# Integrated Market-fit and Affordable Grid-scale Energy Storage (IMAGES)

Annual Progress Meeting


Jihong Wang, Jacek Wojcik, Xing Luo. Wei He, Chris Krupke

Warwick (Engineering)


21 Nov 2016

# Outline of the presentation

1. Overview
2. Report of the project progress
    - 2.1 CAES-TES dynamic modelling and simulation
    - 2.2 Hybrid wind turbine
    - 2.3 Further investigation on HTTS integration
3. Work plan

# 1. Overview

## WPs that Warwick leads

**WP1.2 Task 2.** Update the overview in CAES and other ES technology development.

**WP1.4 Task 2.** CAES specific opportunities in the UK

**WP2.2 Task 1.** Improving the round trip efficiency of large scale adiabatic CAES systems

**WP2.2 Task 2.** Hybrid integration of wind power generation with CAES

**WP2.2 Task 3.** Software tool development for complete CAES processes

**WP2.2 Task 4.** Supporting the whole system techno-economic study

## WPs that Warwick supports

**WP2.3 Integrated ES:** Warwick team has developed a number of thermal storage model and simulation library blocks which can be used by WP2.3.

**WPs1.5/2.4 HTTS:** Using the unique simulation facility at Warwick, Warwick team has conducted the feasibility study of HTTS integration into power plant cycle for both subcritical oil-fired power plant model and supercritical coal-fired power plant model.

# 1. Overview

## Publications/presentations:

- Krupke C, Wang J, Clarke J, Luo X. (2016). Modelling and experimental study of a wind turbine system in hybrid connection with Compressed Air Energy Storage, accepted by *IEEE Trans on Energy Conversion*.
- Luo X., Wang J., Krupke C., Xu H. (2016). "Feasibility study on recovering low pressure exhaust energy from a vehicle engine system via the modified scroll expander technology", Energies, 9, no. 4: 231.
- He W., Wang J. (2016). Dynamic modelling of discharge behaviour of a low temperature adiabatic compressed air energy storage system, Offshore Energy and Storage Symposium and Industry Connector Event (OSES), Malta.
- J. Wang, S. Garvey, P. Eames, D. Evans, M. Waterson, M. Thomson, J. Busby, M. Giulietti, R. MacKay, A. Milodowski, J Wojcik, J Barton, X Luo, L. Flatley, A Pimm, L. Field, P. Romanos, D Parkes, B. Kantharaj, C Krupke, E. Webborn, A.D. Hutchinson, F Liu, M Dooner, B Chen, (2016) A REPORT ON THE PROJECT OF "INTEGRATED MARKET-FIT AND AFFORDABLE GRID-SCALE ENERGY STORAGE (IMAGES)", Offshore Energy and Storage Symposium and Industry Connector Event (OSES), Malta.
- He W., Wang J. (2016). Dynamic modelling of adiabatic compressed air energy storage using packed bed thermal energy storage, UK thermal energy storage (UKTES), London.
- Wang J., Luo X., Dooner M., Krupke C. (2016), a book chapter "Compressed Air Energy Storage" accepted by the World Scientific Series on Current Energy Issues, Volume 4.
- Luo X., Wang J., Krupke C. (2016). "Modelling Study, Optimization and Efficiency Analysis of Large-scale Adiabatic Compressed Air Energy Storage Systems with Low-temperature Temperature Thermal Storage", *Applied Energy*, vol. 162, pp. 589-600.
- Li Y., Miao S., Luo X., Wang J., "Optimization Model for the Power System Scheduling with Wind Generation and Compressed Air Energy Storage Combination", The 22nd IEEE International Conference on Automation and Computing (ICAC'16) Conference, 7-8 September 2016, University of Essex, Colchester, UK.
- Li Y., Miao S., Luo X., Wang J., "Optimization Scheduling Model Based on Source-Load-Energy Storage Coordination in Power Systems", The 22nd IEEE International Conference on Automation and Computing (ICAC'16) Conference, 7-8 September 2016, University of Essex, Colchester, UK.
- Wojcik J, Wang J, Romanos P, Eames P: Initial Study on Power Plant Operational Flexibility Improvement through High Temperature Thermal Storage (HTTS) Integration. UKES2015 Conference in Birmingham, 26th November 2015.
- Luo X., Wang J.(2015). "Mathematical modelling and efficiency improvement study of adiabatic compressed air energy storage systems", UK Energy Storage conference (UKES2015), Birmingham, 26th November 2015.

