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Towards, Competitive, Reliable, Safe and Sustainable Concentrated Solar Power (CSP) Plants

Midterm meeting REA, 18-19 April 2024

POLITECNICO MILANO 1863

DC7 – Task 2.4:

Concentrated solar system for solar fuels production

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1. Introduction

PhD candidate:

Alejandro González Silvestre

Working Experience

[2022 - 2023] Metrology Research & Innovation Consultant

[2020 – 2022] Building installations quality control engineer

Education

[2014-2019] Bachelor's degree in mechanical engineering at Universidad Carlos III de Madrid.

[1] Bachelor's thesis: ***Influence of the curvature of a field of Fresnel heliostats***

A. González-Silvestre, J. Gómez-Hernández. "Influencia de la curvatura de un campo de heliostatos Fresnel". TFG, Universidad Carlos III de Madrid, Madrid, Spain, 2018.

[2021-2022] Master's degree in Industrial Mechanics at Universidad Carlos III de Madrid.

[2] Master's thesis: ***Control of a Fresnel heliostat guidance system using Arduino***

A. González-Silvestre, J. Gómez-Hernández, S. Taramona. "Control de un sistema de guiado de heliostatos Fresnel mediante Arduino". TFM, Universidad Carlos III de Madrid, Madrid, Spain, 2022.

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1. Introduction

PhD Topic/Title: **Concentrated solar system for solar fuels production**

Supervisor: **Marco Binotti** **Co-supervisor:** **Gioele di Marcoberardino**

Host Institution:	POLITECNICO MILANO 1863
Main objective:	**Optimisation** and **techno-economic** performance **analysis** of thermochemical cycles for H2 production to be integrated in a point-focus CSP system.
Main steps:	This PhD will consider the most promising **thermochemical** and **photo-thermochemical** cycles for **H2 production**, and will evaluate their integration in **point-focus CSP** systems. The system **concentration ratio**, **flux distribution** and **operating temperature** will be **optimized** to identify the best operating conditions given by the trade-off between **optical efficiency and reactor yield.** Besides, results in terms of **solar-to-fuel conversion efficiency** under design conditions, **yearly H2 yield**, and **preliminary economic assessment** will be provided.

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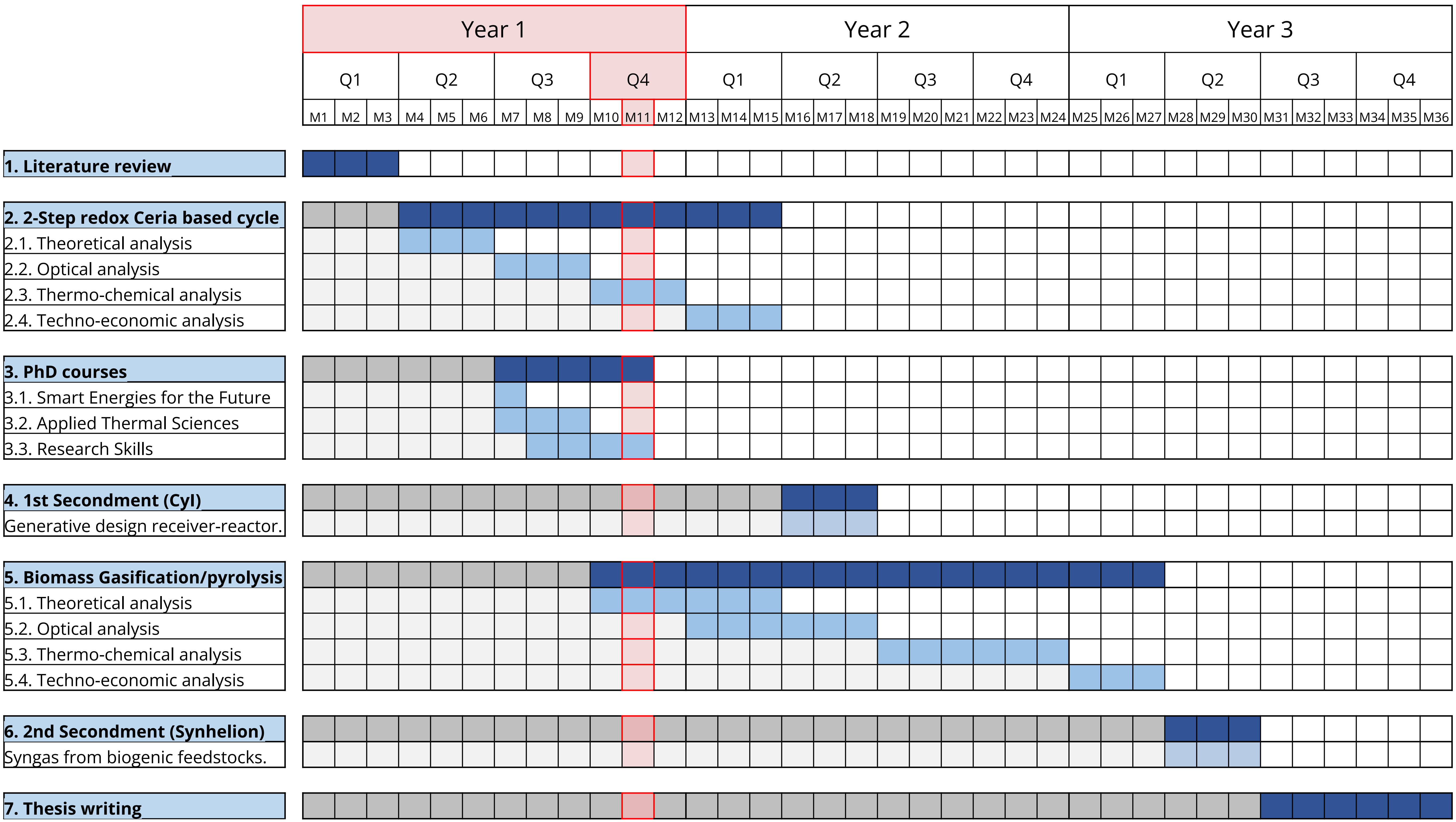
1. Introduction



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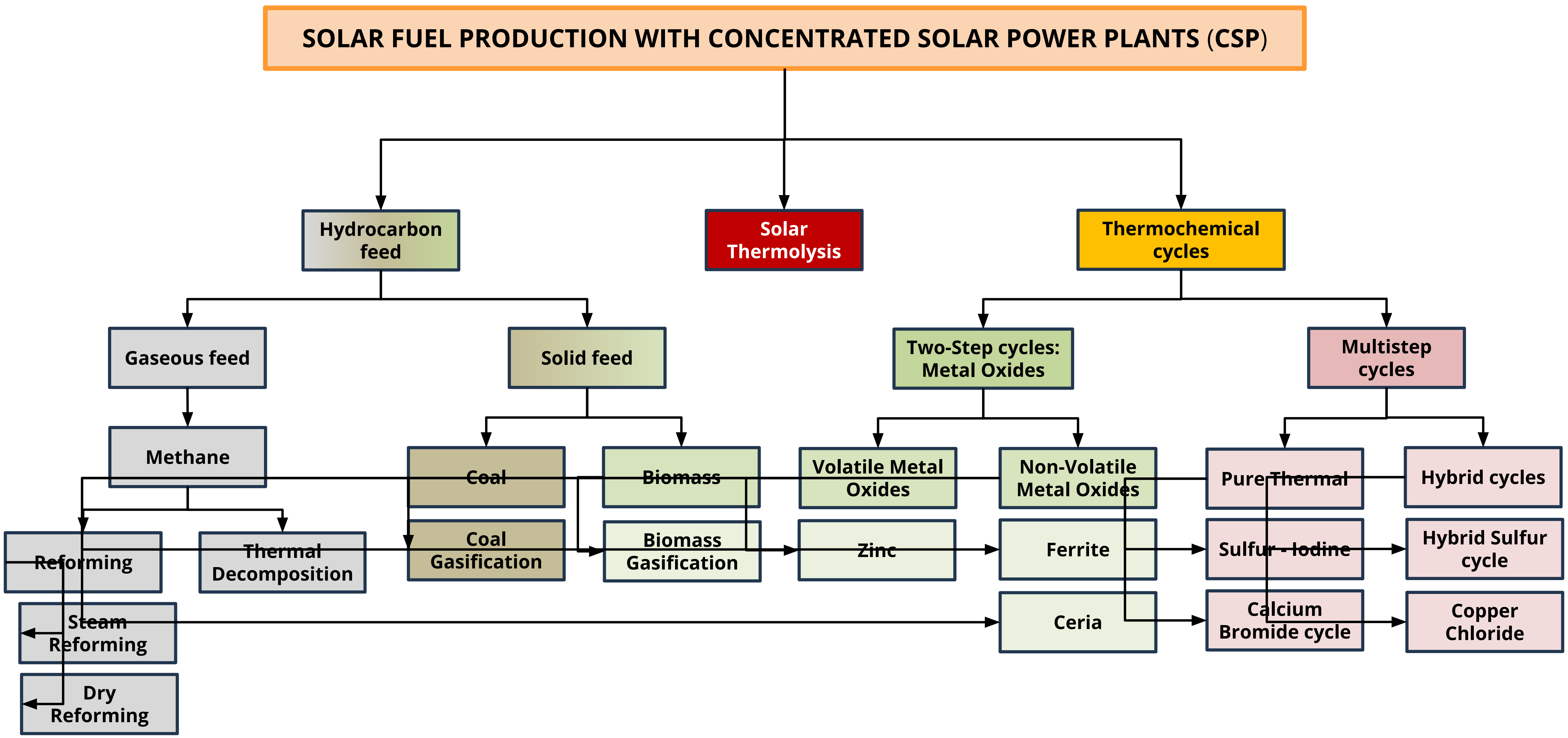
2. Solar Fuel Production with CSP

The **different solar fuel production methods** with CSP can be classified in the following manner:



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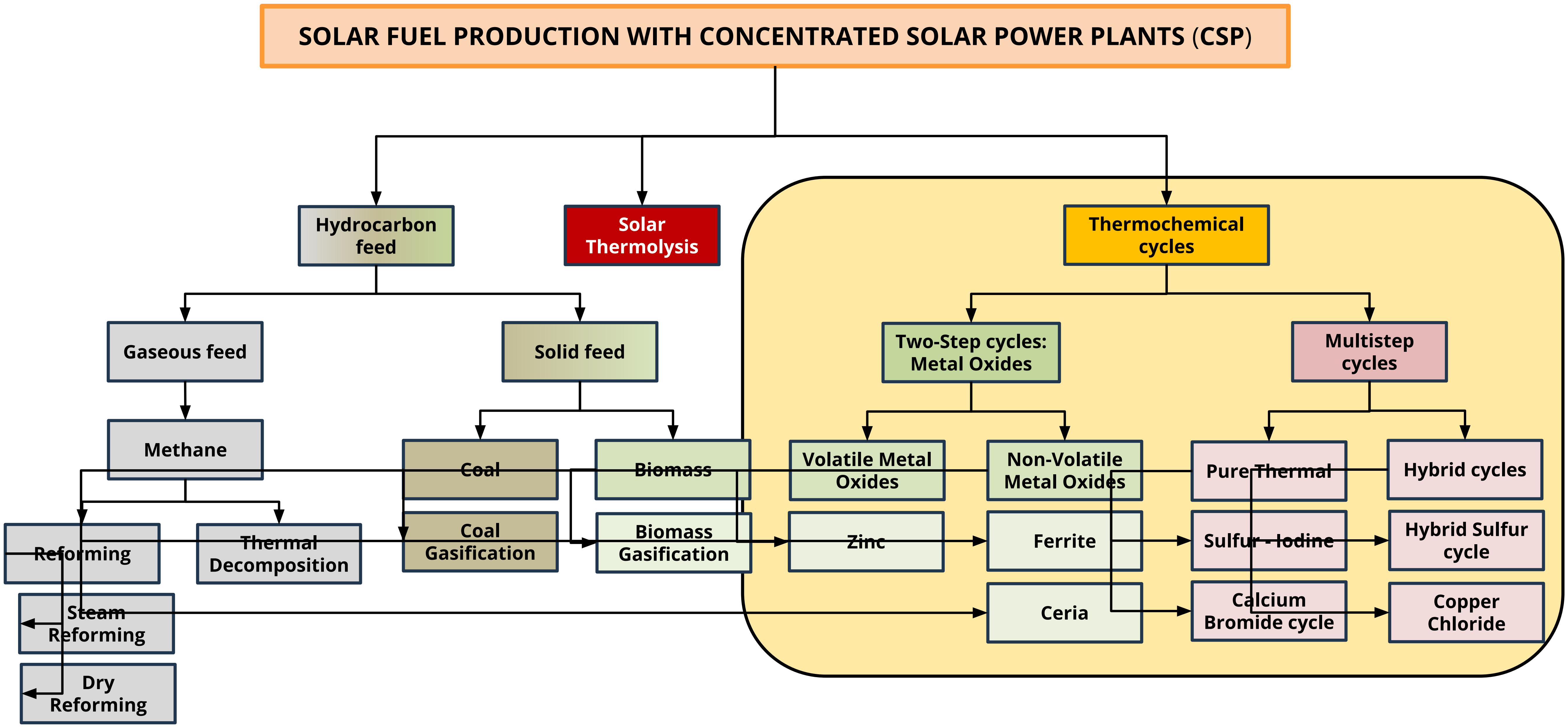
2. Solar Fuel Production with CSP

During the first part of the PhD the **main focus** of the research are **thermochemical cycles**.



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2. Solar Fuel Production with CSP

These **thermochemical cycles** can be classified in two-step and multi-step processes.

Thermochemical

Series of chemical reactions that converts water and carbon dioxide into renewable fuels.

Feedstock:

•Steam (H_2O), carbon dioxide (CO_2).

