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UNIÓN EUROPEA
FONDOS ESTRUCTURALES

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Comunidad de Madrid
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Integration of particle-based systems in central receiver solar power plants

J. González-Aguilar, M. Romero

SolarPACES PTWG WORKSHOP
April 19-20, Al-Izdihar, Riyadh, KSA

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IMDEA Energy Institute

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Not-for-profit Foundation oriented to applied research, innovation and technology transfer

Mission: Promote and conduct **R&D&i** activities on **sustainable energy technologies**

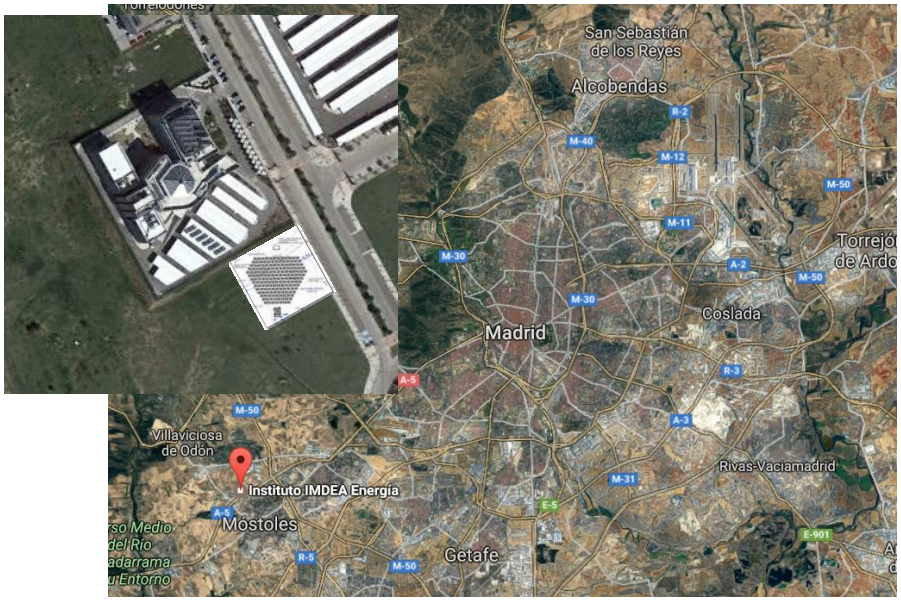
Research topics:

- Production of sustainable fuels (hydrogen and advanced biofuels),
- **Solar Energy**
- Energy storage
- Energy systems with enhanced efficiency
- Power systems and demand management
- Valorization of CO_2 emissions

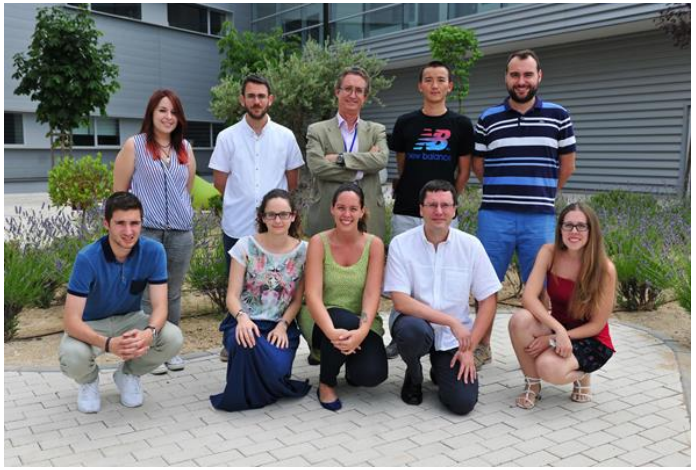
International staff: 83 people

Active R&D project grants in 2016: 50; external funding: 2,6 M€

Collaboration with around 40 companies



High Temperature Processes Unit



R&D Objective

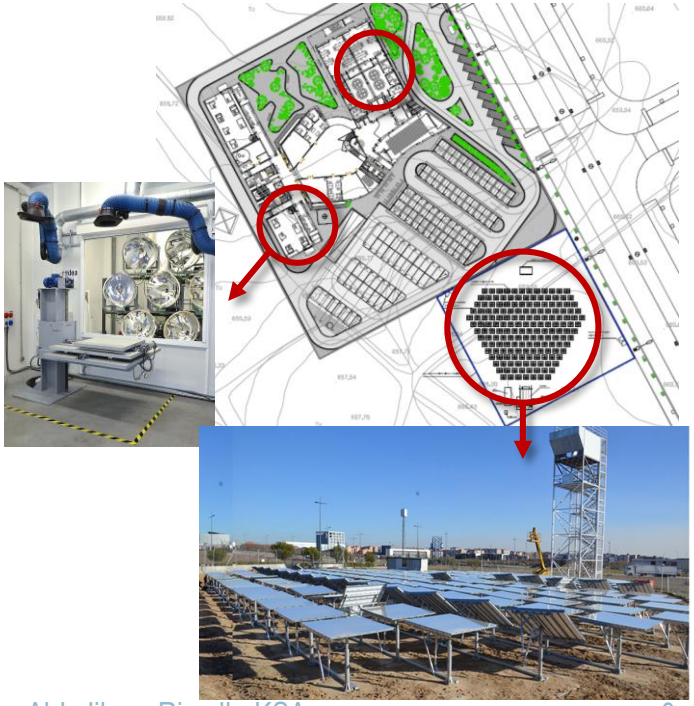
Modular, efficient and dispatchable solar concentrating technologies for power generation, industrial process heat and production of solar fuels and chemicals.

Research lines

- New modular schemes for high-efficient and dispatchable solar thermal power plants and urban integration
- Solar receivers and reactors: cavity, volumetric, rotary kiln, and particle receivers.
- Thermal energy storage (latent heat, thermochemical) for STE/CSP plants.
- Solar fuels and chemicals production using metal oxides
- PCU Integration & environmental impact (advanced cycles, water, glint and glare)

Experimental facilities

- High-flux solar simulators and solar tower.
- Working thermal powers at 1.5kW, 15 kW and 250 kW.



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Our main current activities on *particle* systems

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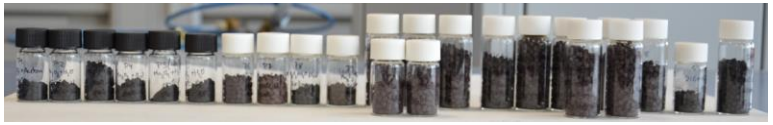


Materials

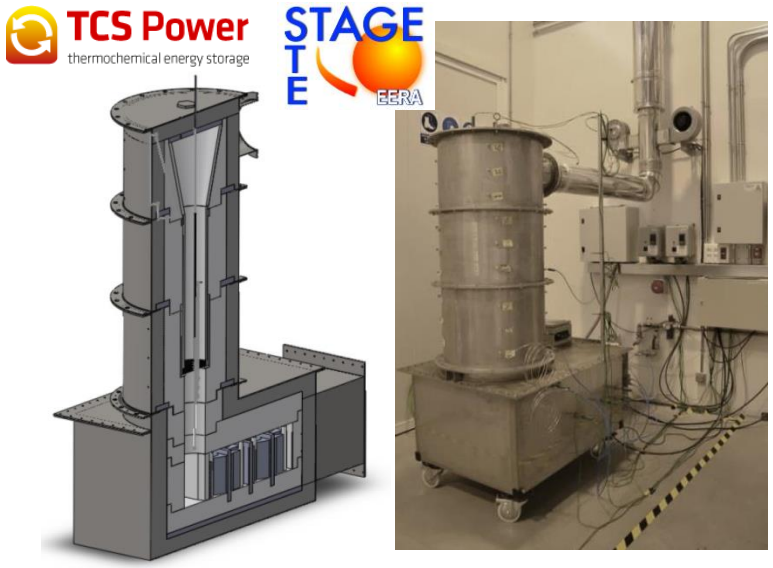
- Reactor materials for very-high temperature applications
- Thermochemical storage materials

