sCO_2 Brayton cycles coupled with linear receivers in concentrated solar power plants

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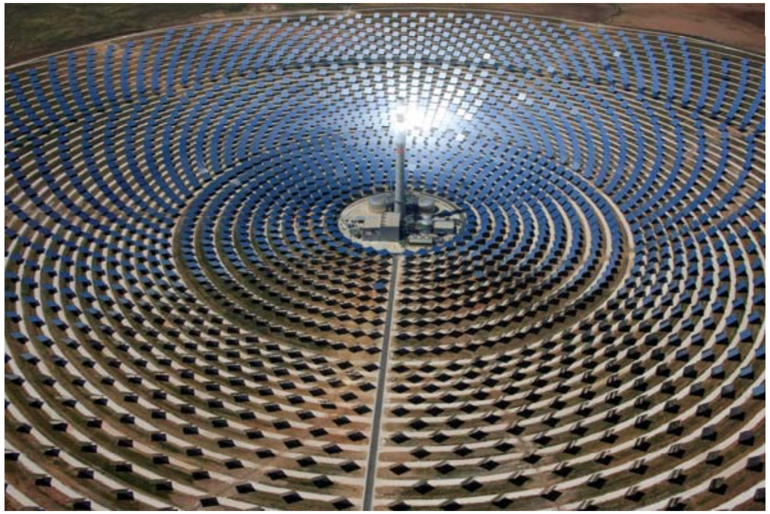
INTRODUCTION

Concentrated Solar Power: what can we do better?

CSP basic idea → to harness sun direct normal radiation (DNI) in the form of thermal energy, to be in turn converted to electrical energy in the power section



- The problem is the LCOE! → current values around 150÷250 \$/MWh vs. <100 \$/MWh for PV
- Moving to sCO_2 Brayton cycles could offer high performances at lower costs
- Brayton cycles would also imply faster transient response, and thus higher flexibility

What we did, and how we did it

Objective:

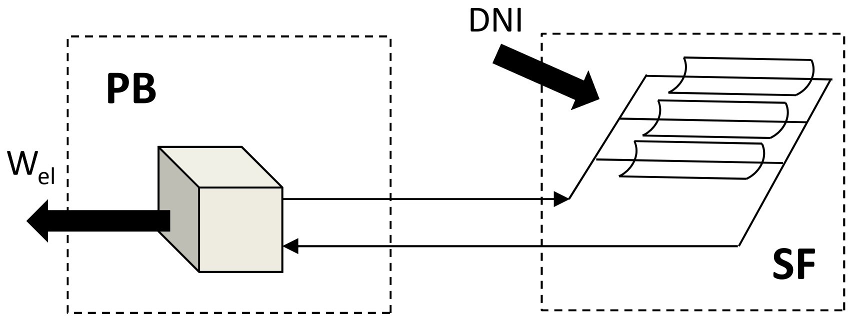
Identify optimal cycle configurations for direct linear CSP plant

Methodology:

1. Select promising cycle configurations
2. For each configuration perform multiple complete plant design, varying each operating parameter in a wide range
3. Select best combination of operating parameters
4. Compare optimal performances between all considered configurations, and identify best solution(s)
5. Evaluate plant annual performances for selected configurations

Plant overview

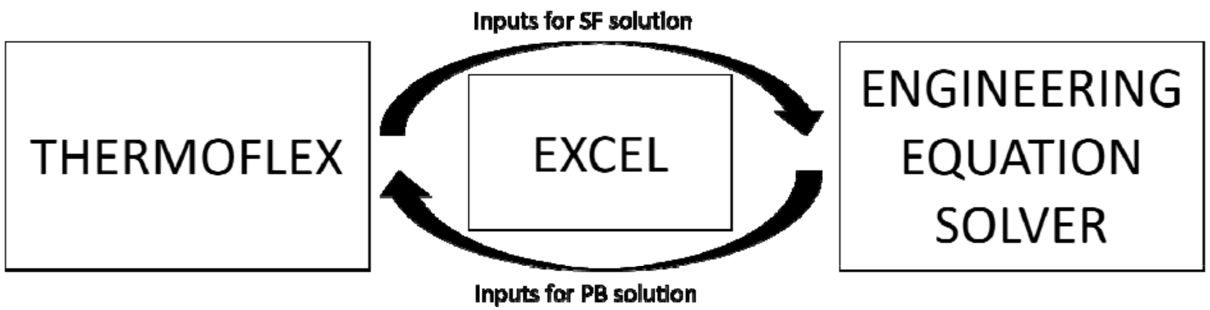
- The power plant can be conceptually divided in two sections: solar field and power block



- No storage is considered, and sCO2 serves both as working fluid in the power block and heat transfer fluid in the solar field

- Each section has been simulated by means of a different tool: Thermoflex for the PB and Engineering Equation Solver for the SF

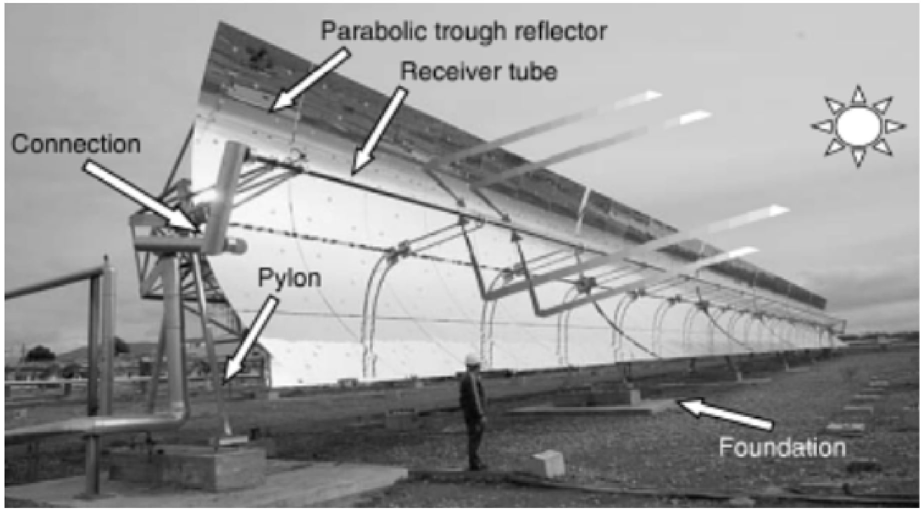
- The independent simulations are then put in communication through Excel

