Supplementary information

SI. Section 1: Modelling of Pyrolysis plants

Ashes composition is taken from the Aspen database. Bio-oil and gaseous products of biomass pyrolysis are very complex combinations of several compounds and it is not possible to identify them easily. Therefore, it is decided to choose a selected group of compounds based on previous studies on woody biomass pyrolysis: the compound species are simplified by merging one or more species of the same specific class to reduce the number of total compounds and complexity of the pyrolysis model [29]. The species are selected from those available in the Aspen Plus database, therefore thermochemical properties of the selected compounds might be slightly different from the study performed by NREL [29]. SI Table 1 describes the details of species involved in the model.

However, few species are not present in the database of Aspen Plus and these compounds belong to high molecular weight lignin A (β-O-4 oligomeric compounds) and lignin B (phenyl-coumaranic compounds). To overcome this problem, thermochemical properties of these compounds are entered manually in the Aspen plus model using the values taken from literature [29].

SI Table 1: Species present in bio-oil composition

Compound	Modeled specie	Formula
Water insoluble		
high molar weight lignin A components	β-O-4 oligomeric compounds	$C_{20}H_{26}O_8$
Low molar weight lignin A components	Dimethoxy stilbene	$C_{16}H_{16}O_2$
Sulphate compounds	Dibenzothiophene	$C_{12}H_8S$
high molar weight lignin B components	Phenyl-coumaran compounds	$C_{21}H_{26}O_8$
low molar weight lignin B components	Dibenzofuran	$C_{12}H_8O$
Extracts	Dehydroabietic acid	$C_{20}H_{28}O_2$
Nitrogen compounds	2,4,6-trimethylpyridine	$C_8H_{11}N$
Water soluble		
Alcohols	1,4-Benzenediol	$C_6H_6O_2$
Acids	Crotonic acid	$C_4H_6O_2$
Aldehydes	3-Methoxy-4-Hydroxybenzaldehyde	$C_8H_8O_3$
Ketones	Acetol (Hydroxyacetone)	$C_3H_6O_2$
Guaiacol	Isoeugenol	$C_{10}H_{12}O_2$
High molecular weight sugars	Cellobiose	$C_{12}H_{22}O_{11}$
Low molecular weight sugars	Levoglucosan	$C_6H_{10}O_5$

Solid species such as sulfur, carbon, bauxite and sand (pure SiO_2) are assumed as conventional solids and their thermochemical and structural composition is already defined in Aspen database. Properties of biomass and ashes are introduced in Aspen Plus according to the data in SI Table 2.

The thermodynamic properties of all gaseous and liquid species in the model are simulated in Aspen Plus using RSK-BM (Redlich-Kwong-Soave equation with Boston-Matias) function. This method is recommended by Aspen for process modeling of petrochemical applications, refinery processes and gaseous species e.g. ethylene plants and gas plants [30]. . Auxiliaries are considered the 0.8% of the heat exchanged at all components [55].

SI Table 2: Properties of unconventional components defined in Aspen model

Ashes	Biomass

Property	Calculation method	Code	Calculation method	Code
Specific heat	Cubic correlation	2 (CP2C)	Modified correlation for biomass [33]	1 (CP1C)
Standard heat of formation	From heat of combustion	1	From heat of combustion	1
Basis of enthalpy	Standard value at 298.2 K & 1 bar	1	Standard value at 298.2 K & 1 bar	1
Heat of combustion	BOIE correlation standard	1 (BOIEC)	HHV on dry bases (user-defined)	6 (HCOMB)

SI Table 3: Assumptions of dryer section used in modeling [29]

Parameters assumed	Stream	Value
Inlet gas pressure	16	1.15 bar
O_2 content in gases	16	< 10% mol
Outlet gas pressure	17	1.08 bar
Temperature of air	25	32.2 ^oC
Moisture in biomass at outlet	02	10%

SI Table 4: Assumption used in pyrolysis reactor modeling

Parameter assumed	Value
Pyrolyzer outlet pressure	1.22 bar
Pyrolyzer outlet temperature	434^oC
Biomass conversion	100%
PHC to dry biomass mass ratio	14.5
Thermal losses of pyrolyzer	1% of Biomass Q_{LHV}
Fluidization gas flow to biomass mass ratio	3

