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PYSOLO

Solar-driven Biomass Pyrolysis Plant for Negative-Emission Biofuels Production

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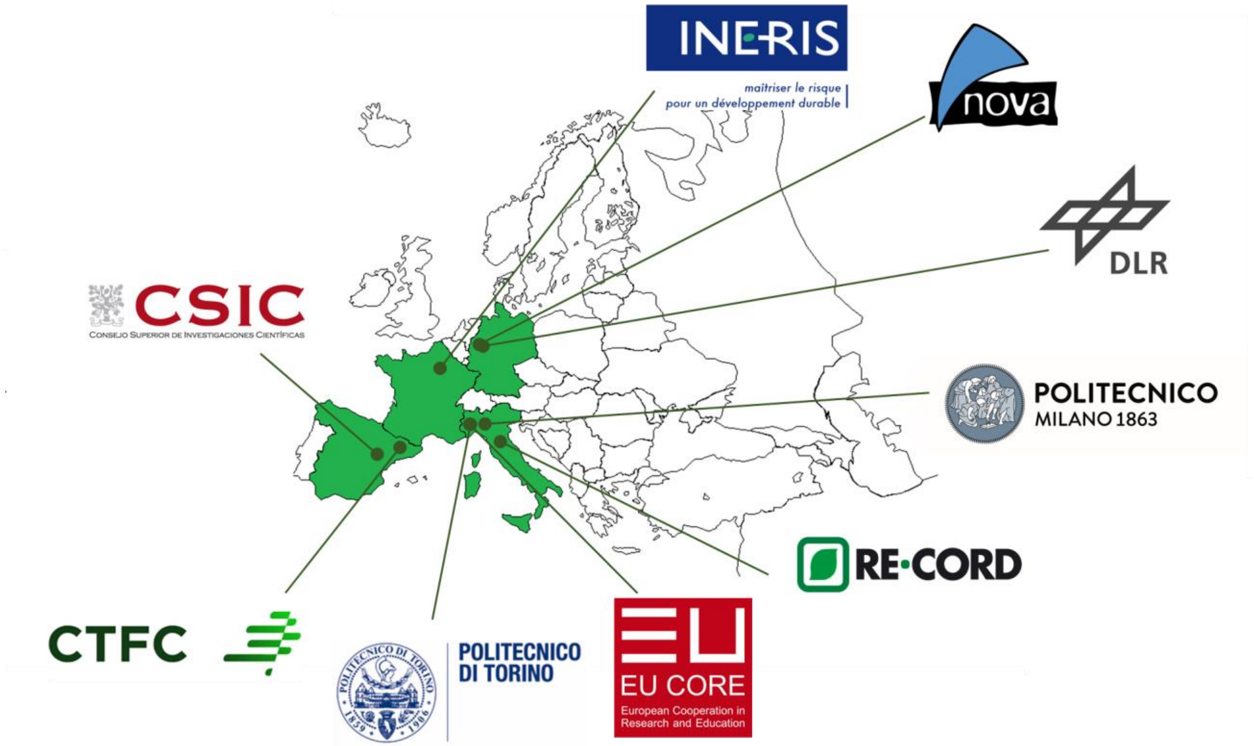
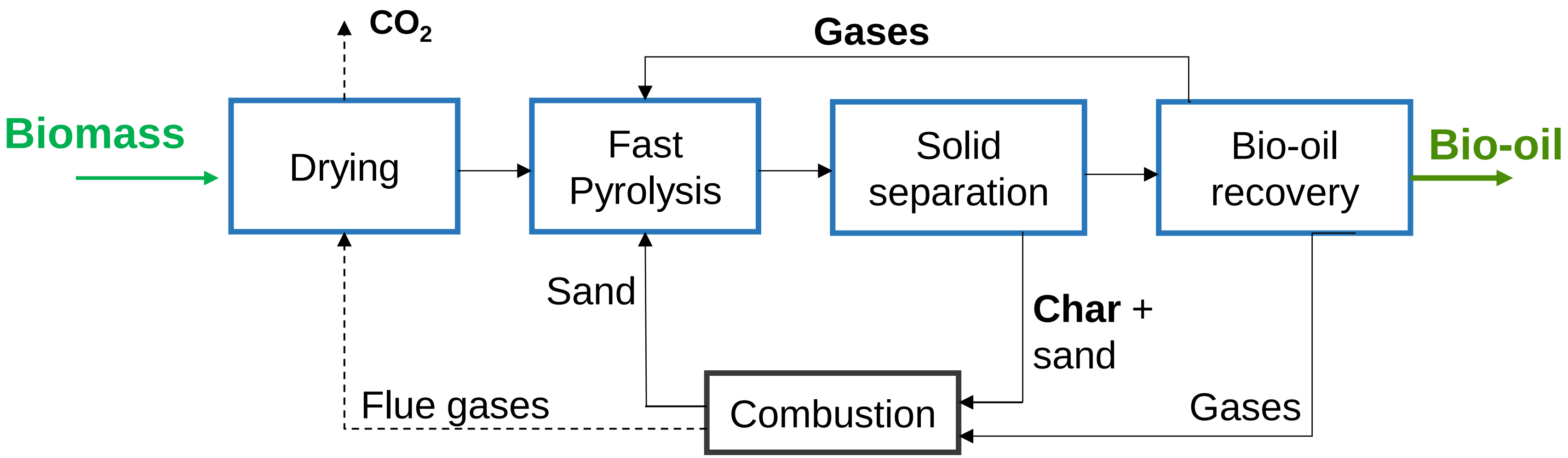
Introduction: the PYSOLO project

- **Title**: **PY**rolysis of biomass by concentrated **SOL**ar p**O**wer
- **Scope**: PYSOLO will **integrate CSP** technology and **biomass pyrolysis** in an innovative and very flexible concept at TRL4 able to produce increased amount of high value bio-products (bio-oil and bio-char) compared to existing technologies and able to efficiently use renewable heat and electricity from variable renewable energies
- **Funding mechanism:** HORIZON Research and Innovation Actions
- **Budget:** 4.9 M€
- **Starting date:** July 2023
- **Duration:** 4 years
- **Coordinator:** Politecnico di Milano
- **Consortium:** 9 partners, 4 countries



