Dynamic simulation of two CSP concepts with sCO_2 Brayton cycle

1st European Seminar on Supercritical CO_2 (sCO_2) Power Systems

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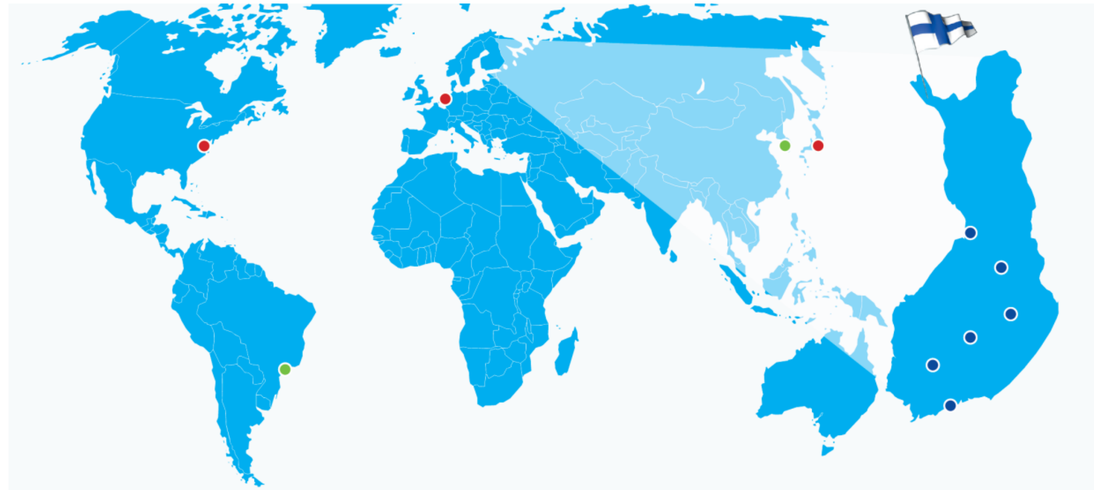
VTT Technical Research Centre of Finland Ltd

- Largest multi-technological applied research organization in Northern Europe
- Applied research for needs arising from industry
- Customers are Finnish and international companies as well as public sector organizations
- Total staff over 2,300
- High focus in future low carbon energy systems



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New renewable energy and RES hybrid concepts and distributed energy production

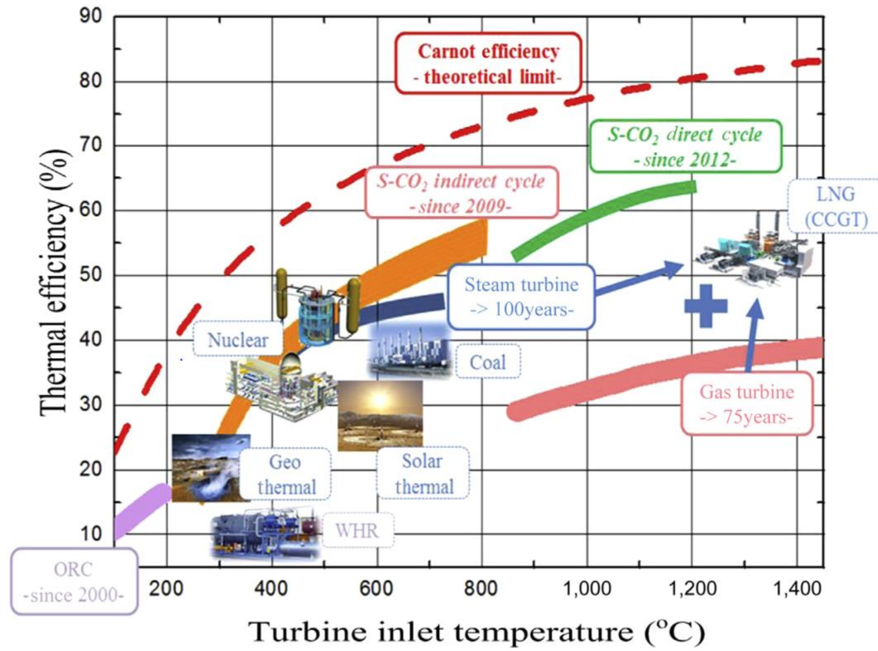
Background: Motivation for the concept development

- New CSP concepts and heat transfer fluids (HTF) needed to improve the efficiency and reduce the levelized cost of electricity

→ One foreseen solution is the introduction of supercritical CO_2 cycles

- **Why supercritical carbon dioxide (sCO_2)?**
  - Inexpensive, abundant and environmentally friendly
  - Moderate critical pressure and temperature
  - Reduced compression work, high temperatures
  - Smaller component sizes
  - Reduced water consumption in cooling process
- The storage option remains a question

→ Molten salts can provide over night storage solution



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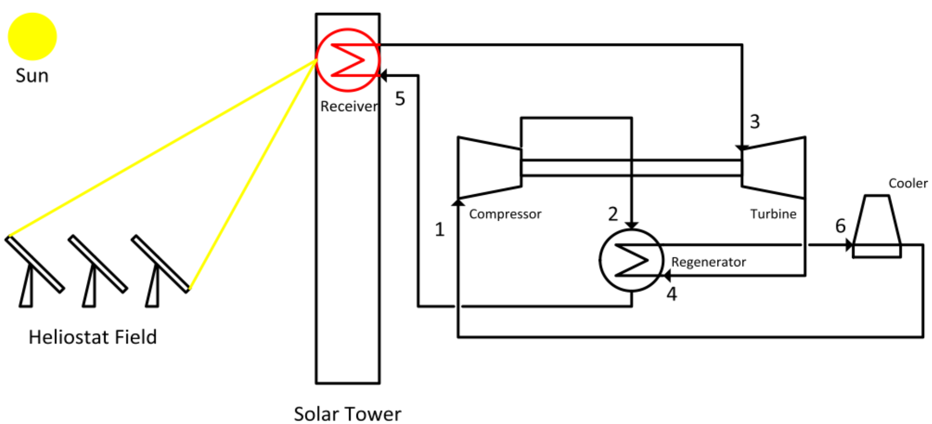
Ref.: Solar Thermal Electricity Global Outlook 2016; Technology Roadmap – Solar Thermal Electricity 2014; Ahn et al. 2015; Ma & Turchi 2011; Singh et al. 2013; Sandia National Laboratories

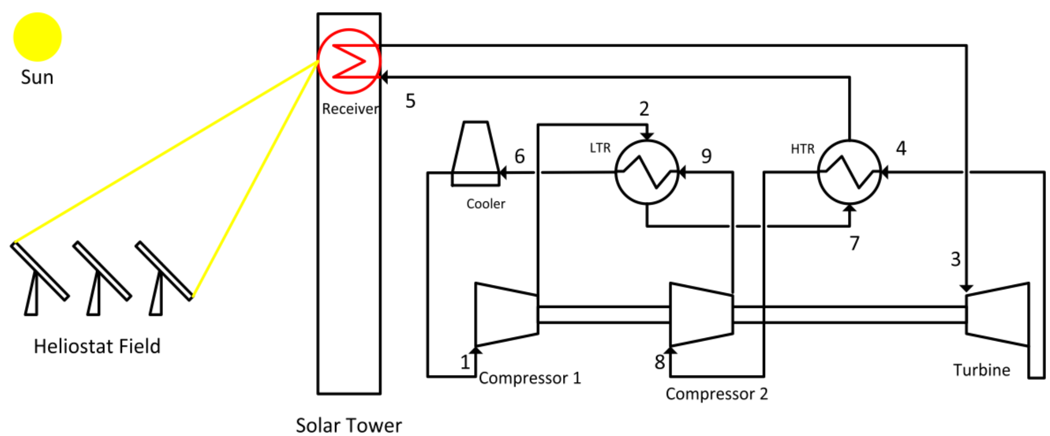
Background: Scope of the work

1. To improve dynamic modelling capabilities of sCO_2 CSP plant based on Linear Fresnel Collector (LFC) technology; HTFs, TES, compression modelling etc.
2. To introduce a novel LFC concept combining sCO_2 and molten salts for improved efficiency while maintaining dispatchability
3. To proof the proper functionality of the models and preliminary control concepts under varying operation modes