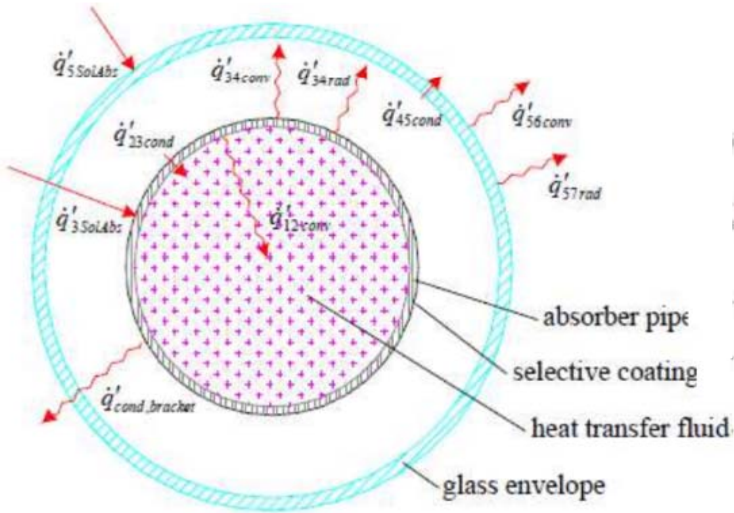


SOLAR FIELD MODELLING

Collectors modelling

- Geometry and materials considered refer to ET100 collector model



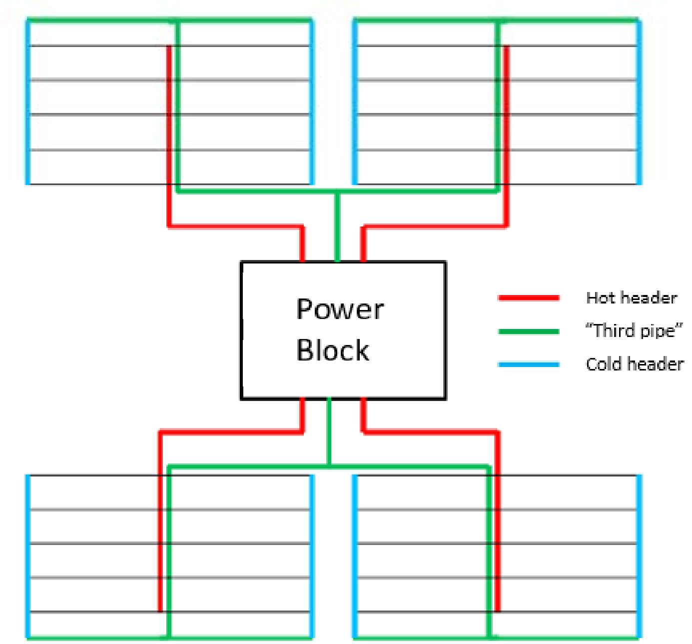


- Heat transfer model developed by R. Forristal at NREL has been adopted

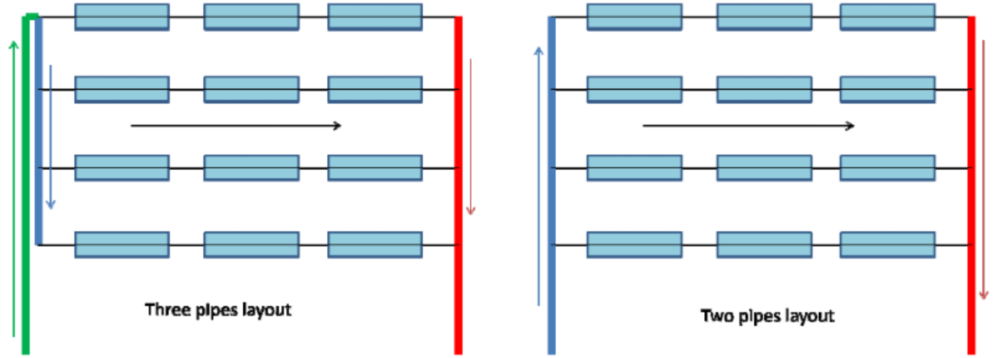
- Code originally developed for liquid heat transfer fluid (HTF) → modified in order to consider compressible HTF (sCO_2)

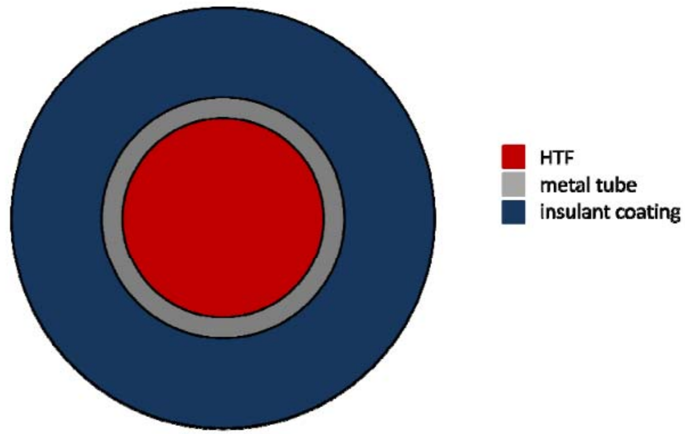
<u>Reference</u>: R. Forristal, *Heat Transfer Analysis and Modeling of a Parabolic Trough Solar Receiver implemented in Engineering Equation Solver*, NREL, 2003