# 2. Report of the project progress

## WPs that Warwick leads

**WP1.2 Task 2.** Update the overview in CAES and other ES technology development.

Wang J., Luo X., Dooner M., Krupke C., "Compressed Air Energy Storage", a chapter in the World Scientific Series on Current Energy Issues, Volume 4, to be published.

Contributions to White Paper - UK research needs in grid scale energy storage technologies and EERA-EASE Roadmap Technology Section – CAES.

Venkataramani, G, Parankusam, P, Ramalingam, V, Wang, J, A review on compressed air energy storage - a pathway for smart grid and polygeneration, *Renewable and Sustainable Energy Reviews*, 62, pp. 895-907, 2016.

# 2. Report of the project progress

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Jihong Wang

## Overview of current development in electrical energy storage technologies and the application potential in power system operation

| | |
|---|---|
| Authors | Xing Luo, Jihong Wang, Mark Dooner, Jonathan Clarke |
| Publication date | 2015/1/1 |
| Journal | Applied Energy |
| Volume | 137 |
| Pages | 511-536 |
| Publisher | Elsevier |
| Description | Abstract Electrical power generation is changing dramatically across the world because of the need to reduce greenhouse gas emissions and to introduce mixed energy sources. The power network faces great challenges in transmission and distribution to meet demand with unpredictable daily and seasonal variations. Electrical Energy Storage (EES) is recognized as underpinning technologies to have great potential in meeting these challenges, whereby energy is stored in a certain state, according to the technology used, and is converted to ... |
| Total citations | Cited by 215 |


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Overview of current development in electrical energy storage technologies and the application potential in power system operation

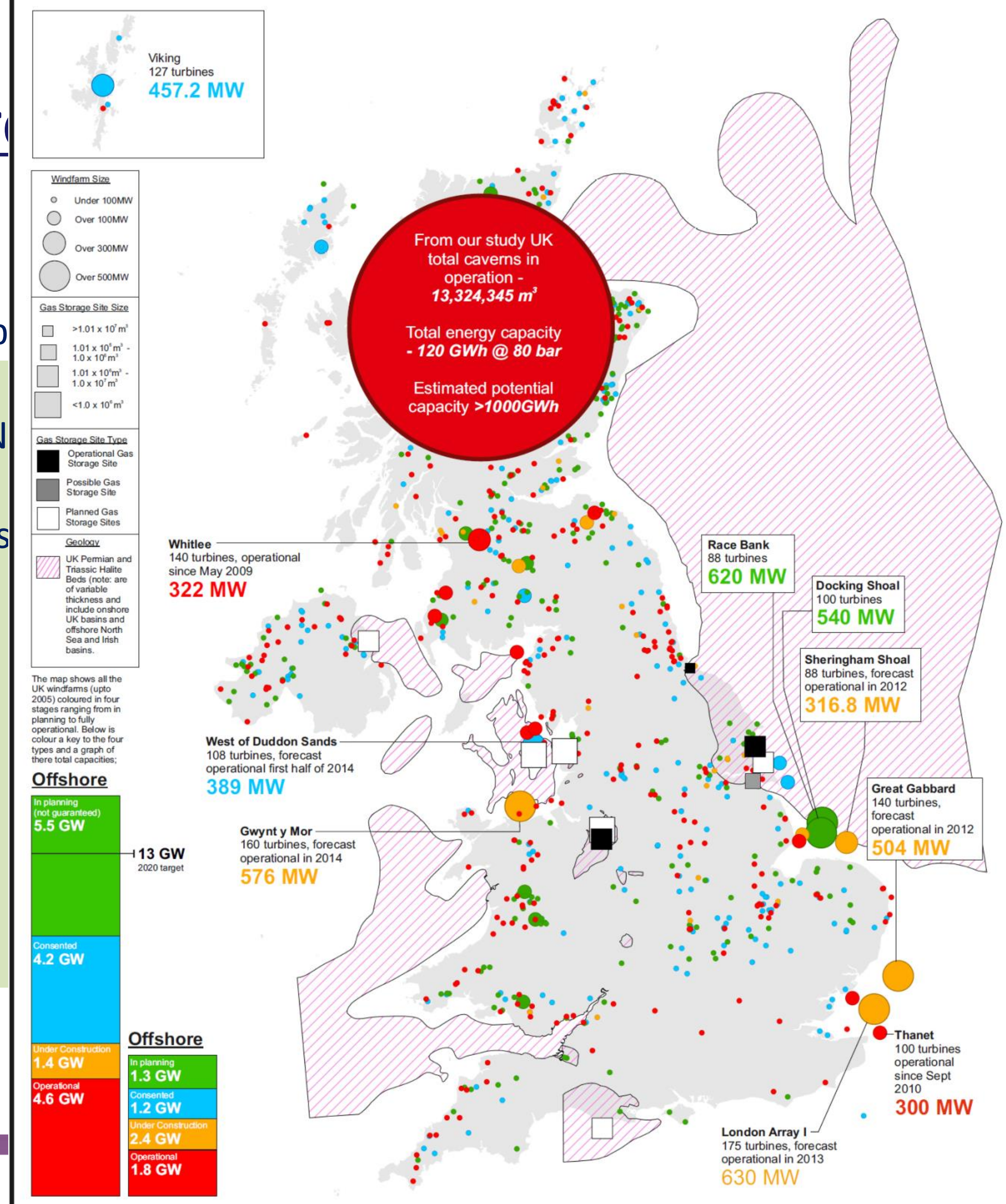
Xing Luo | Jihong Wang | ...