Approach in this study:
Regenerative closed loop Brayton cycle



Another possible approach:
Pre-compression closed loop Brayton cycle



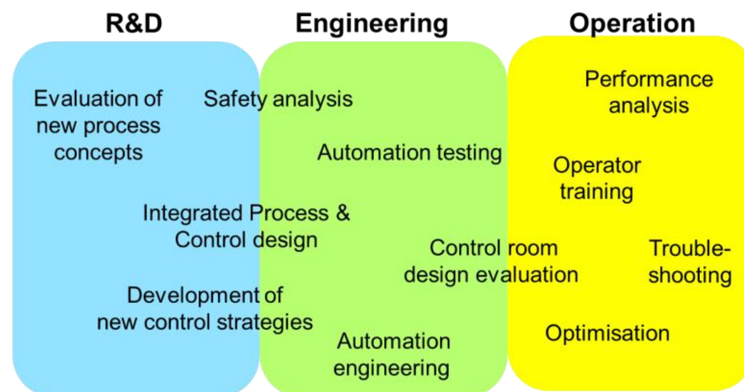
Background: Simulation environment

- Apros® is a software package for modelling and dynamic simulation
- Applied for the wide range of processes
    - Nuclear power plants
    - Combustion power plants
    - Pulp & Paper mills
    - General heating and cooling processes
    - Distributed generation & Smart grids
- Developed since 1986 by VTT and Fortum
- Users in 27 countries

Apros features relevant for this study:

- Accurate process modelling with a set of predefined process components; one-to-one analogous with concrete devices and properly validated
- Sophisticated automation & instrumentation system modelling
- User defined components (User component)
- User definable fluids

Where can be Apros used?



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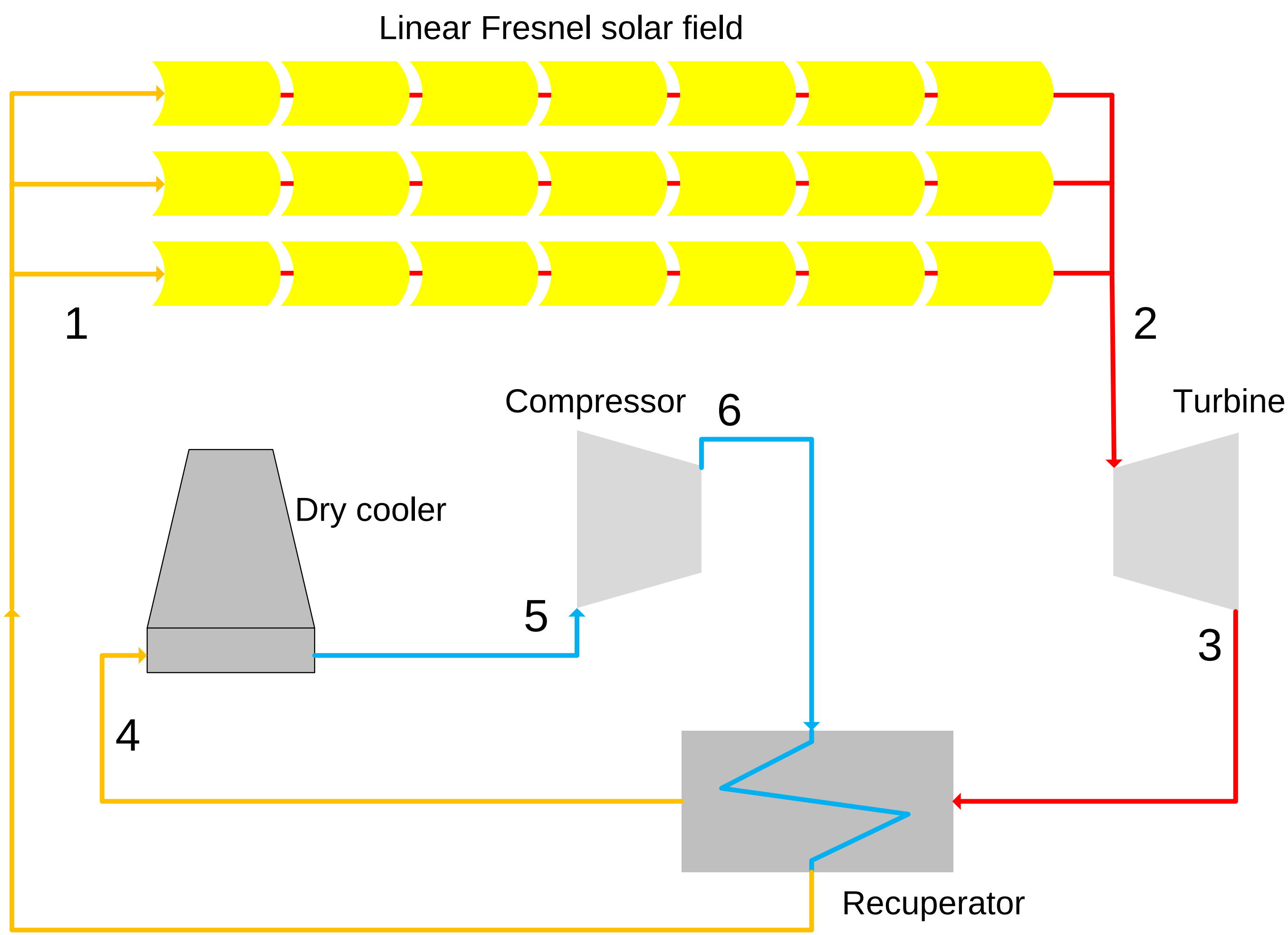
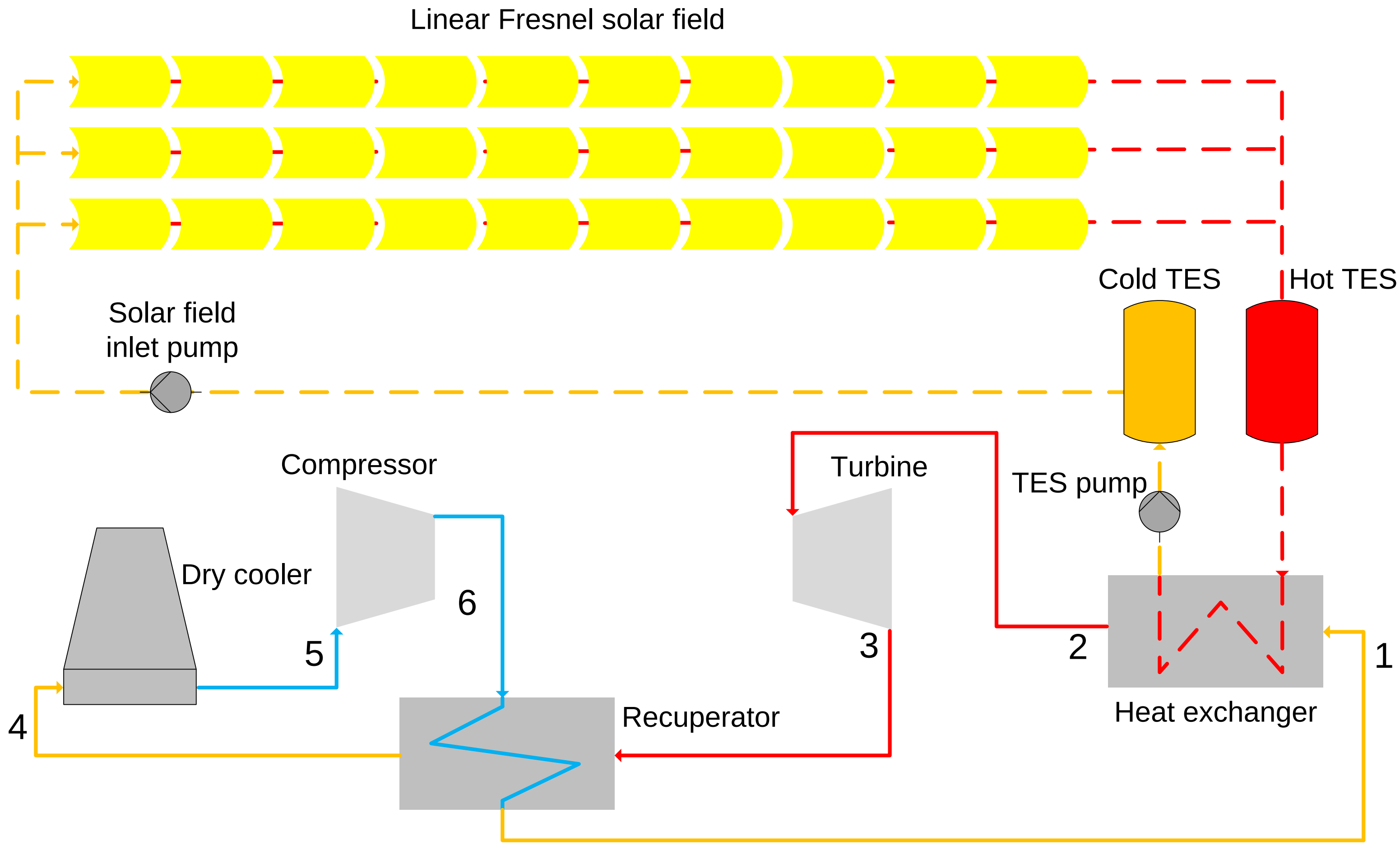
Concept 1: sCO_2 solar field and power cycle