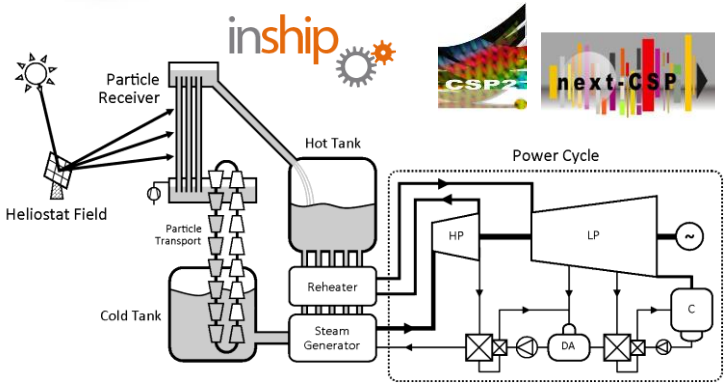
Solar particle receivers and reactors

- Indirect-irradiated receiver upscaling
- Reactor concepts for thermochemical heat storage

Integration of particle-based systems in CST

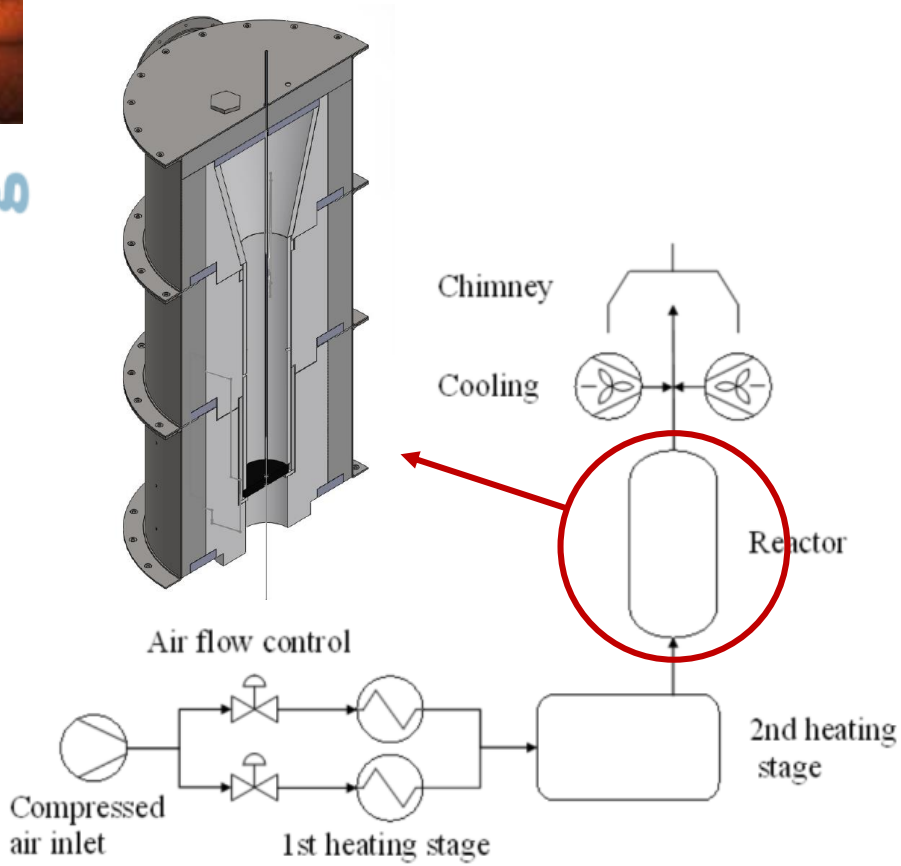
- Assessment of particle-based working fluids in CSP
- Thermal storage
- Integration of advanced cycles
- Assessment on solar fuels and chemicals production using metal oxides





Testing materials for Thermochemical heat storage

100 Wh Reactor



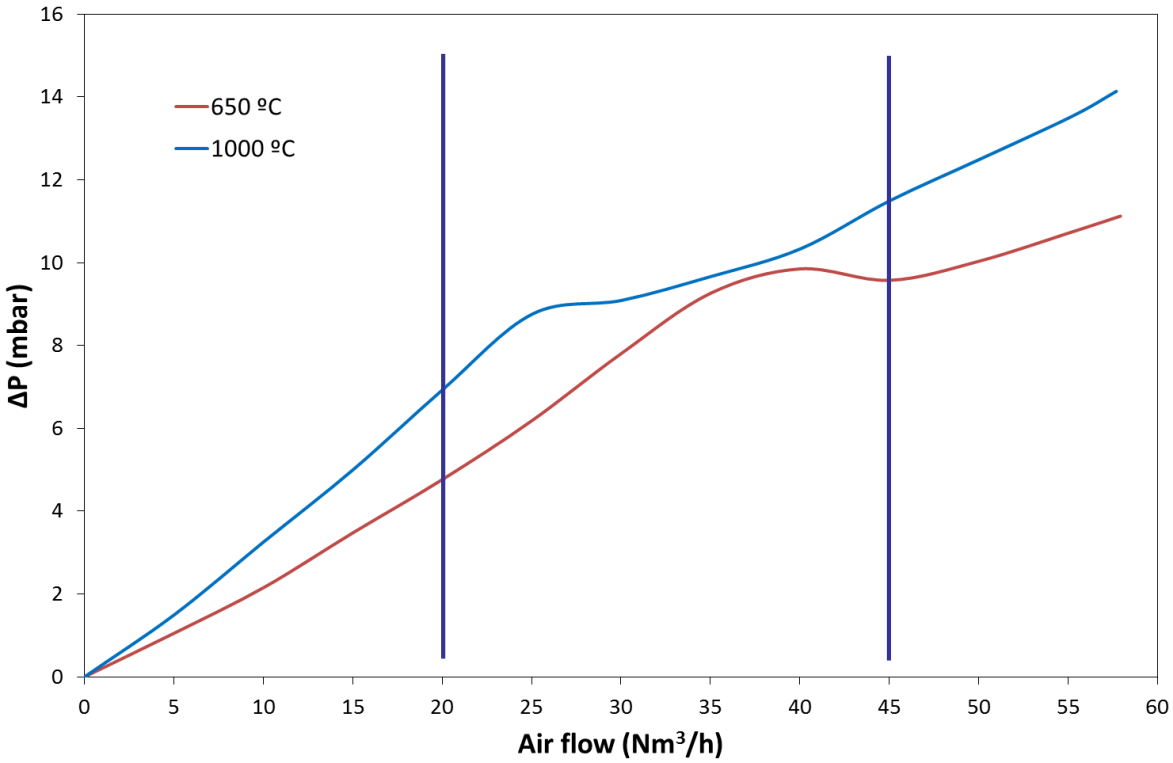
Cylindrical vessel composed of 3 stacked bodies:

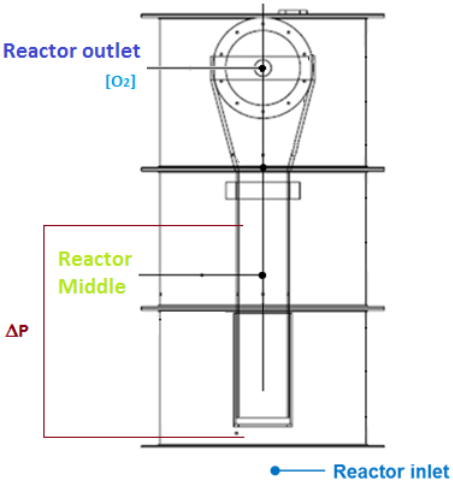
- Avoid entrainment of the particles
- Simple mounting/dismounting/mainte-nance processes
- Easy material charge and discharge
- Technical specifications:
  - Temperature up to 1200 ºC
  - Pressures up to 2 bar
  - Air mass flow rate up to 60 Nm^3/h
- Three concentric layers: Non-porous alumina, insulating material, stainless steel envelop

Álvarez De Miguel, S., Gonzalez-Aguilar, J. & Romero, M., (2013). 100-Wh multi-purpose particle reactor for thermochemical heat storage in concentrating solar power plants. *Energy Procedia*, 49, pp.676–683.