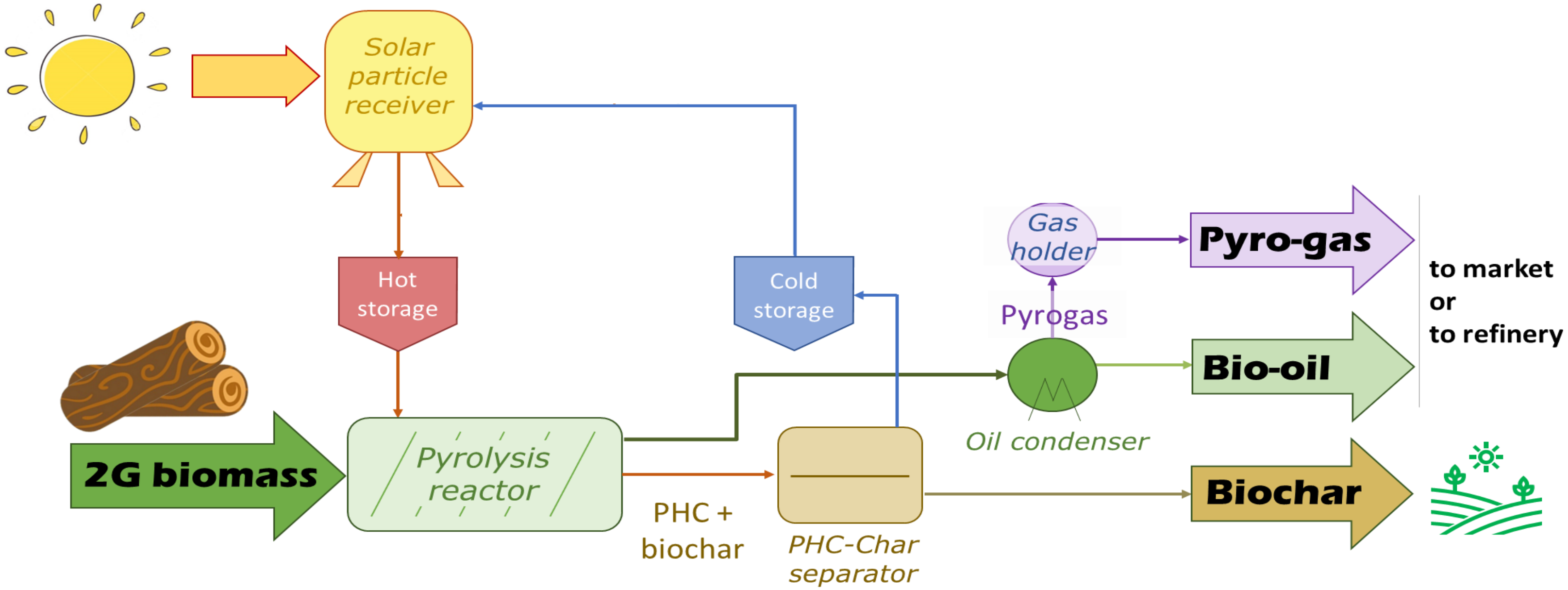
Introduction: Conventional Pyrolysis

1. **Biomass Pyrolysis** is a thermal degradation induced by supplying **heat (250-700°C)** in inert environment
2. The pyrolysis **products** are: **bio-oil**, **pyro-gas** and **char**
3. The **heat** required **for the reaction** is usually provided by **burning a fraction of the pyrolysis products** (pyro-gas/char): this represents an economic and environmentally inefficient step as it involves the loss of high value biogenic carbon emitted as CO_2, causing the reduction of the carbon efficiency and of the overall yield of bio-products



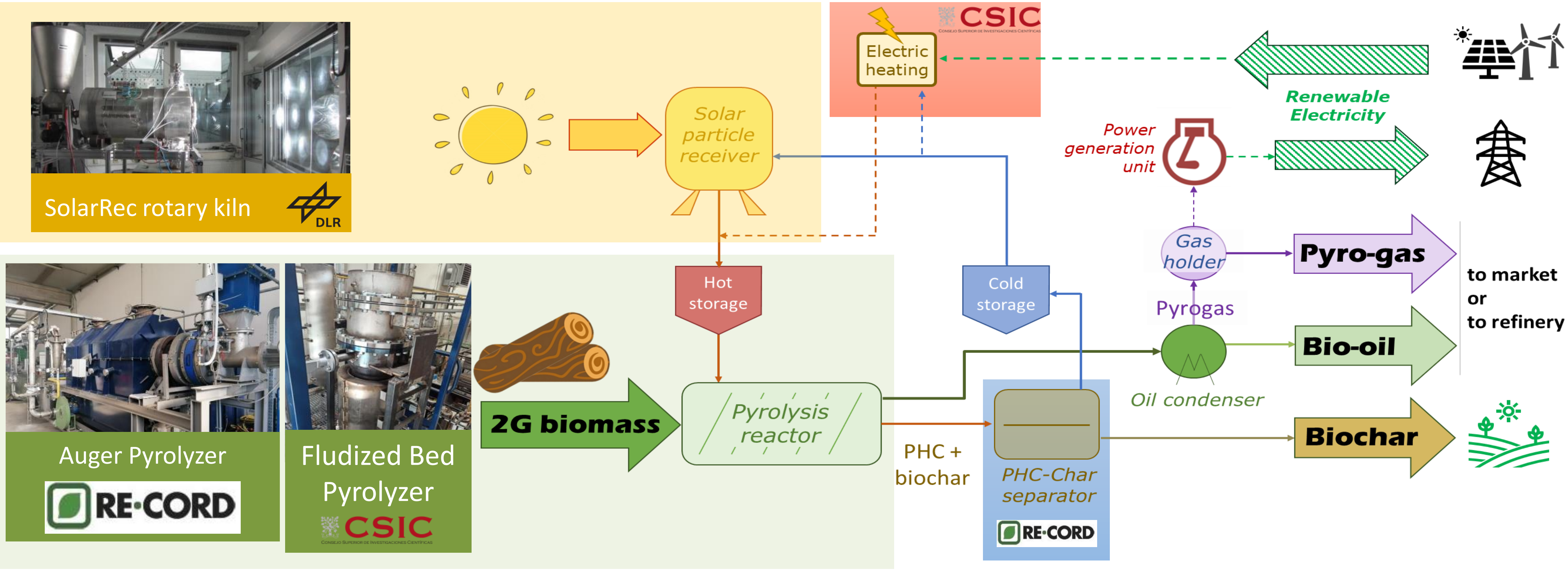
Introduction: the PYSOLO concept

- **Heat for pyrolysis** is provided by **solid particles** (e.g. sand, bauxite) heated in a rotary kiln solar receiver
- Excess thermal power can be stored in a **hot particle storage** to run the pyrolyzer for more hours
- Low cost **excess renewable EE** could be used to **heat** up the **particles** with extra advantages
- If **high EE cost** are expected gas and bio-oil might be burnt in an **Internal Combustion Engine** to produce EE



PYSOLO concept and experimental activity

- **4 different PHC** will be selected for the experimental activity in the pyrolyzers
- Both **stand-alone plants** and plants **integrated** with a **bio-refinery** will be investigated
- Key components will be **tested** at **TRL4:** 2 pyrolyzers, the rotary kiln receiver, the PHC/char separator and the electric heating



PYSOLO concept: previous works

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Techno-economic analysis of a solar-driven biomass pyrolysis plant for bio-oil and biochar production†

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Pyrolysis has become one of the most attractive options for converting carbonaceous biomass into bio-oil or biochar. This study explores a novel solar pyrolysis process intended to produce both bio-oil and biochar, thereby improving carbon efficiency. Aspen Plus and SolarPILOT were used to model a 10 MW biomass pyrolysis plant thermally sustained by hot particles from a falling-particle solar tower receiver. A yearly analysis was carried out for three configurations to estimate the annual production of oil and biochar. The results showed that the hybrid plant, combining solar receiver and biochar backup combustor, leads to the lowest cost of bio-oil (18.7 € per GJ, or 0.29 € per kg) and a carbon efficiency of 83%. Whereas, the plant fully sustained by solar power achieves a carbon efficiency of 90%; however, it results in a significantly higher cost of bio-oil (21.8 € per GJ, or 0.34 € per kg) due to the larger size of particle storage and a lower capacity factor of the pyrolysis plant. In comparison, a conventional pyrolysis plant with no biochar production yielded the most expensive option in terms of the cost of produced bio-oil (27.5 € per GJ) and features the lowest carbon efficiency (74%). Sensitivity analysis shows that the pyrolyzer Capex, operational cost, biochar market price, plant availability and discount rate significantly affect bio-oil production cost.

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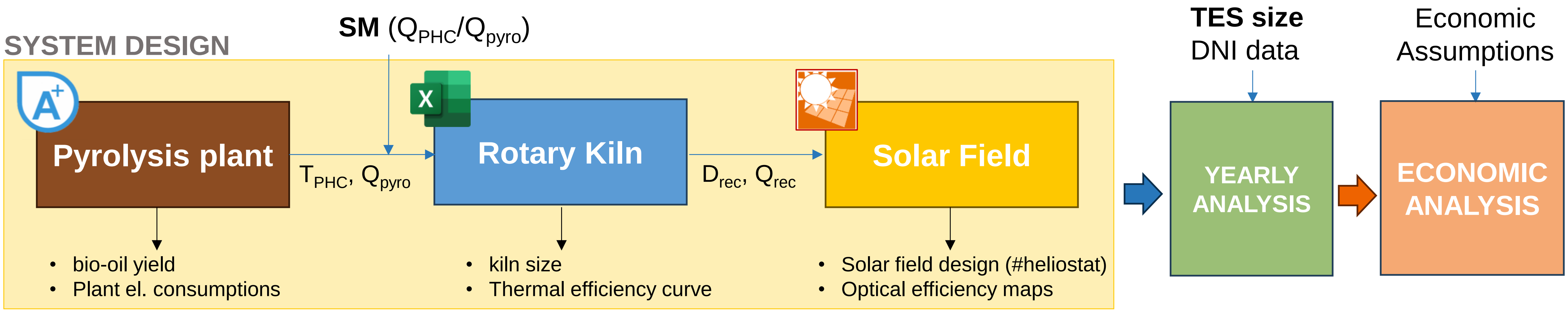
rsc.li/sustainable-energy

[1] M.A. Amjed, F. Sobic, M.C. Romano, T. Faravelli, M. Binotti, “Techno-economic analysis of a solar-driven biomass pyrolysis plant for bio-oil and biochar production”, 2024, Sustainable Energy & Fuels, The Royal Society of Chemistry, http://dx.doi.org/10.1039/D4SE00450G.