Numbers 1 – 6 refer to process state points

Concept 2: Molten salt solar field and sCO_2 power cycle



Numbers 1 – 6 refer to process state points

Modelling approach – Heat transfer fluids

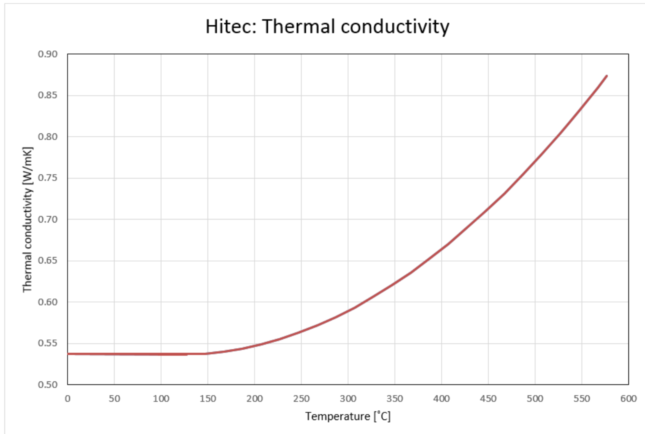
Supercritical carbon dioxide (sCO_2)

- Calculation introduced to Apros a few years ago*)
- Calculation based on densely tabulated property data and interpolation by pressure and enthalpy
- CO_2 can exist as liquid, gas or as a two-phase mixture of liquid and vapor
- Air calculation method similar to CO_2

- Homogeneous (3-equation) pressure flow model for all the fluids used

Molten salt: Hitec

- 53% KNO_3+40% $NaNO_2$+7% $NaNO_3$
- Freezing point: 142 ºC
- Upper temperature limit: 535 ºC
- User definable fluid – New developments:
  - Air as a non-condensable gas
  - Storage tank simulation possible
- Only the liquid phase of the molten salt is considered

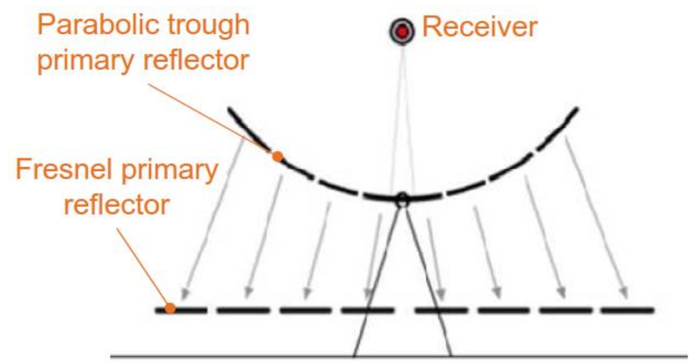


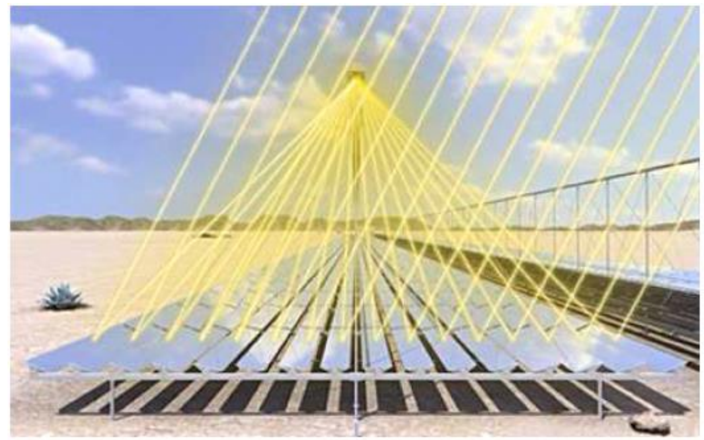
*) Lilja, R.; Hänninen, M.; Lappalainen, J.; Juslin, K., (2010), Extended material properties in Apros for dependable evaluation of new combustion power plant concepts, Proceedings of 7th EUROSIM Congress on Modelling and Simulation, September 6-10, 2010, Prague, Czech Republic, 5 p.

Modelling approach – Solar field

- Linear Fresnel Collectors with vacuum tubes
- Apros User components used for collector modelling
  - Optical behavior
  - Heat transfer
  - Heat losses
- North-South field orientation
- Solar field dimensioned to achieve ~1.2 MW_e power production at design point

Design point conditions	Concept 1	Concept 2
Nr. of collector rows [-]	3	9
Nr. of collectors/row [-]	7	10
Length of the row [m]	314	448
Inlet temperature [ºC]	156	280
Outlet temperature [ºC]	350	550
Thermal power [MWth]	5.37	22.3





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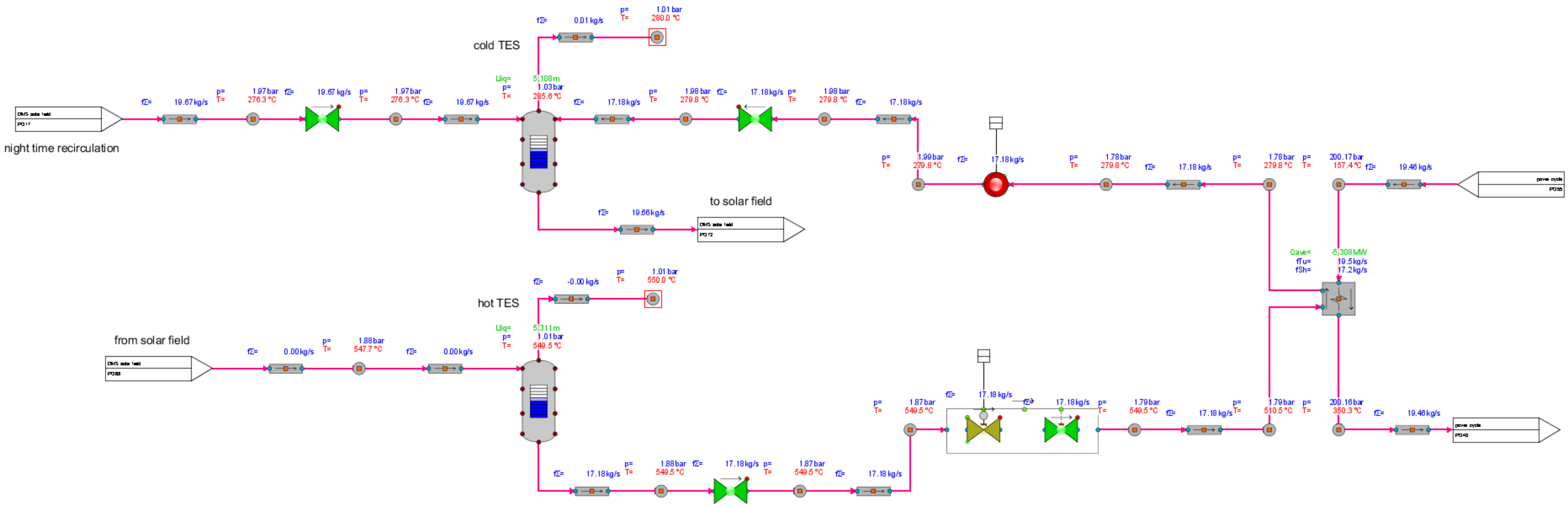
Modelling approach – Storage system