Playing with T and flow rate – Packed vs. fluidized bed

MnOx fluidisation **[2.0, 3.6] mm**; initial volume 2.4 l





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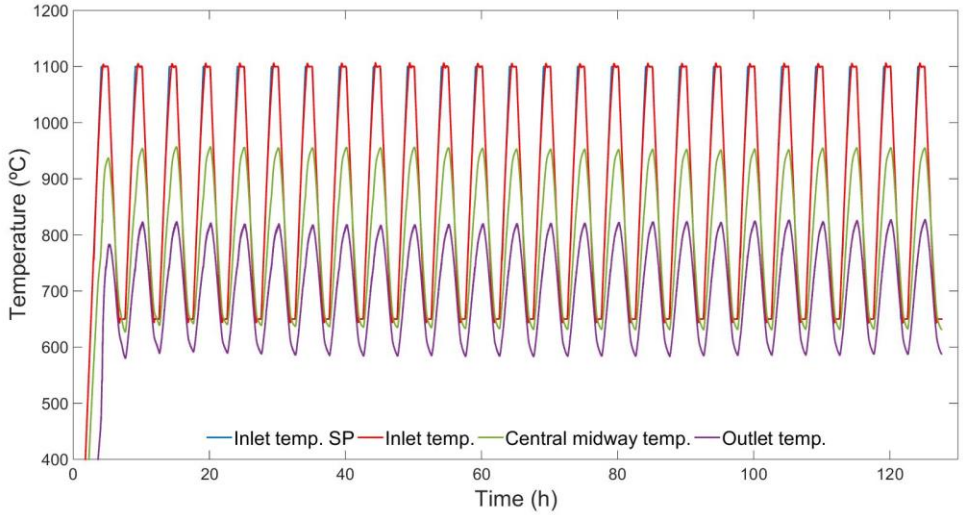
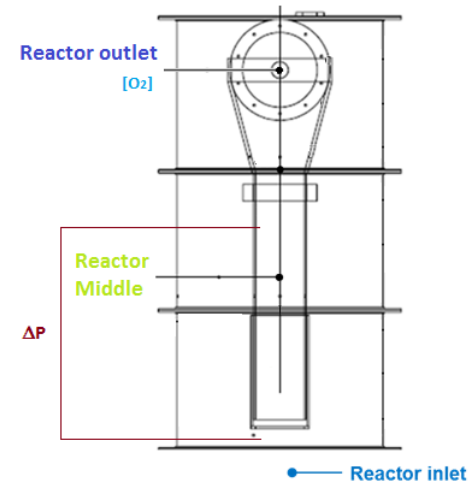
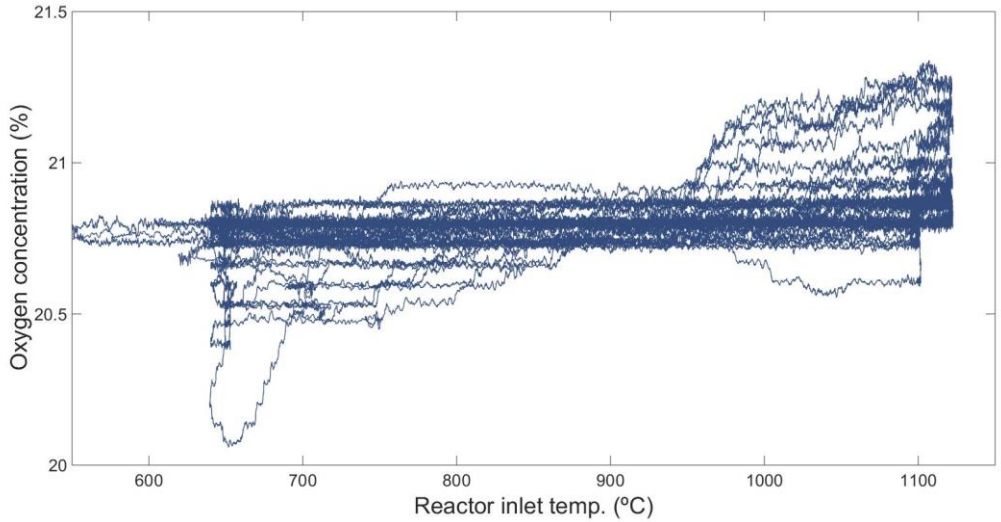
Long–term cyclability for pure and Fe-doped MnOx







- Pure and doped manganese oxide has been tested in fluidization and fixed bed conditions
- Challenges on mechanical (shaping, sintering, attrition) and kinetic performance of TC materials

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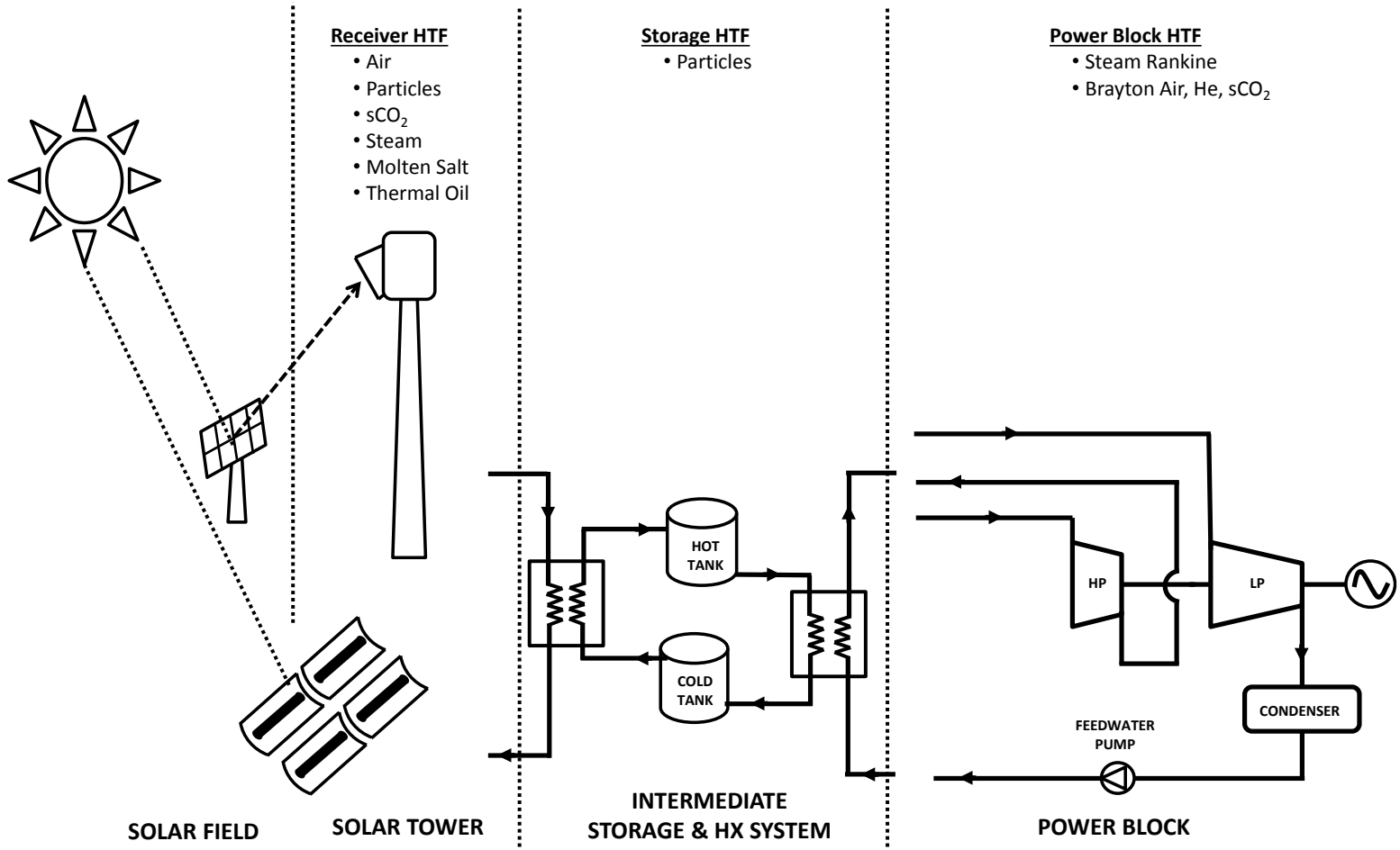
Many potential options



Particles / Particles / subcritical Steam Rankine, see Spelling et al., Energy Procedia 69 (2015) 1160 – 1170

Particles / Particles / sCO2, see Reyes et al., Energy 112 (2016) 17-27

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Benefits vs. Limitations

BENEFITS

- Decoupling the **Solar** loop from the **Storage** loop and the **Power** loop
- Avoiding particles transportation to the receiver
- Improving power block operation mode (transient performance or 24/7)
- Allowing **cheap**, **safe**, **flexible**, high **energy density** and highly **efficient** thermal energy storage (TES) to be used with any kind of heat transfer fluid
- No temperature restrictions. Higher & lower storage temperature compared to TES based on molten salt
- “Easy” integration of thermochemical (i.e. assuming gas-solid reactions) and sensible heat storage

LIMITATIONS

- **Energy** and **exergy losses** if an intermediate loop is necessary
- Cost?