Solar Field layout



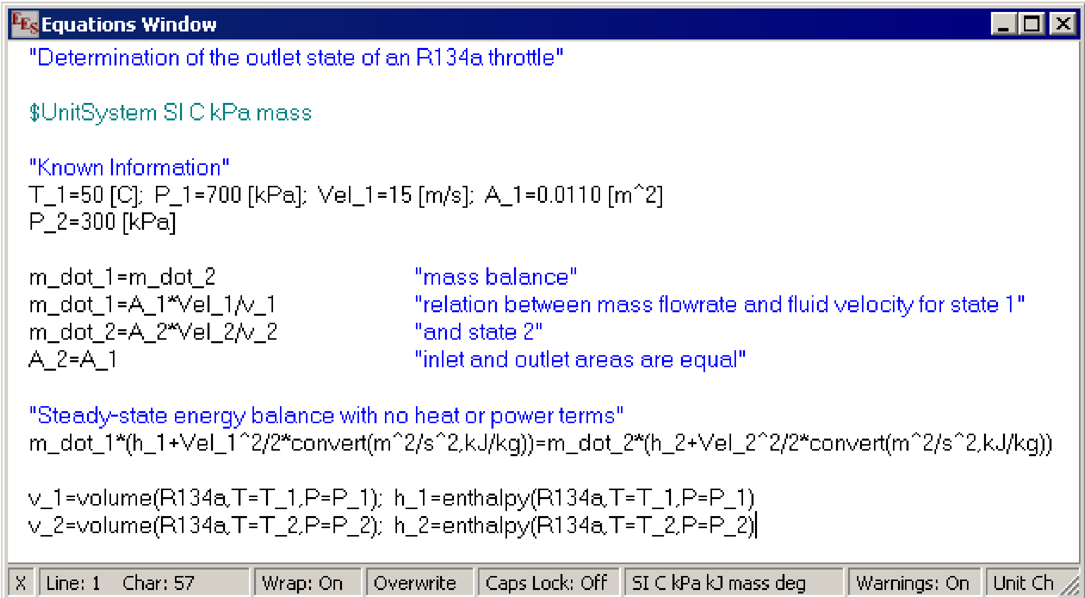
- Distribution headers are considered to admit/collect HTF to/from loops
- A «three pipes» piping system configuration helps pressure balancing along connections between hot header and collectors outlet
- Piping system detailed design is needed in order to correctly calculate piping pressure and heat losses





Modelling software: Engineering Equation Solver

- Engineering Equation Solver (EES) is a commercial software for the solution of a variety of complex equation systems
- It features a large database for thermodynamic and transport properties of a large set of fluids
- It allows to easily monitor and convert each variable unit of measure, and to ensure unit consistency in equations



SF design assumptions

The following assumptions/criteria are adopted for SF design:

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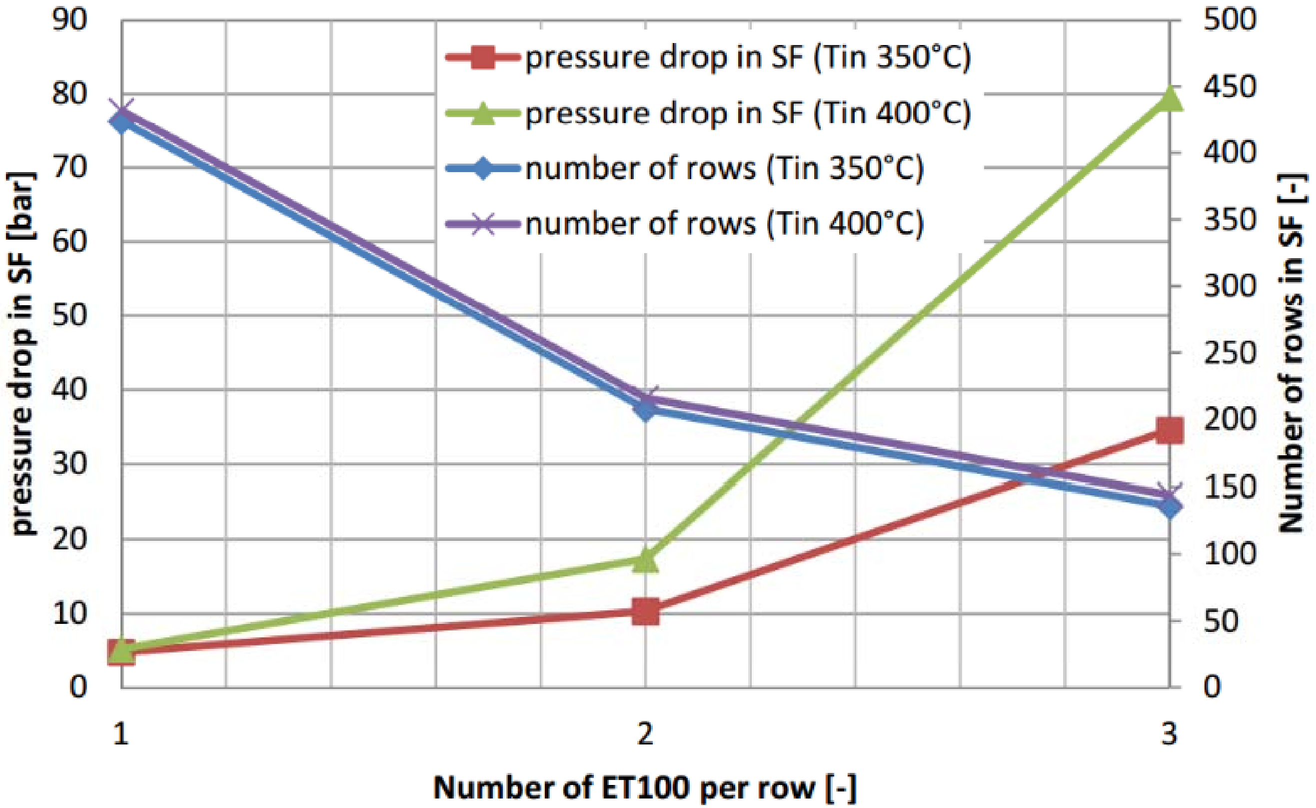


- Intermediate loops output linearly approximated in between first and last loop detailed simulation