# 2. Report of the pr

## WPs that Warwick leads

**WP1.4 Task 2.** CAES specific opp

Working closely with BGS and N
accurate calculation/estimation
of dynamic process of compress



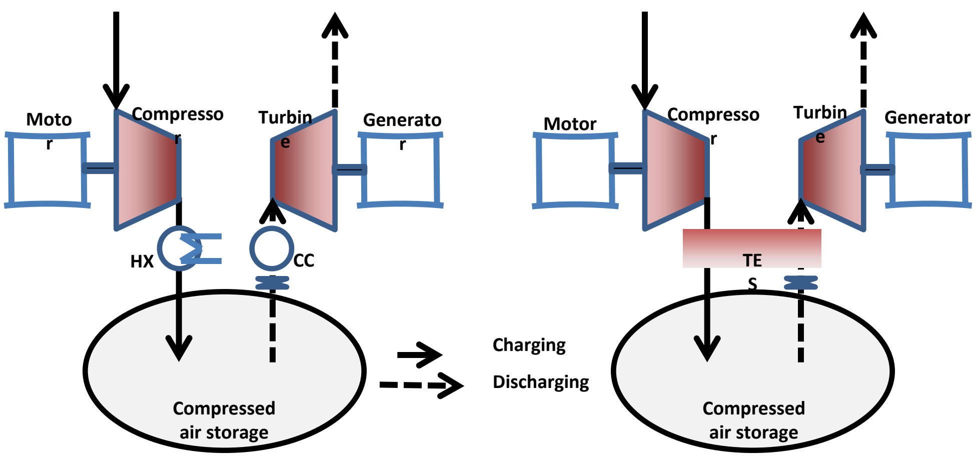
# Exergy storage capacity calculation of cavern-based large-scale CAES system