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What could the better options be?

#	Receiver HTF	Storage HTF	P. Block WTF	Opt.	Comments
1	Air	Particles	Steam		High temperature potential provided by air receiver not exploited at the power block
2	Air	Particles	Air		Allowing for high temperature TES for air cycles
3	Air	Particles	sCO_2		Allowing for high temperature TES for sCO_2 cycles
4	Steam	Particles	Steam		Feasible TES for DSG receivers but energy losses due to pinch limitations (subcritical)
5	Steam	Particles	Air		Feasible TES for DSG receivers but low efficiency of the air cycle (low temperature)
6	Steam	Particles	sCO_2		Feasible TES for DSG receivers coupled to sCO_2 cycles but low temperature (steam)
7	M. Salts	Particles	Steam		Feasible option, but it would be more efficient using molten salts as storage medium
8	M. Salts	Particles	Air		Feasible option, but it would be more efficient using molten salts as storage medium
9	M. Salts	Particles	sCO_2		Feasible option, but it would be more efficient using molten salts direct storage

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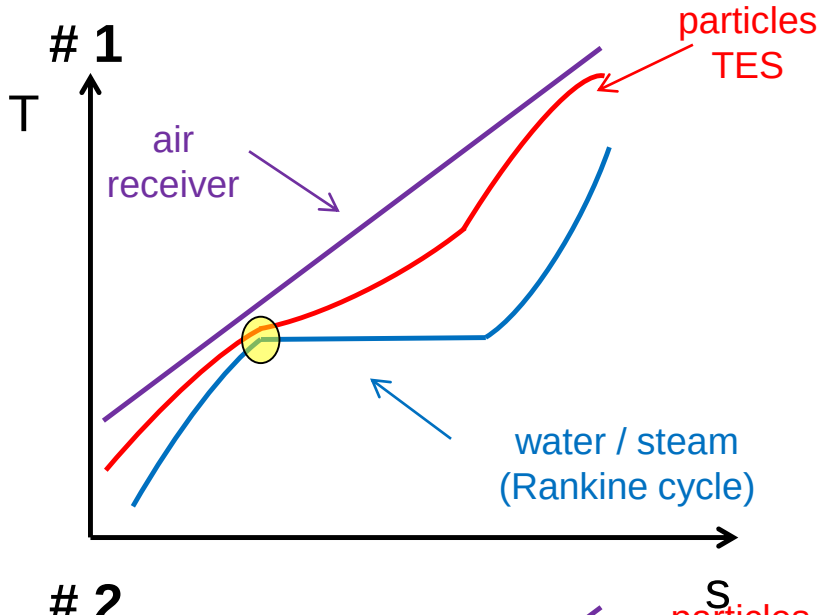
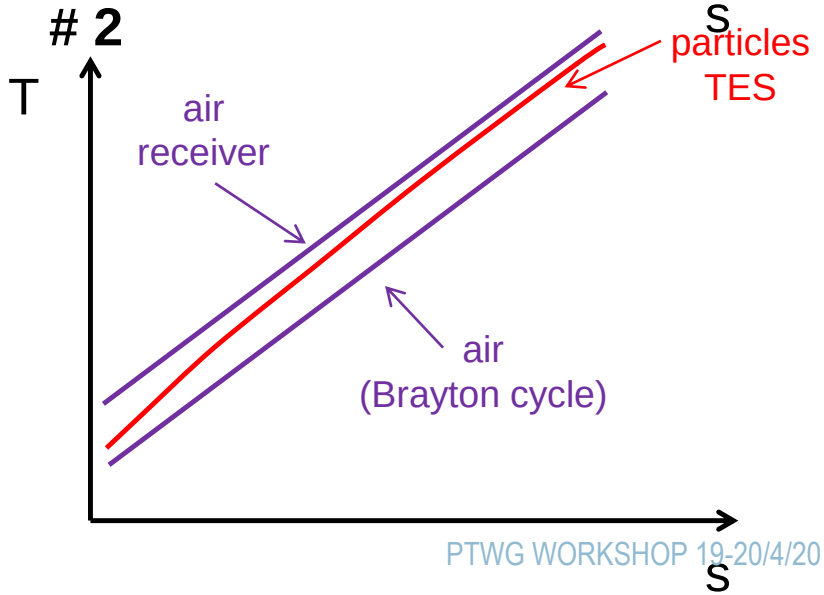
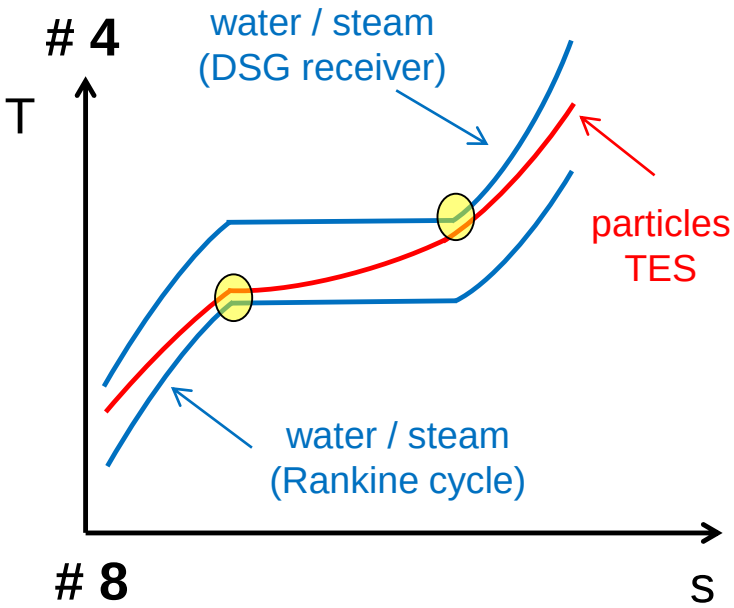
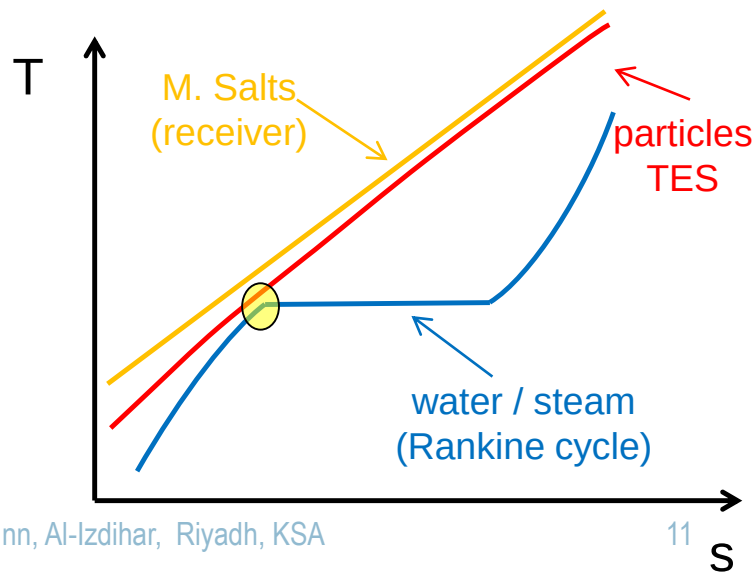
Possible configurations