POWER BLOCK MODELLING

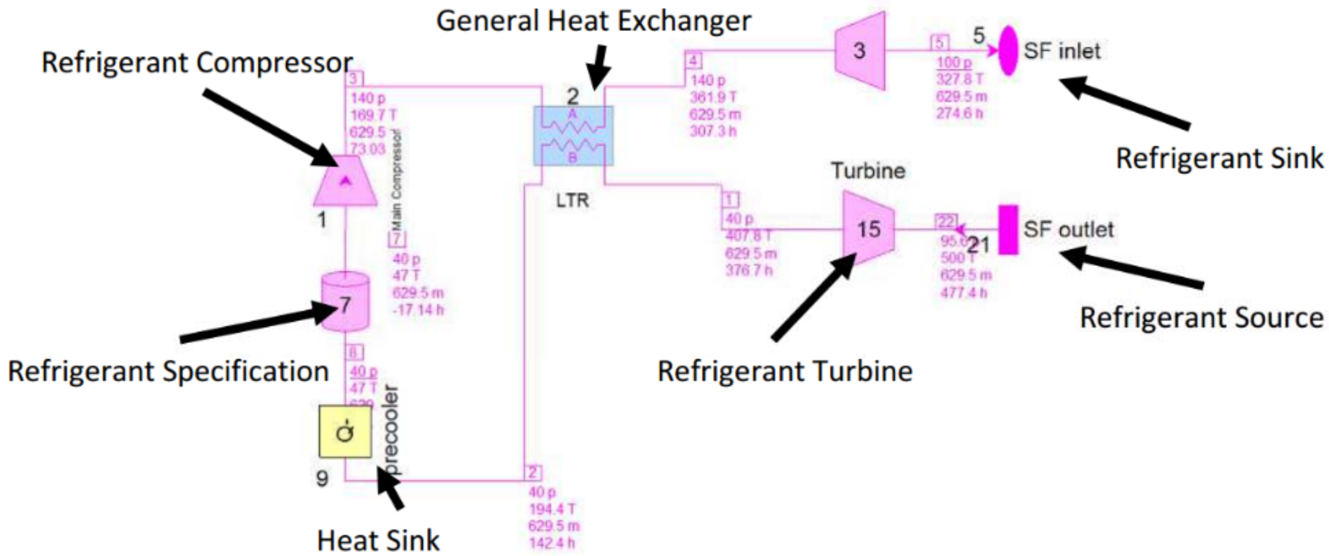
Modelling software: Thermoflex

THERMOFLOW Inc.
Thermal Engineering Software

- Thermoflex is a modular program with a graphical interface, licensed by Thermoflow Inc., for heat and mass balance solution of complex energy systems

- The software allows you to assemble a model from icons representing a large variety of different components

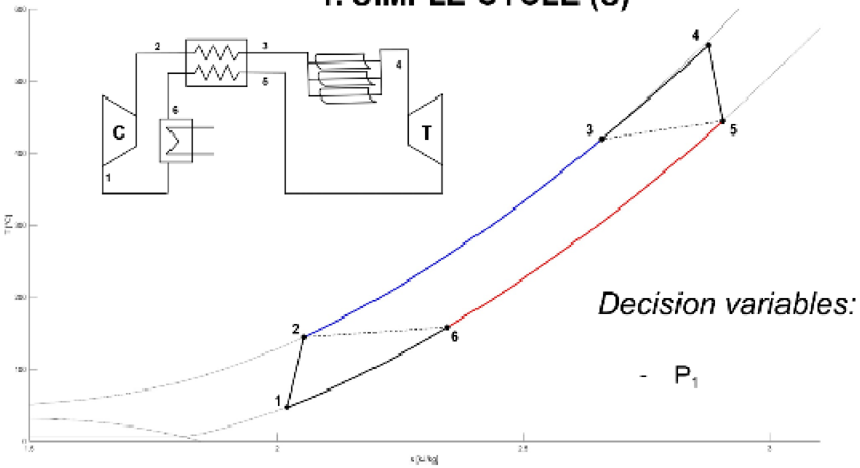
- A specific model was developed in Thermoflex for each cycle configuration explored



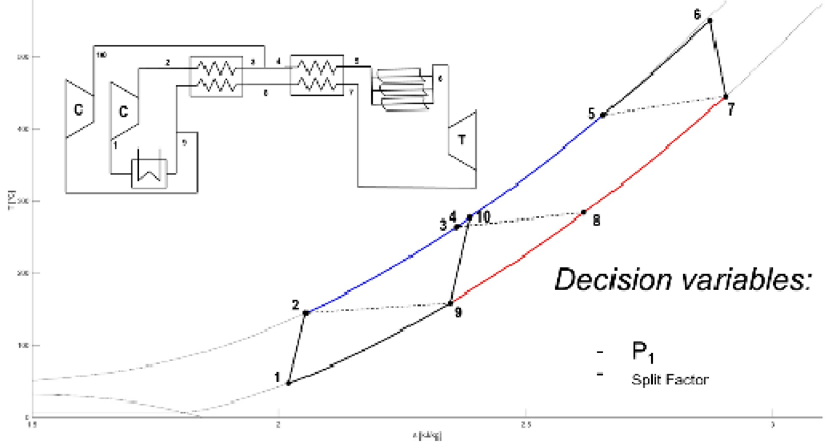
Cycle configurations selected

Three main features have been considered for the Brayton cycles, in addition to recuperation which is always performed:

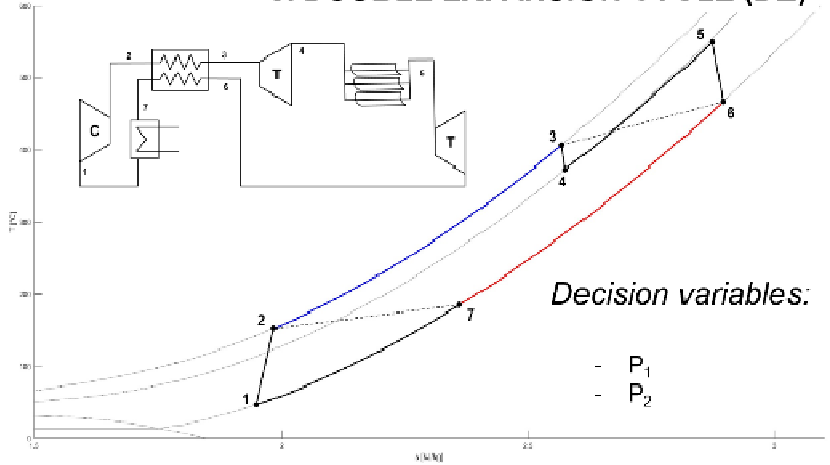
1. SIMPLE CYCLE (S)



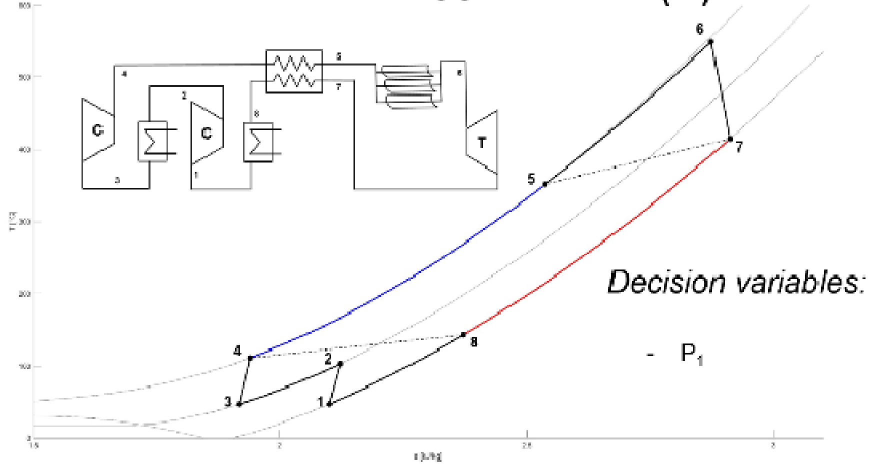
2. RECOMPRESSED CYCLE (R)



