Techno-Economic Evaluation and Optimization of CSP Plants with ColSimCSP

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Minimized water consumption in CSP plants

MinWaterCSP

Table of content

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CSP system simulation tool of Fraunhofer ISE

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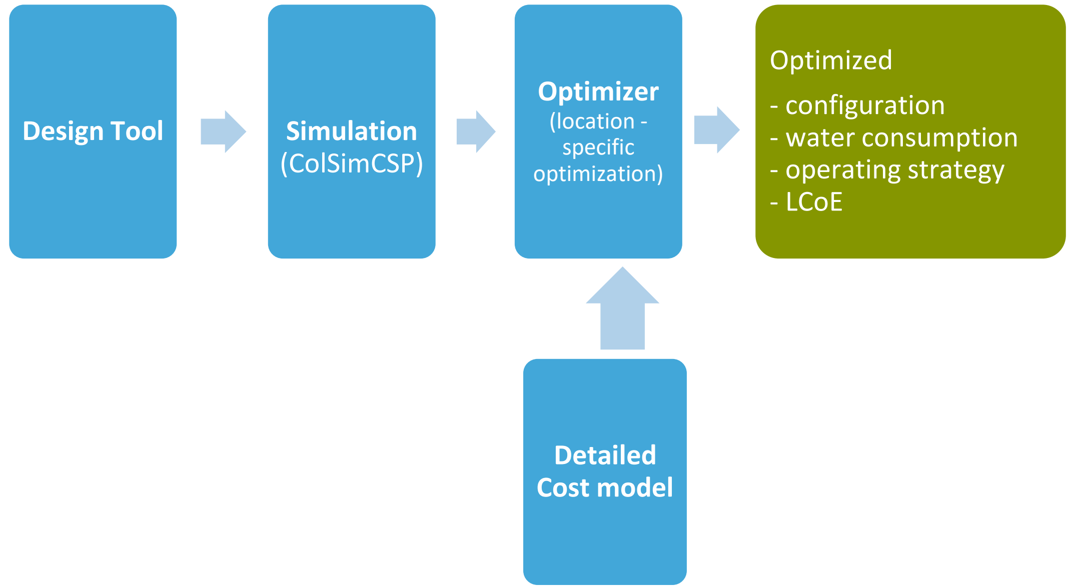
Fraunhofer ISE software tool chain for design, simulation and optimization of CSP plants

From analyzing the weather data and design to cost calculation

- **CSP Technologies**
  - Parabolic Trough Collector
  - Central Receiver Tower
  - Linear Fresnel Collector
- **Cooling Technologies**
  - Hybrid dry/wet
  - ACC
  - WCC



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Fast design tool for CSP plants

The fast design tool provides the required input for ColSimCSP

- **Inputs to the tool:**
  - Weather data and site information
  - Collector technology (PT, LF, HE)
  - Cooling technology + corresponding PB efficiency
  - Heat transfer fluid HTF (Molten Salt or Thermal Oil)
  - Plant nominal capacity
  - Storage size
- **Outputs of the tool:**
  - Design point parameters
  - Solar field size and layout
  - Heliostat size
  - Turbine size
  - Storage tank volume
  - Design HTF mass flow rate

```
Design point:  7907   Month= 11  Day= 26  Hour= 12  Minut
Design point DNI =  975.6 W/m2
Design point Optical efficiency =  0.74332025262 3
Design point Dry bulb temperature =  31.9 degC
Design point Dew point temperature =  1.1 degC
Design point Relative humidity =  14.0 %
Cooling option: wet cooled
WetBulb Temperature 21.6333333333 degC
Power cycle model: General (CSP-Bank data based)
Power block:
Net power of Power block: 50.0 MW
Gross power of Power block: 56.1797752809 MW
Design Power block efficiency: 0.38607550249
Conversion factor: 0.89
Thermal Power required for Power block: 150.015460008 MW
Mass of the Power block: 200000.0 kg
Feed water mass flow rate: 51.1089061406 kg/s
Thermal power in Storage:  300.030920017 MWhth
The number of pairs of the tanks: 1
Indirect Storage & Therminol VP1
temp_sf_htf_in 290.0
temp_sf_htf_out 393.0
temp_coldtank_design 296.0
temp_hottank_design 386.0
Total mass of the molten salt:  7992022.65283 kg
Total volume of hot molten salt:  4332.88442466 m3
Mass flow rate of salt:  1110.00314623 kg/s
self.theoretical_sol_mul 1.27714285714
###
get_solar_multiple (self, design_dni, n_opt)
self.total_aperturearea 264196.913345
total_loops 80.8076285694
total_loops 82
###
Suggested solar field aperture area: 268095.3182 m2
Suggested solar multiple:  1.29598796722
Aperture area of one loop:  3269.4551 m2
```