Output:

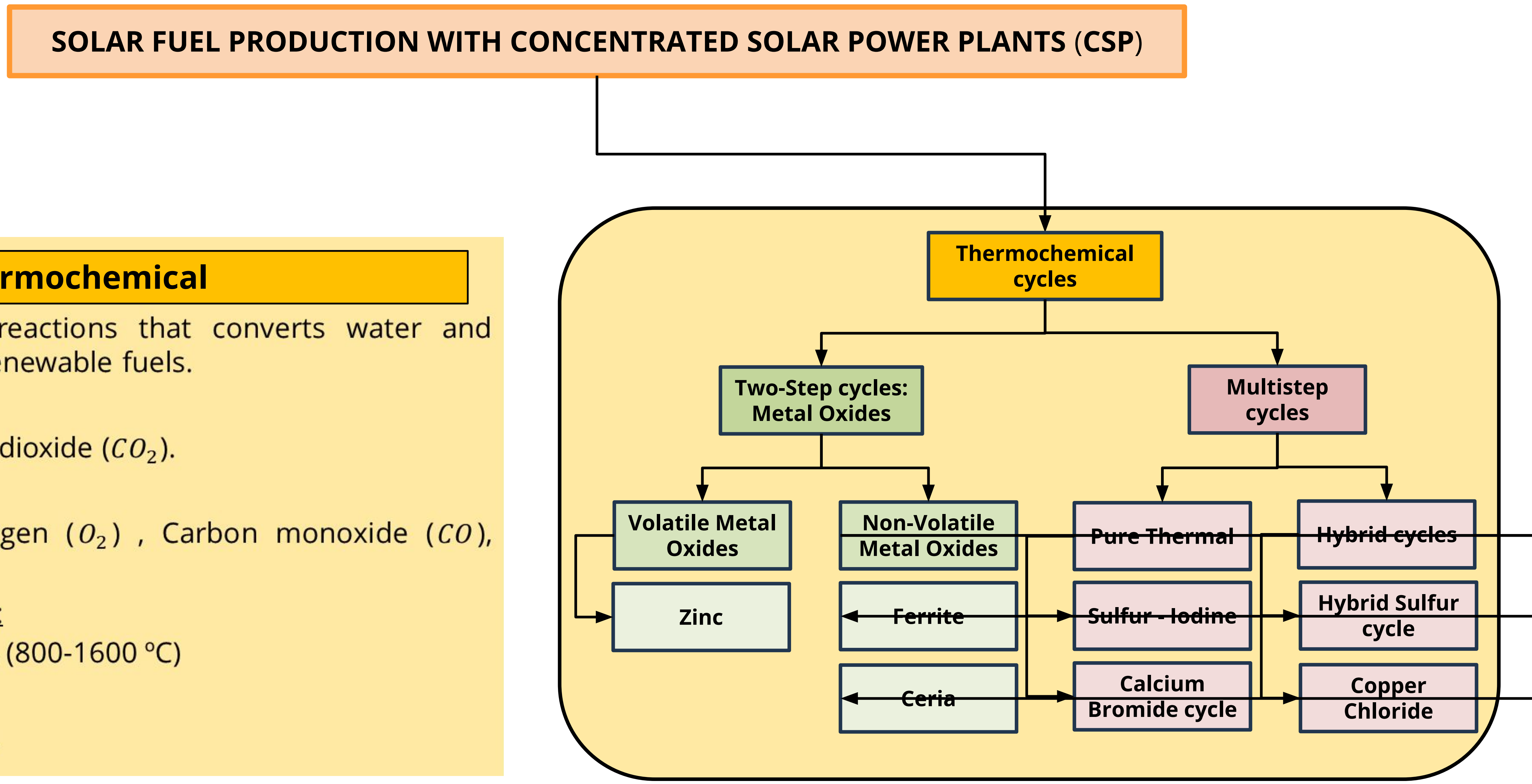
•Hydrogen (H_2), Oxygen (O_2), Carbon monoxide (CO), Syngas (H_2, CO).

Working temperature:

•Varies with the cycle. (800-1600 °C)

Reaction enthalpy:

•Varies with the cycle.



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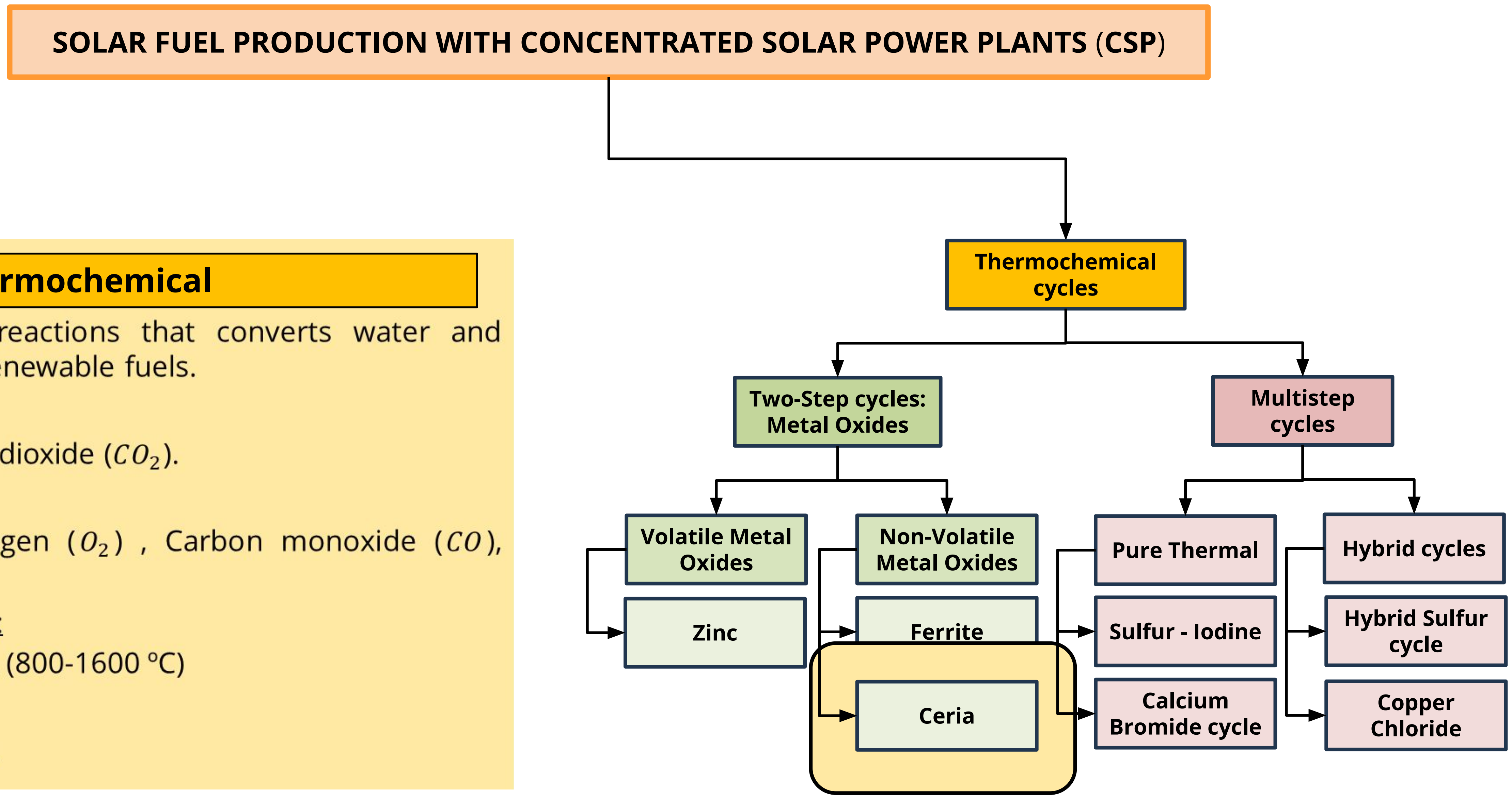
2. Solar Fuel Production with CSP

The **selected process** for the research is the **2-step redox cylce** based on **Ceria** (**CeO2**).



Thermochemical

Series of chemical reactions that converts water and carbon dioxide into renewable fuels.

Feedstock:

•Steam (H_2O), carbon dioxide (CO_2).

Output:

•Hydrogen (H_2), Oxygen (O_2) , Carbon monoxide (CO), Syngas (H_2, CO).

Working temperature:

•Varies with the cycle. (800-1600 °C)

Reaction enthalpy:

•Varies with the cycle.

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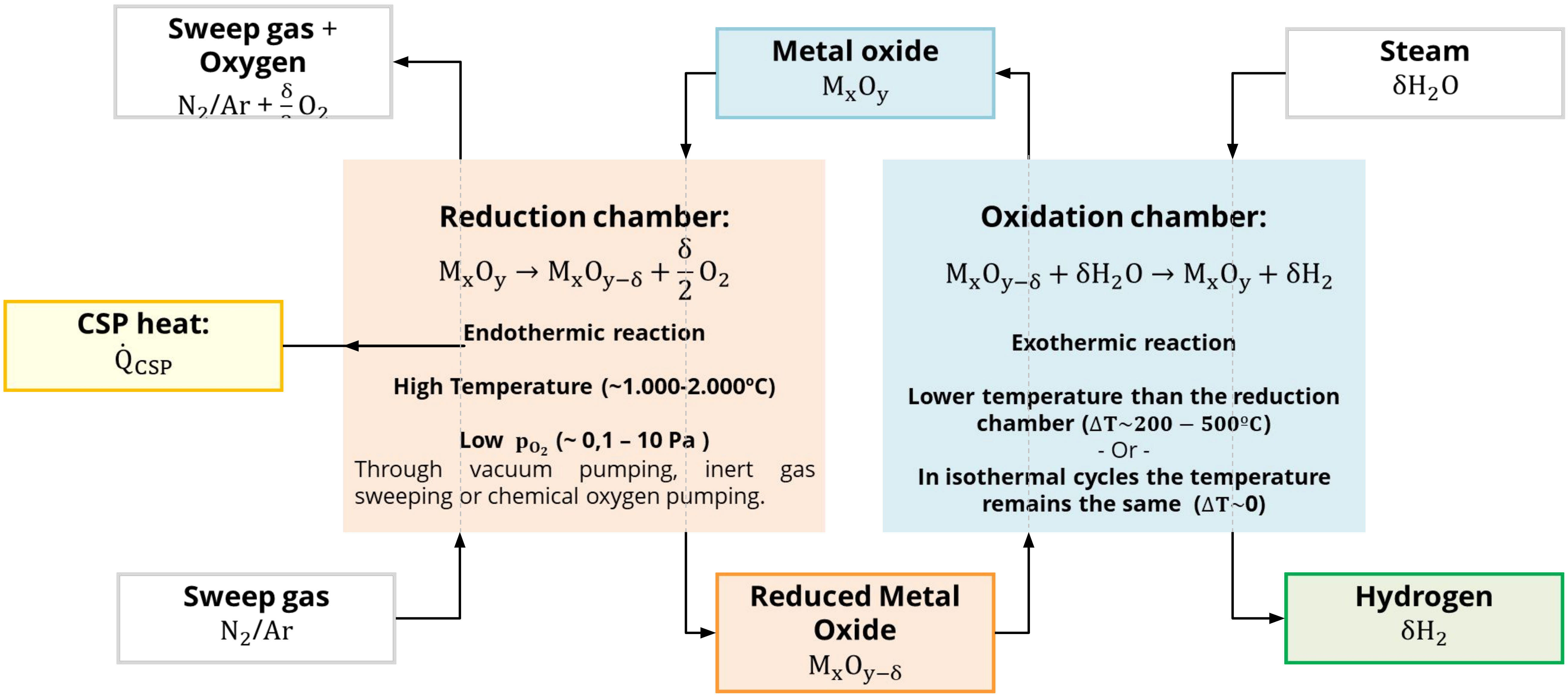
2. Solar Fuel Production: 2-Step Redox Cycle

A common **2-step Redox cycle** can be defined as follows:



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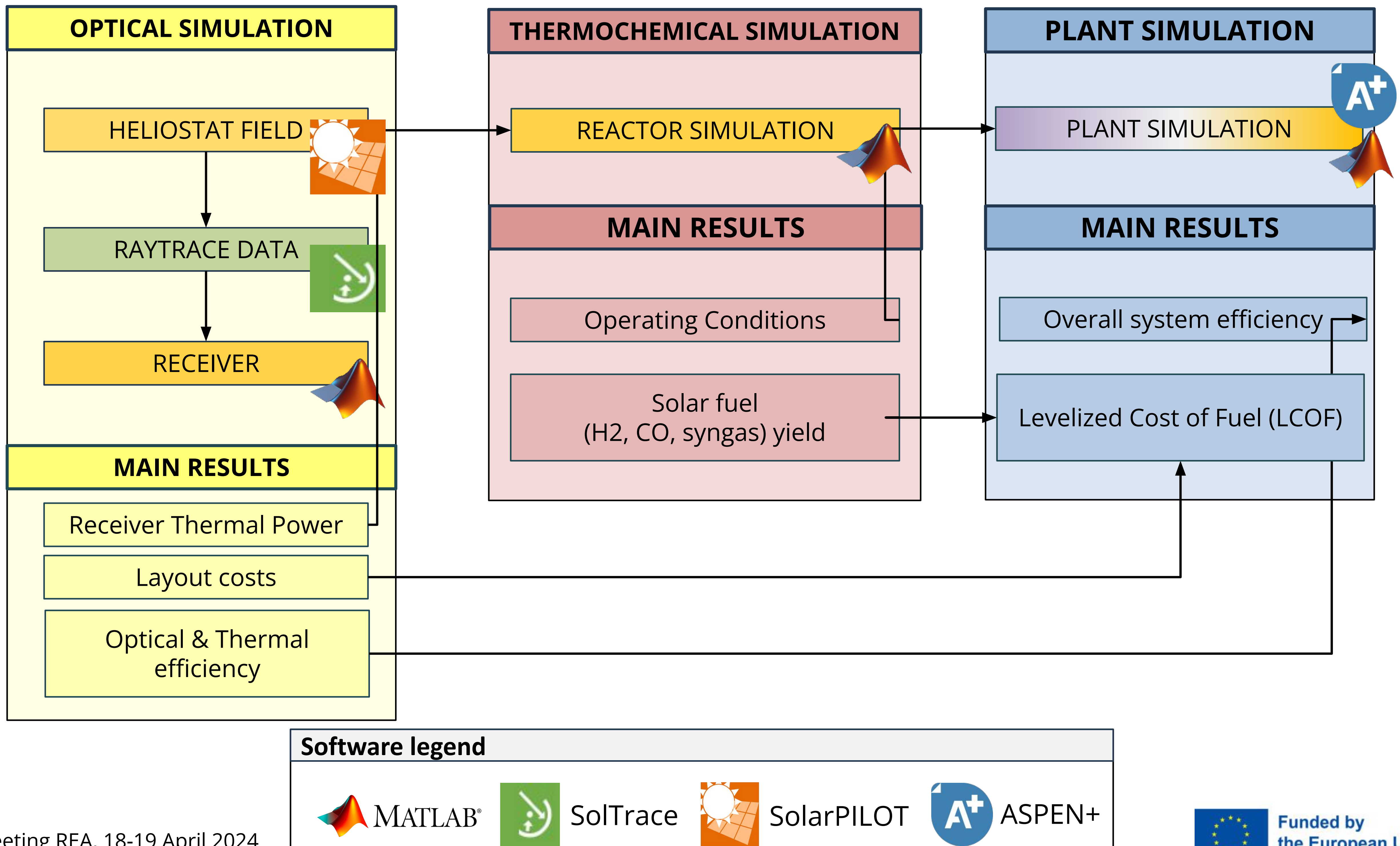
3. System simulation