3. DOUBLE EXPANSION CYCLE (DE)



4. INTERCOOLED CYCLE (IC)



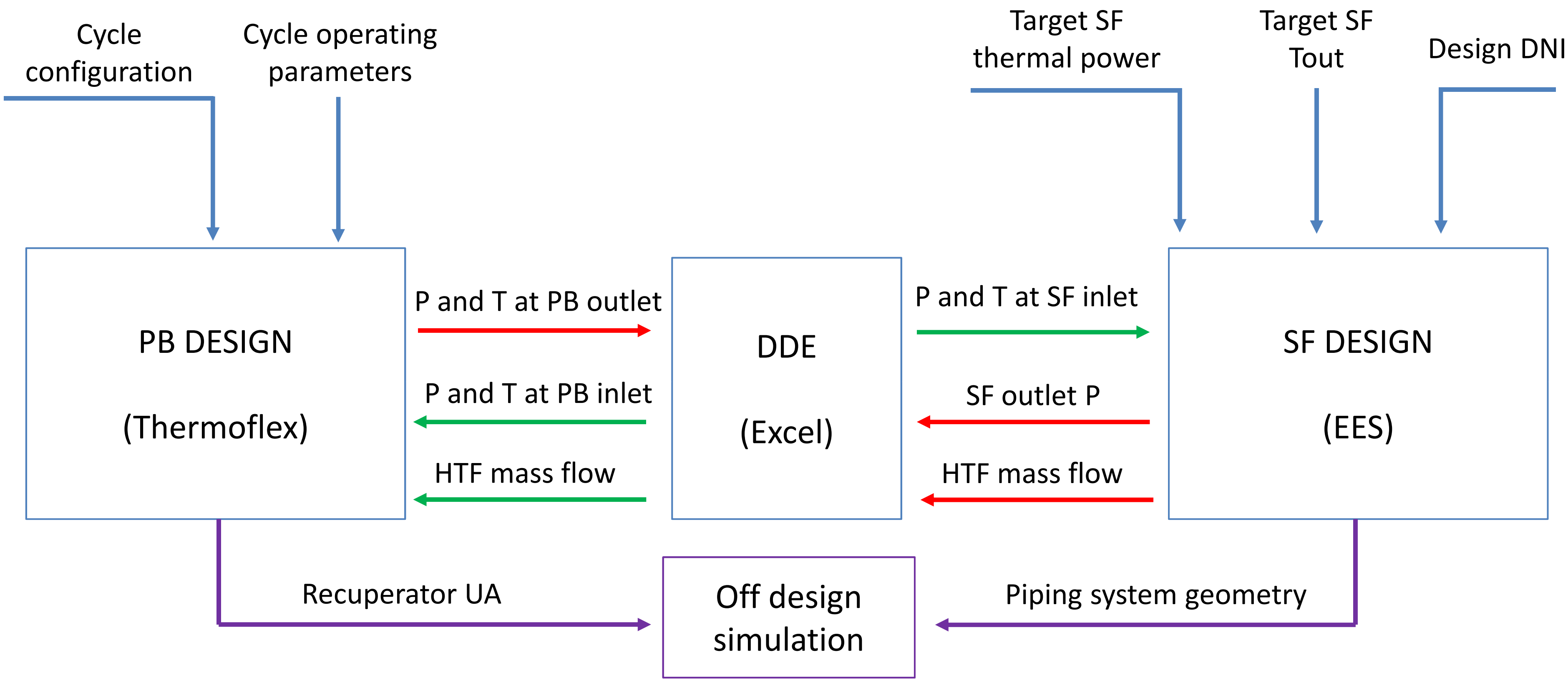
Power Block design assumptions

The following assumptions/criteria are adopted for PB design:

- Compressor isentropic efficiency equal to $\eta_C = 80\%$
- Turbine isentropic efficiency equal to $\eta_T = 85\%$
- Recuperators effectiveness equal to ε=90%
- Heat rejection system ("Precooler") designed to achieve target cycle minimum temperature (47 °C)
- Pressure drops considered only in SF (main pressure drop source)