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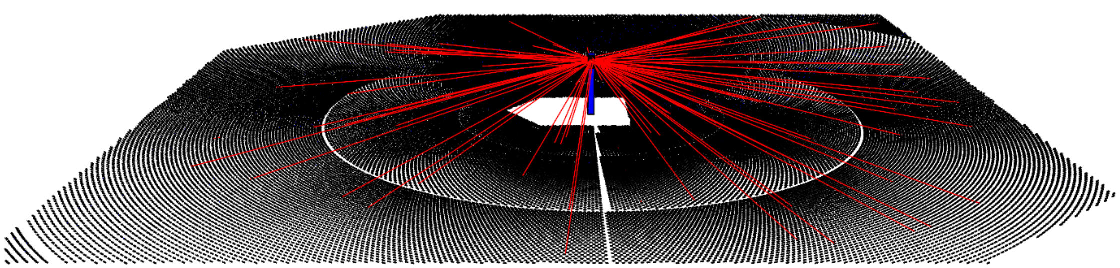
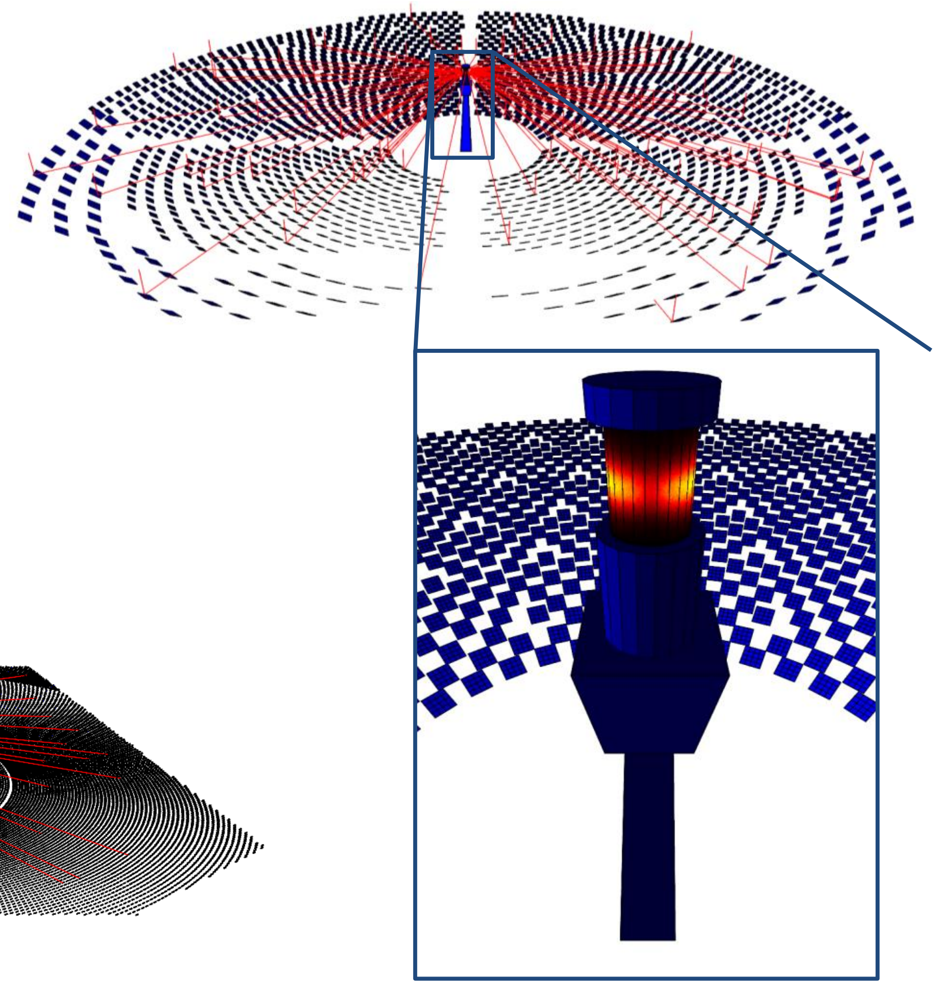
The fast design tool for CSP plants

Heliostats field design

- Monte-Carlo ray tracing
- Simulation of large heliostat fields (>50k heliostats)
- Fast annual simulations with sky discretization approach
- Input for detailed thermo-hydraulic receiver models





Left: *Ivanpah* re-modeling, ~55k heliostats

Right: *Solar Two* model

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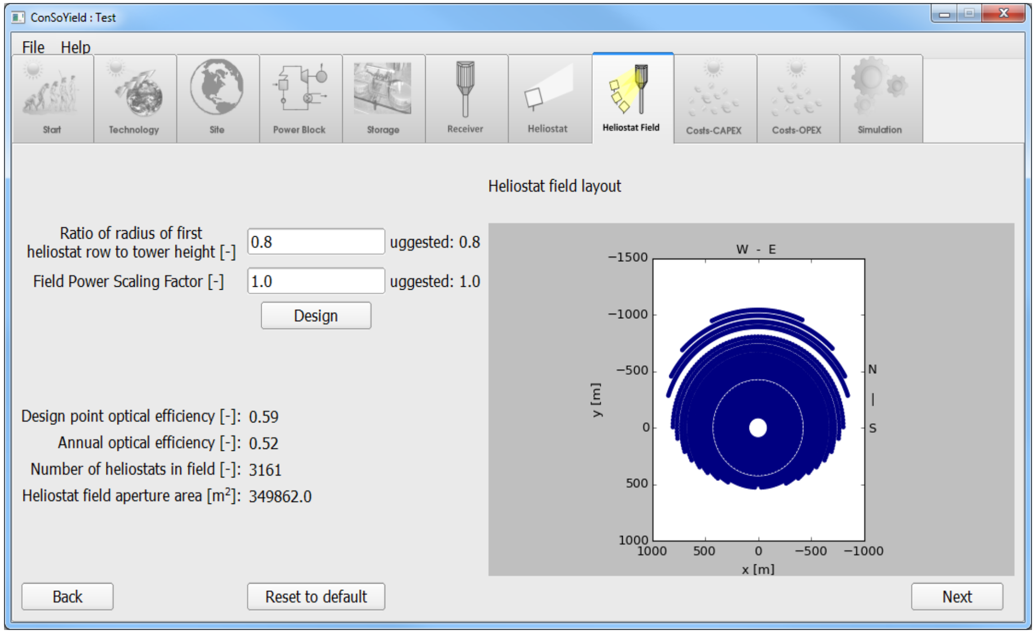
ColSimCSP