Scope of the work

Perform a preliminary techno-economic assessment of the PYSOLO concept, considering the integration of a biomass pyrolysis plant with a rotary kiln receiver (no electrical heating)

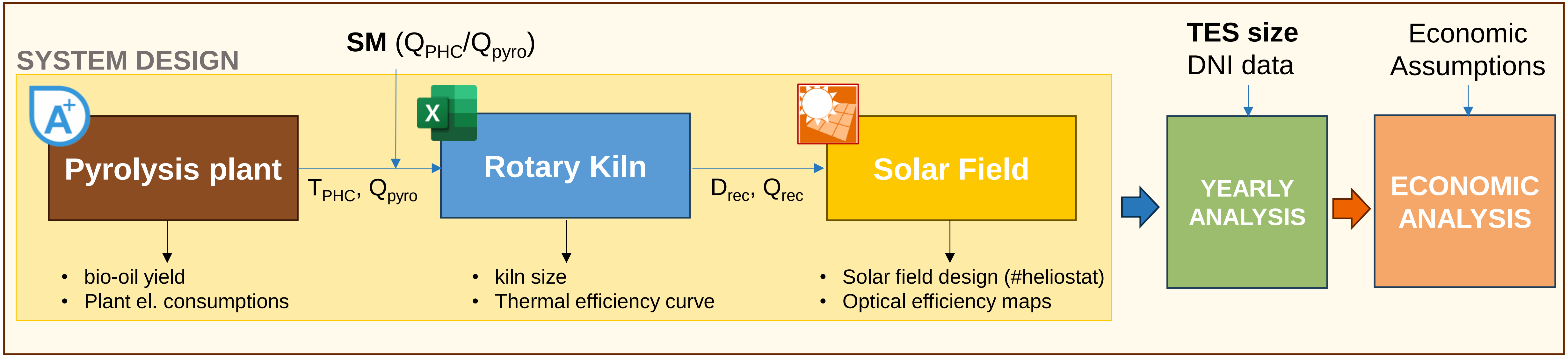
Methodology and KPIs



1. The schematic of the **pyrolysis plant** and the heat and mass balance are taken from Jones et al.[2] and are reproduced in **Aspen Plus**, scaled down to **10 MW** (biomass LHV)
2. Given the **heat demand of the pyrolyzer**, the temperature of the solid heat carrier and the SM, the rotary kiln sizing is obtained considering the constraints on the desired flow regime inside the kiln and its thermal performance are assessed
3. **Solar field** is designed using **solarPILOT**
4. The plant **yearly performance** is assessed with an hourly based simulation and the different plant **technical KPIs** are computed, together with the **economic KPIs**

[2] S. Jones, et al., Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbon Fuels: Fast Pyrolysis and Hydrotreating Bio-Oil Pathway, 2013.

Methodology and KPIs



Plant efficiencies:

$$\eta_{pyro\ plant} = \frac{\sum_i \dot{m}_{prod,i} LHV_{prod,i}}{\dot{m}_{biom} LHV_{biom} + \left(\frac{P_{el} + P_{Aux}}{\eta_{el,ref}}\right) + \dot{Q}_{PHC,pyro}}$$

$$\eta_{opt-th} = \frac{\dot{Q}_{PHC}}{A_h \cdot DNI} = \eta_{opt,SF} \cdot \eta_{th,rec} = \frac{\dot{Q}_{rec}}{A_h \cdot DNI} \cdot \frac{\dot{Q}_{PHC}}{\dot{Q}_{rec}}$$

Carbon yield:

$$\varepsilon_C = \frac{\sum_i \dot{m}_{prod,i} \cdot y_{C,prod,i}}{\dot{m}_{biom} \cdot y_{C,biom}}$$

Net emission-to-oil ratio:

$$ETO_{net} = -\frac{\dot{m}_{char} \cdot y_{C,char} \cdot {}^{44}/_{12}}{\dot{m}_{oil}}$$

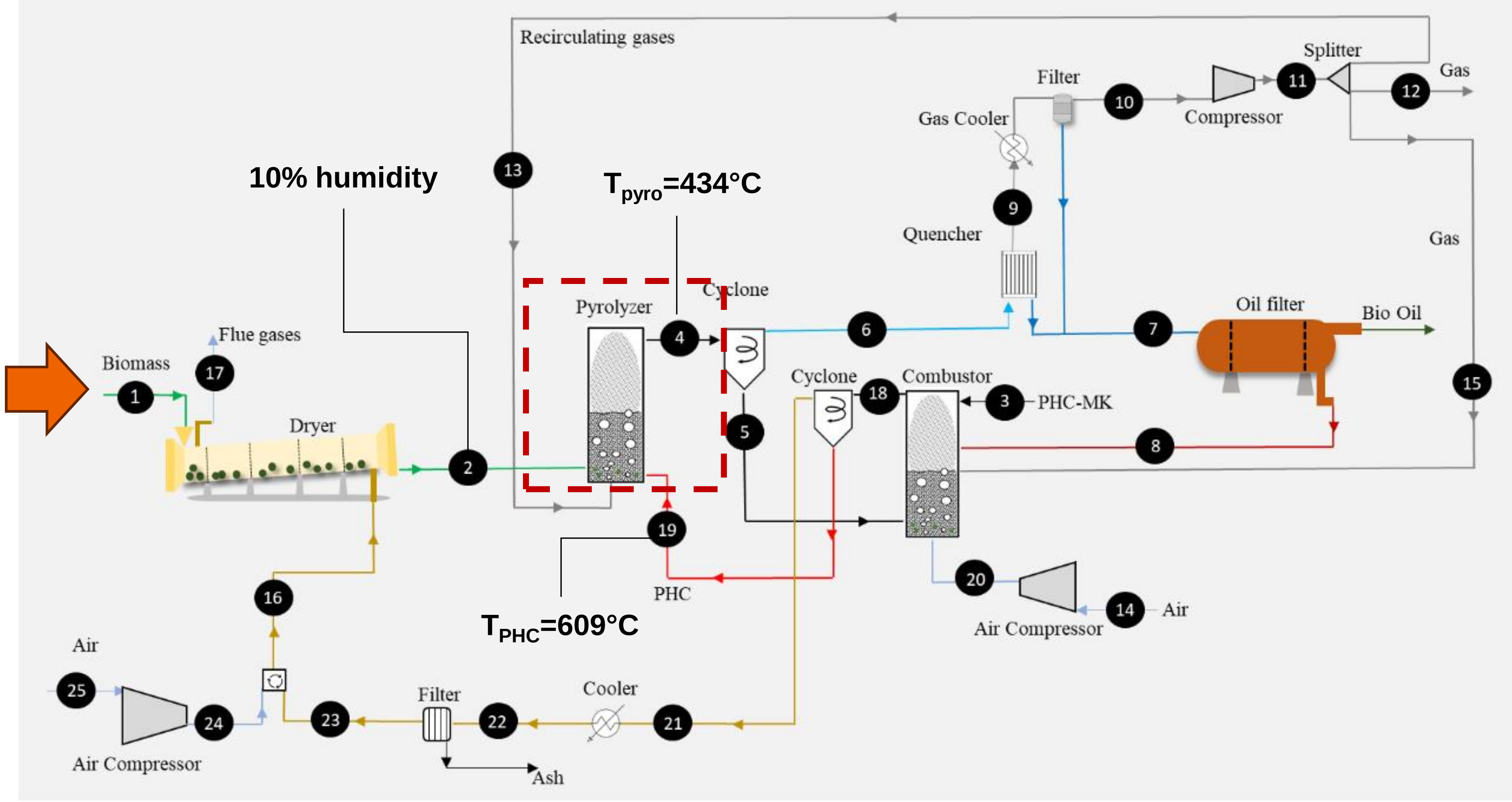
Minimum fuel selling price (MFSP):

$$NPV = -TCI + \sum_{j=-2}^{30} \frac{P_{by-prod} \times M_{y-prod,y_j} + MFSP \times M_{oil,y_j} - T_j - C_{OP,VAR,j} - C_{OP,FIX,j} - L_j}{(1+i)^j} = 0$$