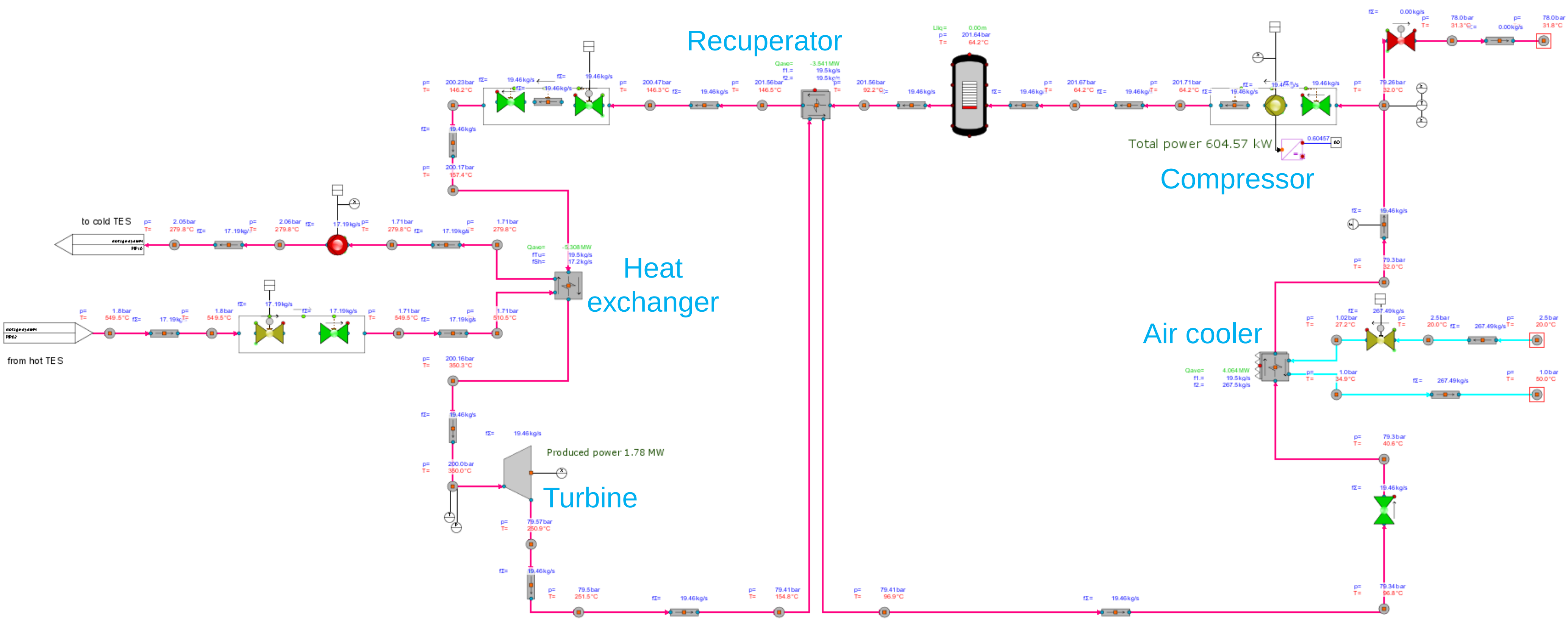
- Two-tank thermal energy storage (TES) system – Only in Concept 2



Modelling approach – Power block

- Power block model basically similar for both concepts – Different heat source

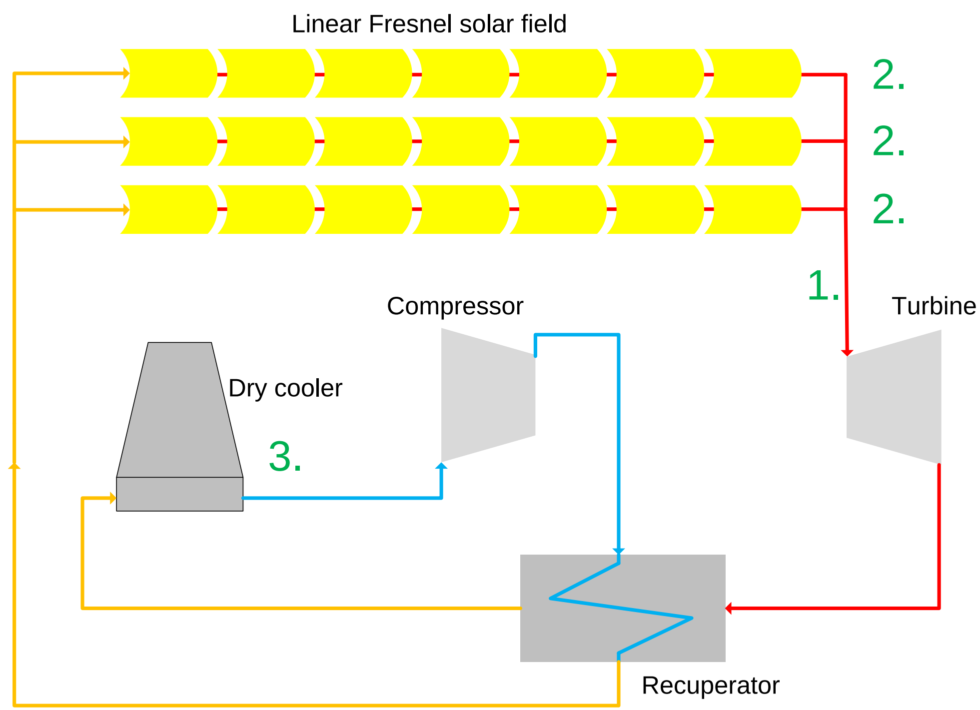
Power block in Concept 2



Modelling approach – Control concept for Concept 1

1. Turbine inlet temperature control
   - Through compressor's rotation speed
2. Collector row outlet temperature control
   - Through the inlet valve position at the inlet of two first collector rows
3. Compressor inlet temperature control
   - Through the cooling air mass flow

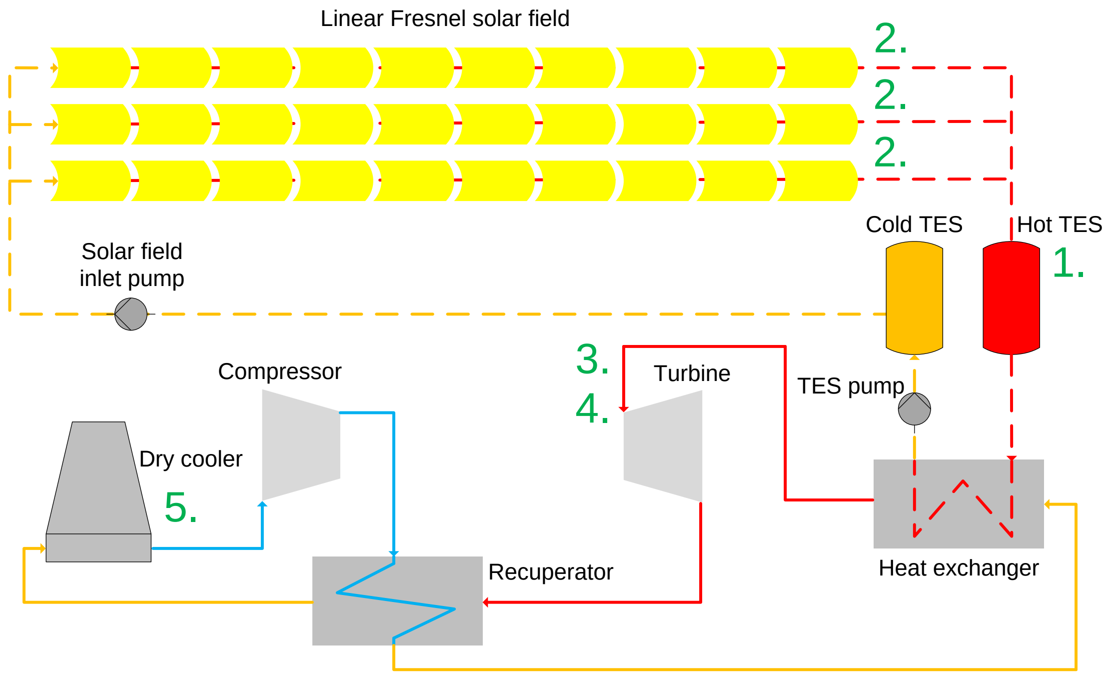
- Start-up and shut down modes: Minimum speed set point for the compressor