The overall **simulation** of the system can be classified in **3 groups**, **optical** simulation, **thermochemical** simulation and **plant** simulation:



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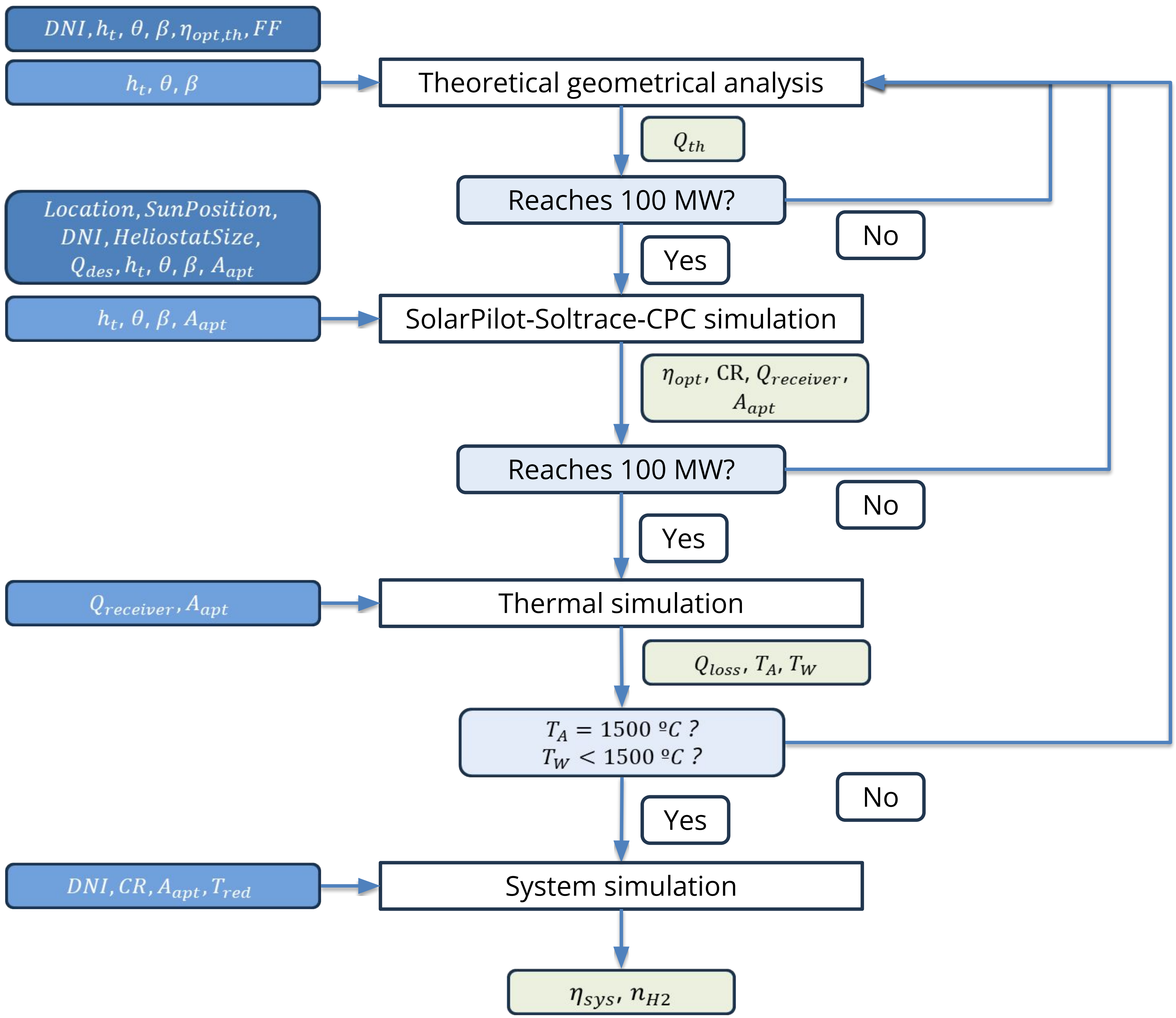
3. System optimization



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3. System optimization

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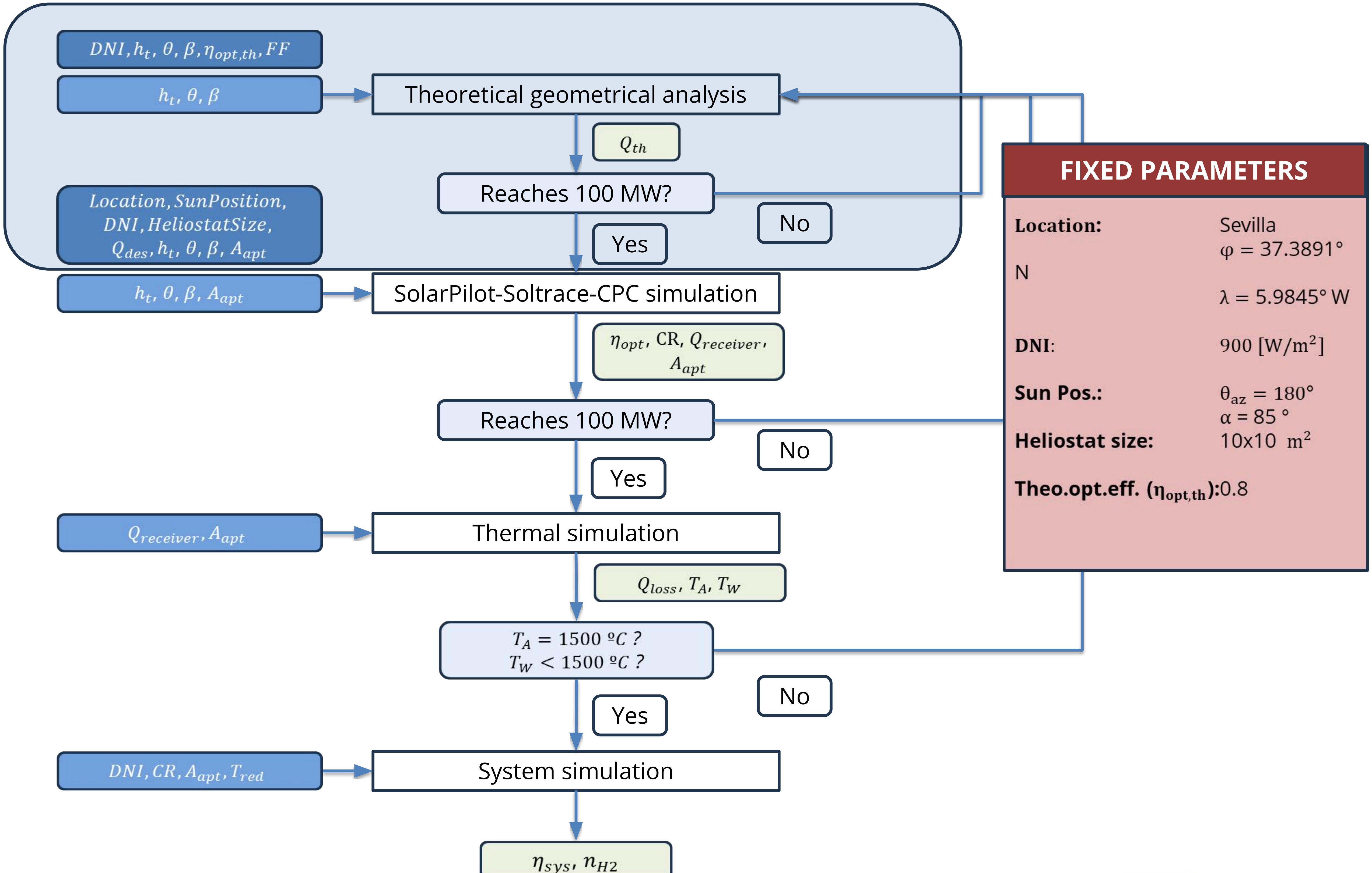

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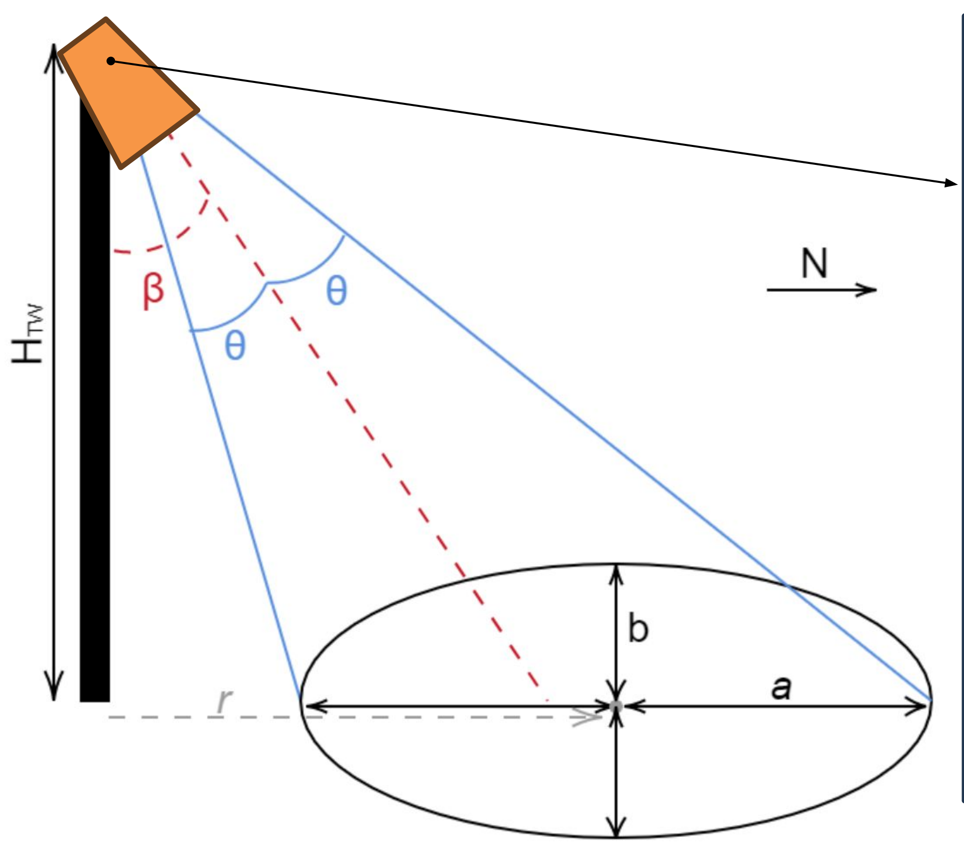
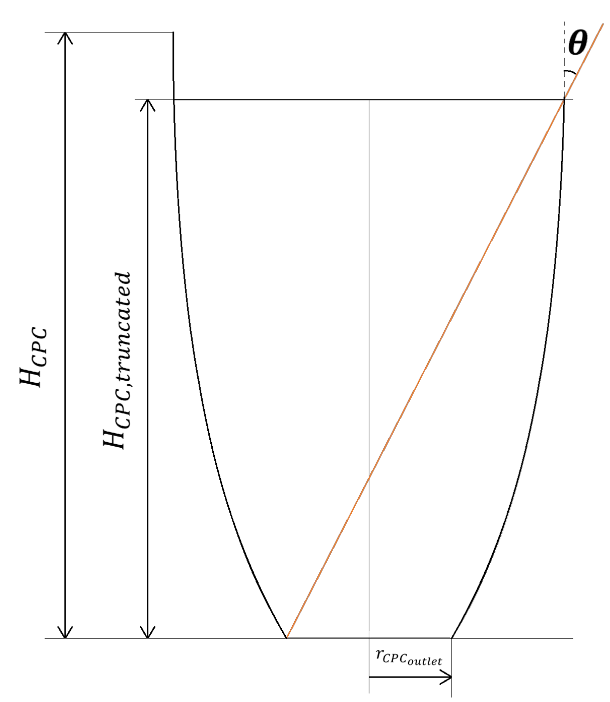
3. Optical simulation: Heliostat field

Temperature required: $\mathbf{T_{reac} = \sim 1.500\ °C}$ → High concentration ratio (**CR**) → Secondary concentrator (**CPC**)

The **solar field** needs to be **optimized** considering the following parameters:

- **Tower Height (H_{TW}):** limited to $\boxed{H_{TW} < 250\ \mathrm{m}}$ considering existing plants
- **Receiver tilt angle. (β):** $\boxed{0° < \beta < 90°}$
- **Receiver Semi-acceptance angle (θ):** $\boxed{10° < \theta < 40°}$ for good concentration ratio
- **Number of receivers:** 1 or more





Also geometrical parameters of the **CPC** need to be **optimized:**

- CPC diameter ($r_{CPC_{outlet}}$): limit to 0.6m
- Semi-acceptance angle of CPC. (θ_{max})
- Truncation of CPC. $\left(\frac{H_{CPC,truncated}}{H_{CPC}}\right)$
- Number of CPC: clustering

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3. Optical simulation: Heliostat field

A preliminary theoretical analysis is performed to identify the **minimum size of the tower**:

$\boldsymbol{H_{TW}}$ found for each $\boldsymbol{\theta_{max}, \beta}$ to reach $\boldsymbol{Q_{th} = 100\ MW_{th}}$

Theoretical expression for the thermal power of the field:

$$\boxed{Q_{th} = DNI \cdot A_{field} \cdot FF \cdot \eta_{opt} \cdot \eta_{cos} \cdot \eta_{att}}$$

From which:

- *Direct Normal Irradiance:* $DNI = 900\ W/m^2$
- *Filling Factor:* $FF = 0.2$
- *Area of the field:* $A_{field} = f(\theta_{max}, \beta, H_{TW})$
- *Optical efficiency:* $\eta_{opt} = 0.95 \cdot 0.88 = 0.836$
- *Cosine efficiency:* $\eta_{cos} = g(\theta_{max}, \beta, H_{TW})$
- *Attenuation efficiency:* $\eta_{att} = h(\theta_{max}, \beta, H_{TW})$