Conventional pyrolysis plant

- Poplar with **30% humidity** is the biomass fed to the pyrolysis unit
- **Drying** process using hot flue gases reduces biomass **humidity** down to **10%**
- The **pyrolyzer** is considered a **black box** with fixed yield

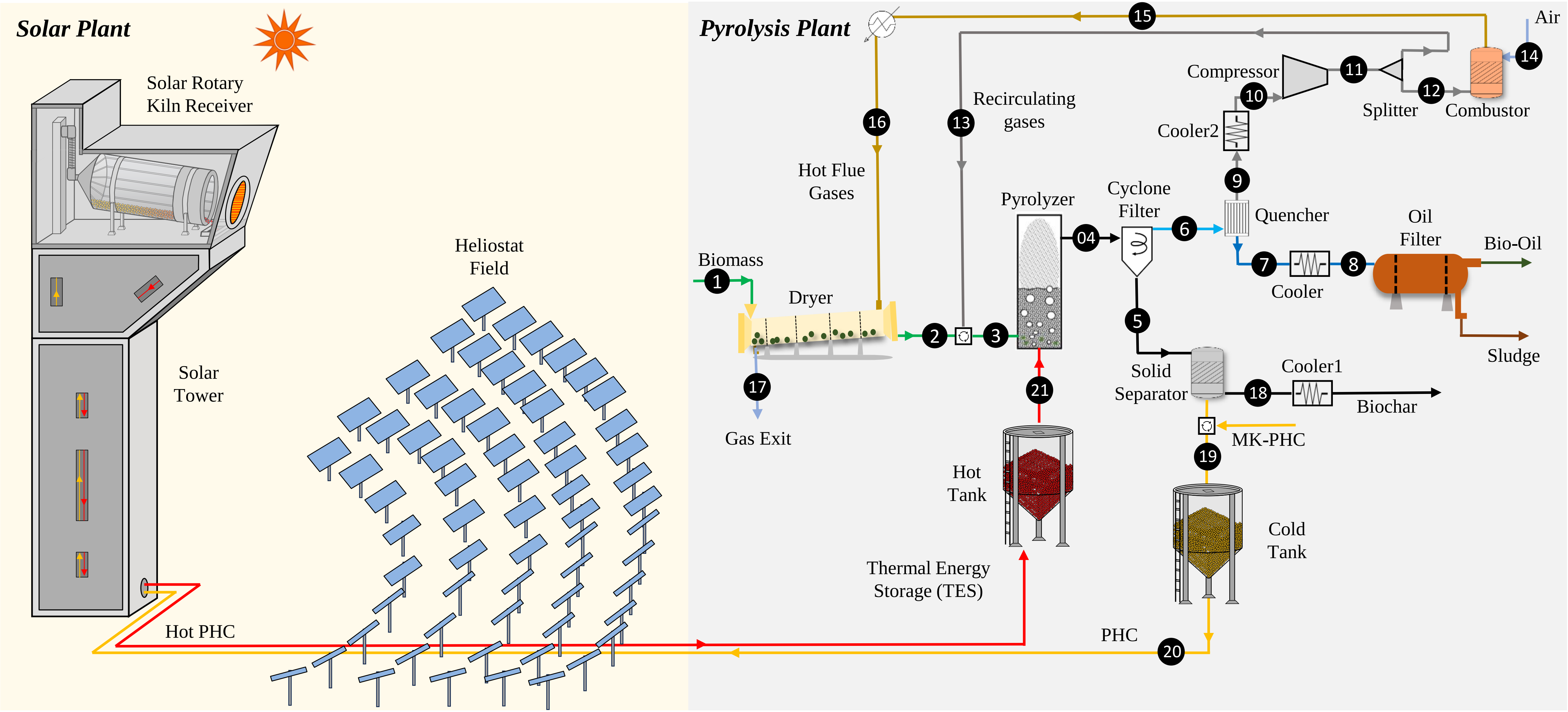
Elemental Analysis (%wt on dry basis)	
C	50.94
H	6.04
O	41.90
N	0.17
S	0.03
Ashes	0.92
HHV [MJ/kg]	14
LHV [MJ/kg]	12.3



Component	Flow [kg/h]	% C Yield
biomass	2928	100.0
Bio-Oil	1732	69.0
Biochar	246	19.6
Sludge	59	2.2
Flue gases	4555	9.2

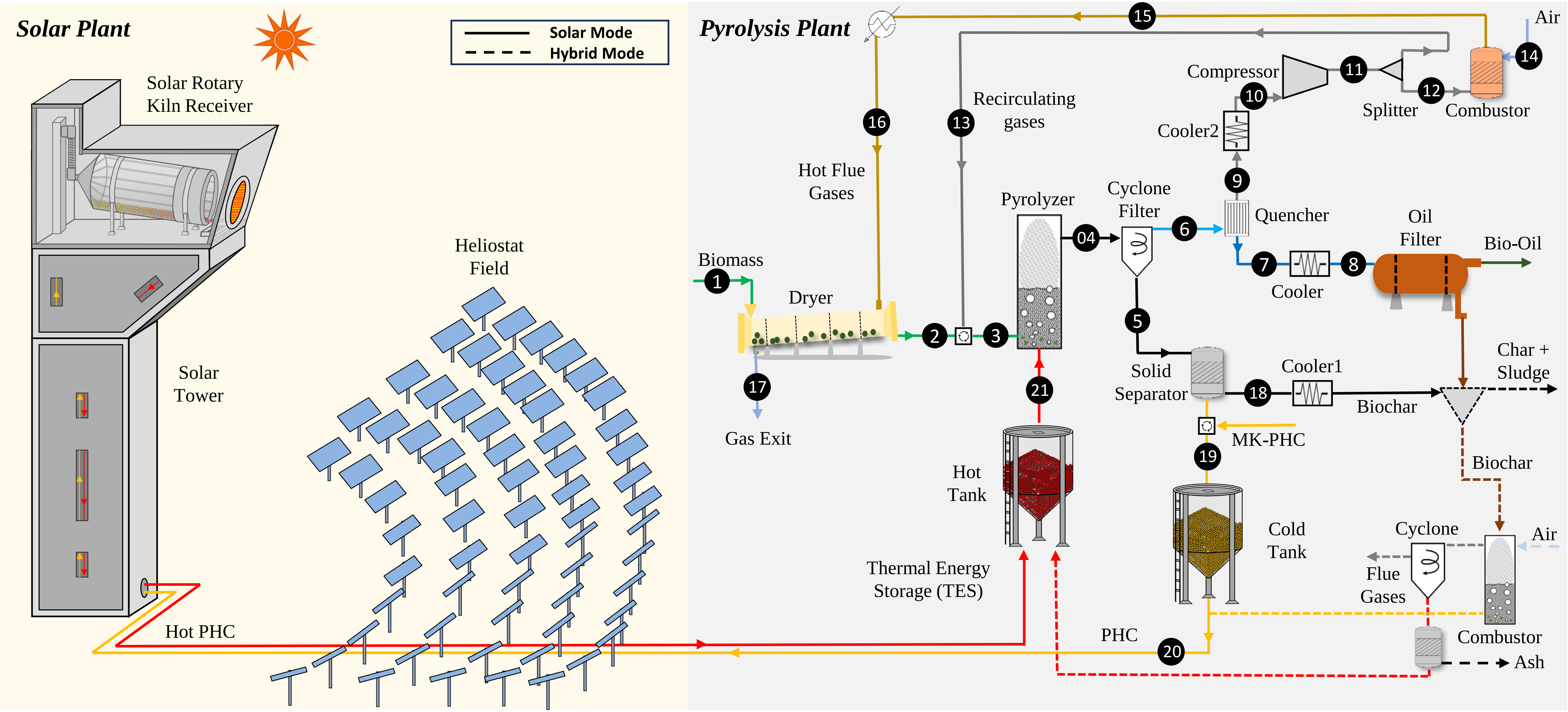
Useful results	Value
Pyrolyzer Net Thermal Request [MW]	1.66
PHC inlet temperature [°C]	609
PHC oultet temperature [°C]	434
Overall Electricity Consumption [kW]	353.2