Modelling approach – Control concept for Concept 2

1. HE inlet temperature control
   - Through solar field inlet pump's rotation speed
2. Collector row outlet temperature control
   - Through the inlet valve position at the inlet of two first collector rows
3. Turbine inlet pressure control
   - Through compressor's rotation speed
4. Turbine inlet temperature control
   - Through the valve position and TES pump's rotation speed
5. Compressor inlet temperature control
   - Through the cooling air mass flow

- Night mode: Molten salt circulation from cold TES through solar field back to cold TES



Simulation cases

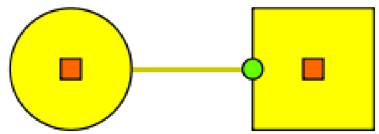
- Daily performance of two concepts compared with the purpose to
  - Study the sCO_2 heat transfer fluid performance and controllability under varying operation modes
  - Study the molten salt TES operability together with sCO_2 Brayton cycle
  - To compare the daily performance between dispatchable and non-dispatchable systems

Simulation location	Ourzazate, Morocco
Latitude	31.004 ^{o}N
Longitude	6.864 ^{o}W
Simulation date	21st June i.e. summer solstice
Height from see level	1,143 m
Ambient temperature	25 ^{o}C
$^{*)}$Turbidity Linke factor	5.0
$^{*)}$MOS-corrected DNI	2,669 kWh/m^2/year

$^{*)}$ Data provided by Vaisala

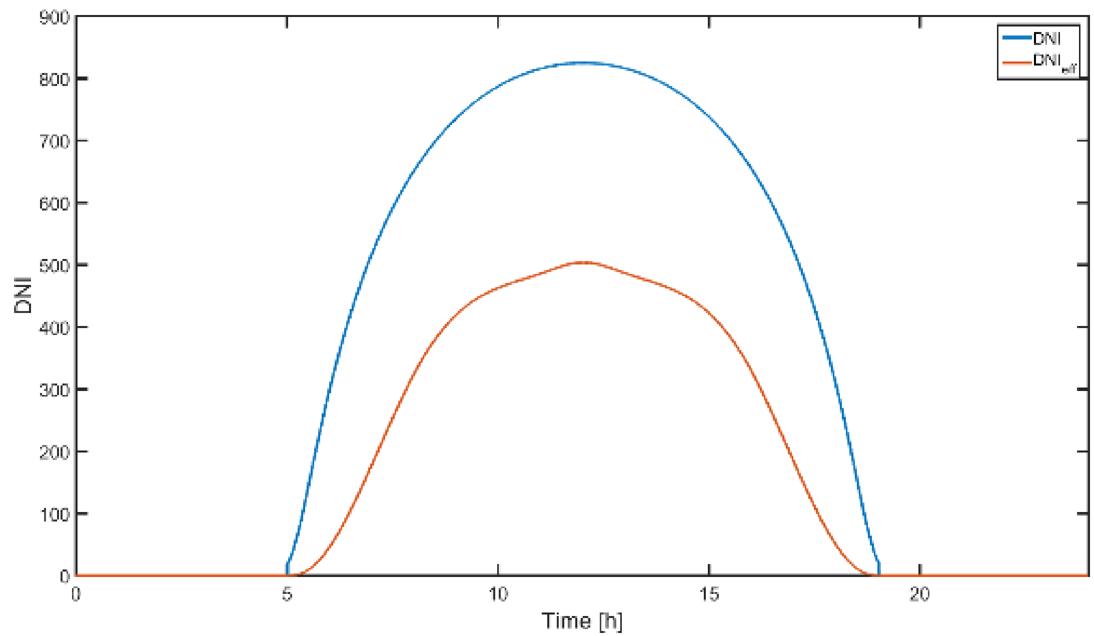
Results: DNI conditions

- Clear sky DNI data generated in Apros with Solar Radiation module and Solar Irradiation Processor module



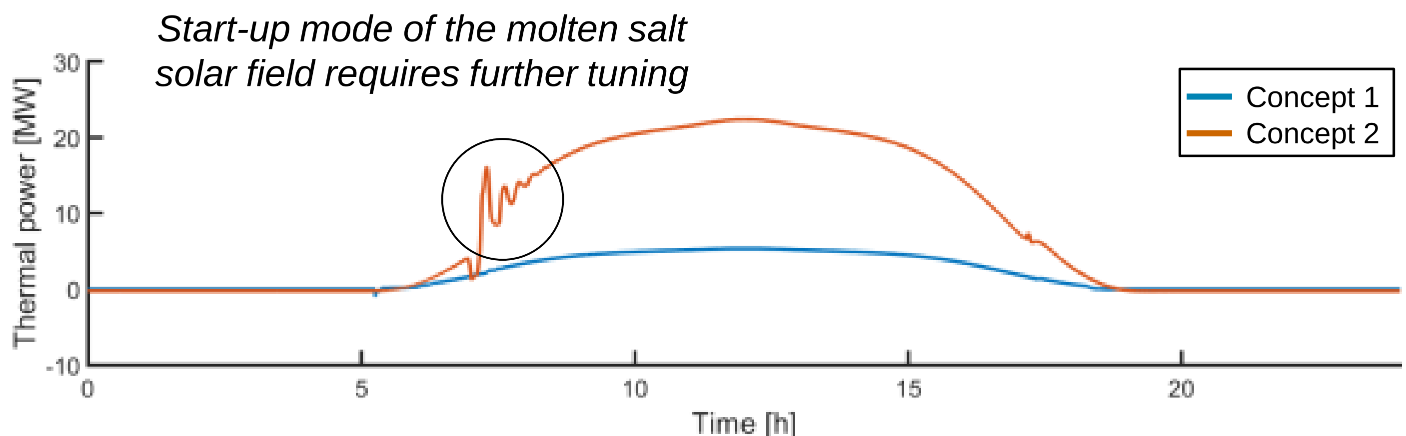
SOR01 : SolarRadiation (Solar Radiation)

Property	Value	Unit
Type	SOLAR_RADIATION	
Name	SOR01	
Label		
Description		
Included In Simulation	true	
Connection (1)	SOI01 SOL_IRR_INPUT_SOL...	
Measurement (1)	GI05	
Measurement (2)	GI08	
Measurement (3)	GI10	
Latitude	31.004	deg
Local longitude	6.864	deg
Standard meridian longitude	6.864	deg
Solar constant	1367	W/m2
Turbidity Linke factor	5	
Elevation from sea level	1143	m
Beam component of clear-sky index	1	
Diffuse component of clear-sky index	1	
Current standard time	6 :21:12:0	m:d:hr:min
Current solar time	6 :21:11:59	m:d:hr:min
Zenith angle	7.55835911132857	deg
Solar altitude	82.4416408886714	deg
Solar azimuth	-1.74392237884553	deg
Beam irradiation on horizontal surface	817.597446080468	W/m2
Diffuse irradiation on horizontal surface	192.886585340182	W/m2
Extraterrestrial irradiation	1322.05605758589	W/m2
Day number	172	