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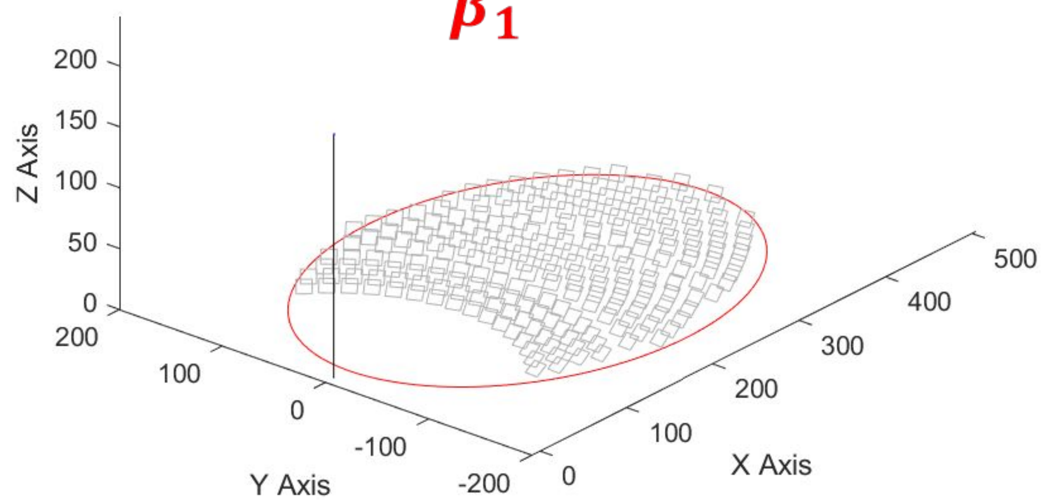
3. Optical simulation: Heliostat field

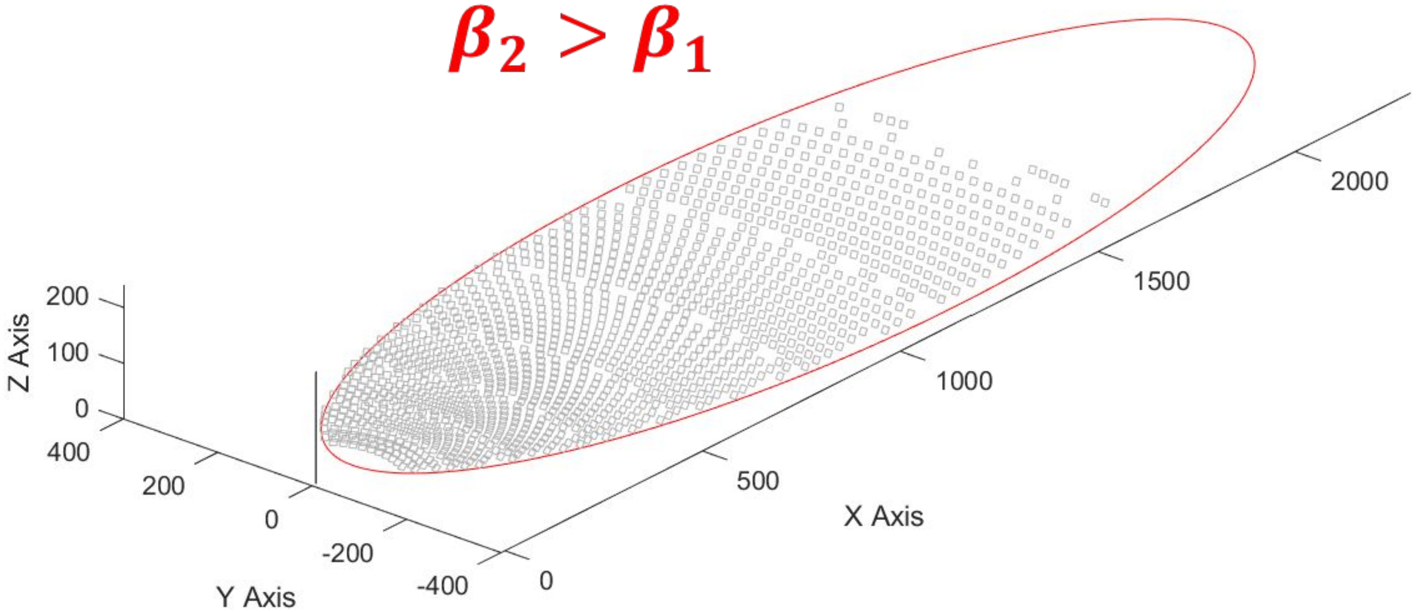
Theoretical assessment of the impact of the field design parameters on the power/efficiency

Effect of receiver tilt

β_1

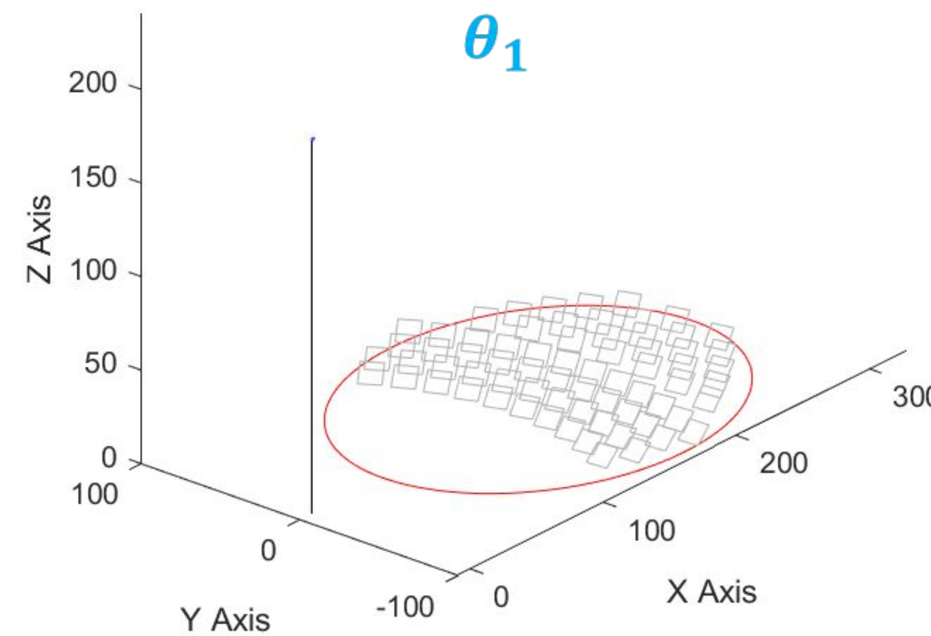


$\beta_2 > \beta_1$

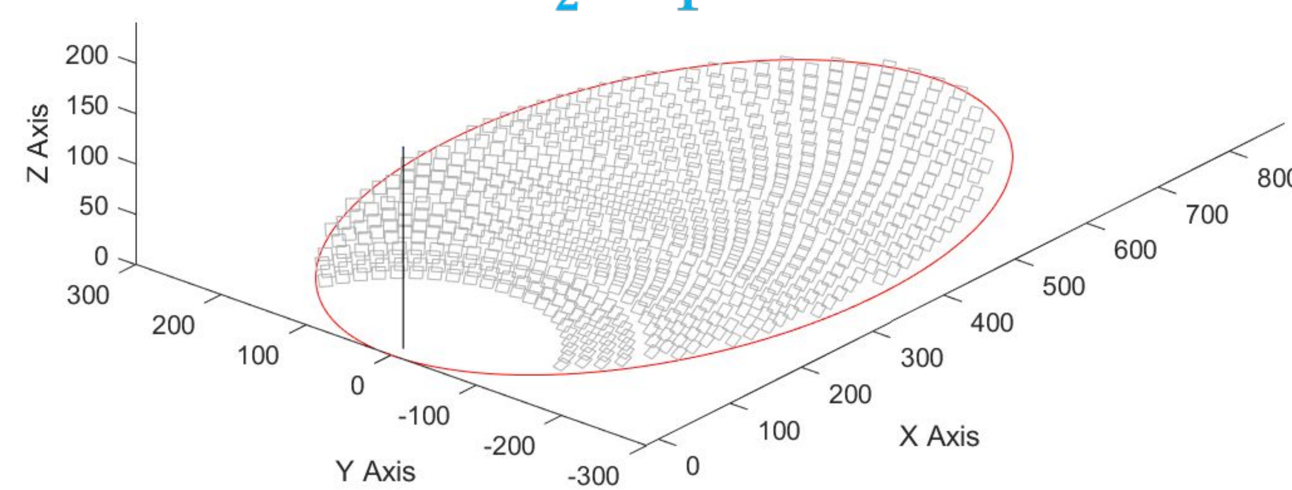


Effect of receiver acceptance angle

θ_1



$\theta_2 > \theta_1$



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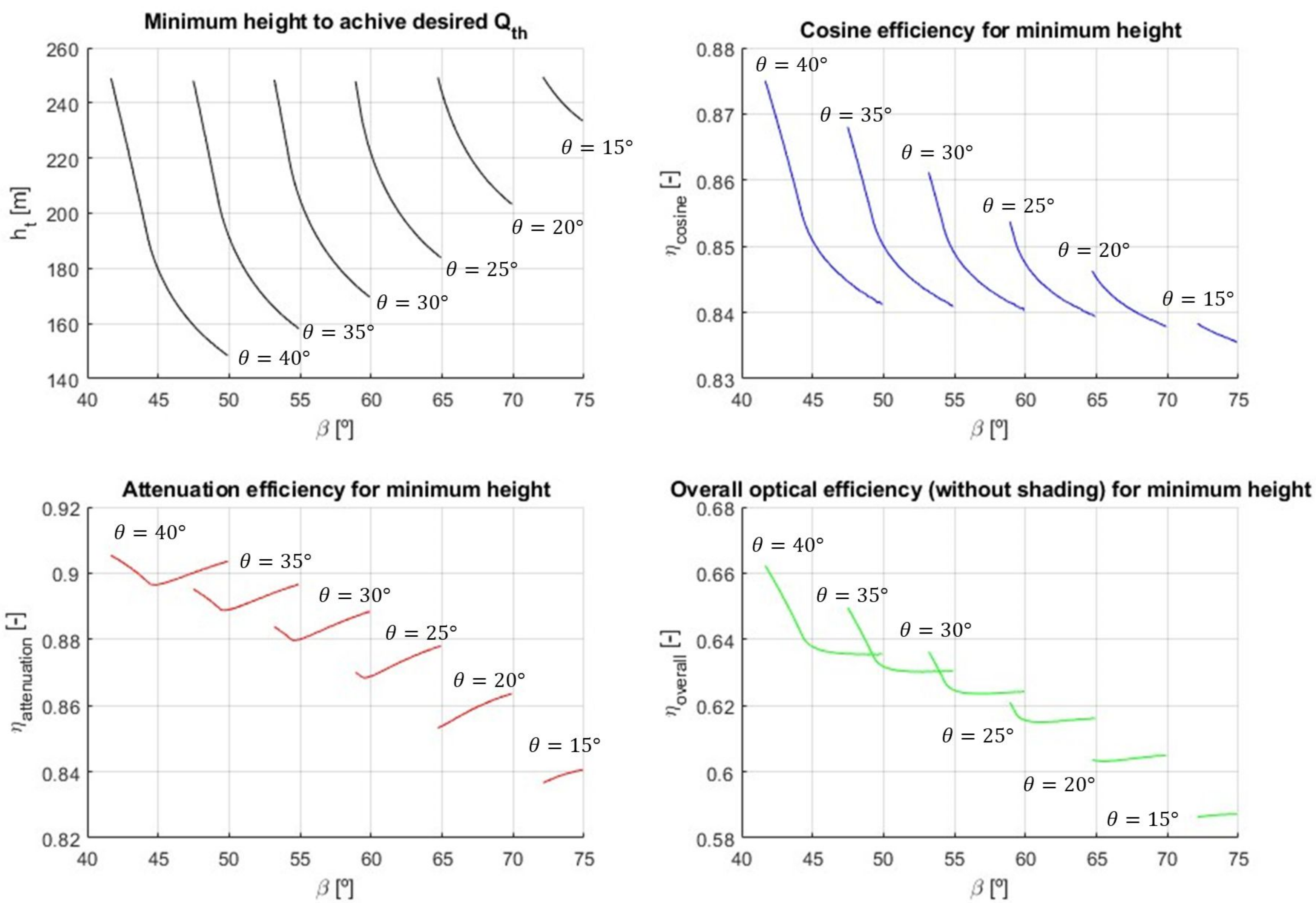
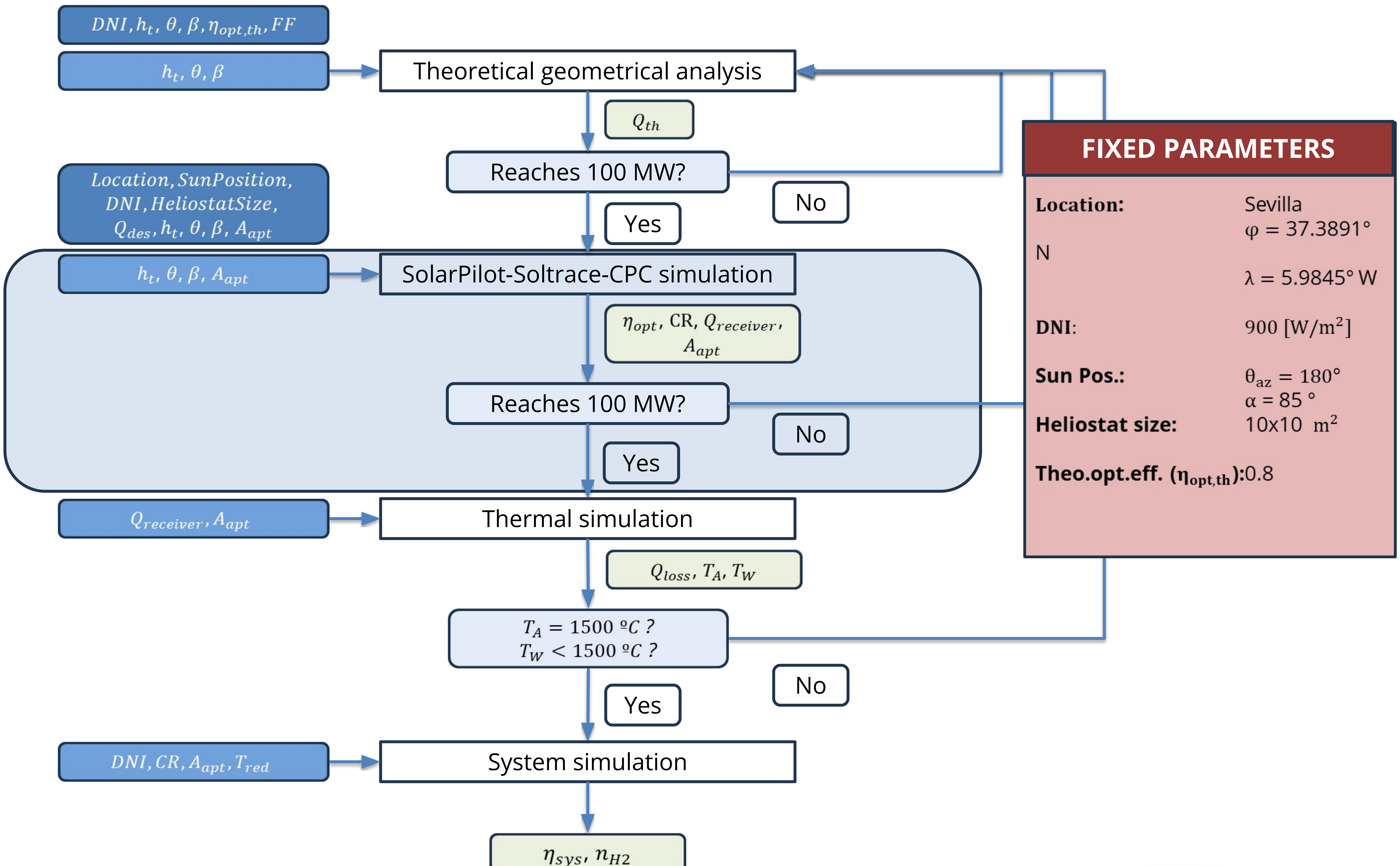
3. Optical simulation: Heliostat field