SI Table 5:Assumptions used in bio-oil recovery modeling

Parameters	Stream/Component	Value
Gas flow temperature after quenching	10	45^oC
Pressure after quenching	10	1.24 bar
Temperature of volatiles leaving 1st quencher	9	70^oC
Compression ratio	Compressor	1.59
Solid filter removal efficiency	Quencher	100%
Bio-oil filter leak	Quencher	3% by weight
Compressor electro-mechanical efficiency	Compressor	90%
Compressor isentropic efficiency	Compressor	72%
Oil outlet temperature	07	54^oC

Percentage gas share to combustor	Splitter	2%
Percentage gas share to pyrolyzer	Splitter	96%

SI Table 6: Assumptions used in combustion section modeling

Parameters	**Stream/Component**	**Value**
Combustor outlet temperature	18-19	609 ^{o}C
Excess air	Combustor	25%
Thermal loss	Combustor	1% Biomass Q_{LHV}
Compression ratio	Compressor-2	1.43
Ash removal filter efficiency	SEP-02	100%
PHC removal filter efficiency	SEP-01	100%

SI Table 7: Parameters used in CSP based modeling based on changes made in conventional pyrolysis model

Parameters	**Stream/Component**	**Value**
PHC-char separation efficiency	Solid separator	100%
Char by-product kg_{char}/kg_{fixedC}	Biochar	1.2
Sludge by-product kg_{Sludge}/kg_{fixedC}	Sludge	2.6
Temperature difference at receiver and reactor outlets	CSP/PYRO	175˚C
PHC temperature at pyrolyzer inlet	CSP	609˚C
PHC types used in model	CSP	Sand/CARBO ACCUCAST ID 50

SI. Section 2: Model validation with reference case

Model validation

Model results are compared to the ones obtained by Jones et al. [29]. The product comparison in SI Table 8 illustrates the elemental compositions of different products, which is consistent with Jones et al. [29], therefore the model developed in this work can be considered satisfactory. However, the calorific values (HHV) of the oil and char are slightly higher due to different thermal properties of species in Aspen libraries and database (see section 2.2).

SI Table 8: The product compositions and its comparison with literature

Product	**Compound or property**	**Jones et al.** [29]	**This study**
Bio-oil	Mass fraction of dry biomass	64%	64.09%
	Carbon	56.61%	56.61%
	Hydrogen	6.61%	6.61%
	Oxygen	36.77%	36.78%
	HHV (MJ/kg)	16.9	17.56

Reaction water	Mass fraction of dry biomass	12%	12%
Gases	Mass fraction of dry biomass	12%	12%
	CO	46%	46.1%
	CO_2	43%	43.5%
	CH_4	6%	6.1%
	C_2+	5%	4.2%
	H_2	<1%	0.03%
Char & Ash	Mass fraction of dry biomass	12%	12%
	Ash	7.69%	7.6%
	Carbon	83.2%	82.8%
	Hydrogen	1.14%	1.67%
	Oxygen	6.58%	6.54%
	Nitrogen	1.37%	1.37%
	HHV (MJ/kg)	28.81	29.6

SI. Section 3: Physical properties of PHC

Two types of PHC material Accucast ID 15 and Sand are used for CSP plant modelling. The physical properties of PHC assumed during CSP modeling are provided below.

SI Table 9: PHC physical properties

Properties	**ACCUCAST ID 50**	**SAND**	**References**
Solar absorptivity (-)	0.906	0.550	[56], [57]
Thermal emissivity (-)	0.754	0.715	[56]
Density (kg/m^3)	3300	2650	[56], [58]
Specific heat (J/kgK)	$365 \cdot T^{0.18}$	1000	[57], [58]
Diameter (μm)	280	280	[57], [58]

SI. Section 4: Economic assumption and breakdown of costs.

In economic analysis some assumptions were considered which are described below. Moreover, the detailed description and break down of fix cost, fixed variable cost and variable operation cost of pyrolysis plant are described. The correlation used and economic parameters used for CSP plant economic analysis are also given in this section.