- Temperature evolution decision-maker









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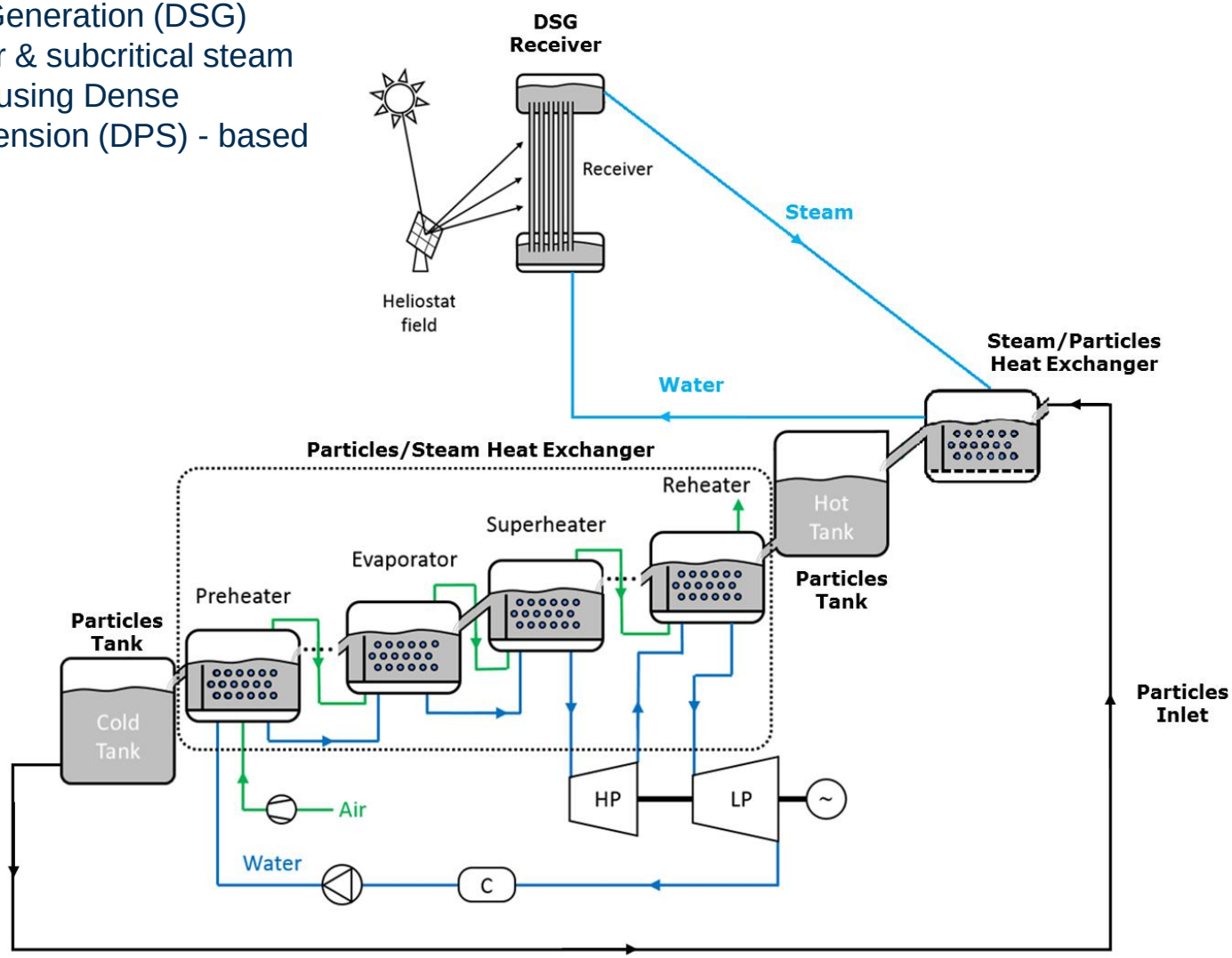
Plant layout proposal

Direct Steam Generation (DSG) central receiver & subcritical steam Rankine cycle using Dense Particles Suspension (DPS) - based TES



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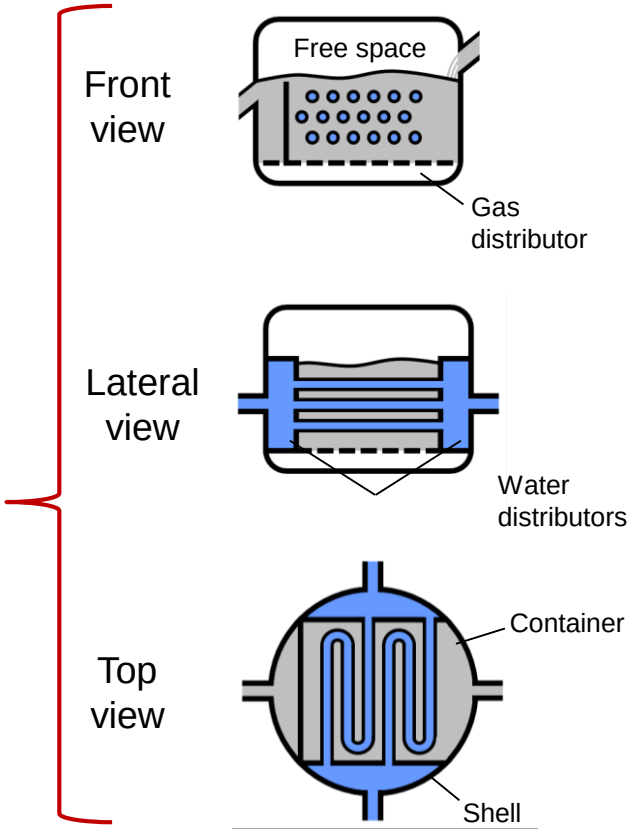
Heat exchanger description

- DPS heat exchanger coupling the solar loop with the power block
- DPS HX model required for more realistic & accurate power plant system analysis

Each stage consists of a cylindrical shell divided in four main sections with an external layer of thermal insulation.

- A truncated-cylindrical container with N bundles of tubes where the particle fluidization takes place.
- Two semicircular distributors next to the container that enable the inlet and outlet water into the tubes.
- A gas distributor on the bottom of the heat exchanger allowing a homogeneous fluidization of particles.
- A free space on the top of the fluidized bed to prevent the particle drag out of the heat exchanger.



Heat Exchanger Modelling in Central Receiver Solar Power Plant Using Dense Particle Suspension, SolarPACES 2016**,** *Reyes-Belmonte et al.*

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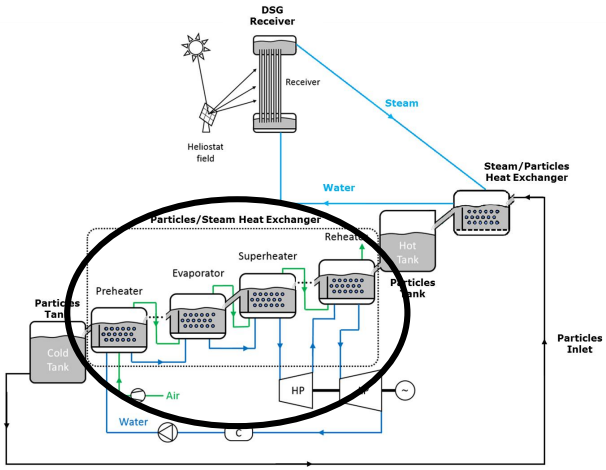
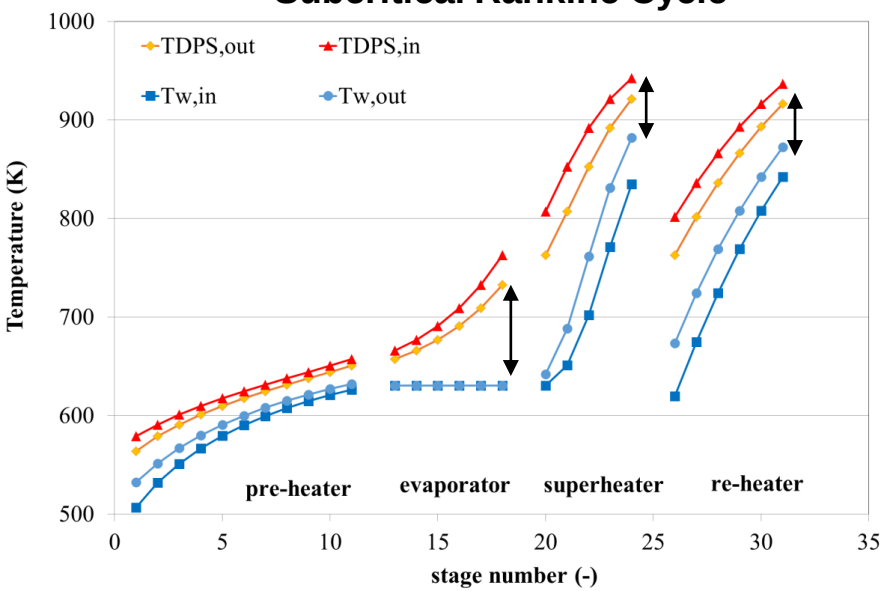
steam Rankine cycle, subcritical vs. supercritical