- The **minimum tower height** to achieve the desired power is obtained considering a first rough **optical efficiency** estimate
- This optical efficiency includes simple geometrical effects: cosine efficiency and attenuation



This analysis can significantly reduce the number of required ray-tracing simluations

3. System optimization



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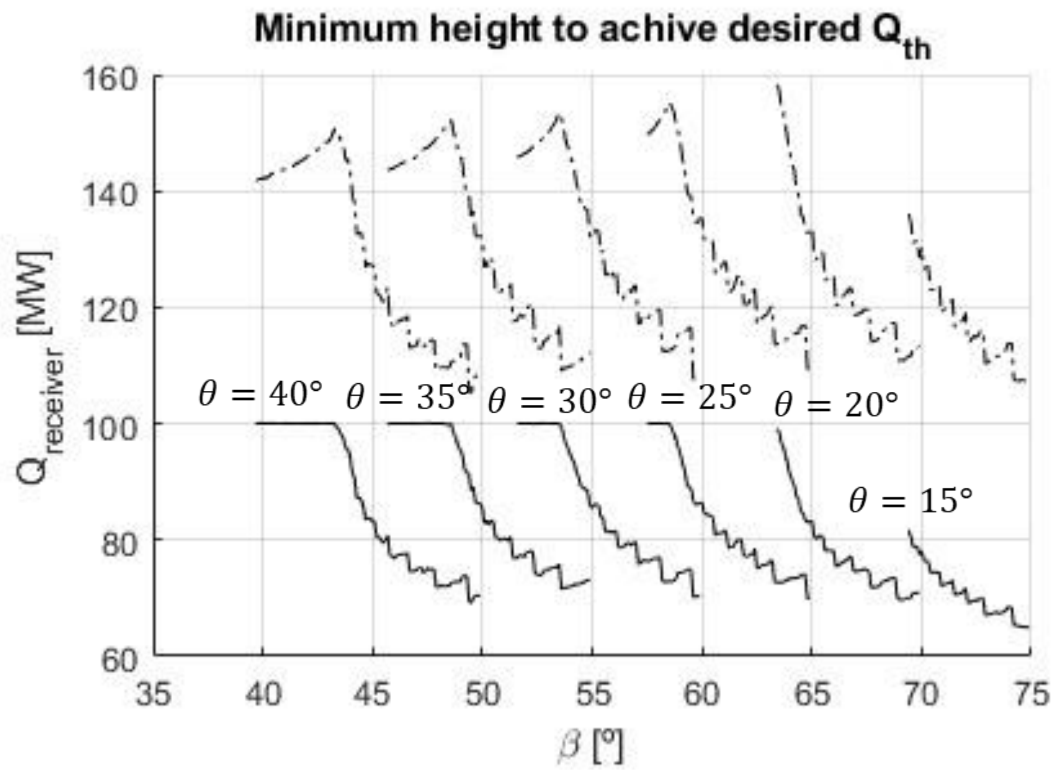
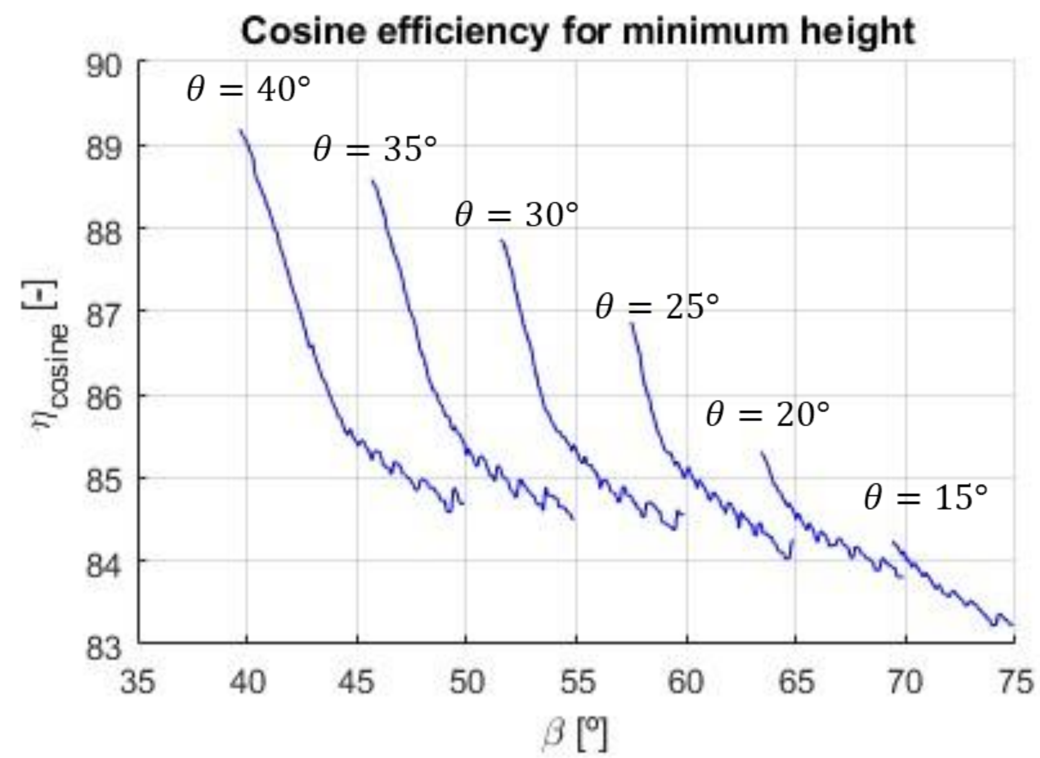
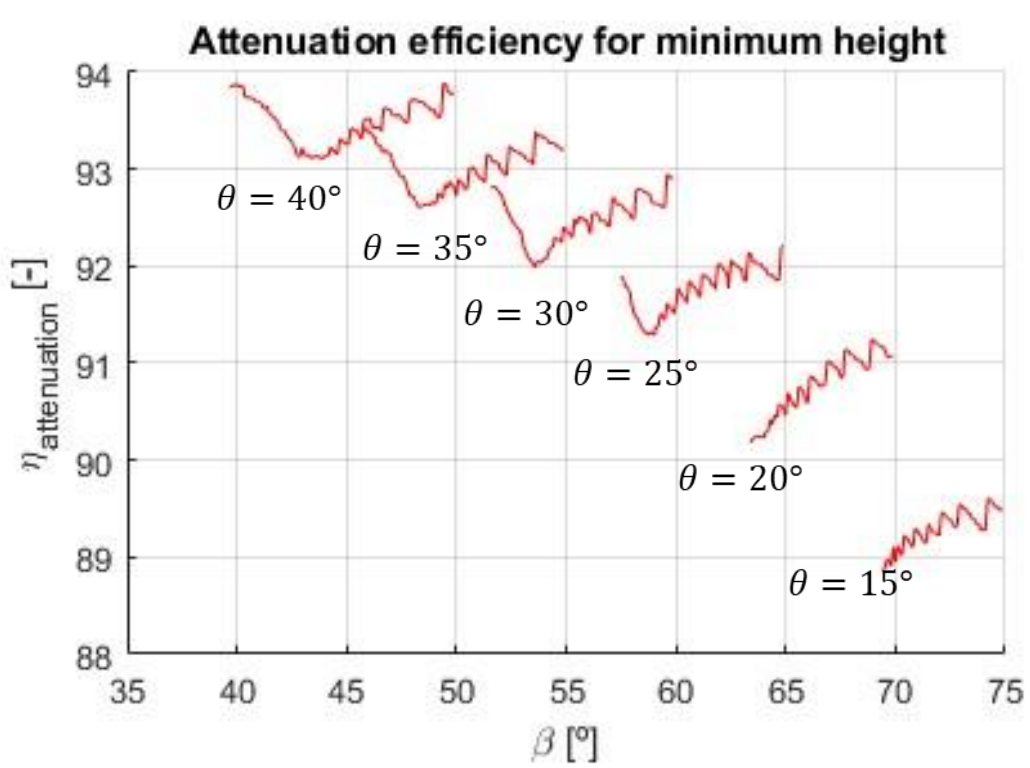
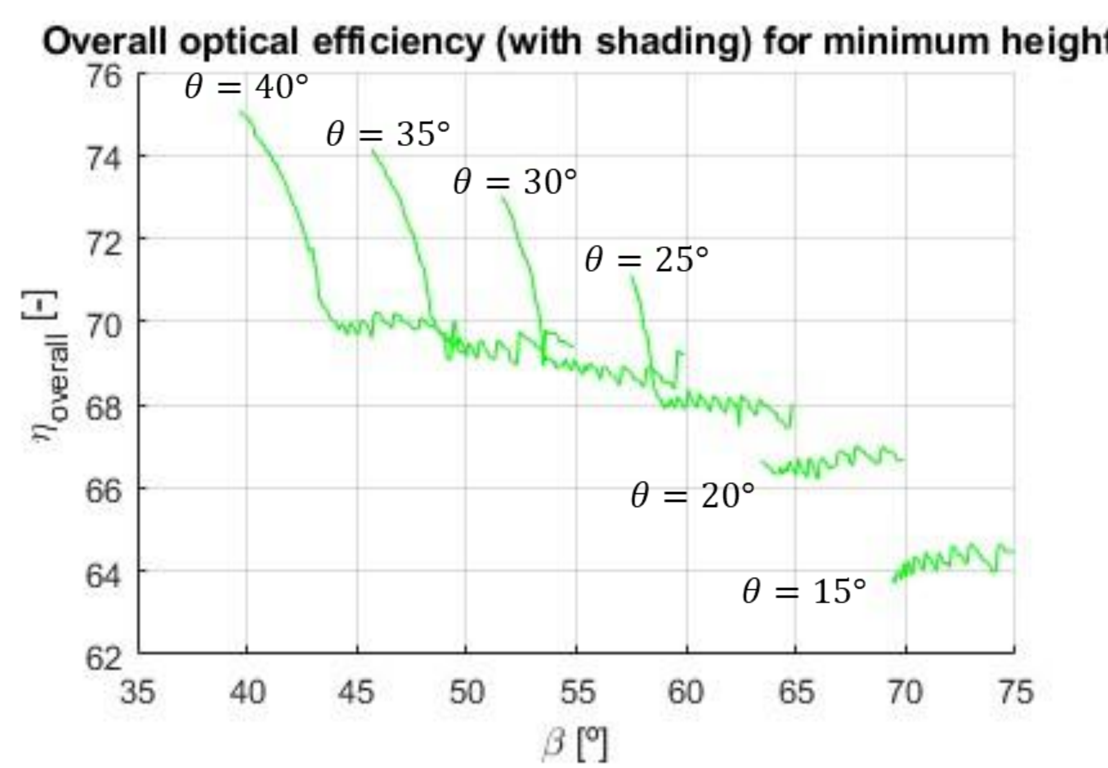
3. Optical simulation: Heliostat field