Field of application

- **Everything between static and dynamic system simulation**
  - Adjustable level of detail
  - Variable time step length
- **Annual yield simulations**
- **Plant performance testing**
- **Assessment of different operating strategies**
- **Accessible source code enables interface to other internal software**



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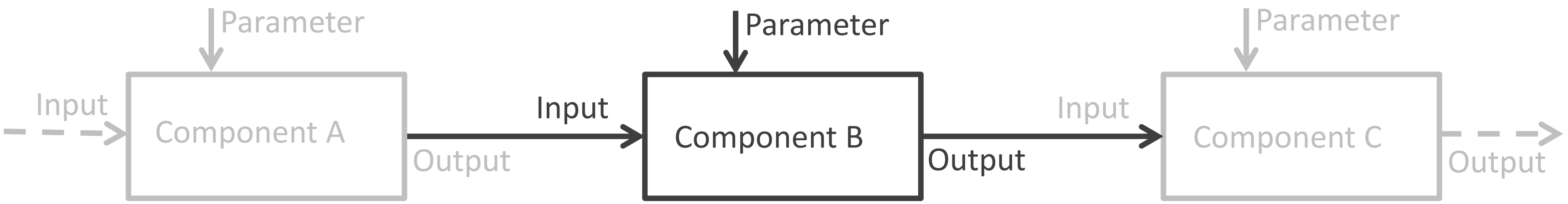
ColSimCSP
Functioning overview

- **Model for each component with inputs, outputs and parameters**



- **Quasi dynamic system simulation**
  - Capacity of HTF and piping considered
  - Modeling of transient behavior
- **Integration of component models into system model**

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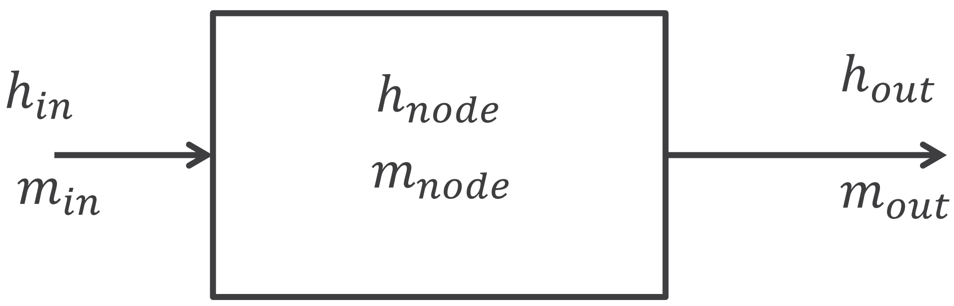
Capacity node

Capacity of component can be considered:



$t-1$ Previous time step
t Current time step

$$m_{in} = m_{out}$$

$$m_{node,t} = m_{node,t-1}$$

$$h_{node,t} = \frac{h_{node,t-1} \cdot m_{node,t-1} + h_{in} \cdot m_{in}}{m_{node,t} + m_{in}}$$

$$h_{out} = h_{node,t}$$

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ColSimCSP

Runtime

Very fast compared to other simulation software

- Compiled programming language C/C++

Runtime highly depends on level of detail, simulation time step and iterations within models

- Annual simulations in hourly time steps: ~ 10 s
- Annual simulation of system with steam drum (lots of iterations) and one minute time steps: ~ 15 min

➢ **Multiple simulations can be parallelized**

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Component library

- Solar field (PTC, LFC)
- Stationary collector (FPC/ETC)
- Tower receiver
- Pump
- Heat exchangers
- Pipes
- Valves
- Two tank storage
- Stratified storage
- PCM storage
- Detailed power block
- Black box power block
- Steam drum
- Feed water tank
- Auxiliary heater / boiler
- …

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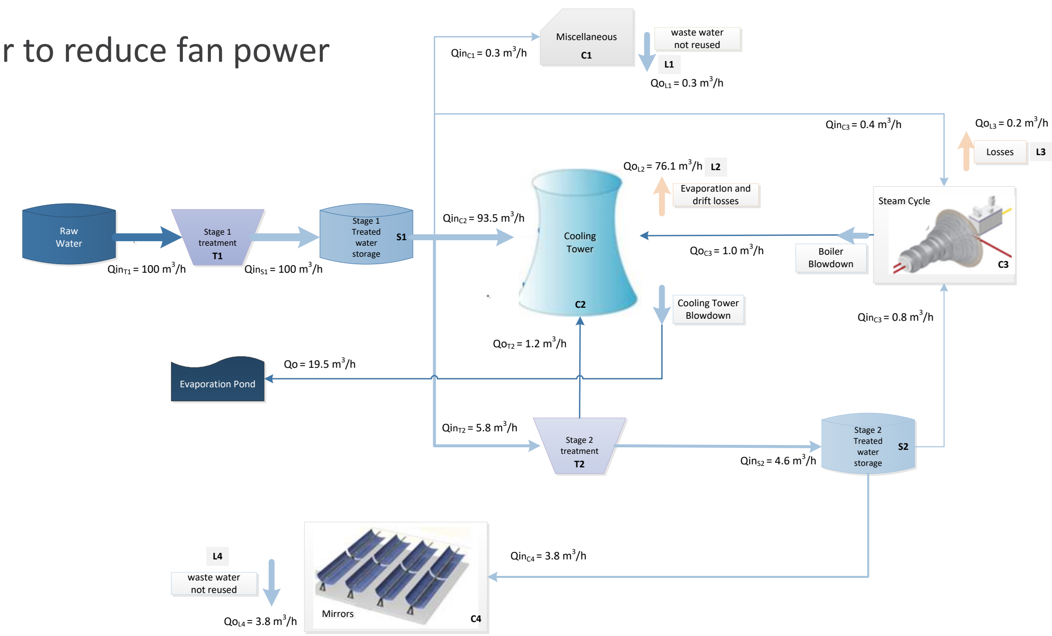
Novel features