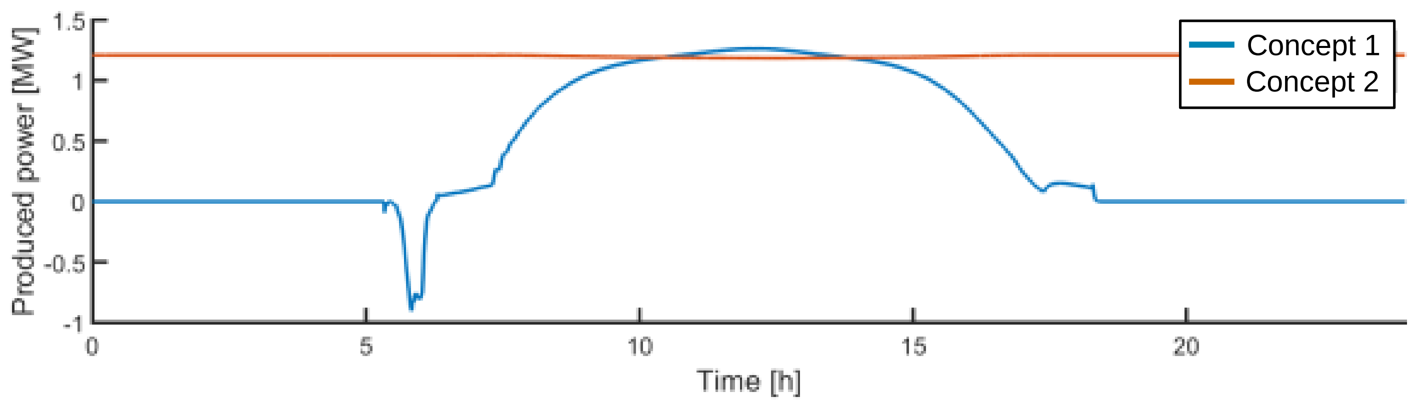


Results: Overall performance

- Produced power follows the load i.e. DNI in Concept 1
- Concept 2 produces constant power due to dispatchability through TES system