Towler & Sinnott correlation [59] (equation SI-1) is used to estimate the purchase cost of cylindrical combustor/furnace based on required heat duty (*D*) for both solid char and gas combustors. In this equation a and b are constant having value of 80000 and 109000 respectively while n is the exponent factor equal to 0.8. This cost is scaled according to selected year of 2019 using $CEPCI_{2019}$.

$$C_p = a + bD^n \quad \text{(SI-1)}$$

SI Table 10: Economic assumptions

Description	**Value assumed**
Discount rate (i) (DR)	10%
Investment finance with debt/equity	60% / 40%
Debt interest rate	8% per year
Debt financing term	10 years
Plant's useful life	30 years
Taxes on profits	35%
Working capital cost	5% of the FCI
Capital amortization	7 years according to the MACRS program
Duration of construction	3 years (8% for the first year, 60% for the second and 32% for the third year)
Duration of start-up	6 months
Costs during the start-up and revenues	Variable costs: 75% of the nominal value
	Fixed costs: 100% of the nominal value
	Revenues: 50% of the nominal value
Euro to USD exchange rate	1.09

SI Table 11: Reference year price index and direct cost in 2019 of the various components of the plant without CSP and hybrid

Components	Ref. year	CEPCI	C_x **(TPC) €M in 2019**	f *installation*	C_{inst} **(TIC) M€ in 2019 (Conventional)**	C_{inst} **(TIC) M€ in 2019 (CSP based)**	C_{inst} **(TIC) M€ in 2019 (Hybrid)**
Plant (Pyrolizer, and oil recovery system)	2009	521.9	3.18	2.7	8.53	8.53	8.53
Solid char combustor	2010	550.8	0.31	3.0	0.94	-	0.94
Gas combustor	2010	550.8	0.16	3.0	-	0.48	0.48
Biomass pretreatment	2005	468.2	0.50	2.47	1.24	1.24	1.24
Utilities and auxiliaries	2005	468.2	0.17	2.93	0.48	0.48	0.48
Total			**-**	**-**	**11.19**	**10.78**	**11.67**

SI Table 12 shows the breakdown of total capital investment (TCI) for the pyrolysis plant in its basic configuration working without a CSP section.

SI Table 12: The breakdown of the total capital investment of the pyrolysis plant with basic configurations

	Conventional M€	CSP based M€	Hybrid M€

Total purchase cost (TPC)		4.16	4.01	4.32
Total Installed cost (TIC)		11.19	11.42	11.84
Other direct costs	Assumptions/Considerations			
Material stock up	4% of TPCs	0.17	0.16	0.17
Additional components	4.5% of TPCs	0.19	0.18	0.19
Site development	10% of TPCs	0.42	0.40	0.43
Land cost		0.10	0.10	0.10
Total direct costs (TDC)		12.05	11.57	12.56
Indirect costs	60% of the TDC	7.23	6.94	7.54
Total fixed capital (FCI)		**19.29**	18.51	20.10
Working capital	5% of the mutual funds	0.96	0.93	1.01
Total capital investment (TCI)		**20.25**	19.43	21.11

SI Table 13: CSP cost parameters and factor

Parameter	**Value**	**Reference**
Land specific cost c_{land} (€/m^2)	1.75	[47]
Heliostat specific costs c_{hel} (€/m^2)	133	[31]
Heliostat field preparation costs $c_{field,prep}$ (€/m^2)	14.67	[31]
Receiver specific cost c_{rec} (€/m^2)	34312	[41]
Tower specific costs c_{tow} (€/m$^{1.9274}$)	148.4	[37]
Thermal Energy Storage (TES) specific cost c_{TES} (€/m^2)	1000	[60]
Particles specific cost $c_{particles}$ (€/kg)	1.4	[35]
Particle elevator specific cost $c_{elevator}$ (€·s/m·kg)	53.55	[41]
Contingencies factor $f_{contingencies}$	7%	[61]
Construction factor $f_{construction}$	13%	[61]

SI Table 14 summarizes the breakdown of costs of optimized plant components for both hybrid and CSP based.