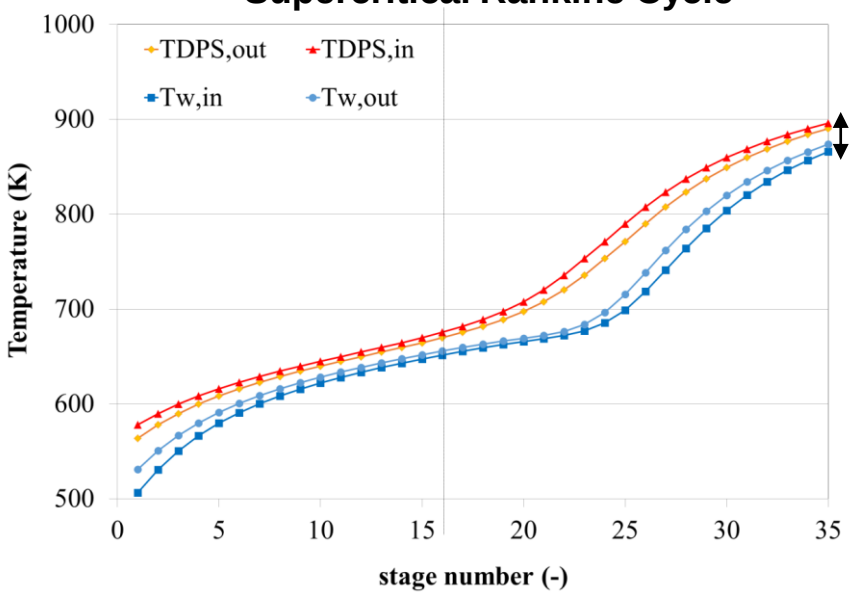
- Assuming same turbine inlet steam temperature
- No pinch-point restrictions for supercritical cycle.



Subcritical Rankine Cycle



Supercritical Rankine Cycle



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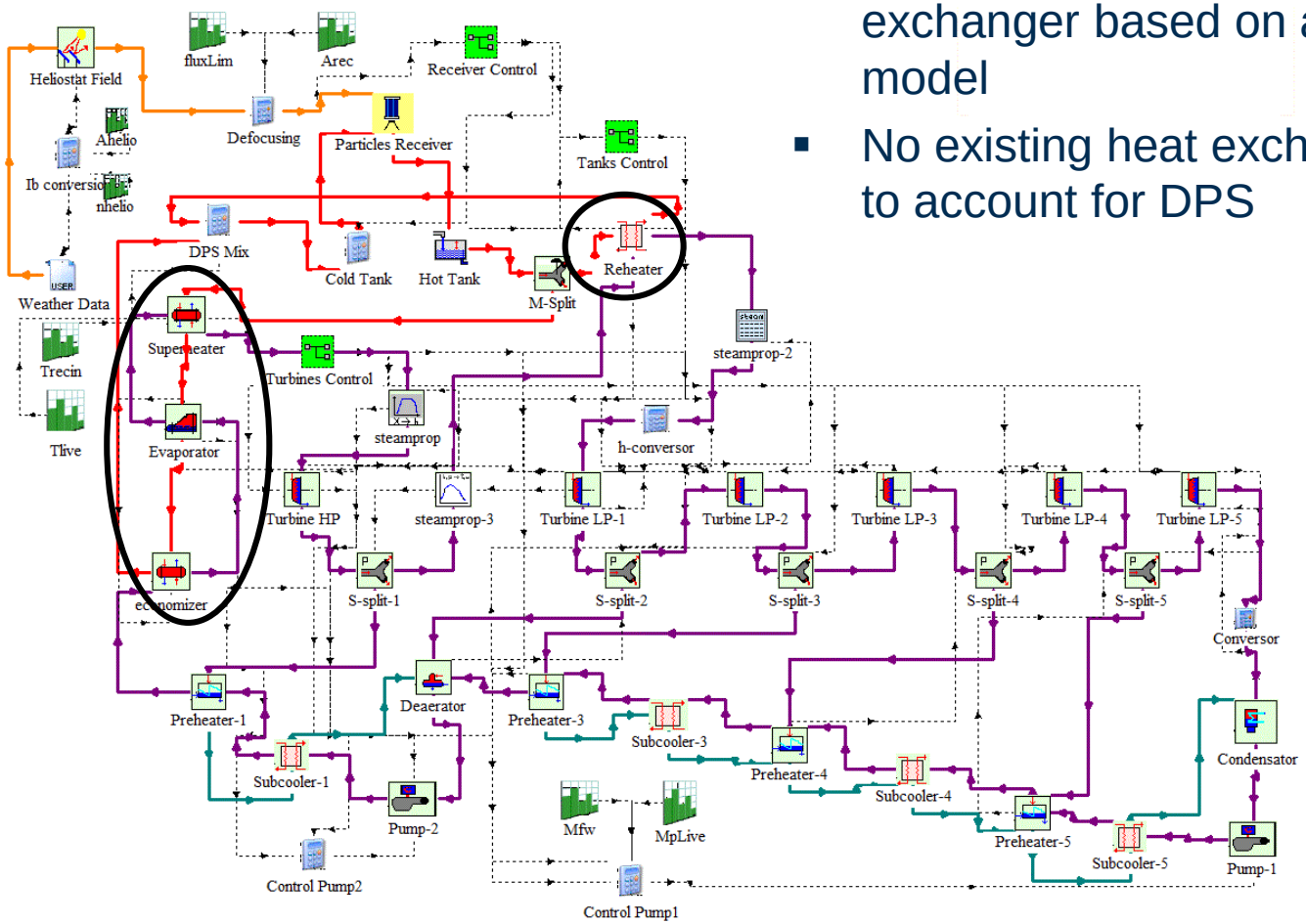
What's next? Development of components in TRNSYS

- Developing a TRNSYS component of the DPS - water/steam heat exchanger based on a detailed model
- No existing heat exchanger model to account for DPS



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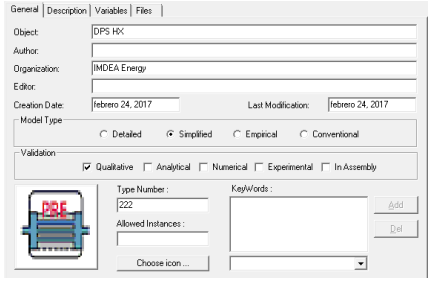
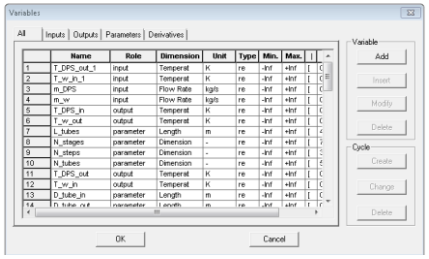
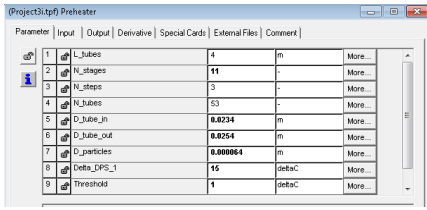
Development of components in TRNSYS

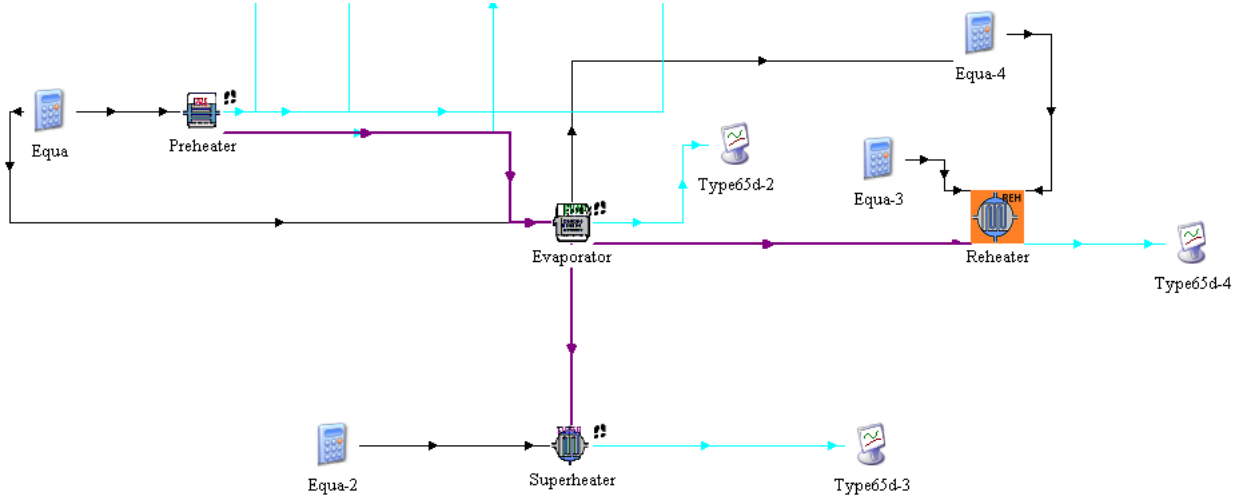
Fortran programming for each DPS-HX component (preheater, evaporator, superheater & reheater)