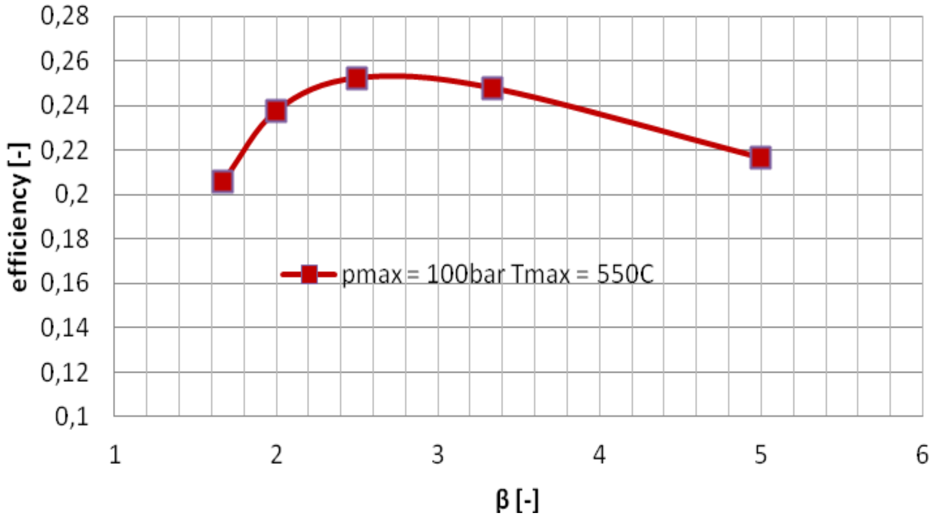
SF AND PB INTERCONNECTION

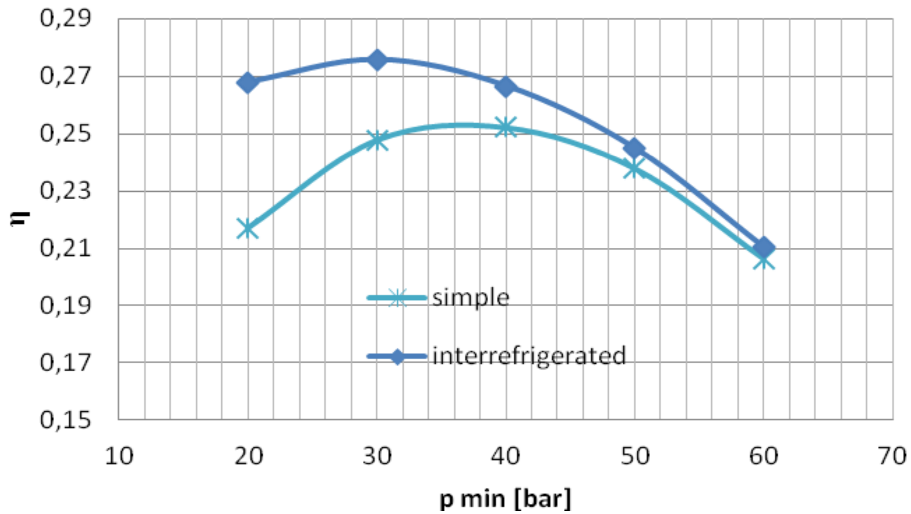
Plant design solution algorithm



DESIGN ANALISYS RESULTS

Optimal solution of each cycle configuration (1/2)

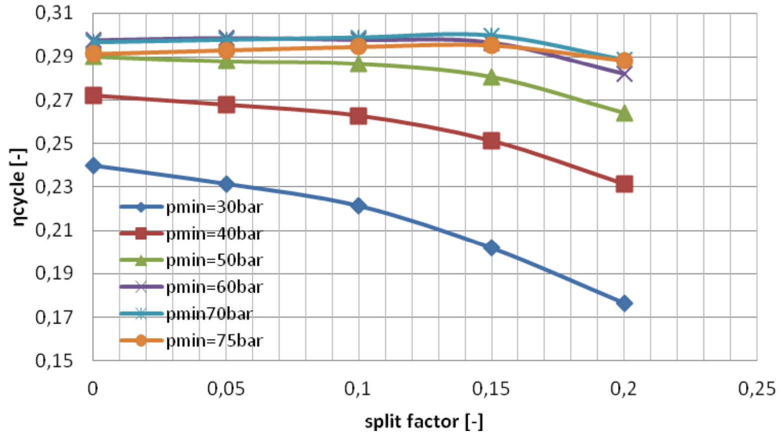


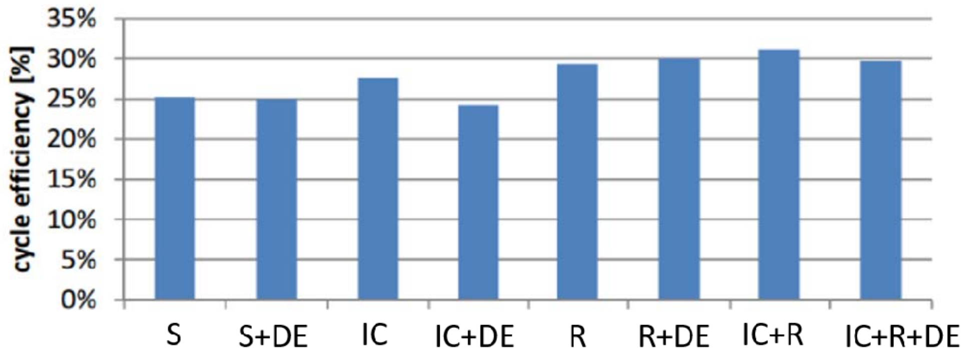


- Simple cycle attains maximum efficiency with compression ratio 2.7, implying a lower pressure too far from CO_2 critical point to observe real gas effects
- Performing intercooling moves the second compression stage closer to the saturation line, sensibly improving cycle efficiency
- On the contrary, addition of double expansion generally worsen cycle performance

Optimal solution of each cycle configuration (2/2)

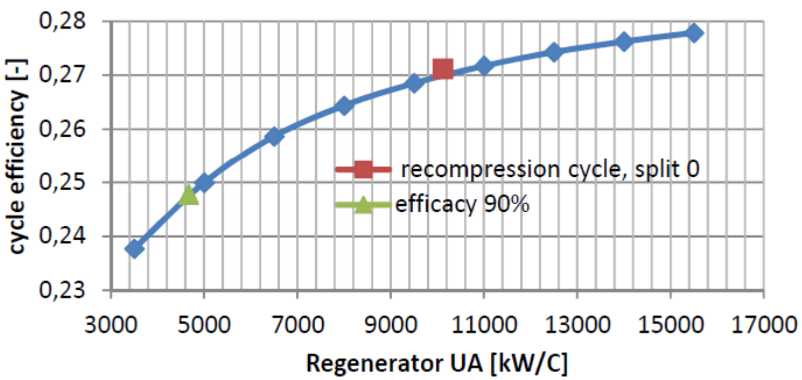
- Recompression has a negative effect on cycle performance, unless coupled with double expansion (higher maximum cycle pressure allowed)



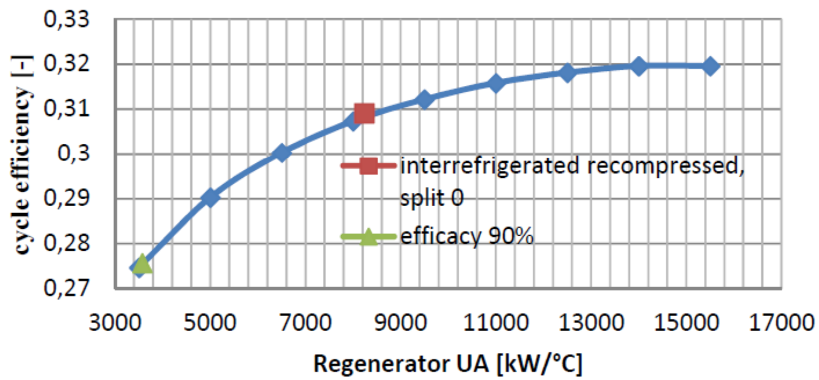


- Higher efficiency values attained by recompressed cycles are only due to the presence of more than one recuperator (each with 90% effectiveness)