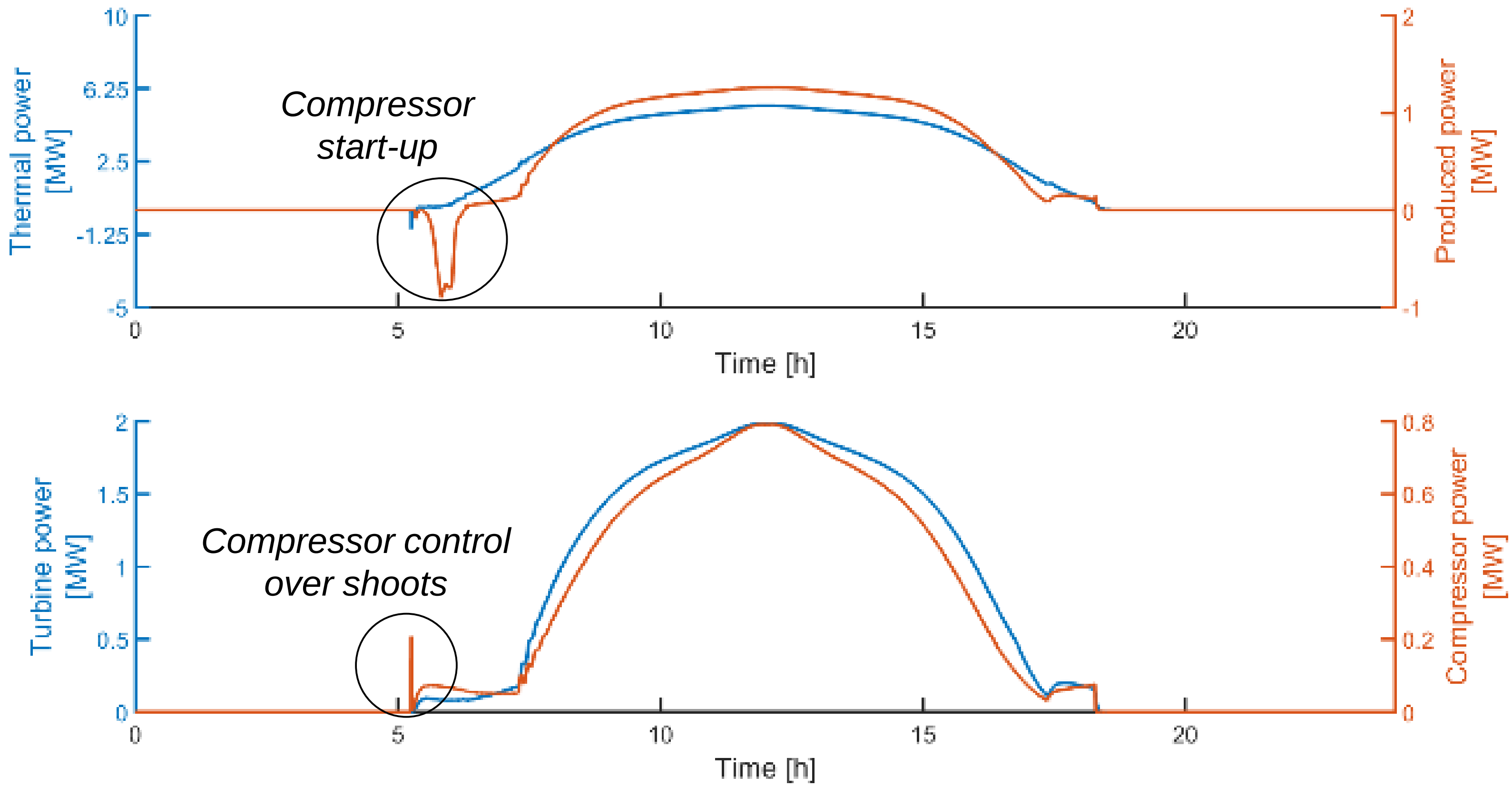


$$P_{produced} = P_{turb} - P_{compr} - P_{pumps}$$



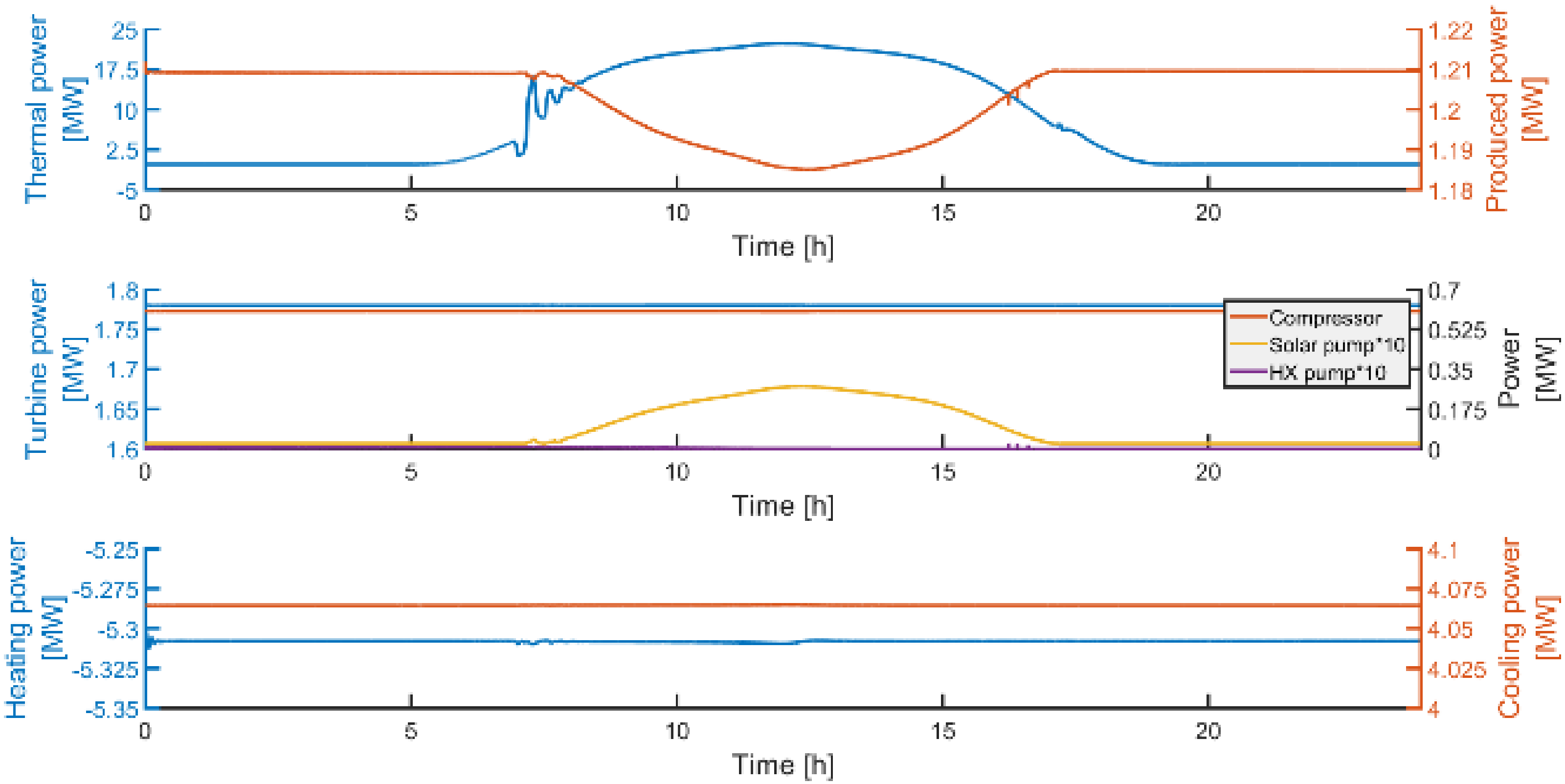
Results: Concept 1 thermal performance

- Production figures and compressor power consumption follow the DNI trend

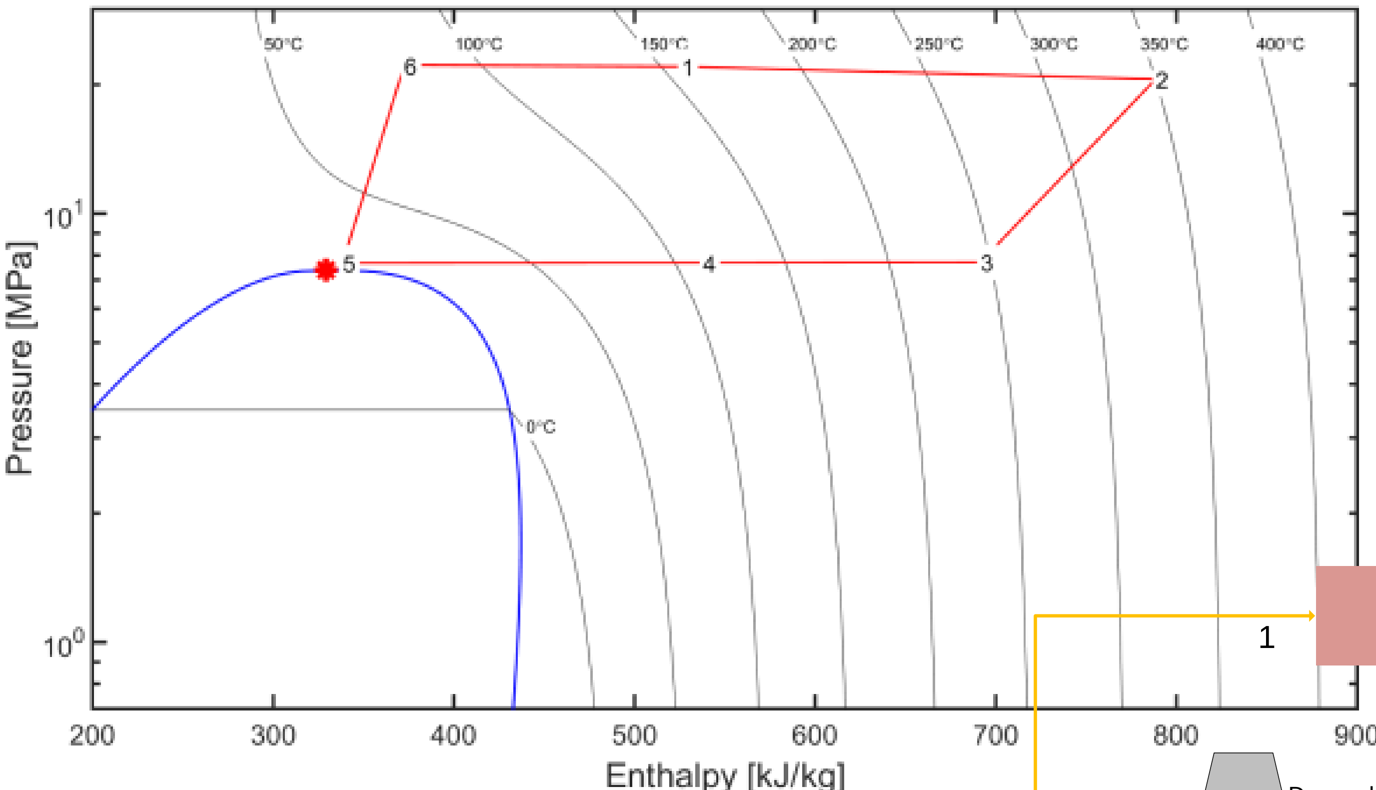


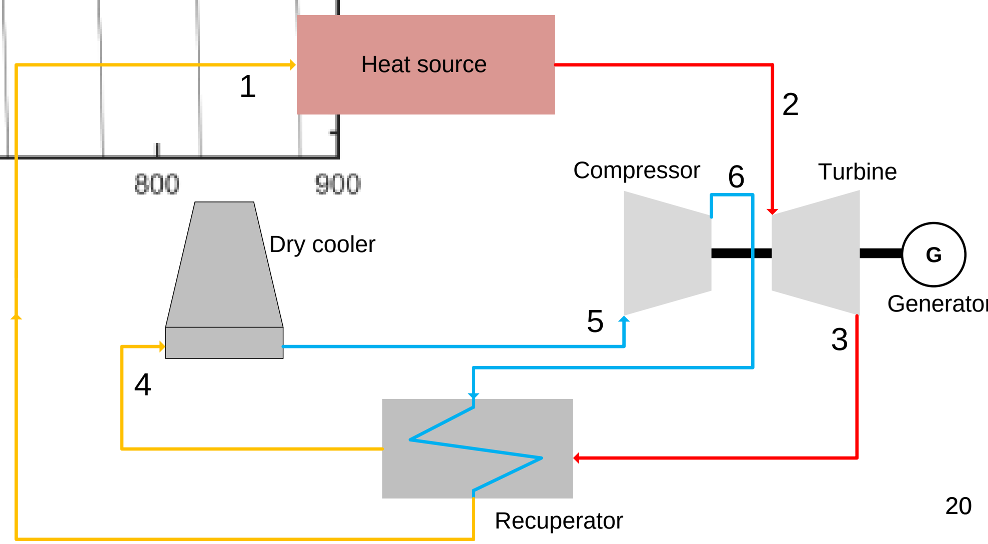
Results: Concept 2 thermal performance

- Constant round the clock turbine power achieved through storage operation
- Produced power not constant due to load-following solar field and HE pumps



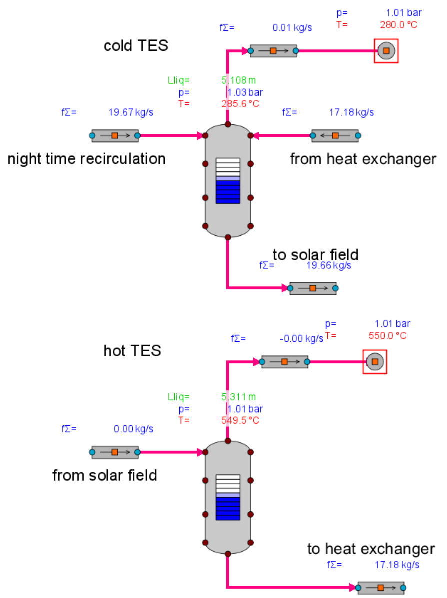
Results: Process state points of both concepts