SI Table 14: CSP cost correlations and final cost of components for optimized case

Component	**Correlation**	**CSP**	**Hybrid**	**Reference**

		(M€)	(M€)	
Heliostat field	$C_{hel,field} = (c_{hel} + c_{field,prep}) \cdot A_{hel}$	3.32	2.35	[41]
Receiver	$C_{rec} = c_{rec} \cdot A_{aperture}$	0.69	0.49	[41]
Tower	$C_{tow} = c_{tow} \cdot H_{tow,opt}^{1.9274}$	0.20	0.15	[37]
Thermal Energy Storage (TES)	$C_{TES,\,hot/cold} = c_{TES} \cdot \left(1 + 0.3 \cdot \frac{T_{TES,hot/cold} - 600}{400}\right) \cdot A_{TES}$	0.72	0.68	[60]
Particles	$C_{particles} = 1.1 \cdot c_{particles} \cdot m_{particles}$	0.04	0.04	[37]
Particle elevator	$C_{elevator} = c_{elevator} \cdot H_{elevator} \cdot \dot{m}_{particles}$	0.16	0.09	[41]
Fixed capital investment	$FCI = C_{hel,field} + C_{rec} + C_{tow} + C_{TES,\frac{hot}{cold}} + C_{particles} + c_{elevator}$	5.14	3.82	-
Total direct cost	$C_{direct} = (1 + f_{contingencies}).FCI$	5.50	4.1	[41]
Land Cost	$C_{Land} = c_{land} \cdot A_{Land/m2}$	0.3	0.2	[29]
Total Indirect cost	$C_{indirect} = (f_{construction.}\ C_{direct}) + C_{Land}$	1.01	0.73	[41]
Total Capital investment (TCI)	$C_{Total} = C_{direct} + C_{indirect}$	6.51	4.8	[41]

The number of employees is assumed on two factors: the size of the plant and the day considered to have three shifts. Contrarily, the wages are obtained from the literature with respect to 2011 and scaled up for the reference year 2019 using the indices from American Bureau of Labor Statistics Data [62], where the reported salary indices in 2011 and 2019 are 21.46 and 25.46 respectively. Moreover, employee benefits are also taken into account along with their respective costs assuming to be equal to 90% of the total salaries, while 0.7% of the mutual fund is estimated for the expenses for taxes and insurance whereas, the maintenance costs are assumed to 3% of the total FCI. SI Table 17 illustrates the breakdown of fixed operation cost and assumptions.

SI Table 15: Variable operating costs in pyrolysis plant

Commodities	**Consumption**	**specific cost**	**Cost €/h**	**Annual cost €/y**
Biomass	54.7 ton/d	17.05 €/t	35.5	340,275
Electricity	374 kWh/h	0.06 €/kWh	23.7	207,395
makeup water	0.65 m^3/h	0.20 €/ m^3	0.1	1,149
makeup PHC	0.08 ton/d	45.3 €/ton	0.1	1,263
Ash disposal	2.3 ton/d	17 €/ton	1.6	13,983
water disposal	0.48 gpm	0.03 €	0.7	6,944
Total variable operative cost				571,009

SI Table 16: Number of staffs hired and wages

Job	**Positions**	**Specific salary, €/y**	**Wages, €/y**
Plant engineer	1	83,594	83,594
maintenance supervisor	1	68,138	68,138
Operation supervisor	2	57,362	114,725
Laboratory technician	1	47,784	47,784
maintenance technician	2	47,784	95,568
Turn operators	6	57,362	344,174
construction site clerk	3	33,416	100,248

Administrative clerk	1	42,995	42,995
Total Salaries	**17**		**897,226**

SI Table 17: Fixed operating cost of pyrolysis plant

Entities	Assumptions/Considerations	Conventional M€/y	CSP based M€/y	Hybrid M€/y
Benefits and overhead	90% of total salaries	0.81	0.81	0.81
maintenance	3 % of FCI	0.58	0.56	0.60
insurance & taxes	0.7% of FCI	0.13	0.13	0.14
Total Salaries	-	**0.9**	**0.9**	**0.9**
Fixed Operation cost	-	**2.42**	**2.39**	**2.45**

SI Table 18: The operational cost of solar plant for optimized CSP and hybrid cases

Entities	CSP-based Cost €	Hybrid pyrolysis Cost €
O&M (annual)	130,267	96,448
Electricity (annual)	4,038	2,481
Total Annual	134,305	98,929

SI. Section 5: Additional results.