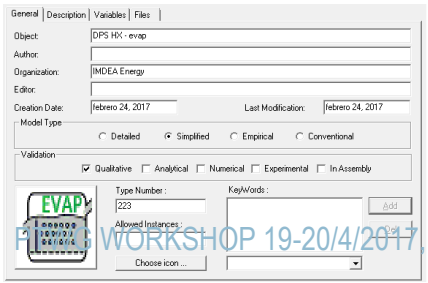
```
C-----------------------------------------------------------------------
C   REQUIRED BY THE MULTI-DLL VERSION OF TRNSYS
     !DEC$ATTRIBUTES DLLEXPORT :: TYPE222              !SET THE CORRECT TYPE NUMBER HERE
C-----------------------------------------------------------------------
C-----------------------------------------------------------------------
C   TRNSYS DECLARATIONS
     IMPLICIT NONE            !REQUIRES THE USER TO DEFINE ALL VARIABLES BEFORE USING THEM

     DOUBLE PRECISION XIN     !THE ARRAY FROM WHICH THE INPUTS TO THIS TYPE WILL BE RETRIEVED
     DOUBLE PRECISION OUT     !THE ARRAY WHICH WILL BE USED TO STORE THE OUTPUTS FROM THIS TYPE
     DOUBLE PRECISION TIME    !THE CURRENT SIMULATION TIME - YOU MAY USE THIS VARIABLE BUT DO NOT SET IT!
     DOUBLE PRECISION PAR     !THE ARRAY FROM WHICH THE PARAMETERS FOR THIS TYPE WILL BE RETRIEVED
     DOUBLE PRECISION STORED  !THE STORAGE ARRAY FOR HOLDING VARIABLES FROM TIMESTEP TO TIMESTEP
     DOUBLE PRECISION T       !AN ARRAY CONTAINING THE RESULTS FROM THE DIFFERENTIAL EQUATION SOLVER
     DOUBLE PRECISION DTDT    !AN ARRAY CONTAINING THE DERIVATIVES TO BE PASSED TO THE DIFF.EQ. SOLVER
     INTEGER*4 INFO(15)       !THE INFO ARRAY STORES AND PASSES VALUABLE INFORMATION TO AND FROM THIS TYPE
     INTEGER*4 NP,NI,NOUT,ND  !VARIABLES FOR THE MAXIMUM NUMBER OF PARAMETERS,INPUTS,OUTPUTS AND DERIVATIVES
     INTEGER*4 NPAR,NIN,NDER  !VARIABLES FOR THE CORRECT NUMBER OF PARAMETERS,INPUTS,OUTPUTS AND DERIVATIVES
     INTEGER*4 IUNIT,ITYPE    !THE UNIT NUMBER AND TYPE NUMBER FOR THIS COMPONENT
     INTEGER*4 ICNTRL         !AN ARRAY FOR HOLDING VALUES OF CONTROL FUNCTIONS WITH THE NEW SOLVER
     INTEGER*4 NSTORED        !THE NUMBER OF VARIABLES THAT WILL BE PASSED INTO AND OUT OF STORAGE
     CHARACTER*3 OCHECK       !AN ARRAY TO BE FILLED WITH THE CORRECT VARIABLE TYPES FOR THE OUTPUTS
     CHARACTER*3 YCHECK       !AN ARRAY TO BE FILLED WITH THE CORRECT VARIABLE TYPES FOR THE INPUTS
C-----------------------------------------------------------------------


C-----------------------------------------------------------------------
C   USER DECLARATIONS - SET THE MAXIMUM NUMBER OF PARAMETERS (NP), INPUTS (NI),
C   OUTPUTS (NOUT), AND DERIVATIVES (ND) THAT MAY BE SUPPLIED FOR THIS TYPE
     PARAMETER (NP=9,NI=4,NOUT=44,ND=0,NSTORED=0)
C-----------------------------------------------------------------------

C-----------------------------------------------------------------------
C   REQUIRED TRNSYS DIMENSIONS
     DIMENSION XIN(NI),OUT(NOUT),PAR(NP),YCHECK(NI),OCHECK(NOUT),
     &   STORED(NSTORED),T(ND),DTDT(ND)
     INTEGER NITEMS
C-----------------------------------------------------------------------
C-----------------------------------------------------------------------
C   ADD DECLARATIONS AND DEFINITIONS FOR THE USER-VARIABLES HERE


C   PARAMETERS
     DOUBLE PRECISION L_tubes
     DOUBLE PRECISION N_stages
     DOUBLE PRECISION N_steps
     DOUBLE PRECISION N_tubes
     DOUBLE PRECISION D_tube_in
     DOUBLE PRECISION D_tube_out
     DOUBLE PRECISION D_particles
     DOUBLE PRECISION Delta_DPS_1
     DOUBLE PRECISION Threshold

C   INPUTS
     DOUBLE PRECISION T_DPS_out_1
     DOUBLE PRECISION T_w_in_1
     DOUBLE PRECISION m_DPS
     DOUBLE PRECISION m_w

     DOUBLE PRECISION XIN_INT(NI)

C    LOCAL VARIABLES DECLARATION
     DOUBLE PRECISION p_atm, ebsilon_mf, f
     DOUBLE PRECISION width, S_act, A_i, A_e
     INTEGER i, j
     DOUBLE PRECISION error(50,11), error2
     DOUBLE PRECISION T_DPS_out(50, 11), T_w_out(50, 11) ! Definir el vector con el numero de etapas N_stag
     DOUBLE PRECISION T_DPS_in(50, 11), T_w_in(50, 11)
     DOUBLE PRECISION delta_DPS(50, 11)
     DOUBLE PRECISION OUT_T_DPS_in(11), OUT_T_DPS_out(11)
     DOUBLE PRECISION OUT_T_w_in(11), OUT_T_w_out(11)
     DOUBLE PRECISION OUT_delta_DPS(11), OUT_error(11)

     DOUBLE PRECISION Q_DPS_total, Q_w_total, Q_DPS
     DOUBLE PRECISION Ar, Re_mf, U_mf, U_g, m_g, Q_g, Q_w, T_w_avg
```