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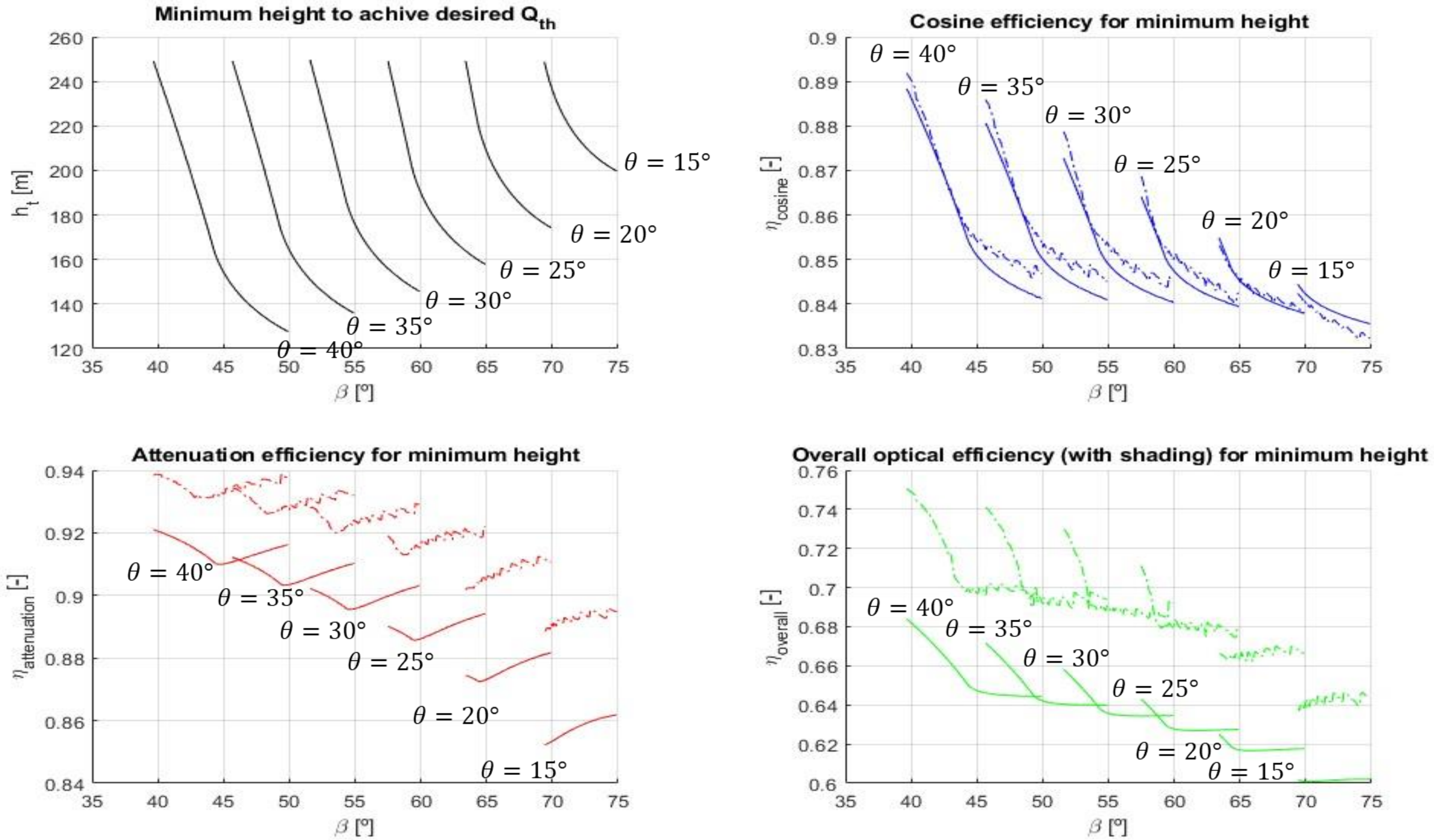
3. Optical simulation: Heliostat field

This analysis will eventually allow us to find and select the configurations:

- That have **higher efficiency**.
- That have **lower costs**.



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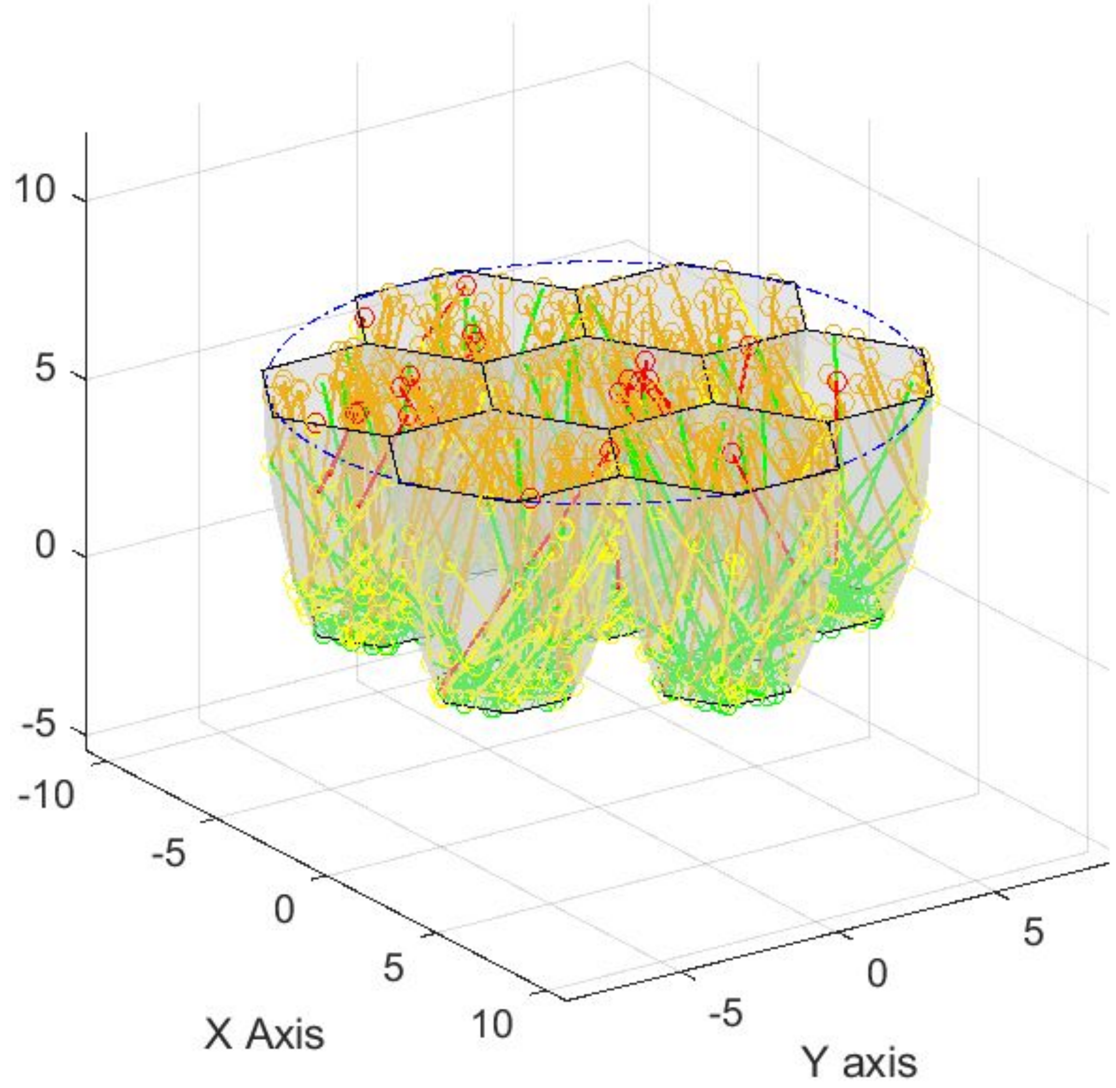
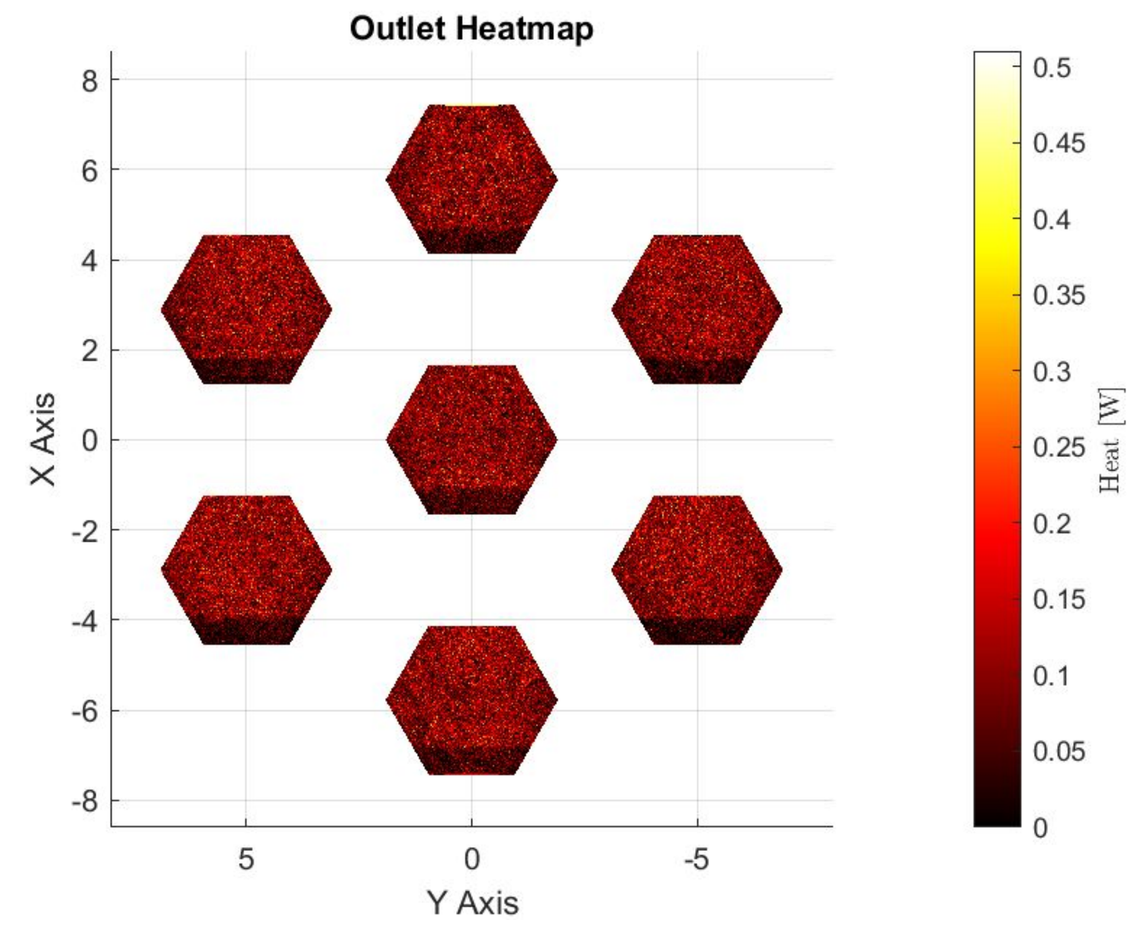
3. Optical simulation: Heliostat field

With the data form the heliostat field, we can simulate the raytracing on the **CPC:**