The detailed stream results of Conventional pyrolysis plant and CSP-based plant are provided below. Furthermore, the CSP plant capacity factor and CO_2 emissions with respect to SM_T and storage sizes are shown in this section.

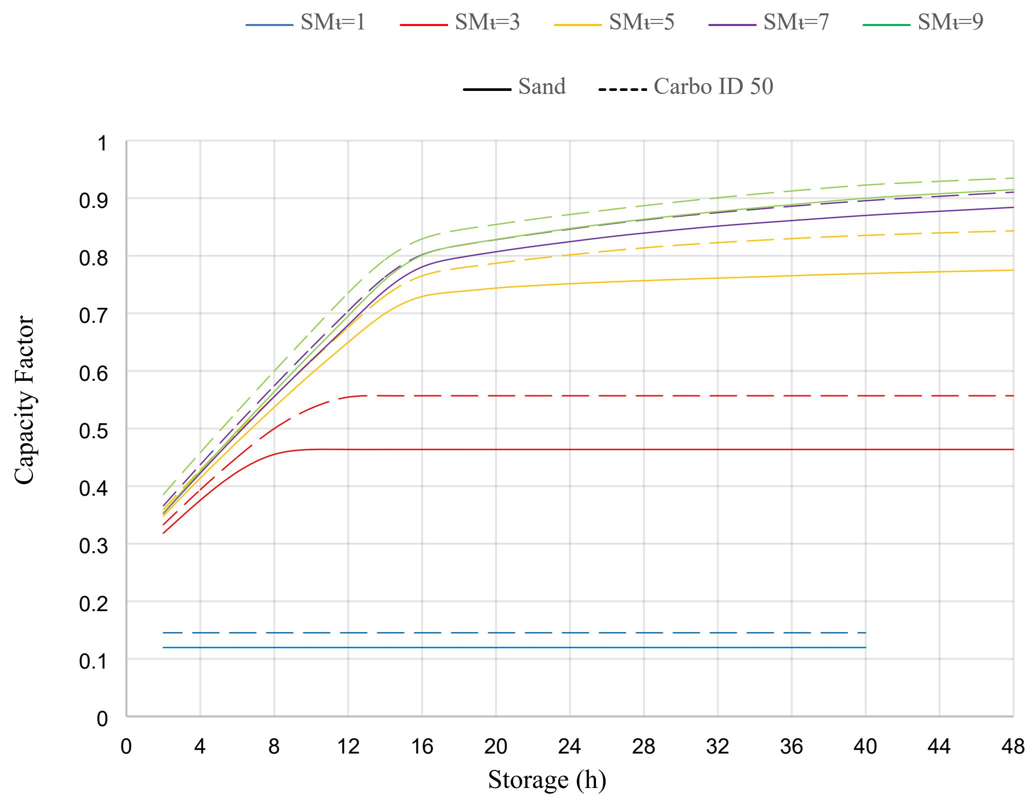
SI Table 19: Stream results of conventional biomass pyrolysis. Stream numbers refer to the schematic in Figure 2.