Pyrolysis Integration with CSP: solar-only



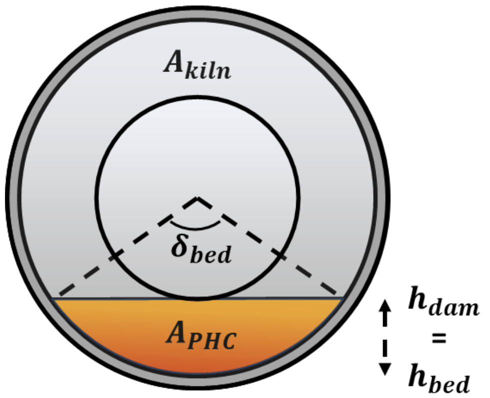
When integration with CSP is performed, char combustion is avoided and PHC is heated in the solar receiver

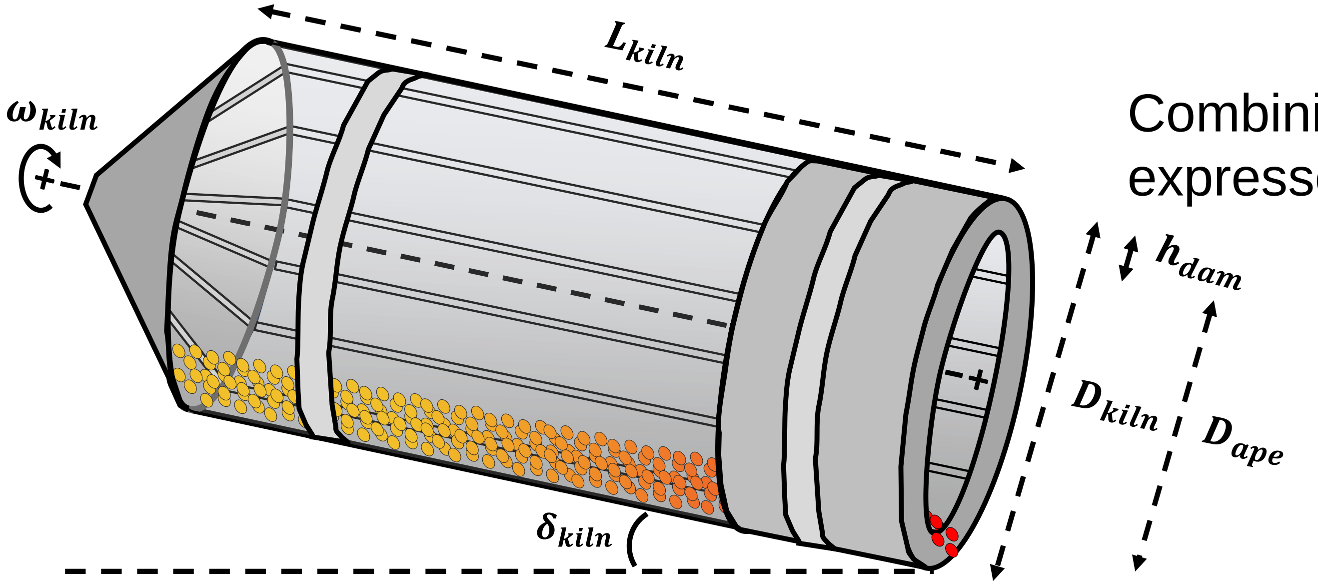
Pyrolysis Integration with CSP: hybrid solution



The hybrid layout can either work with solar heat or by burning char/sludge when no solar heat is available

Rotary Kiln design





Residence Time (Lee and Lin, 2010)[3]

$$\tau_{res} = 0.19 \cdot \frac{L_{kiln}}{D_{kiln}} \cdot \frac{1}{\delta_{kiln} \cdot \omega_{kiln}}$$

Dam Height (Gallo et al, 2016) [4]

$$h_{dam/bed} = \frac{D_{kiln}}{2} \cdot \left\{1 - \cos\left[\frac{\tilde{\delta}_{bed}(FR)}{2}\right]\right\}$$

Froude Number

$$Fr = \frac{\omega_{kiln}^2 \cdot D_{kiln}}{2g}$$

Fill Ratio

$$FR = \frac{\dot{m}_{PHC} \cdot \tau_{res}}{V_{kiln} \cdot \rho_{PHC}} \cong \frac{A_{PHC}}{A_{kiln}}$$

Combining these equations, the kiln diameter is expressed as function of $\dot{m}_{PHC}$, ρ_{PHC}, δ_{kiln}, FR and Fr:

$$D_{kiln} = \left(\frac{1.52\, \dot{m}_{PHC}}{\rho_{PHC}\, \delta_{kiln}\, FR \sqrt{2\, g\, Fr}}\right)^{2/5}$$

[3] C.C. Lee, S. Lin (Eds.), Handbook of Environmental Engineering Calculations, McGraw-Hill, New York, 2000
[4] A.Gallo et al., “Considerations for using a rotary kiln for high temperature industrial processes with and without thermal storage”, International Solar Energy Society conference proceedings, 2016

Rotary Kiln design

- The appropriate flow regime (i.e. cascading-rolling motion) requires specific FR and Fr number
- The appropriate flow regime should be verified even at part load (i.e. $\dot{m}_{PHC,min} = 0.2 \times \dot{m}_{PHC,des}$)

Basic form	Slipping motion		Cascading ("tumbling") motion			Cataracting motion	
Subtype	Sliding	Surging	Slumping	Rolling	Cascading	Cataracting	Centrifuging
Schematic							
Physical process	Slipping			Mixing		Crushing	Centrifuging
Froude number Fr [-]	$0 < Fr < 10^{-4}$		$10^{-5} < Fr < 10^{-3}$	$10^{-4} < Fr < 10^{-2}$	$10^{-3} < Fr < 10^{-1}$	$0.1 < Fr < 1$	$Fr \geq 1$
Filling degree f [-]	$f < 0.1$	$f > 0.1$	$f < 0.1$	$f > 0.1$		$f > 0.2$	
Wall friction coeff. μ_w [-]	$\mu_W < \mu_{W,c}$	$\mu_W \geq \mu_{W,c}$	$\mu_W > \mu_{W,c}$			$\mu_W > \mu_{W,c}$	
Application	no use		Rotary kilns and reactors; rotary dryers and coolers; mixing drums			Ball mills	no use