- **Detailed modelling of the plant "water management plan" including the water flow, losses, and quality**
  - Using nested structure for chemical properties
- **CSP plant simulation with variety of cooling systems**
  - 3 integrated cooling systems (selectable as a parameter among ACC/ WCC / and Hybrid dry/wet)
  - Integrated feedforward controller to reduce fan power
- **Energy consumption for water supply and treatment**
- **Implementation of mirror cleaning schedules in plant simulation**



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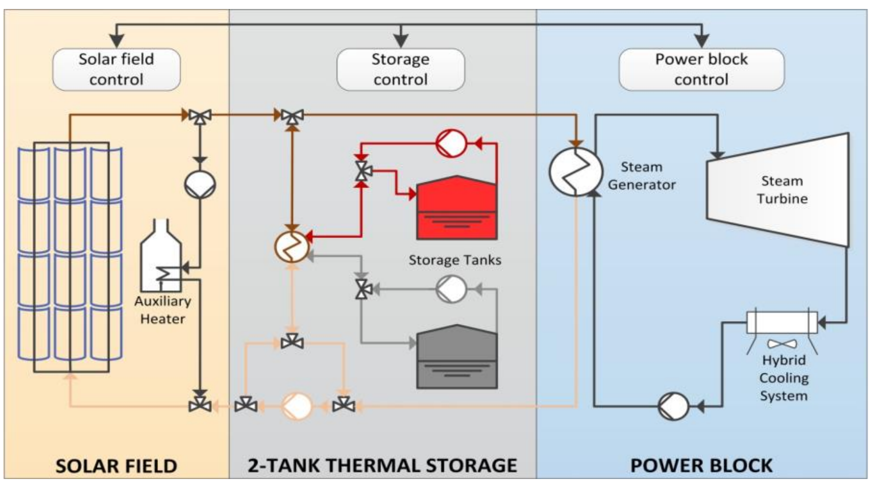
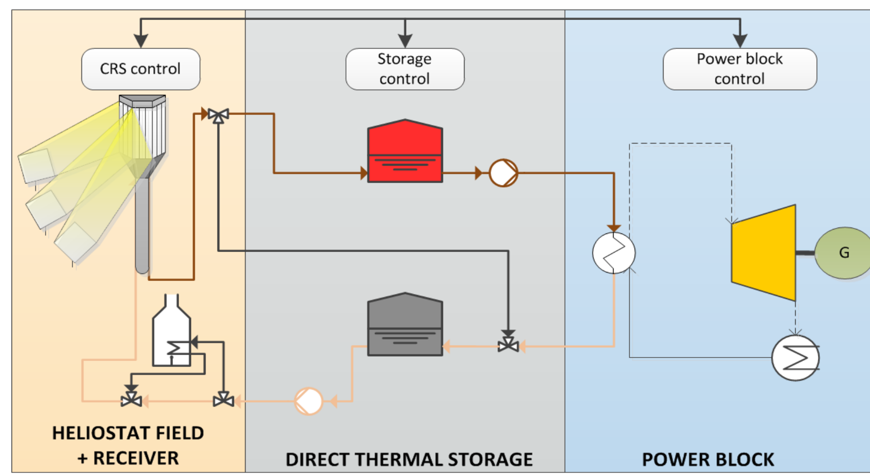
Performance models

- Four CSP technologies (PTC-oil/ PTC-salt/ tower-salt/ LFC-oil)
  - involved in **ORC-PLUS** project in Morocco (validation of Fresnel model and storage scale-up)
- Three thermal storage integration (indirect two-tank, direct two-tank, and stratified storage)
  - **Stratified storage test stand** at ISE for validation of the models
- Four storage dispatch controls (operation strategies) with a forecaster unit



Simplified schematic of PTC model with indirect two-tank thermal storage integration



Simplified schematic of CRS model with direct two-tank thermal storage integration