Stream	T (°C)	P (bar)	Flow rate (kg/s)	Composition (%wt)							Phase (mass basis)		
				C	H	O	S	N	Ash	PHC	Solid	Vapor	Liquid
Section 1 "biomass pretreatment"													
Biomass	20	1.013	0.814	35.7	7.6	56	0.02	0.1	0.6	0	1	-	-
2	71.7	1.013	0.633	45.8	6.6	46.6	0.03	0.2	0.8	0	1	-	-
16	345	1.15	1.78	4.3	0.4	24.9	0.01	70.4	0.0	0	-	1	-
17	71.7	1.013	1.96	3.9	1.4	30.9	0.01	63.8	0.0	0	-	1	-
23	482.4	1.42	1.19	6.4	0.5	24.9	0.01	67.8	0.4	0	-	1	-
24	47.4	1.15	0.59	0.01	0.2	24.6	0.00	74.3	0.9	0	-	1	-
Section 2 & 3 "Pyrolization & solid removal"													
4	433.8	1.22	10.6	9.1	0.8	12.1	0	0	0	77.9	0.78	0.22	-
5	433.8	1.22	8.33	0.7	0	0.1	0	0	0.1	99.2	0.99	0.001	-
6	433.8	1.22	2.27	40.1	3.5	56.5	0	0	0	0	-	1	-
13	72.3	1.59	1.71	39.6	2.3	58.1	0	0	0	0	-	1	-
19	608	1.42	8.26	0	0	0	0	0	0	100	1	-	-
Section 4 "Bio-oil Recovery"													
7	54.4	1.24	0.5	41.5	7.8	50.4	0	0.01	0.1	0.2	0.002	-	0.99
8	54.4	1.24	0.016	38.3	7.2	46.6	0	0	2.4	5.4	0.08	-	0.92
9	45	1.24	1.78	39.6	2.3	58.1	0	0	0	0	-	1	-
11	72.3	1.59	1.18	39.6	2.3	58.1	0	0	0	0	-	1	-
BIO-OIL	54.4	1.24	0.48	41.6	7.8	50.6	0	0.01	0	0	-	-	1
12	72.3	1.59	0.04	39.6	2.3	58.1	0	0	0	0	-	1	-
Section 5 "Combustion"													
18	609	1.43	9.45	0.8	0.1	3.1	0	8.5	0.1	87.5	0.87	0.13	-
20	72.5	1.43	1.08	0	0.2	24.8	0	75.0	0	0	0	1	-
21	609	1.43	1.19	6.4	0.5	24.9	0.01	67.7	0.4	0.1	0.005	0.99	-
PHC-MK	32.2	1.22	0.001	0	0	0	0	0.0	0	100	1	-	-

Ash	609	1.43	0.006	0	0	0	0	0.0	85.6	14.4	1	-	-

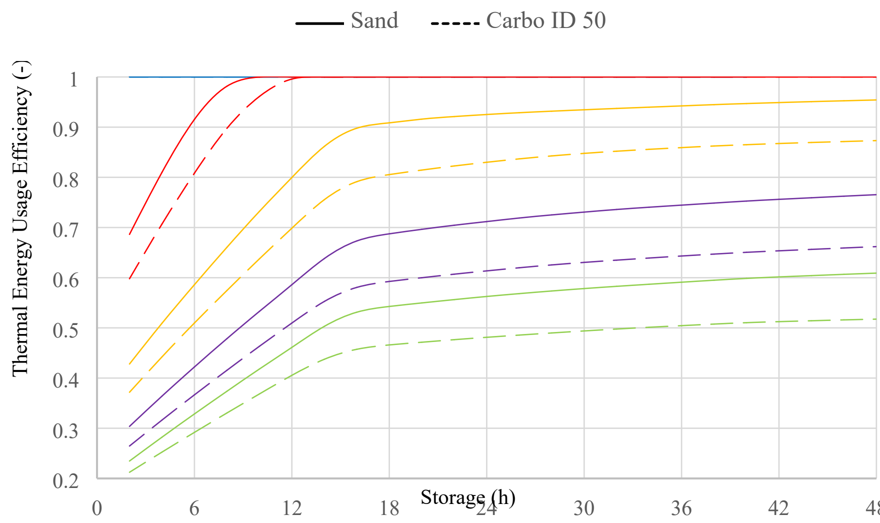
SI Table 20: Stream results of CSP-based biomass pyrolysis. Stream numbers refer to the schematic in Figure 3.