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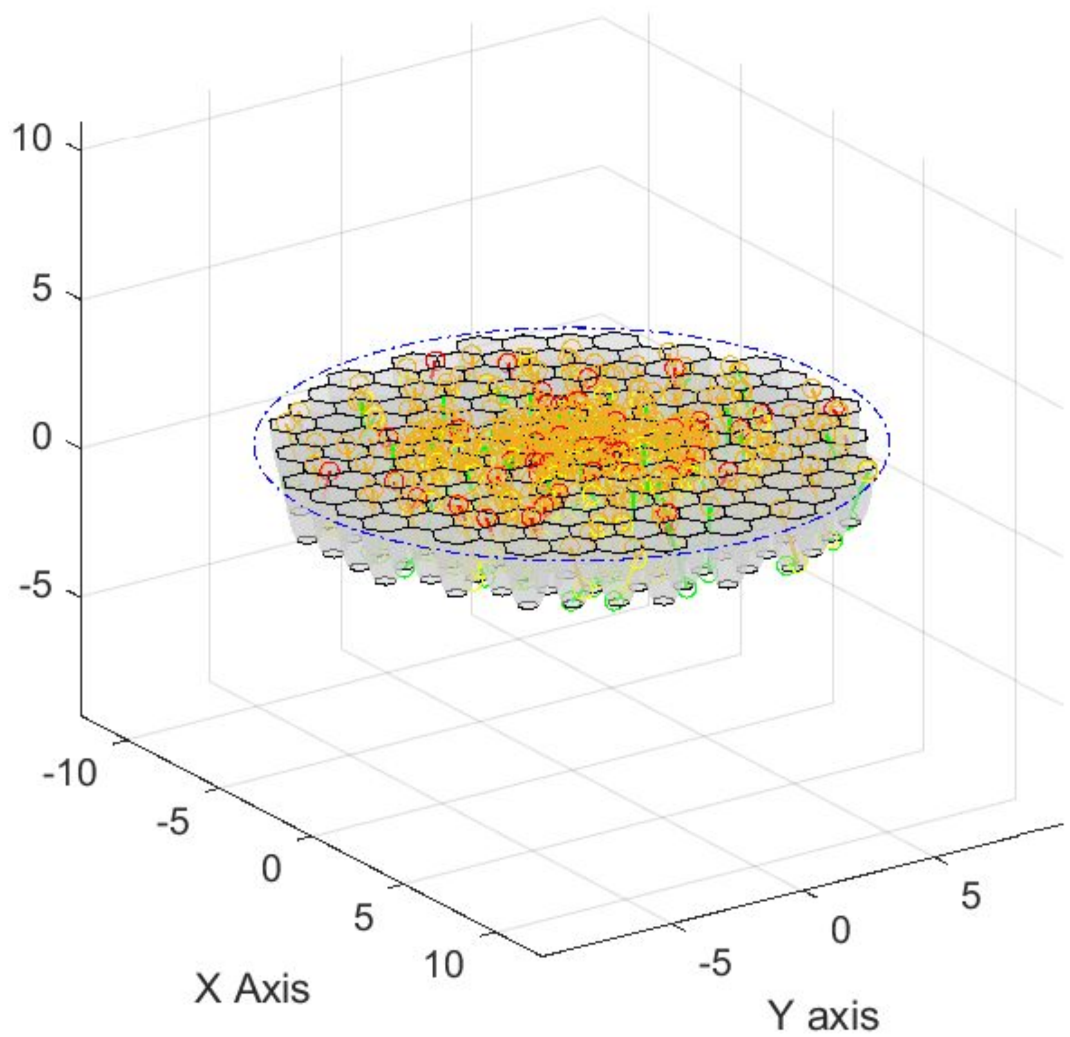
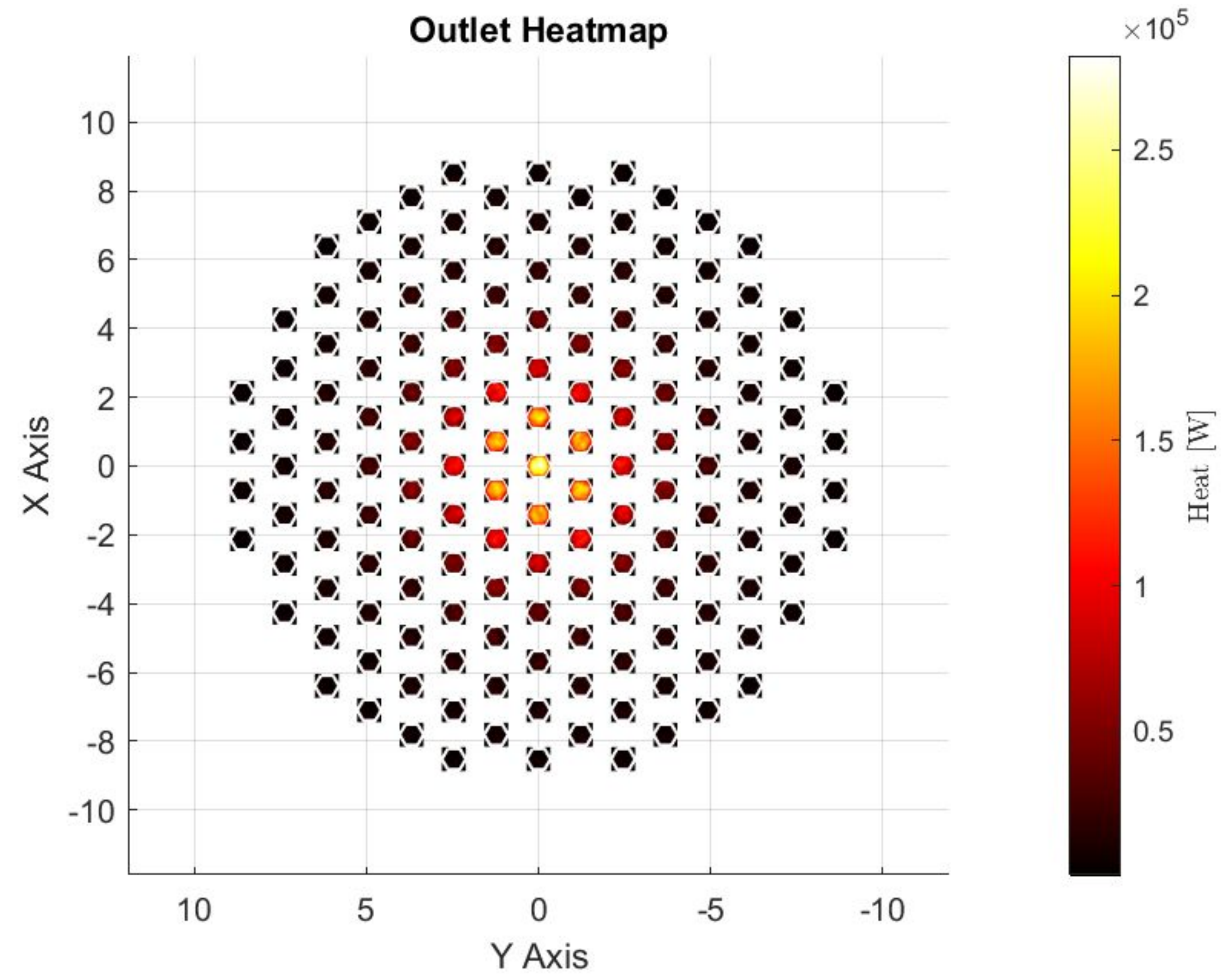
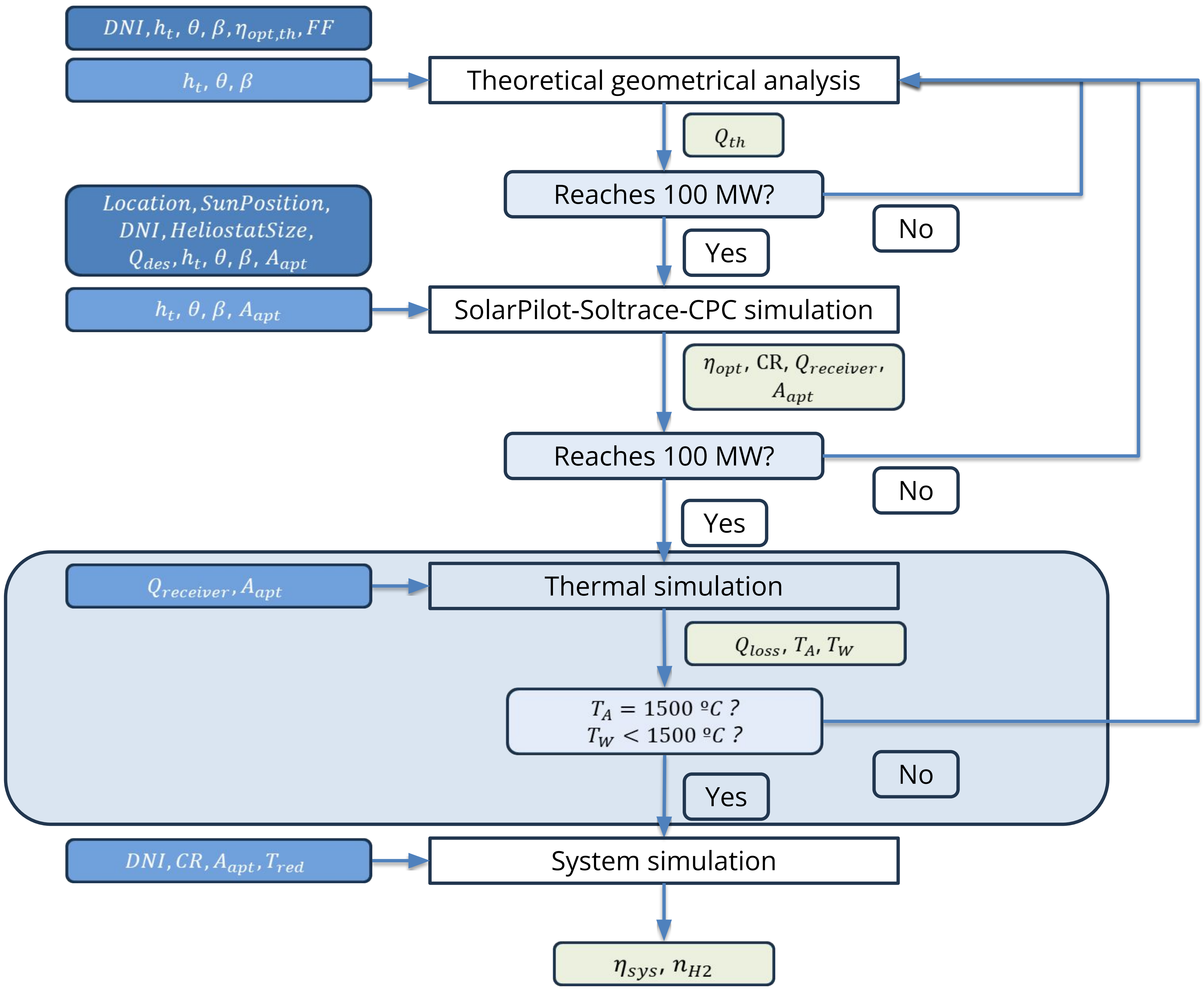




3. System optimization



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3. Reactor simulation: Thermal performance

Due to the **high temperatures** reached at the reactor, is necessary to estimate the **thermal losses** due to the aperture. Other considerations include a limit on the **quartz window** maximum operating **temperature**, which will be considered **at 800 ºC.**
Therefore, a **MATLAB code** is being implemented:

J.-P. Säck et al. / Solar Energy 135 (2016) 232–241

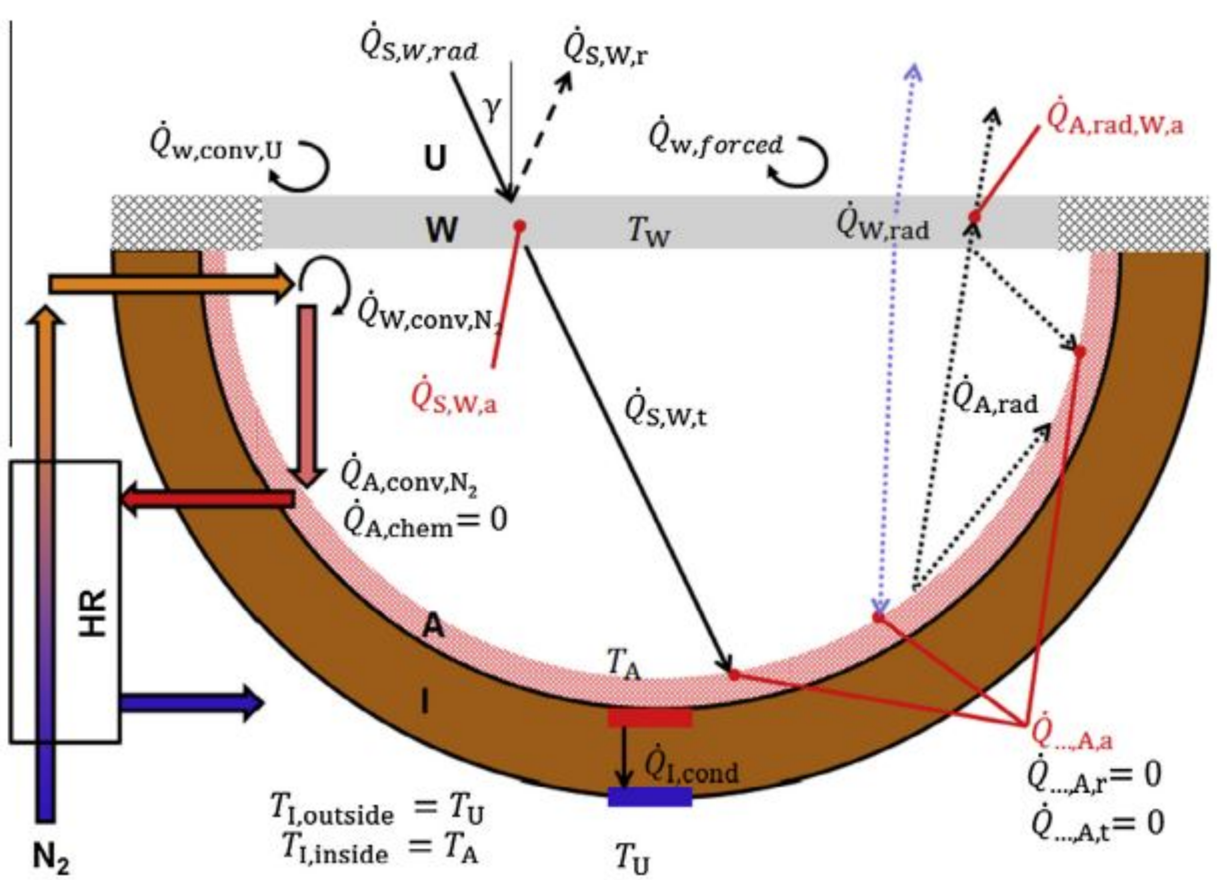
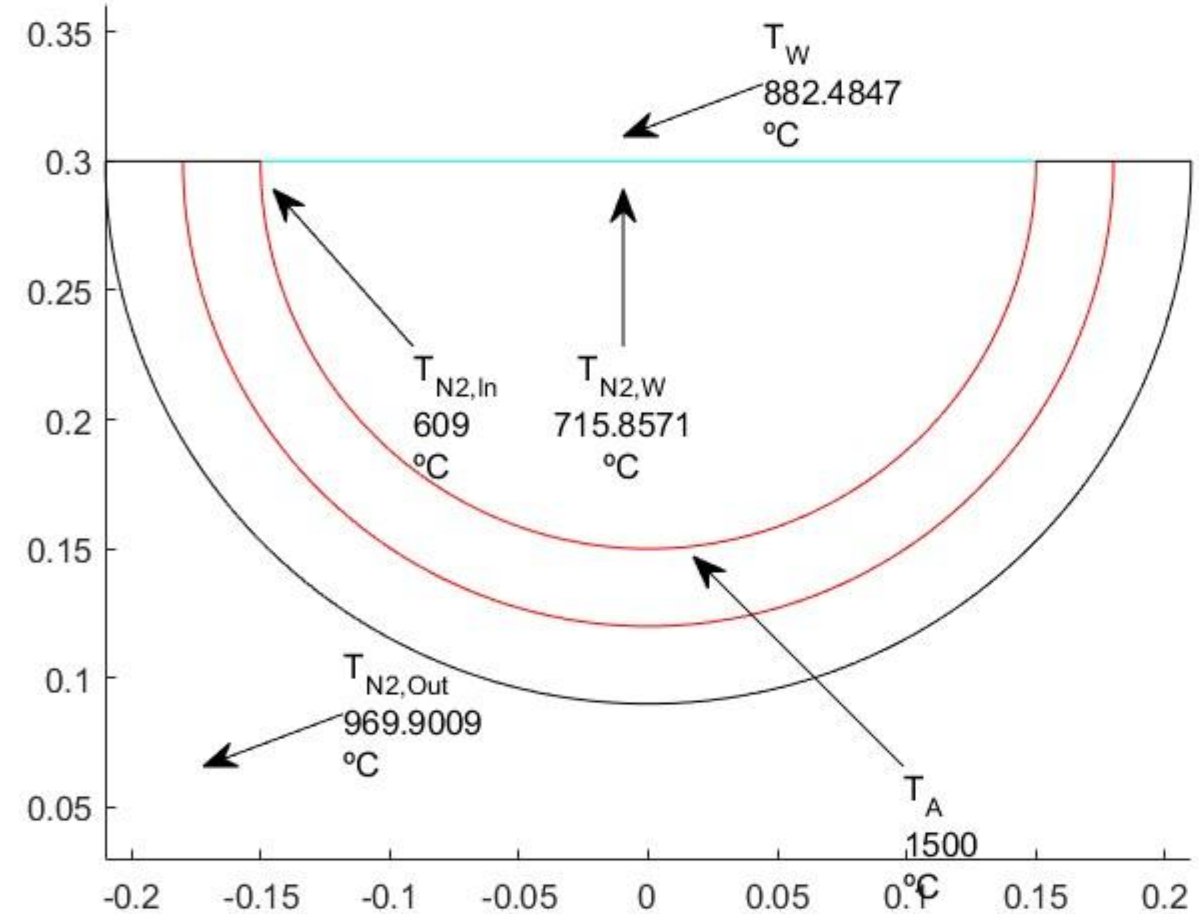


Fig. 10. Scheme of the reactor thermodynamic model.