## Large-scale CAES system

- Diabatic CAES
- Adiabatic CAES

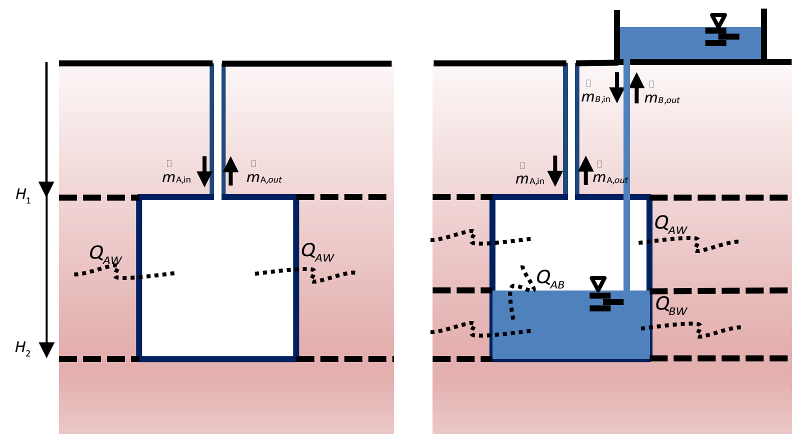
## Cavern operational scenarios

- Uncompensated isochoric cavern
- Compensated isobaric cavern




Diabatic CAES

Adiabatic CAES

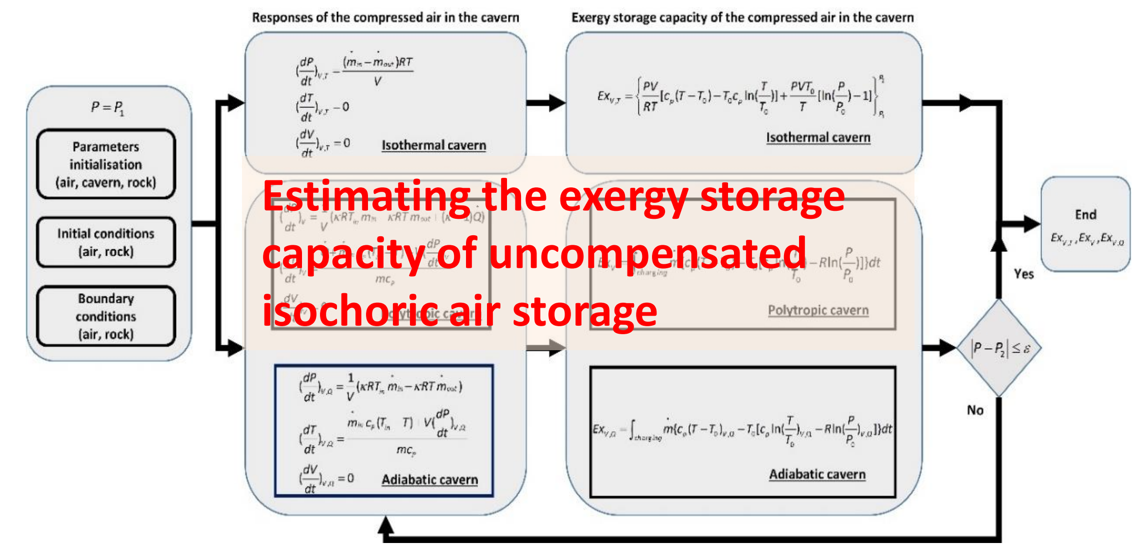



Uncompensated isochoric cavern

Compensated isobaric cavern

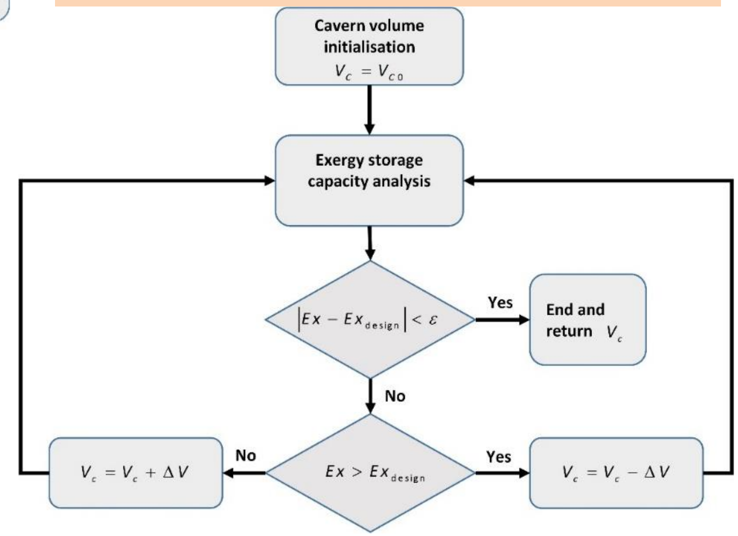
# 2. Report of the project progress

Exergy storage capacity of uncompensated isochoric air storage

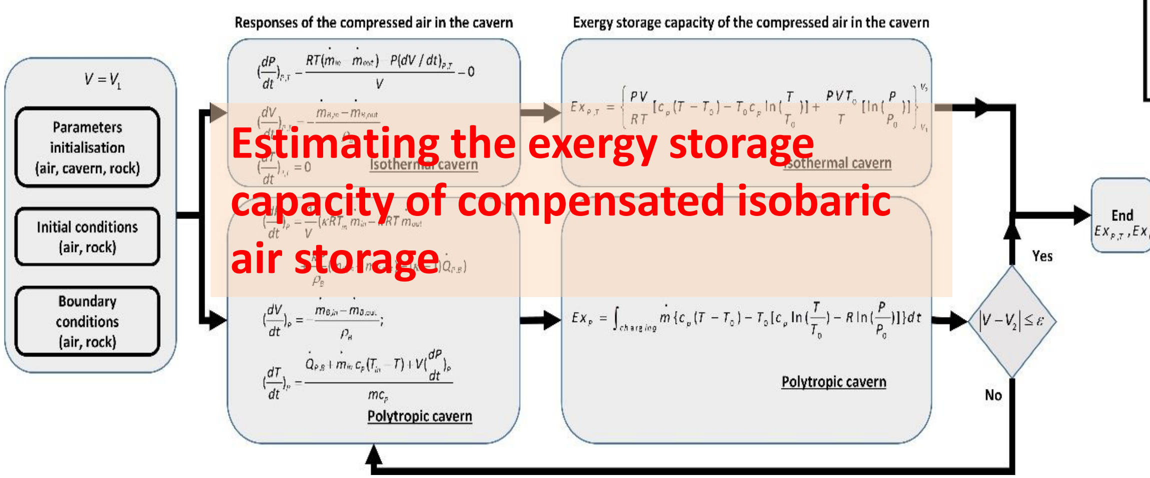



**Estimating the exergy storage capacity of uncompensated isochoric air storage**

**Cavern volume calculation subject to the CAES system specifications**




Exergy storage capacity of compensated isobaric air storage

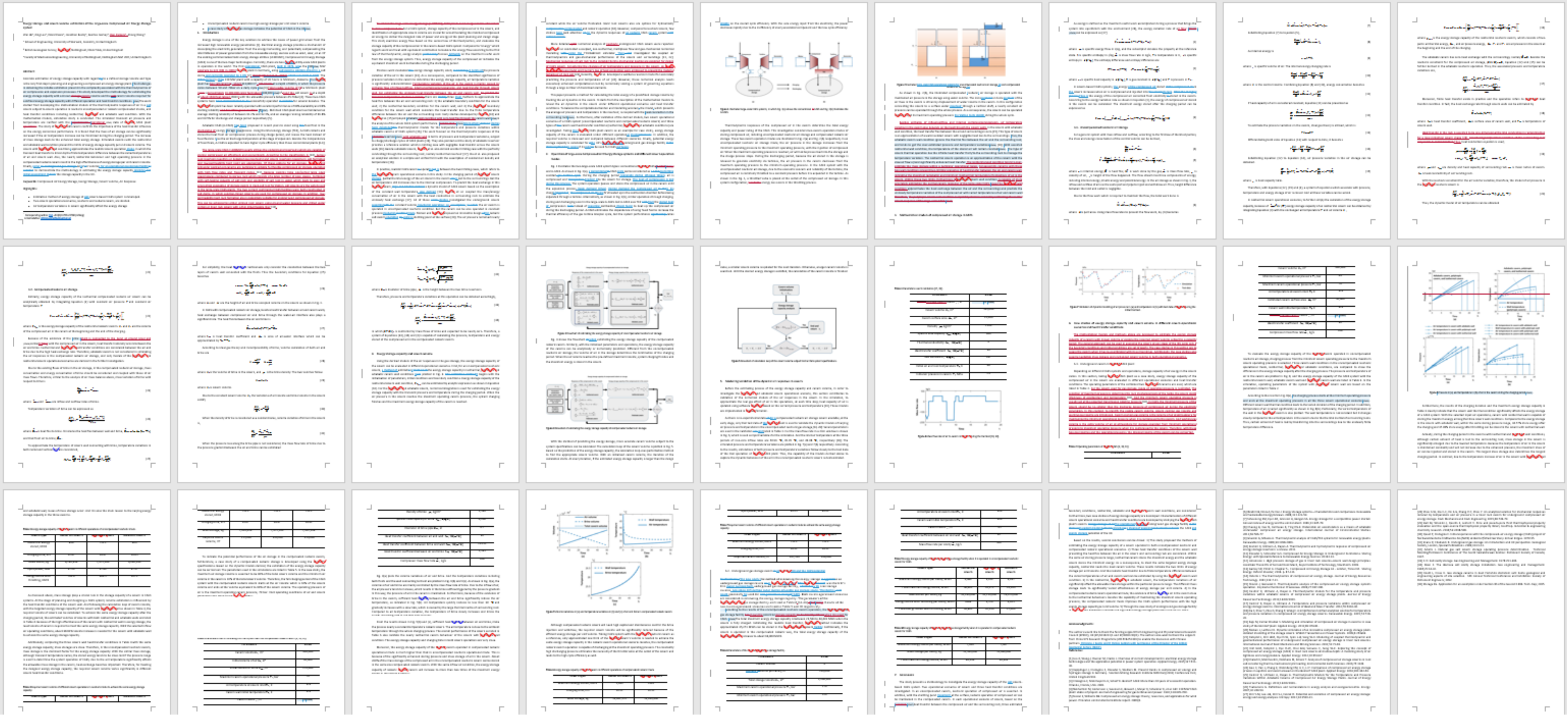