[5] B.Bisulandu, F.Huchet, "Rotary kiln process: An overview of physical mechanisms, models and applications", Applied Thermal Engineering, Volume 221, 2023, https://doi.org/10.1016/j.applthermaleng.2022.119637.
[6] Hlosta, J et al, "DEM Investigation of the Influence of Particulate Properties and Operating Conditions on the Mixing Process in Rotary Drums: Part 2—Process Validation and Experimental Study", *Processes* 2020. https://doi.org/10.3390/pr8020184

$$FR = \frac{\dot{m}_{PHC} \cdot \tau_{res}}{V_{kiln} \cdot \rho_{PHC}} = Const = 0.1$$

$$Fr\Big|_{min} = \frac{\omega_{kiln}^2 \cdot D_{kiln}}{2g} = 10^{-4}$$

At partial load, keeping constant FR:

$$Fr \propto \omega^2 \propto (\dot{m}_{PHC})^2$$

$$\downarrow \; :/ \; Fr_{0.2} = 10^{-4}$$

Design Froude Number:

$$Fr_{des} = Fr_{0.2} \cdot \left(\frac{1}{0.2}\right)^2$$

$$\boldsymbol{Fr_{des} = 2.5 \cdot 10^{-3}}$$

Rotary Kiln design

Rotary kiln energy balance and **size**, determined by the **flow regime constraints** are thus **strongly bound**.

$$D_{kiln} = \left(\frac{1.52\, \dot{m}_{PHC}}{\rho_{PHC}\, \delta_{kiln}\, FR\, \sqrt{2\, g\, Fr}} \right)^{2/5}$$

$$\dot{m}_{PHC} = 8.79 \frac{\text{kg}}{\text{s}} (SM = 1) \qquad \rho_{PHC} = 2000 \frac{kg}{m^3} \text{ (Bauxite)}$$

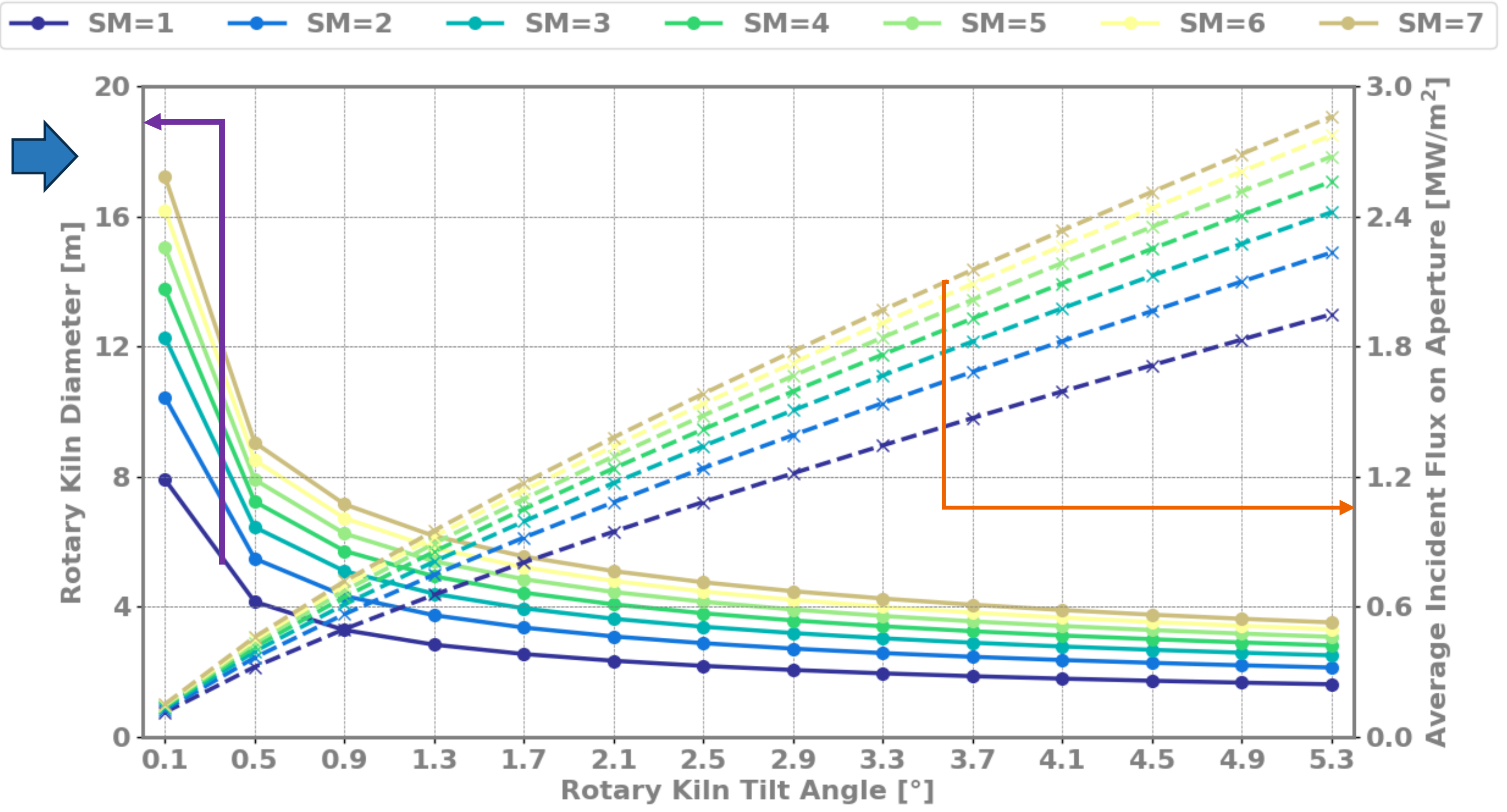
Varying the tilt and the SM ($\dot{m}_{PHC}$) it is possible to compute the kiln diameter and thus the kiln aperture together with the average flux hitting the receiver

At **same SM**, **if** $\boldsymbol{\delta_{kiln}} \uparrow$:

$\boldsymbol{D_{kiln}} \downarrow$, $\boldsymbol{D_{aperture}} \downarrow$,

$\boldsymbol{\varphi_{flux}} \uparrow$, $\boldsymbol{\eta_{opt}} \uparrow\downarrow$, $\boldsymbol{\eta_{th}} \uparrow$

Maximum achievable heat flux would limit kiln tilt



Rotary kiln design: thermal losses

The thermal performance of the rotary kiln is computed with the following simplified approach[4]:

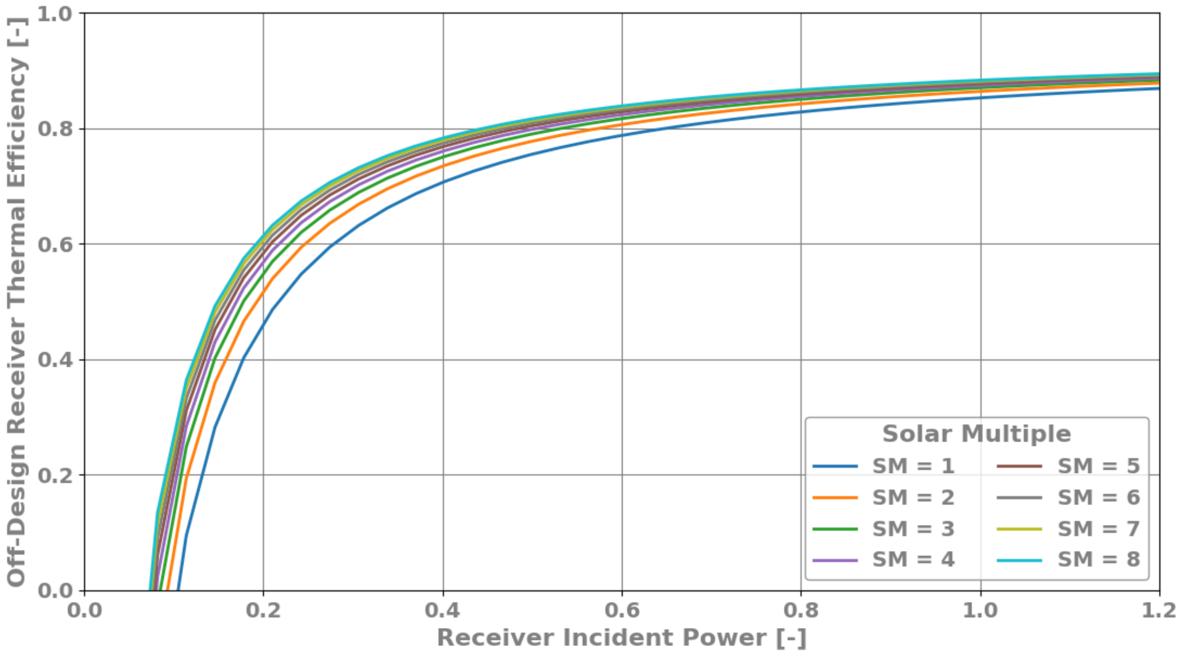
$$\dot{Q}_{PHC} = \dot{Q}_{rec}\alpha - \sigma\varepsilon A_{ape}\left(T_{kiln}^4 - T_{amb}^4\right) + h_{cv}A_{ape}\left(T_{kiln} - T_{amb}\right)$$