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3. Reactor simulation: Thermal performance

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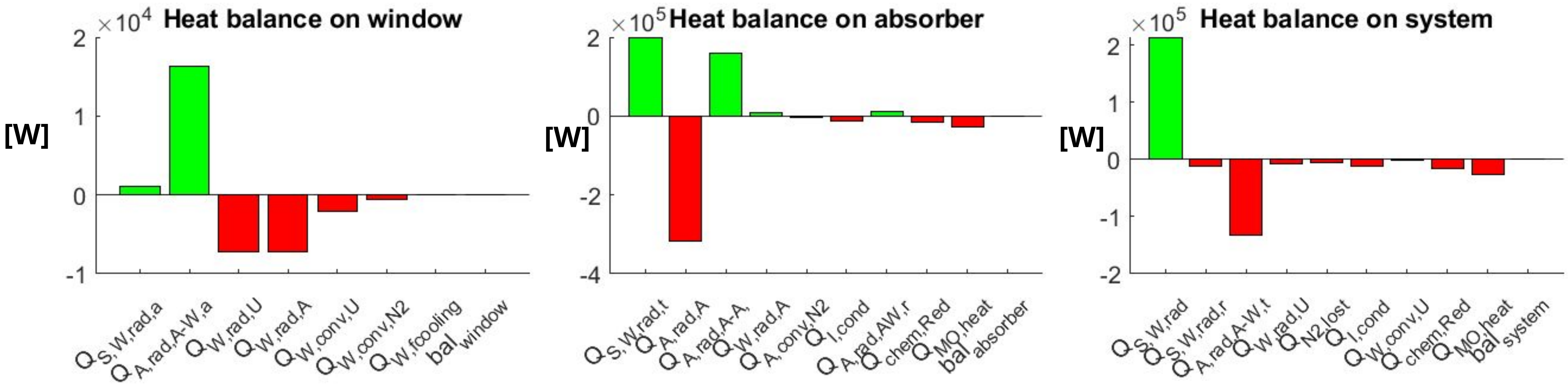

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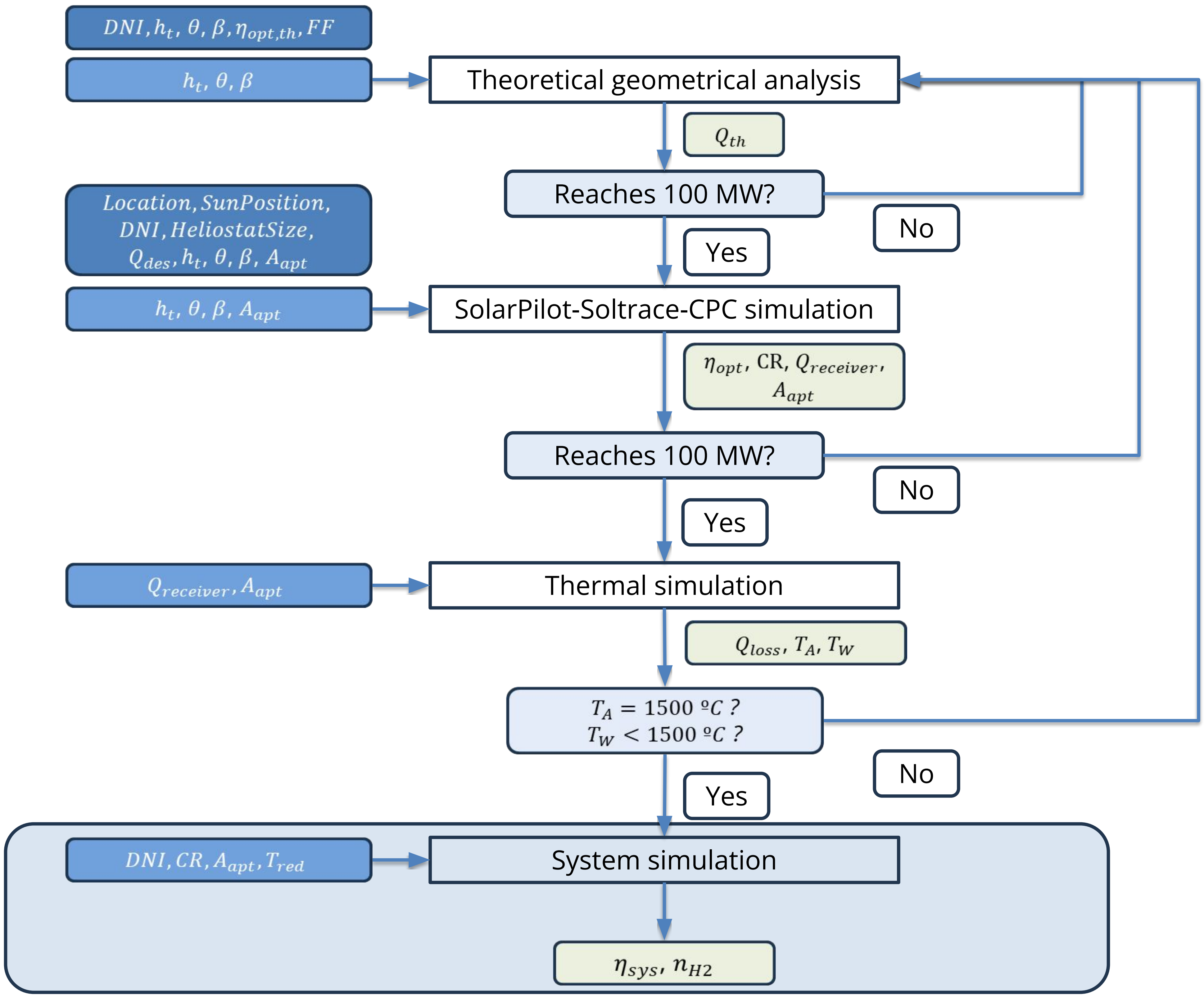
3. System optimization



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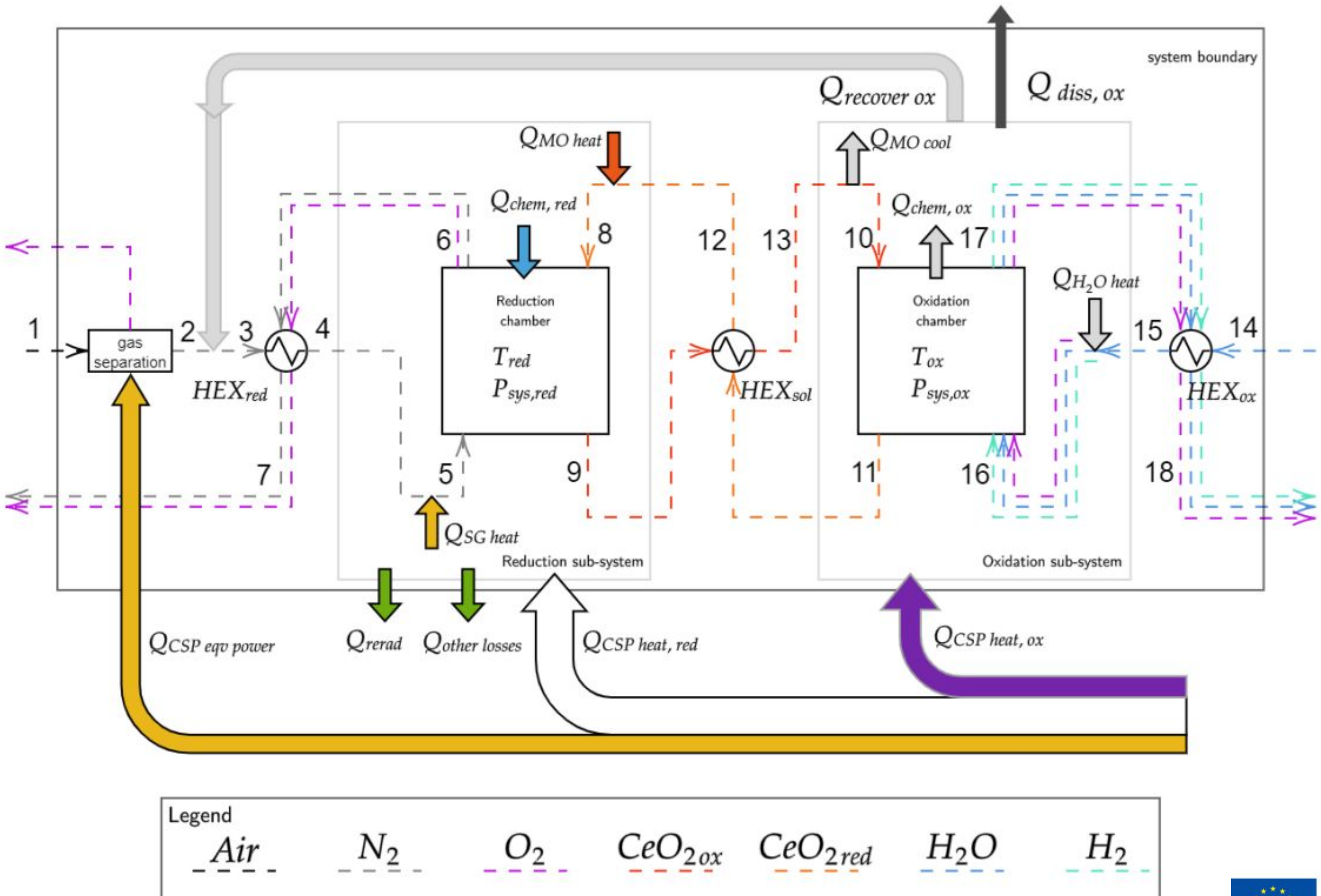
3. Reactor simulation: Chemical performance

Once the heat input is provided, it is possible to compute the **thermochemical cycle performance**. The thermochemical cycle takes place at two different reactors, the **reduction reactor** and the **oxidation reactor**.



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3. Reactor simulation: Chemical performance

Specific energy demand for fuel production:

4252.5 MJ/kmol$_{H_2}$

2109.4 MJ/kg$_{H_2}$

Efficiency (solar->H_2)= 6.72 %

H2O splitting
Reactor model: rev
Auxiliary: yes

OPERATING CONDITIONS:
p_{red}=1.0 bar
p_{ox}=1.0 bar
T_{red}=1900 K

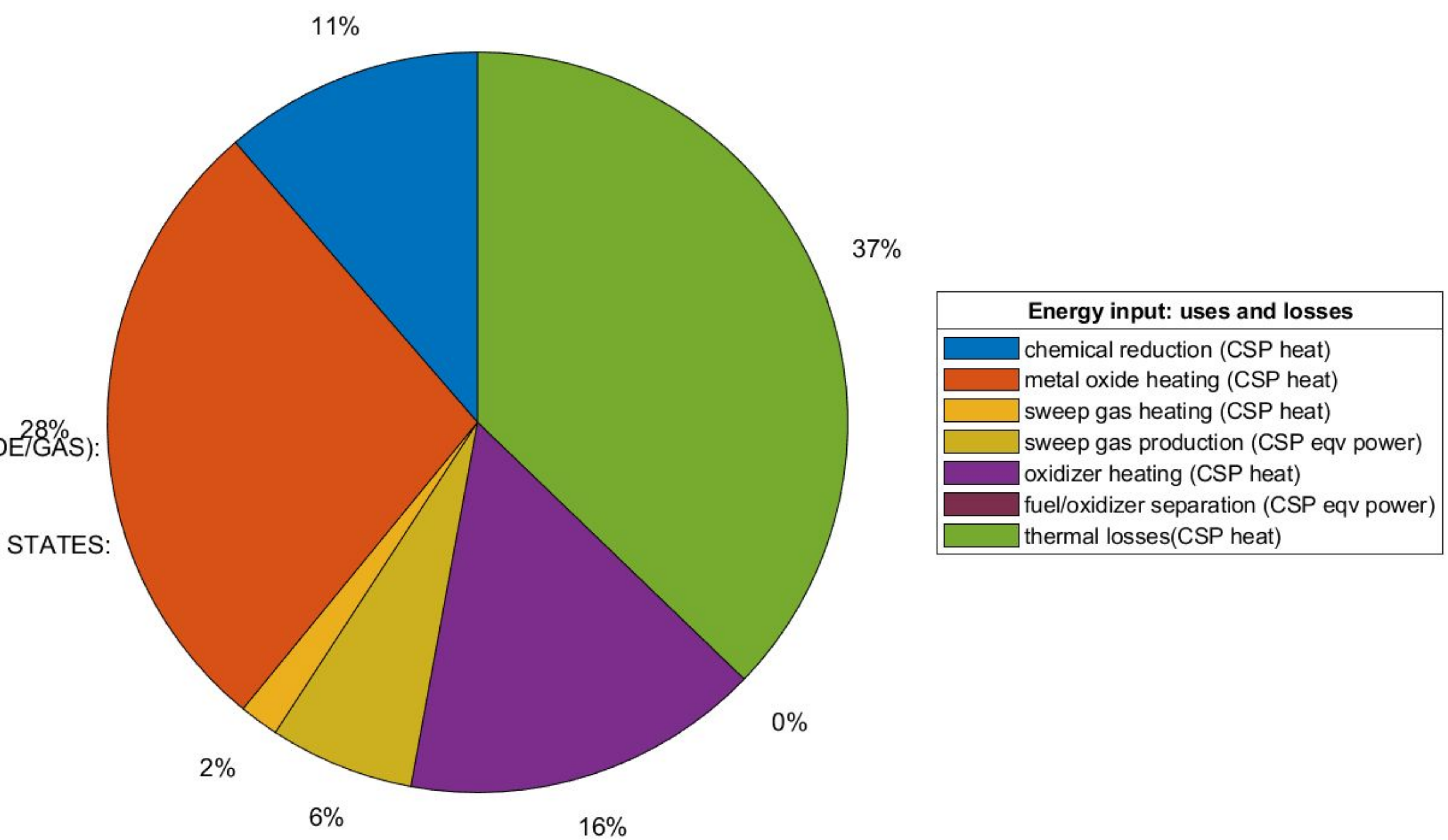
T_{ox}=1458 K
$p_{O2,in}$=1.00e-06 bar
n_{N2}/n_{MO}=0.18
n_{H2O}/n_{MO}=1.60

FLOW CONFIGURATION (METAL OXIDE/GAS):
CF (red) - CF (ox)

METAL OXIDE NON-STOICHIOMETRY STATES:
δ_{red}=0.0366
δ_{ox}=0.0044
$\Delta\delta$=0.0322

HEAT RECOVERY CONDITIONS:
- solid-to-solid:
0 %
- gas-reduction side (sweep gas):
75 %
- gas-oxidation side (H2O):
DTpp=10 K

SOLAR HEAT: USES AND LOSSES



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4. Next Steps

CPC Optical analysis

- Compute the **CPC analysis** on the selected cases.

Thermodynamic model of the reactor

- We are working on a **thermodynamic model** of the receiver.

Whole system coupling

- With the thermodynamic model is finished, we will be able **to simulate all the parts of the system.**

Techno-economic analysis of the system

- A **techno-economical analysis** of the overall system will be carried out.

Study of different thermochemical processes

- **Other thermochemical processes** will be studied and modelled:
  - **Methane-driven two-step ceria cycle.**
  - **Biomass gasification/pyrolysis.**

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