**Estimating the exergy storage capacity of compensated isobaric air storage**

# 2. Report of the project progress

## WPs that Warwick leads

**WP1.4 Task 2.** CAES specific opportunities in the UK



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# 2. Report of the project progress

## WPs that Warwick leads

**WP2.2 Task 1.** Improving the round trip efficiency of large scale adiabatic CAES systems ✔ Completed
**WP2.2 Task 2.** Hybrid integration of wind power generation with CAES ✔ Completed
**WP2.2 Task 3.** Software tool development for complete CAES processes ✔ On-schedule
**WP2.2 Task 4.** Supporting the whole system techno-economic study ✔ On-going

## WPs that Warwick supports

**WP2.3 Integrated ES:** Warwick team has developed a number of thermal storage model and simulation library blocks which can be used by WP2.3. ✔ On-schedule

**WPs1.5/2.4 HTTS:** Using the unique simulation facility at Warwick, Warwick team has conducted the feasibility study of HTTS integration into power plant cycle for both subcritical oil-fired power plant model and supercritical coal-fired power plant model. ✔ On-schedule

# 2.1 CAES-TES dynamic modelling & software

- CAES is a complex system with integration of multi-physical components with different time scales.
- Complicated interactions between system component dynamics
- Interconnection with grid operations
- Individual component/device optimal design does not lead to system optimal design
- Variable load patterns and generation output requirement require dynamic optimal control strategy
- Efficiency depends on the optimal integration and cooperation of system components.