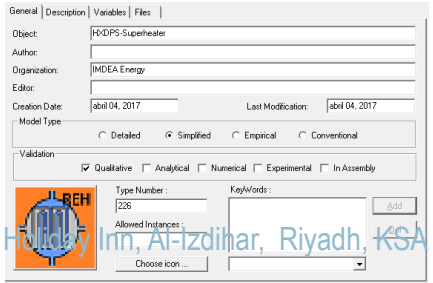


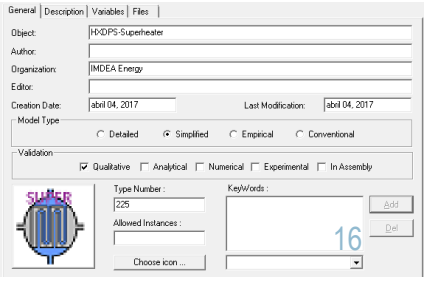




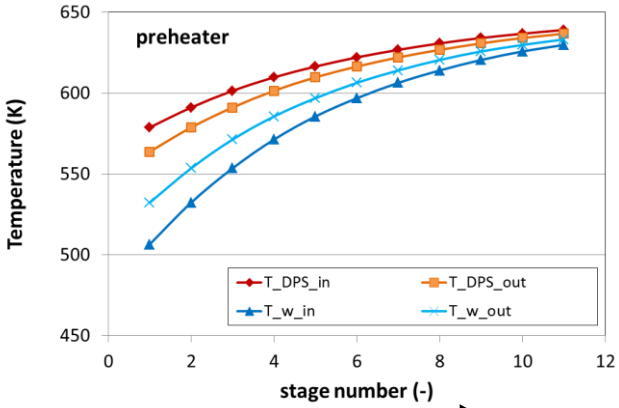




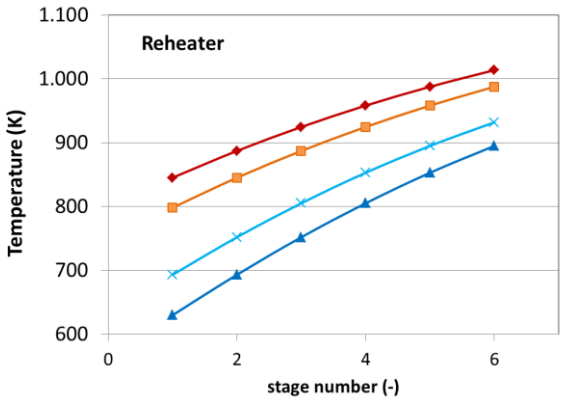




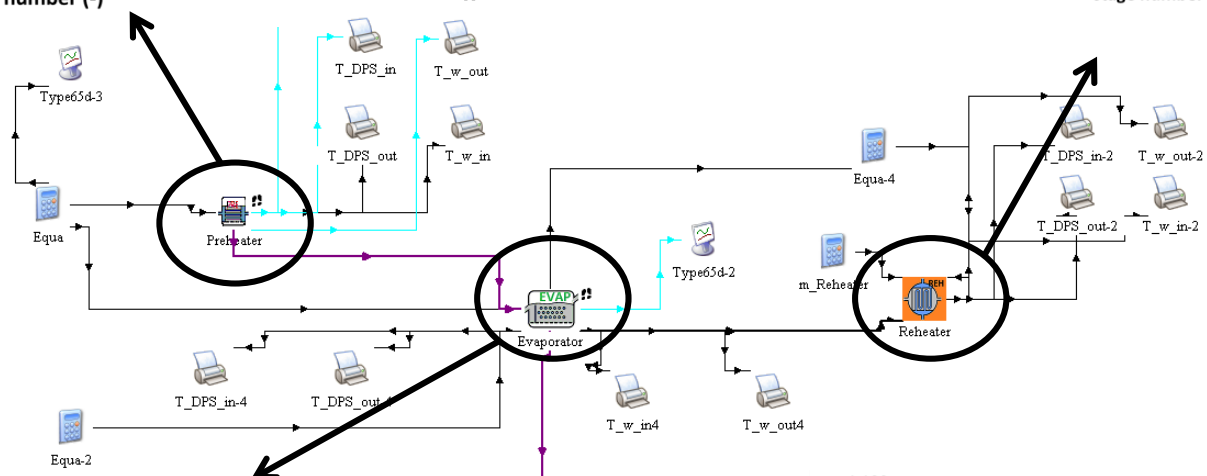
TRNSYS Simulations results

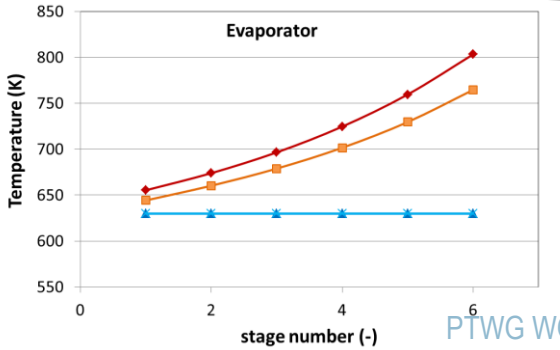


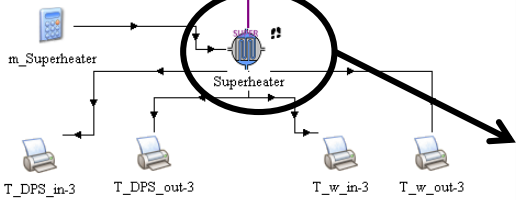
Inputs	Value
DPS cold tank temperature	563.8 K
Water inlet temperature to DPS-HX	506.5 K
DPS flow rate	66.25 kg/s
Water flow rate	7.86 kg/s

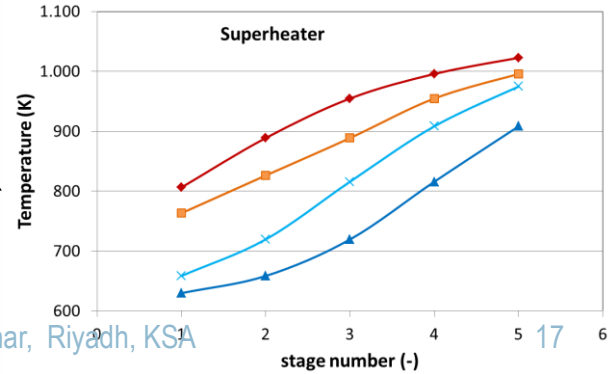


Inputs	Value
Rankine cycle power	10 MW_e
Solar field power	57 MW_{th}









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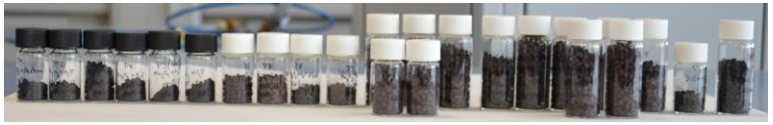
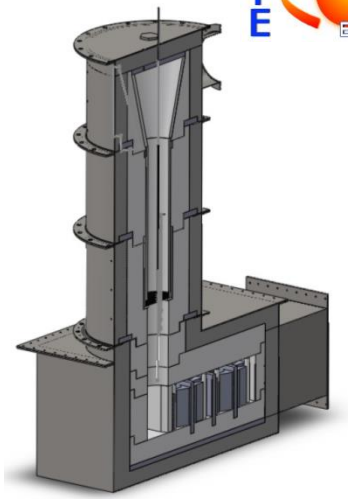
Possible collaborations in this WG (current ideas, but may be tomorrow…)



Materials

- Testing materials for very-high temperature applications (reactors and reactants)
- Physico-chemical characterization

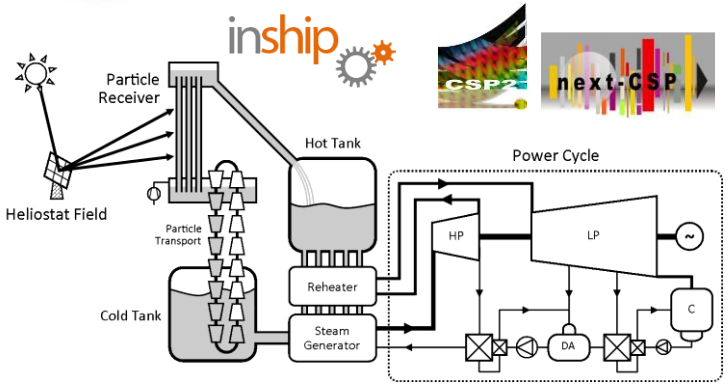


Solar particle receivers and reactors

- Analysis/Evaluation indirect-irradiated receivers and reactors
- Contribute with future developments at 10kW scale

Integration of particle-based systems in CST

- Annual analyses, transients
- Developed TRNSYS types or modules validated using experimental data from SolarPACES community
- Round Robin Tests on Assessment on solar fuels and chemicals production using metal oxides



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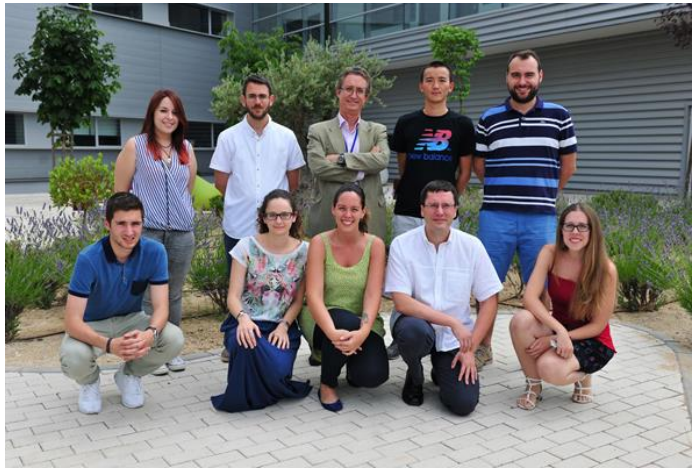
Thanks for your attention



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