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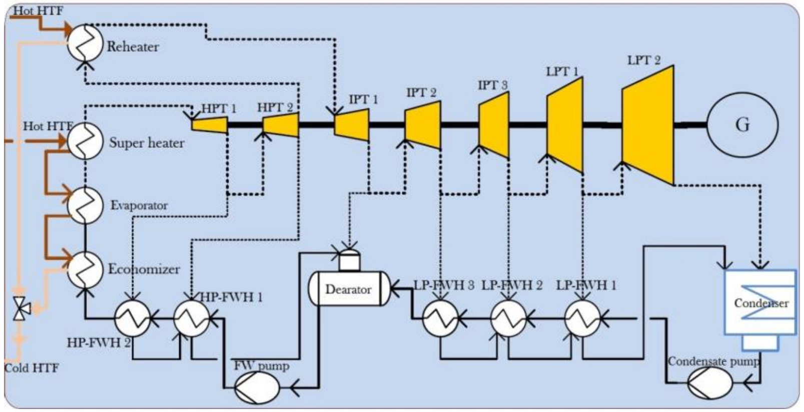
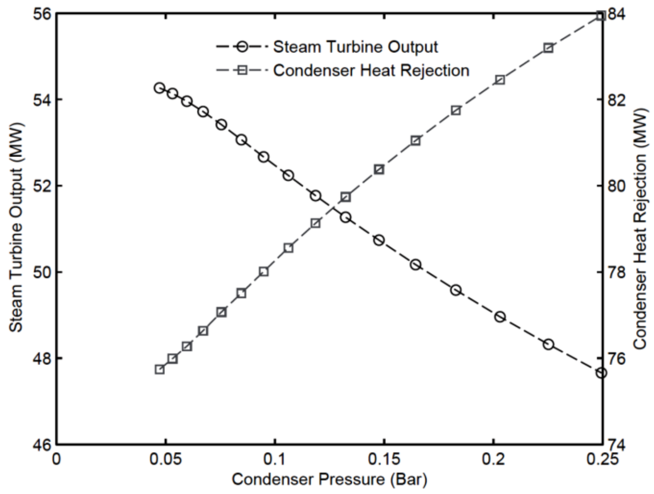
Rankine cycle model

- The implemented black box power block uses correlations which apply to an equivalent detailed Rankine cycle configuration
- **The power output is a function of:**
  - inlet HTF temperature
  - thermal load
  - condenser pressure
  - fluid-specific correlations for calculating the HTF outlet temperature





Source: (O'Donovan & Grimes, 2014)

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Minimized water consumption in CSP plants
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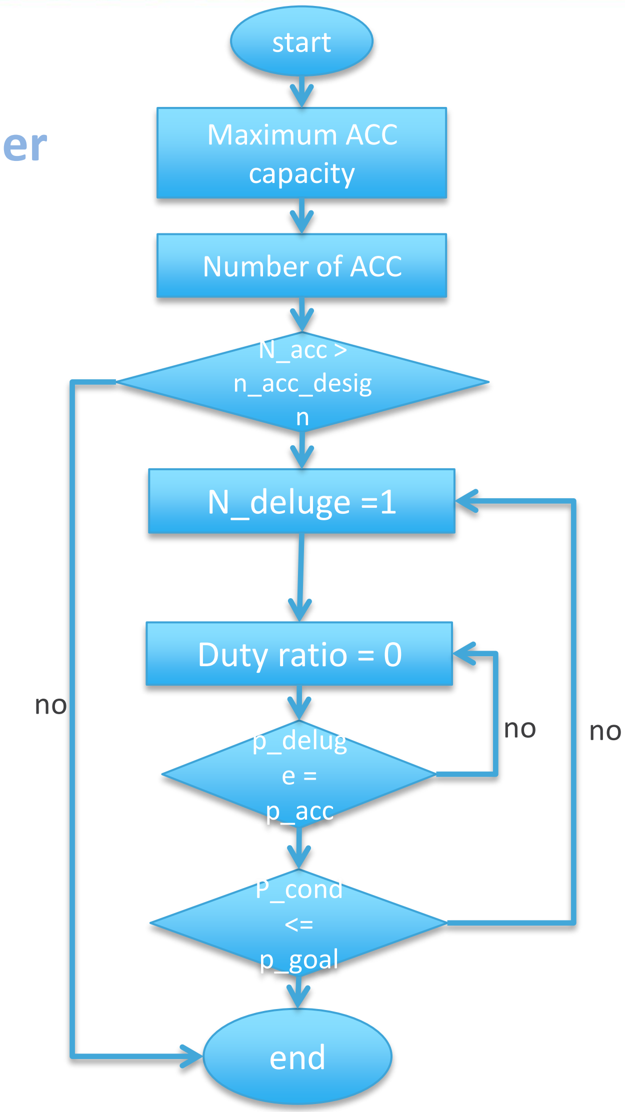
Simplified flow chart of the hybrid condenser controller



Condenser controller loop

- **Turbine back-pressure** is directly controlled
  - Minimizing the turbine back pressure
  - Setting the dry/wet ratio
  - Minimizing water consumption
  - Minimizing fan power

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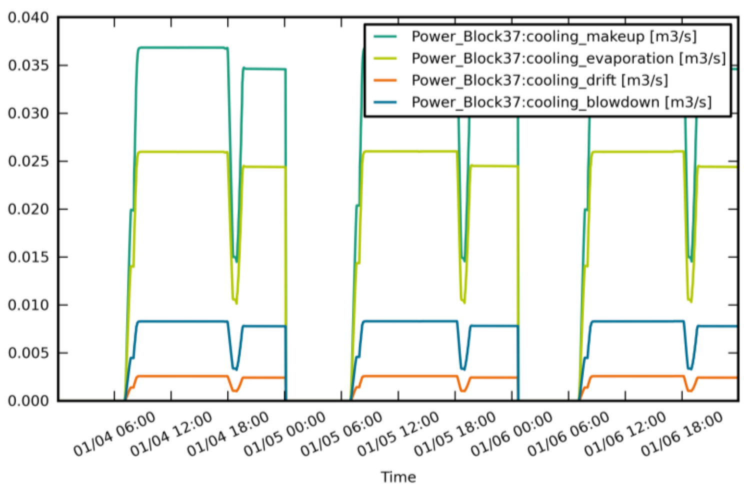
Modeling of water streams