Simple cycle



Interrefrigerated cycle



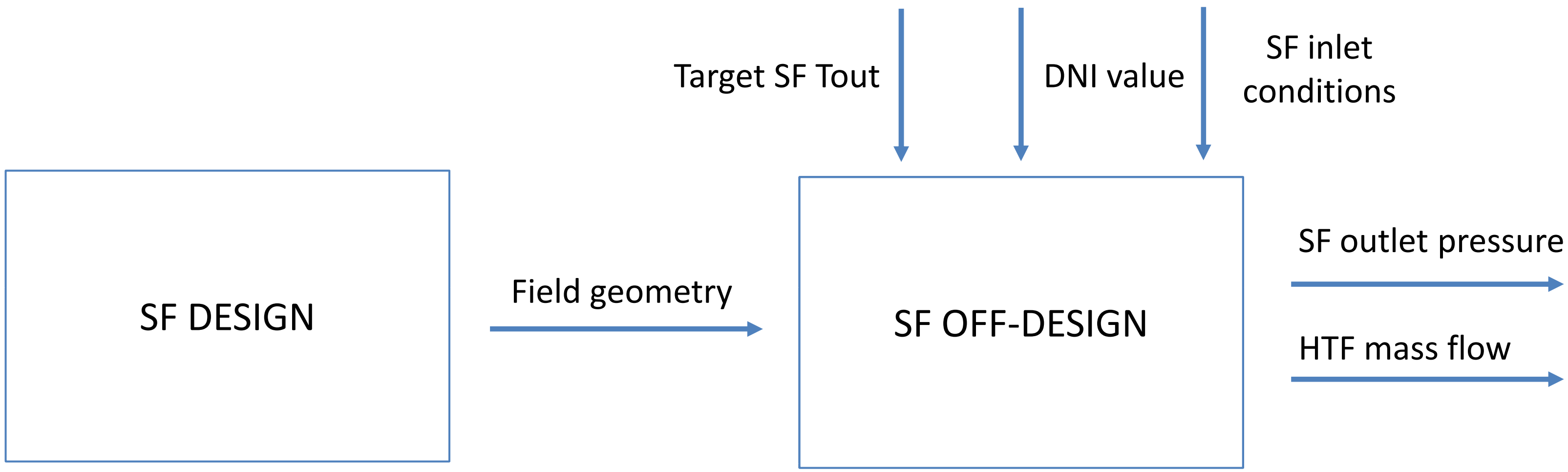
Design analysis conclusions

- Recompression and double expansion do not prove to be feasible for linear CSP application
- Intercooled and simple cycles are proven to attain maximum efficiencies competitive with more complex cycle configurations, given that the same overall recuperator UA is considered
- Intercooled cycle performs better than simple cycle, at the cost of a minor additional cycle complexity
- Annual performance evaluation might help establishing the optimal solution

ANNUAL PERFORMANCE EVALUATION

Components off-design (1/2)

- SF off-design model takes as input the geometry defined by the design code
- Fixing SF and piping dimensions, the code adapts HTF flow elaborated by the field, in order to achieve the desired outlet temperature

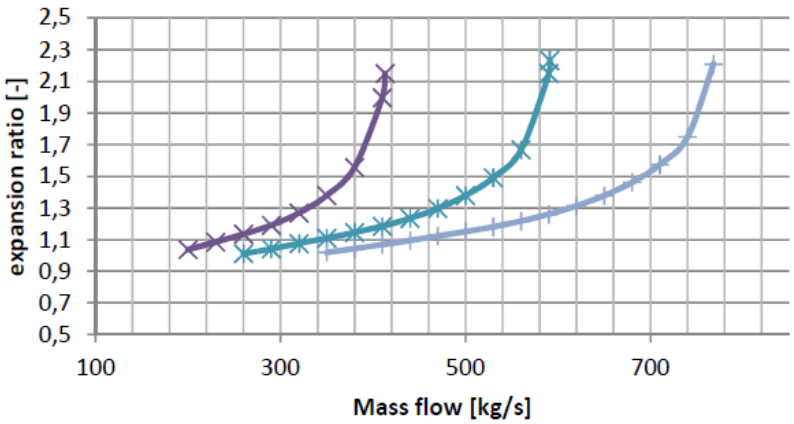


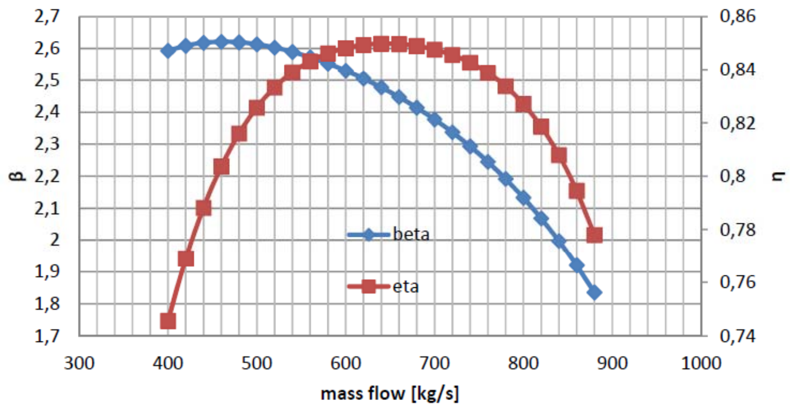
- Heat exchangers off-design is computed by LMTD method, matching the overall UA value obtained by Thermoflex in design simulation, adapted in accordance to the following formula:

$$UA_{off} = UA_{design} \cdot \left(\frac{\dot{m}_{off}}{\dot{m}_{design}}\right)^{0.7}$$

Components off-design (2/2)

