 tons of biomass needs to be processed per hour, the volume of one heap should be sufficient to hold 20 tons of biomass (including the (air) void volume).

4.2 SMB (practice)

The SMB CCE installation will consist of heaps on a concrete floor. The floor has gutters with a pump pit for each heap. Here water is collected and pumped to the next column. Conveyer belts are used to transport the biomass to the heaps (it runs over the space where the heaps are). A shovel is used to remove the biomass after washing. The shovel could be replaced by some automatic system to move biomass to another conveyer belt that brings the biomass to the next unit operation (pressing).

4.2.1 Case EFB

Assumed: 9 ton DM/hour
Measured: 122 kgDM/m^3 stacking density

Based on the simulations, the size of the heap dimensions should be as follows:
Heap diameter: 6 m
Heap height: 5.5 m

Based on the heap diameter, the size of the concrete floor and the conveyer belt was estimated:
Concrete floor: 28 m^2/heap x 24 heaps x 2 = 1344 m^2

Conveyer belt: 24 x 6m + 50m = 194 m (belt runs over the columns and 50 m extra needed to connect to the shredder).

In total 25 pumps will be needed (1 per column + 1 to feed the system)
Pumps: 25

4.2.2 Case SCT

Assumed: 9 ton DM/hour
Measured: 58 kgDM/m^3 stacking density

Based on the simulations the dimensions of the heaps should be as follows:
Heap diameter: 8 m
Heap height: 6.5 m

Based on the heap diameter, the size of the concrete floor and the conveyer belt was estimated:
Concrete floor: 50 m^2/heap x 24 heaps x 2 = 2400 m^2
Conveyer belt: 24 x 6.5 + 50 = 206 m (belt runs over the columns and 50 m extra needed to connect to the shredder)

In total 25 pumps will be needed (1 per column + 1 to feed the system
Pumps: 25

5 Literature

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To explore the potential of nature to improve the quality of life

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The mission of Wageningen University & Research is "To explore the potential of nature to improve the quality of life". Under the banner Wageningen University & Research, Wageningen University and the specialised research institutes of the Wageningen Research Foundation have joined forces in contributing to finding solutions to important questions in the domain of healthy food and living environment. With its roughly 30 branches, 6,800 employees (6,000 fte) and 12,900 students, Wageningen University & Research is one of the leading organisations in its domain. The unique Wageningen approach lies in its integrated approach to issues and the collaboration between different disciplines.