- ***Implemented water use models:***
  - *Cooling make-up*
  - *Cooling blow-down*
  - *Cooling evaporation*
  - *Cooling drift*
  - *Mirror cleaning with water spray*
  - *Mirror cleaning with brushes*



Simulation results: Plot of water use for three days

```
struct waterChemProp
{
  double flag; // 0: upstream water (fresh) 1: downstream water (used)
  double mdot; // Mass flow rate [kg/s]
  double p; // Pressure [Pa]
  double conduct; // Conductivity
  double ph; // PH
  double tds; // Salinity
  double hard; // hardness
  double toc; // Total Organic Carbon
  double alkal; // Alkaline Earth (Ca2+ , Mg2+)
  double cl; // Chloride (Cl-)
  double so; // Sulfate (SO42-)
  double sio; // SiO2
};

struct waterStreams
{
  struct waterChemProp makeup;
  struct waterChemProp blowdown;
  struct waterChemProp evaporation;
  struct waterChemProp drift;
  struct waterChemProp loss;
};
```

Implementation of water structure in source code

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Validation of PTC model

- Modeling approach based on CSPBankability project / Solar Paces guideline
- Validated against real operating data of a conventional large-scale CSP plant in Spain (PTC).

➢ **Annual energy yield mean deviation: 1.37%**

Source: S. Rohani, T.P. Fluri, F. Dinter, Peter Nitz, Modelling and simulation of parabolic trough plants based on real operating data, Solar Energy, Volume 158, 2017, Pages 845-860, ISSN 0038-092X, https://doi.org/10.1016/j.solener.2017.10.023.

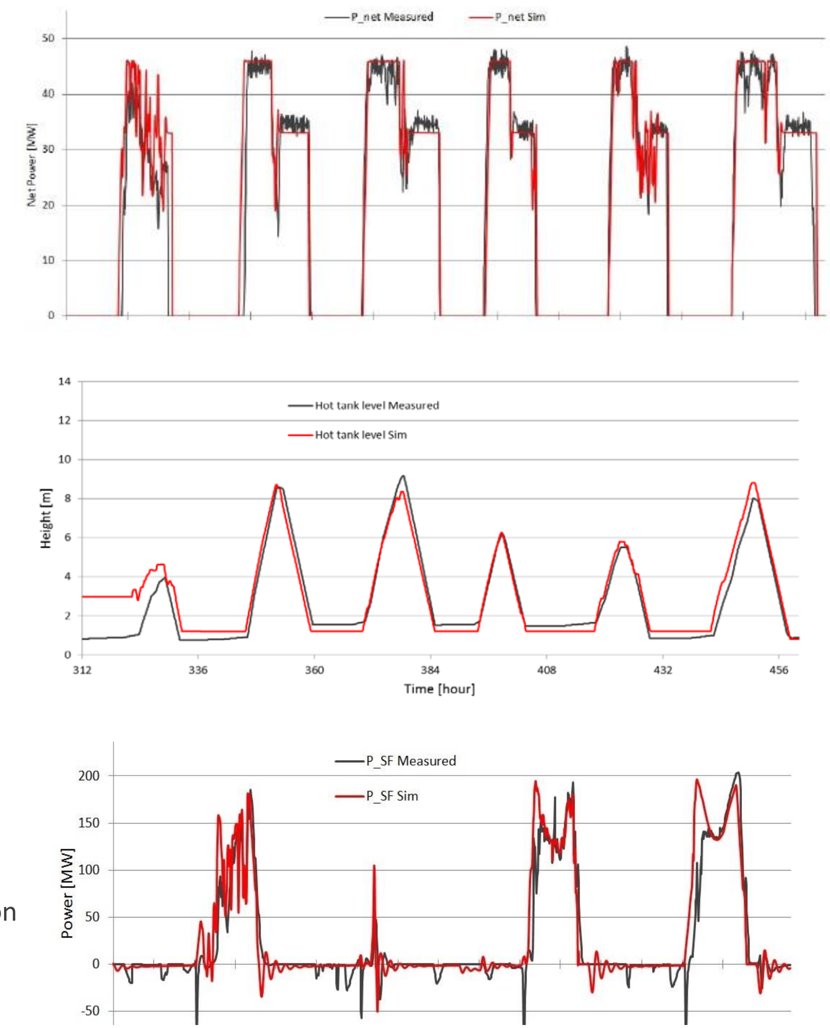

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Table of content

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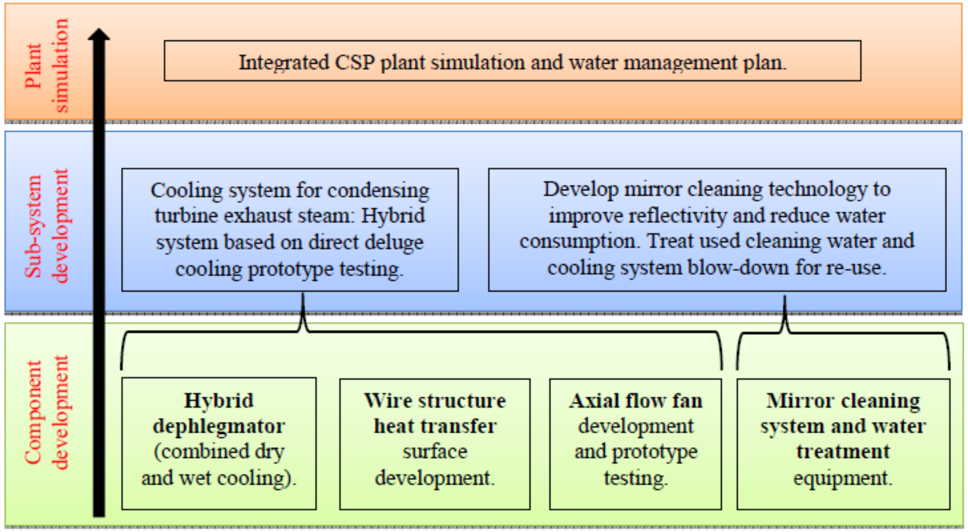
Objectives