$$h_{n,cv} = \frac{k}{D_{kiln}} 0.088 \cdot Gr^{\frac{1}{3}} + [\cos(\delta_{kiln})]^{2.47}\left(\frac{D_{ape}}{D_{kiln}}\right)^{1.12-0.982\left(\frac{D_{ape}}{D_{kiln}}\right)}$$

$$h_{f,cv} = \frac{k}{D_{kiln}} Nu_{f,cv} = \frac{k}{D_{kiln}} 0.1967 \cdot v_{wind}^{1.849}$$

Effective cavity emissivity, ε [-]	0.9
Effective cavity absorptivity, α [-]	0.95
Wind speed at receiver height [m/s]	10

For lower incident solar power (**part load**) **radiative** and **convective losses** are assumed constant: the receiver thermal performance curve is obtained

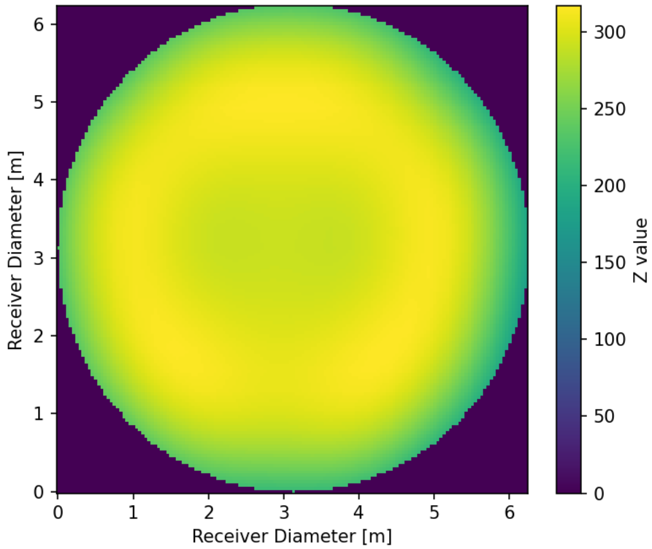


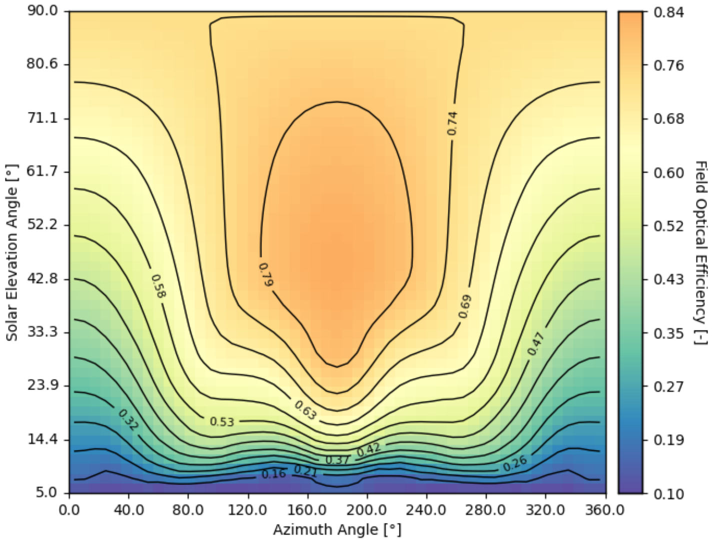
[4] A.Gallo et al., "Considerations for using a rotary kiln for high temperature industrial processes with and without thermal storage", International Solar Energy Society conference proceedings, 2016.

Solar field design

- The **solar field design** is performed with SolarPILOT for **different Solar Multiple** ($SM=Q_{PHC}/Q_{pyro}$) varying **receiver tilt** (δ_{tilt}) and **tower height**
- A **flat plate receiver** is used to mimic the rotary kiln aperture and a circular flux shape is imposed on the flat plate receiver
- For every solar field the **optical efficiency map** is obtained varying the sun position

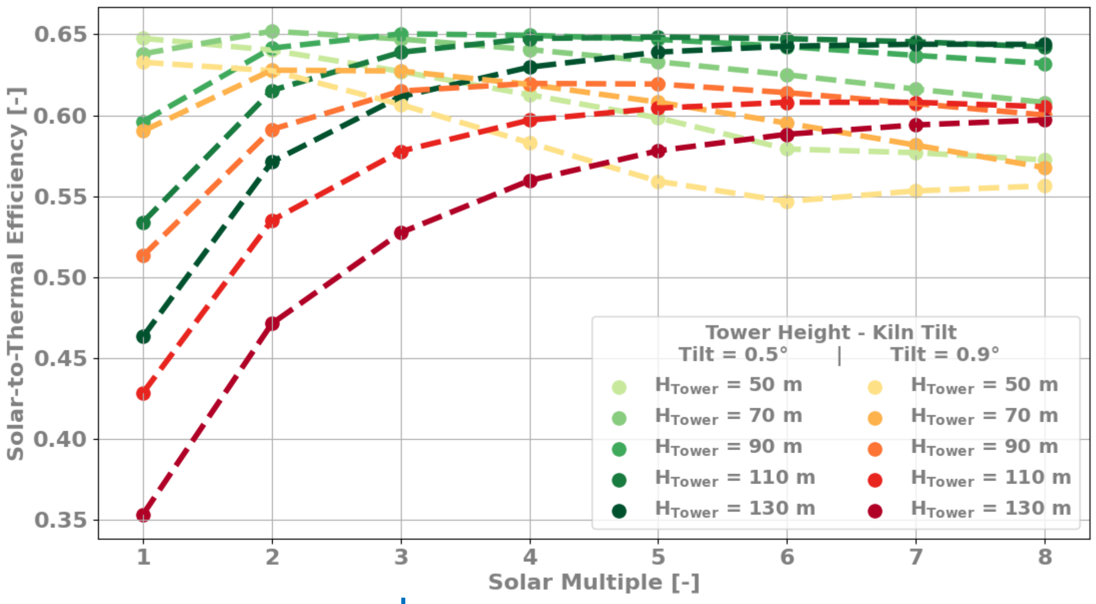
Parameter	Value
Design DNI [W/m^2]	900
Design Point	21st June, Solar Noon (Seville)
Heliostat size [m^2]	16
Heliostat focusing type	At slant
Heliostat error [mrad]	3.07
Heliostat reflectivity [-]	0.95
Receiver acceptance angle [°]	75
Lift efficiency	0.80