Stream	T (˚C)	P (bar)	Flow rate (kg/s)	Composition (%wt)							Phase (mass basis)		
				C	H	O	S	N	Ash	PHC	Solid	Vapor	Liquid
12	72.3	1.59	0.068	39.6	2.3	58	0	0	0	0	-	1	-
16	453	1.51	1.09	2.5	0.1	25.7	0	71.7	0	0	-	1	-
17	71.7	1.013	1.28	2.15	1.7	34.7	0	61.5	0	0	-	0.98	0.02
18	434	1.22	0.07	83.1	1.7	6.6	0.2	1.4	7.1	0	0.90	0.1	-
19	434	1.22	8.26	0	0	0	0	0	0	100	1	-	-
Sludge	54.4	1.24	0.02	40.5	7.6	49.3	0	0	2.6	0	0.08	-	0.92

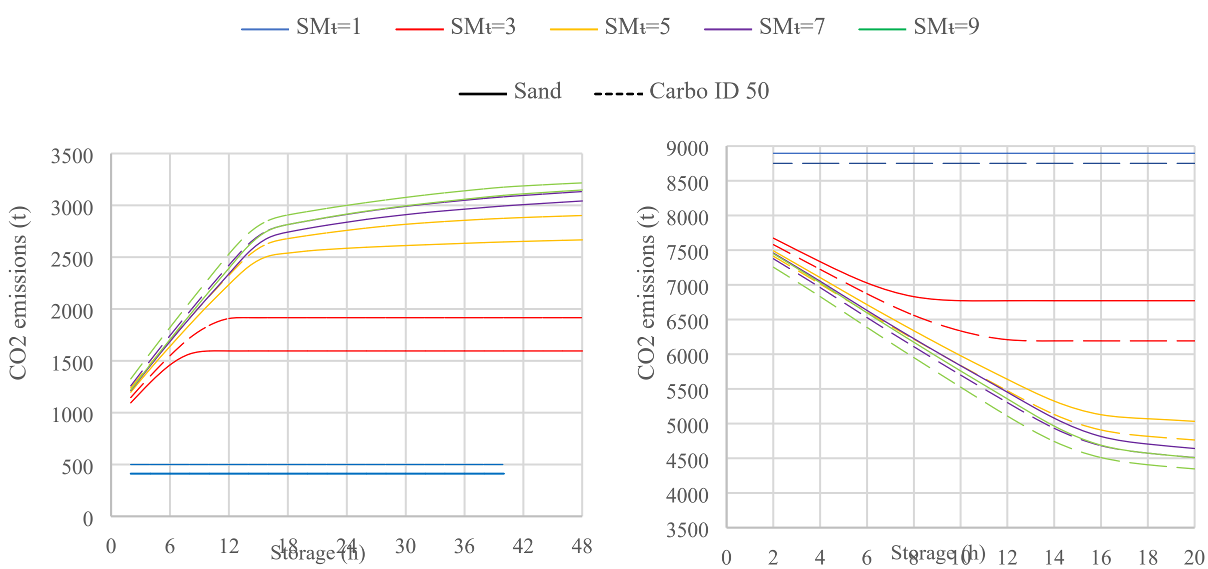


SI Figure 1: Capacity factor of the pyrolysis unit of the CSP-based plant as function on the SM_T and storage size

For the CSP-based pyrolysis plant, also the energy usage efficiency is analyzed on yearly basis (see equation 4). Just like MFSP analysis, similar range of SM_T and storage sizes are used to assess the energy usage efficiency and SI Figure 2 shows the trends Energy usage efficiency is lower at bigger SM_T and smaller storage sizes, while it increases quickly by increasing the size of storage. The smallest SM_T have higher energy usage efficiency because they generate less solar thermal energy and even smaller storages can accommodate its excess energy, which can be used later. PHC type also affects this efficiency, Carbo ID50 has a lower power efficiency than sand at the same size of CSP plant because carbo ID50, generates more overall energy than sand at same size due to it higher thermal efficiency. During sunshine hours at the same SM_T if storage is full, any excess of energy from CSP will be lost by defocusing. The power usage efficiency depends on how much energy is wasted therefore, the higher thermal efficiency of carbo ID50 allows the storage to fill up faster and the rest of the energy goes waste. The trends of energy usage efficiency for CSP-based and hybrid cases are same.



SI Figure 2: Hybrid and CSP based plant energy usage efficiency curves at various SM_T and storage sizes



(a) (b)

SI Figure 3: CO_2 emissions as function of SM_T and storage size in (a) CSP-based case and (b) hybrid case