- Detailed evaluation of overall CSP plant performance and water consumption (**LFC, PTC, Tower**) for different reference plants with MinWater technologies
- Multi-objective optimization
  - Optimized **water management plan** that minimizes water consumption
  - Optimized plant configuration and **operating strategy** to minimize the LCoE
  - Optimized mirror **cleaning schedules** for optimal utilization of water



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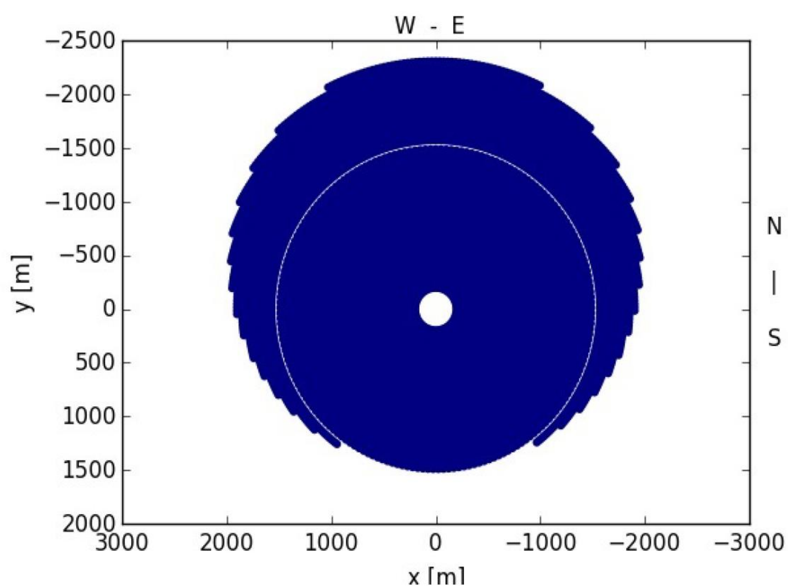
Reference case

- Tower technology
- 100 MW net capacity
- 15 full load hours of thermal storage
- Ouarzazate (the site of Noor 3 plant)



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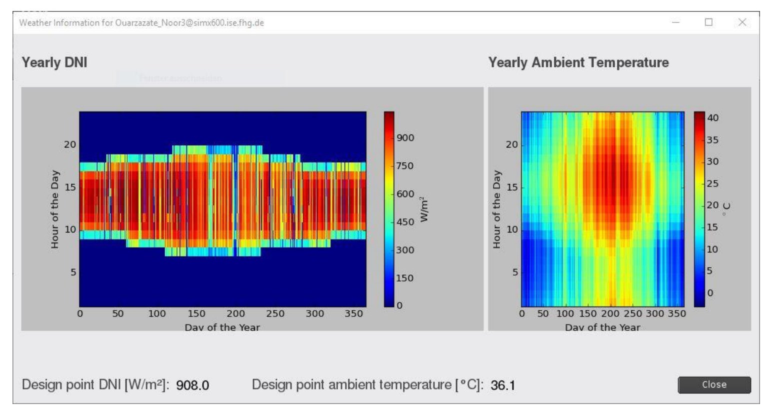

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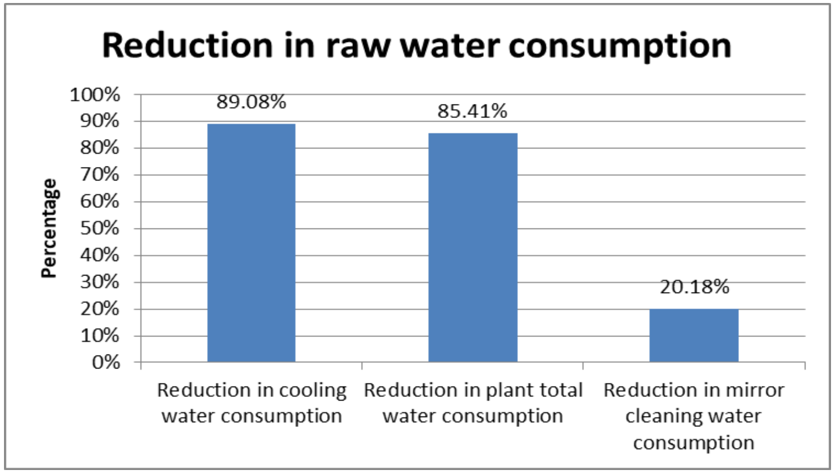
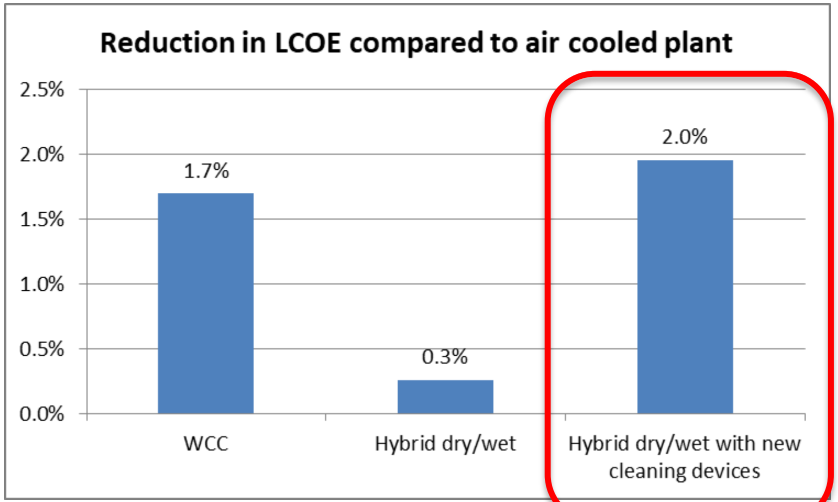
Preliminary evaluation result
LCOE and water consumption