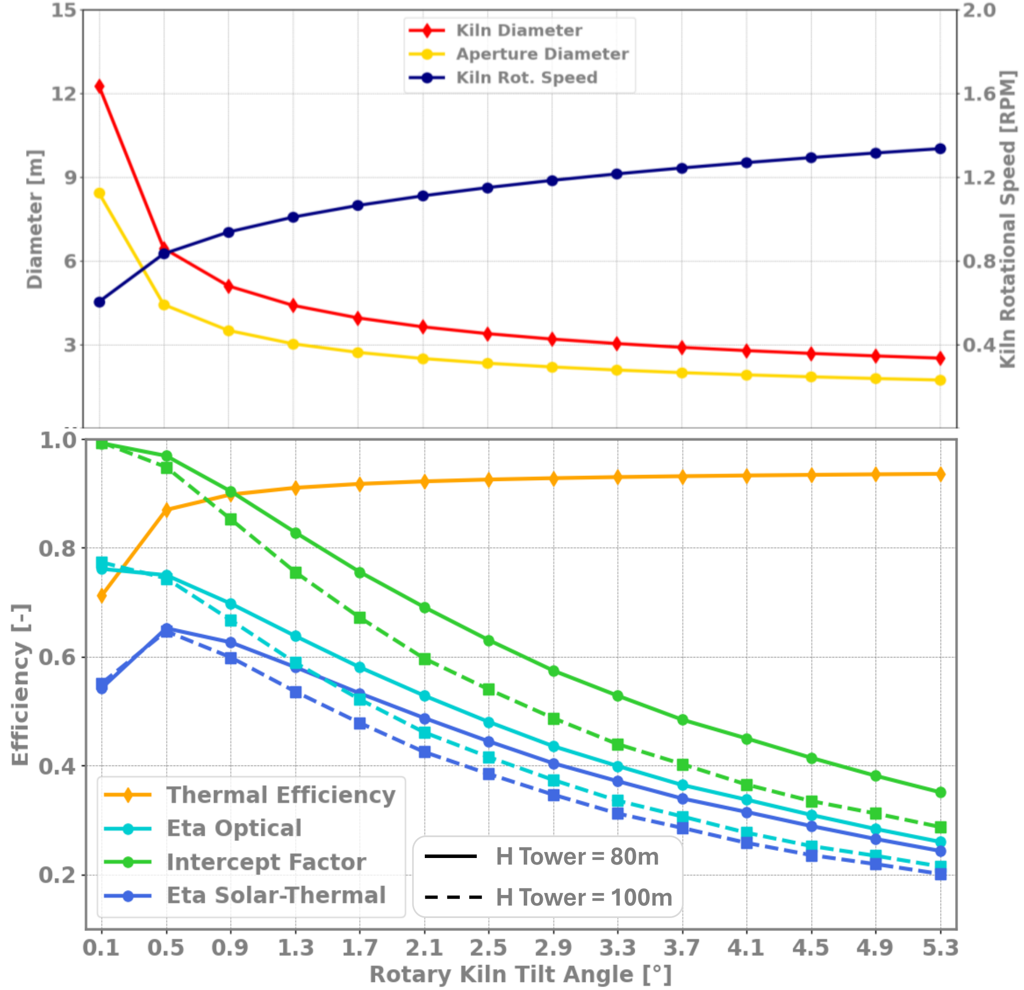


Solar field design

- A trade off exists between tilt variation, optical efficiency (intercept factor) and thermal losses
- For every considered SM the tilt and tower height that **maximise** the **solar-to-thermal efficiency** are selected



SM=3



Economic analysis

Pyrolysis plant **components costs** are taken from Jones et al.[1], **adapted** considering the smaller plant size and actualized. Factors accounting for installation, other direct costs, indirect costs and land costs are also consdiered according to Jones et al.[1]

$$C_{inst,2019} = f_{inst} \times C_{0,x} \times \left(\frac{S_X}{S_0}\right)^{0.7} \left(\frac{CEPCI_{2019}}{CEPCI_x}\right)$$

[M€$_{2019}$]	Conventional	Solar-only	Hybrid
Pyrolizer + oil recovery sys	8.91	8.91	8.91
Char combustor	0.94	-	0.76
Gas combustor	-	0.48	0.48
Biomass pretreatment	1.24	1.24	1.24
Utilities and auxiliaries	0.48	0.48	0.48
Total Installed cost	**11.57**	**11.12**	**11.87**

CSP section components are computed based on literature data (not specific for rotary kiln):

Heliostat Field Cost [€/m^2]	133	M. J. Wagner and T. Wendelin, "**SolarPILOT**: A power tower solar field layout and characterization tool," Sol. Energy, vol. 171, 2018,
Receiver Specific Cost [k€/m^2]	76.3	Reiner Buck, Jeremy Sment, "Techno-economic analysis of multi-tower solar particle power plants", Solar Energy, Volume 254, 2023, Pages 112-122
Tower Specific Cost [€/m$^{1.9274}$]	148.4	C. Frantz, R. Buck, and L. Amsbeck, "Design and Cost Study of Improved Scaled-Up Centrifugal Particle Receiver Based on Simulation," *J. Energy Resour. Technol. Trans. ASME*, vol. 144, no. 9, 2022
Thermal Energy Storage Specific Cost [€/m^2]	1000	R. Buck and S. Giuliano, "Impact of CSP design parameters on sCO2-based solar tower plants," *2nd Eur. Supercrit. CO_2 Conf.*, 2018.
Bauxite Particles Cost [€/kg]	400	Q.Kang et al., Particles in a circulation loop for solar energy capture and storage, 2019 Particuology
Particle Elevator Cost [€ s/m kg]	53.55	L. F. González-Portillo, K. Albrecht, and C. K. Ho, "Techno-economic optimization of CSP plants with free-falling particle receivers," Entropy, vol. 23, no. 1, 2021

Techno-Economic Analysis: Results

Both for solar-only and hybrid plants the SM and the TES are optimized (maximum TES size = 24h)

Techno-Economic Analysis		Conventional	Solar-only	Hybrid
Solar Field Design	Optimal SM [-]/ Optimal tilt [°]	-	6 / 0.5	3 / 0.5
	Receiver Aperture Area [m2]	-	26.8	15.4
	Optical efficiency [-]	-	0.736	0.750
	Thermal Efficiency [-]	-	0.879	0.870
	Optimal Equivalent Storage Hours [h]	-	24*	13
Economics	Pyrolysis Plant CAPEX [M€]	20.89	20.07	21.44
	Solar Plant CAPEX [M€]	-	9.60	5.23
	Total CAPEX [M€]	**20.89**	**29.67**	**26.67**
Annual Performance	Annual Solar-Thermal Efficiency [-]	-	0.551	0.549
	Pyrolysis Plant Efficiency [-]	0.740	0.790	0.790
	Carbon Efficiency [-]	0.743	0.903	0.844
	Char Selling Revenue [M€/y]	0	3.41	2.98
	MFSP [€/GJ_{OIL}]	**28.85**	**25.71**	**21.36**

* Maximum investigated size

M€	Solar-only	Hybrid
Heliostat Field	3.42	1.70
Receiver	2.58	1.48
Tower	1.62	0.87
Thermal Energy Storage (TES)	1.03	0.72
Particles	0.49	0.28
Particle Elevator	0.43	0.16

HP: $C_{sell,biochar} = 1.889 \frac{€}{kg}$

State of the Biochar Industry 2014
A Survey of Commercial Activity in the Biochar Sector

Conclusions & future development

- The performance of a solar-driven pyrolysis process using rotary kiln receiver has been assessed
- **Rotary kiln energy balance and size**, determined by the **flow regime** constraints are **strongly bound**. This limits maximum allowed tilt (1-2°) and thus the system optical efficiency for the considered case.
- **Solar-based pyrolysis** can achieve over **90% carbon efficiency** (70% in bio-oil, 20% in biochar), 21% higher than the conventional case. Solar-only mode and the hybrid mode achieve net negative emissions of -27.06 and -22.46 kgCO2/GJ_{OIL}.
- **MFSP reduction of 11% and 26% are** obtained with respect to the ref. plant for the solar-only and hybrid case respectively
- **Improve components modelling** (rotary kiln thermal model, pyrolyzer black box), taking also advantage of the experimental activity within PYSOLO
- Extend the analysis to **other PHC types** (e.g. sand, olivine) and evaluate the **trade offs between maximum and minimum PHC temperatures** directly impacting on receiver performance, storage cost and bio-oil yield

Thank you for your attention!

www.pysolo.eu

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