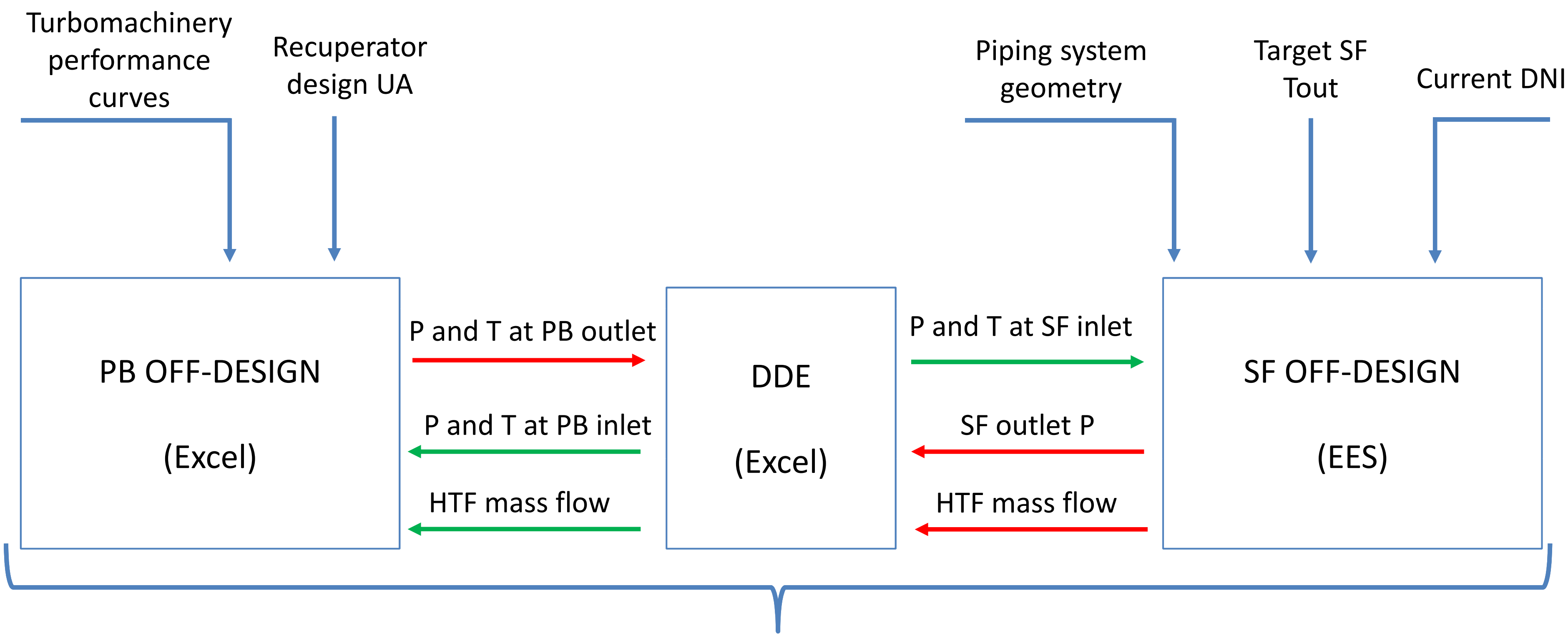
- Turbines off-design maps are obtained from a software developed by Polimi to perform turbomachinery design, adapted to work with fixed geometry





- Compressors off-design maps have been calculated combining preliminary machine design (using Baljè charts) and semi-empiric dimensionless curves developed by Dyreby on the basis of Sandia compression loop experimental results

Plant off-design solution algorithm

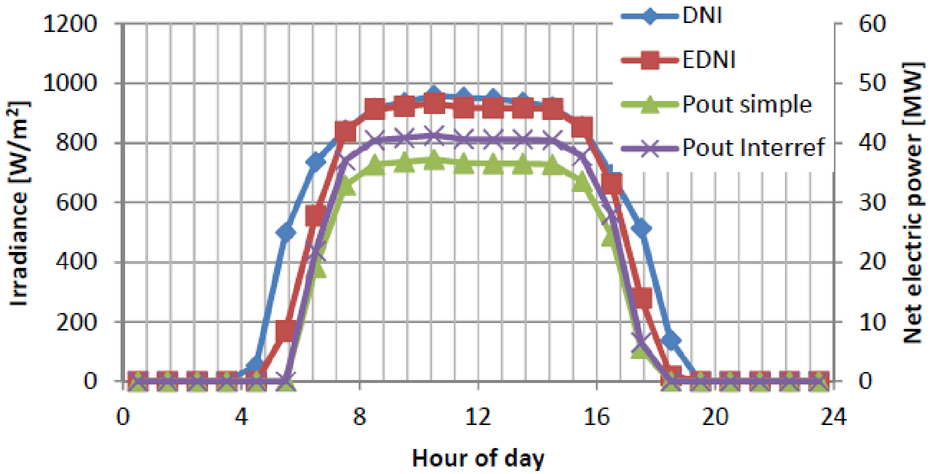


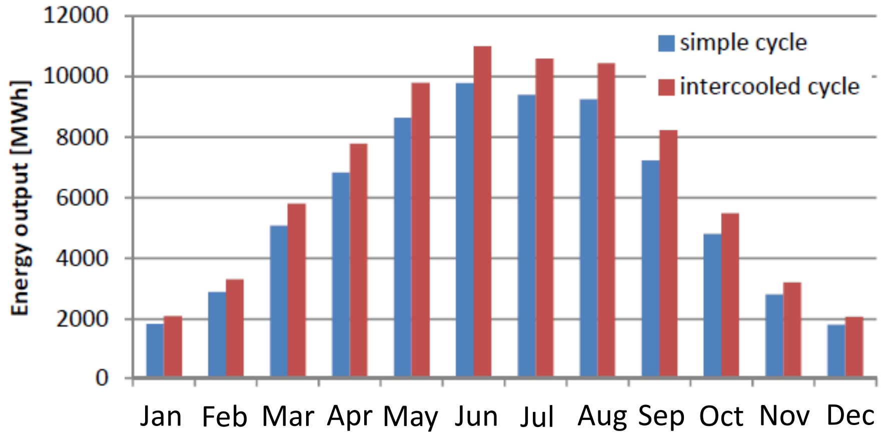
$$\eta_{solar-to-electric}(t) = f(plant\ design, DNI(t), sun\ position(t))$$

Hourly radiation intensity & sun position database

Annual power plant energy production

Off-design results (1/2)





- Intercooled cycle consistently performs better than simple cycle in all months of the year
- Economic analysis is needed to assess additional earnings due to higher productivity
- It is expected that the advantages of a higher plant solar-to-electric efficiency will more than compensate the higher investment (1 additional compressor + intercooler)

Off-design results (2/2)

- The annual performance results are summed up below:

	$\eta_{th,year}$ [%]	$\eta_{el,year}$ [%]	$\eta_{overall}$ [%]	W_{year} [GWh]
simple	73.50	28.01	12.52	70.366
intercooled	74.71	31.26	14.21	79.829

- SF thermal efficiency is strongly penalized by high HTF average temperature in piping and collectors (high thermal losses)

- PB electric efficiency results to be lower than traditional Rankine cycles → values might be improved with higher investment on recuperators

- Annual solar-to-electric performance needs to be improved!

SUMMARY

Conclusions

- Thermodynamic performance of different sCO2 Brayton cycle configurations have been compared

- Simple and intercooled cycles are shown to be the most suitable configurations for linear CSP application

- Annual performance analysis has been performed for the optimal design of the two selected configurations

- LCOE estimate is necessary in order to draw conclusions about profitability of additional investment cost required by intercooled configuration, and to assess the economic impact of the low annual performances observed