- lower **installation cost** due to reduction in number of cooling units
- higher **turbine efficiency** due to a better condenser pressure maintenance
- lower plant **self-consumed** power due to fewer numbers of fans
- more efficient cleaning which provides a **higher reflectance**
- Lower **raw water and treatment cost** for cooling and cleaning processes





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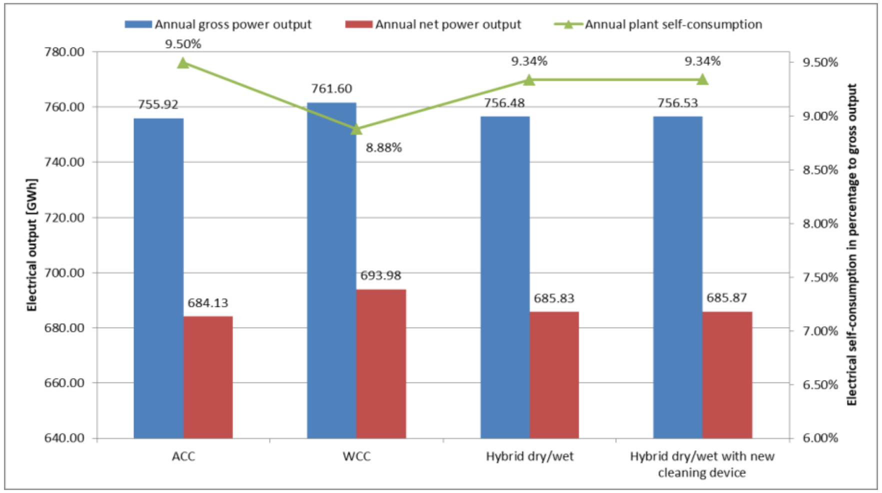
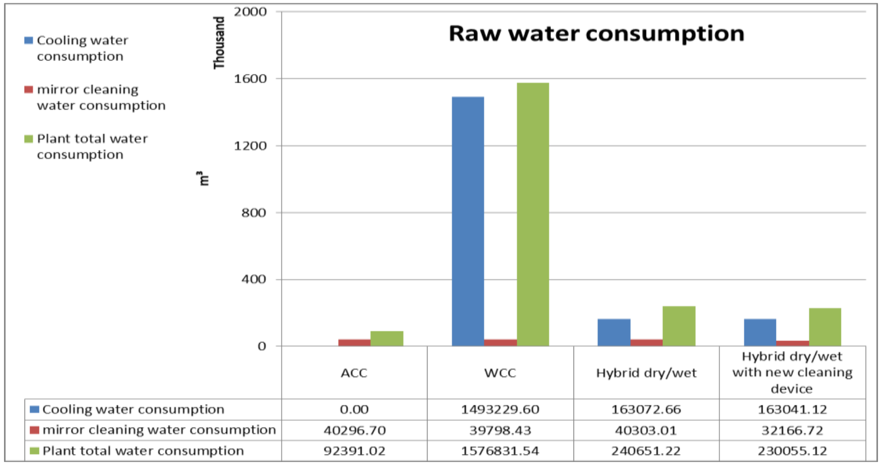
Preliminary evaluation result

Annual output and raw water consumption

- **lowest auxiliary power** consumption due to fewer numbers of cooling fans
- better maintenance of the **condenser pressure**





	ACC	WCC	Hybrid dry/wet	Hybrid dry/wet with new cleaning device
Cooling water consumption	0.00	1493229.60	163072.66	163041.12
mirror cleaning water consumption	40296.70	39798.43	40303.01	32166.72
Plant total water consumption	92391.02	1576831.54	240651.22	230055.12

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Conclusion

- Preliminary simulation results show a **large potential** for water consumption reduction in CSP plants by employing the MinWaterCSP water saving technologies.
- It is expected to achieve a **better performance** and a **higher water saving rate** in the final evaluation at the end of the project since **optimization** will be carried out, the models will be **adapted to the project test results**, and additional improved technologies will be added to the models (i.e. the **new cooling fan, the wire structure heat exchanger,** and the **improved water management plan**.
- The software tool chain of Fraunhofer ISE has been expanded . It is now capable of doing **reliable technology evaluations** and **annual simulations** integrating the **water management plan** of the plant.

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Thank you for your attention!

Minimized water consumption in CSP plants

MinWaterCSP

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