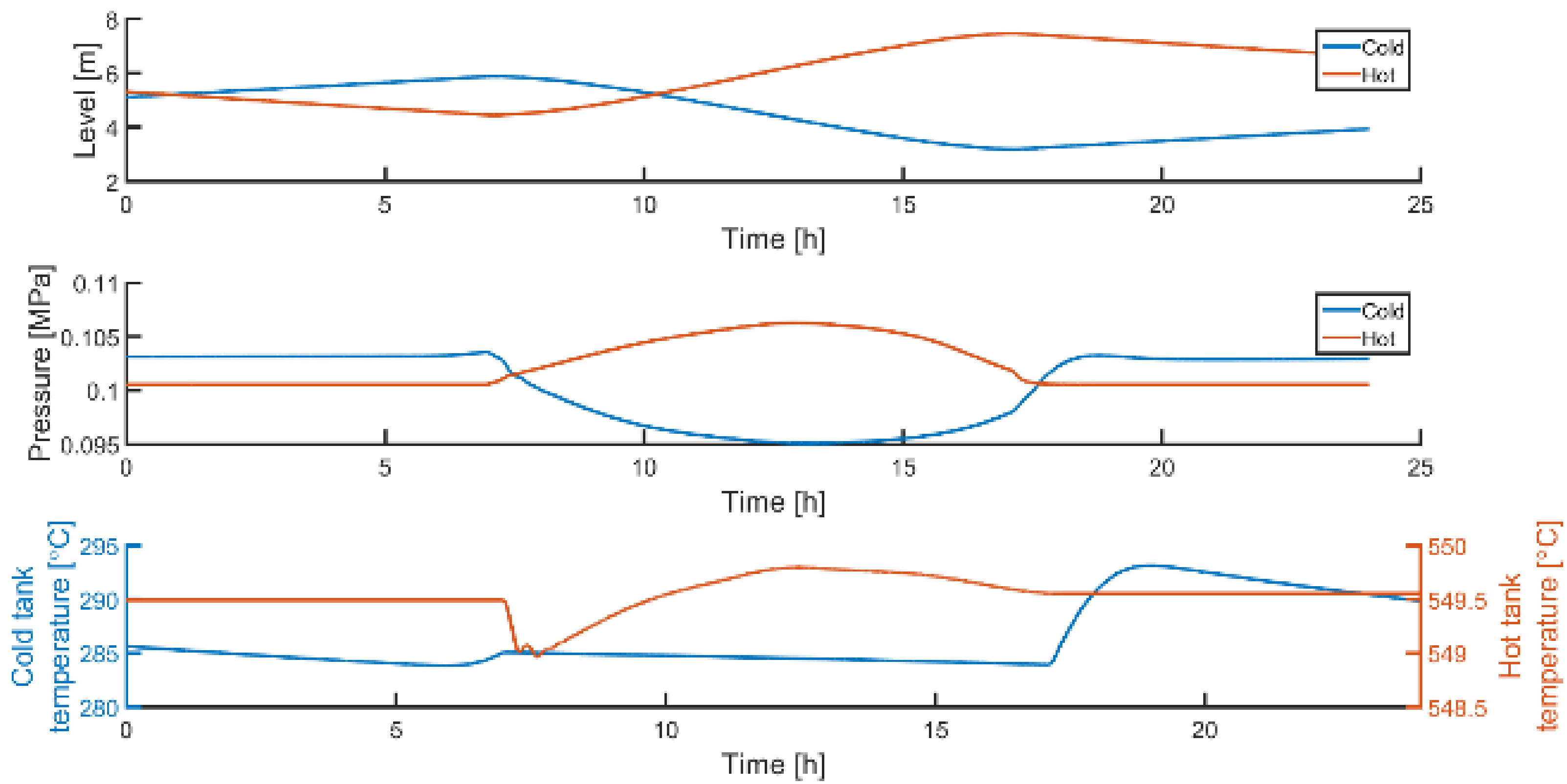


Results: Storage operations in Concept 2

- In the evening, molten salt accumulated in the hot TES; in the morning, in the cold TES
- The switch between normal operation/night time modes causes minor changes in storage tank temperatures



Hot TES Tsp: 550 ºC
Cold TES Tsp: 280 ºC



Results: Concept comparison

- Over 12-fold total solar thermal production is needed by Concept 2 with respect to Concept 1 on June 21st
  - In this case, constant power production → Load following power production
- Produced power by Concept 2 around 3-fold higher with respect to Concept 1

→ Solar multiple 4.2 rather high under design conditions

- During off-design conditions high solar multiple needed
- Higher temperature levels needed to increase the efficiency

	Concept 1	Concept 2
Produced power [MWh]	9.6	28.9
Thermal energy [MWh]	14.8	186.4
Solar multiple	1	4.2
Thermal efficiency at design point	0.235	0.223

$$\eta_{therm} = \frac{\text{produced power}}{\text{thermal input}}$$

Conclusions

- Overall comparison of the daily behavior of two concepts was given
  - Also details, such as control approaches, start-up and shut down sequences, and component dimensioning, were studied
  - Both concepts looked technically feasible according to detailed dynamic analysis; dispatchability vs. variable production
- To execute a complete comparison between the concepts, yearly performance and economic analyses are needed
  - Local conditions important (need for dispatchability, weather conditions)
  - Detailed behavior under different off-design conditions must be paid attention → An important issue especially in Concept 1
- Future work: Compression work verification, control system development, going into more details in component design
- Apros allows to test and compare also more complex sCO_2 Brayton cycles and analyze the room for efficiency improvements

Thank you for your attention!

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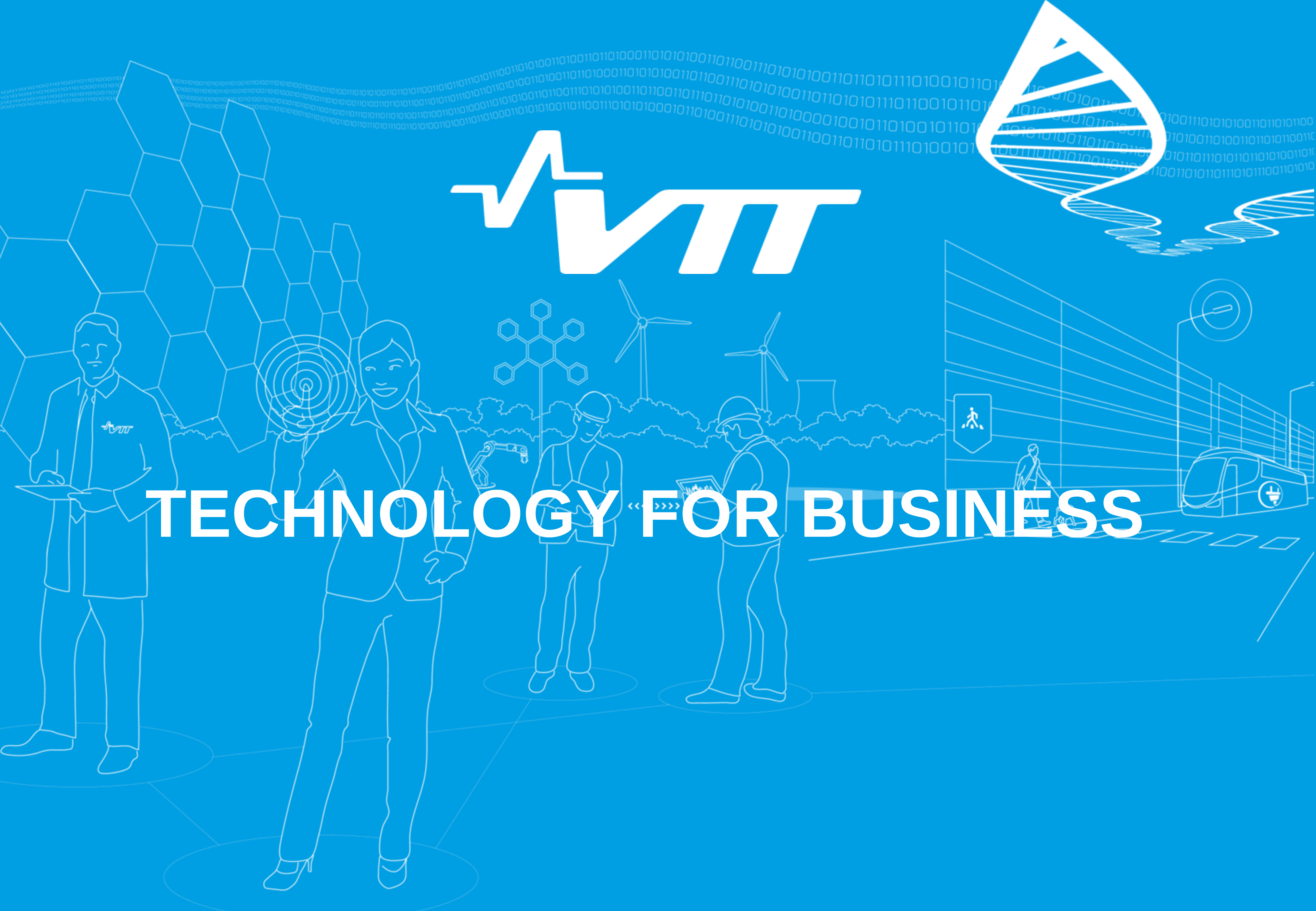
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