# 2.1 CAES-TES dynamic modelling & software

Overview of potential software for CAES-TES modelling

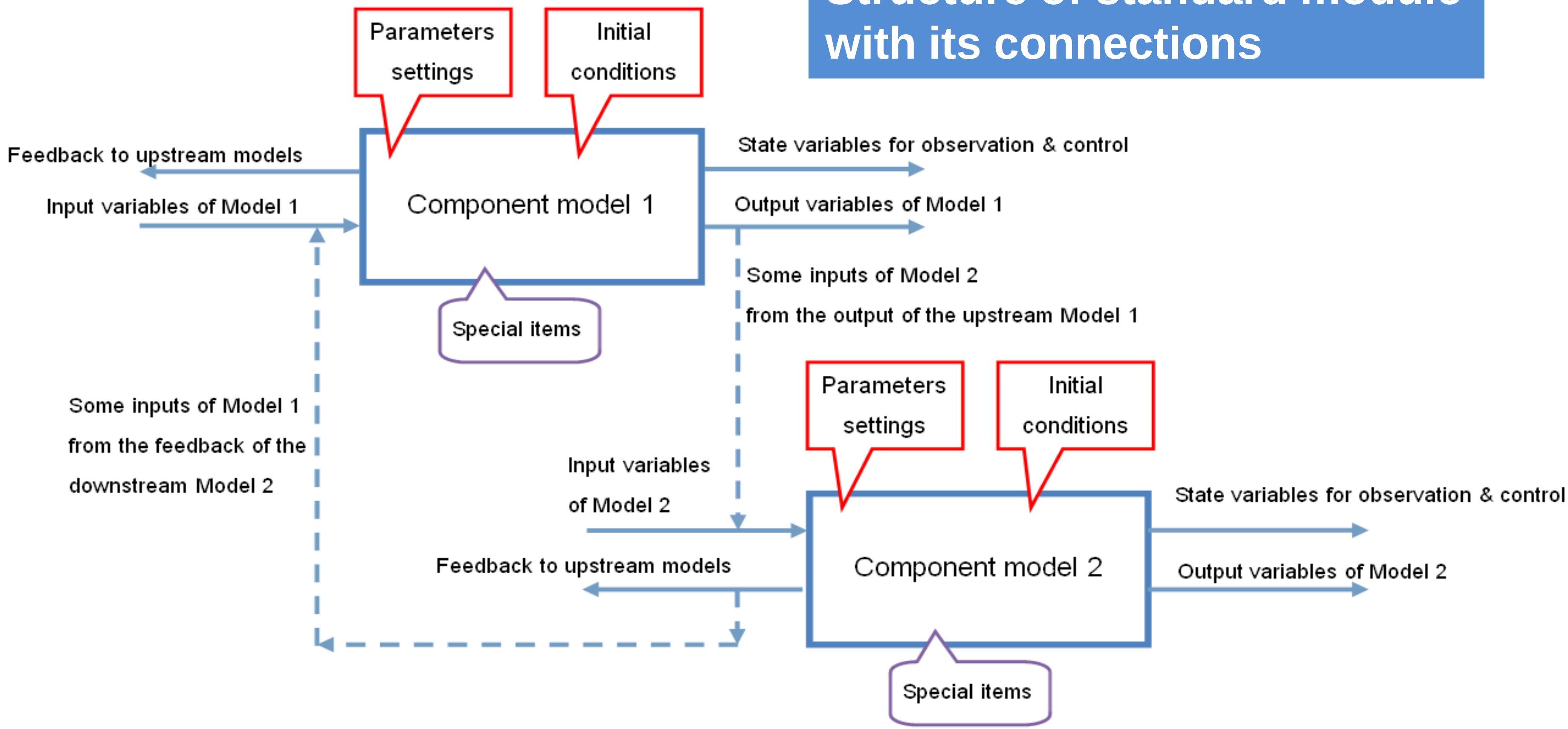
None of them can service the full purpose

A comparison of software with EES modelling capabilities

| Software & toolbox | Homer | Energy Plus | Power world | Energy 2020 | Thermolib | Aspen Plus | Protrax |
|---|---|---|---|---|---|---|---|
| Economic/ technical study | Both | Both | Both | Mainly on economics | Technical analysis | Both | Technical analysis |
| EES pertinence | Yes | Yes | Yes | Yes | No | No | No |
| Types of EES technologies | flywheels, battery, hydrogen | Thermal | Battery | Pumped hydro, fuel cell | N/A | N/A | N/A |
| Round-trip efficiency | Yes | No | No | Yes | N/A | N/A | N/A |
| Power/energy scale | Small-scale | Small/mid. scales | Multi-scale | Multi-scale | Multi-scale | Multi-scale | Multi-scale |
| Steady/dynamic state analysis | Steady | Steady | Both | Possible | Steady | Both | Possible |
| Multi-physics analysis | No | No | No | No | No | No | No |
| Real-time simulation | No | No | No | No | No | Yes | Yes |
| Dynamic control | No | No | Possible | No | No | Yes | Yes |
| User defined function | No | No | Possible | No | Yes | Yes | Yes |
| Co-simulation | No | No | No | No | Matlab/ Simulink | Fortran | Fortran |

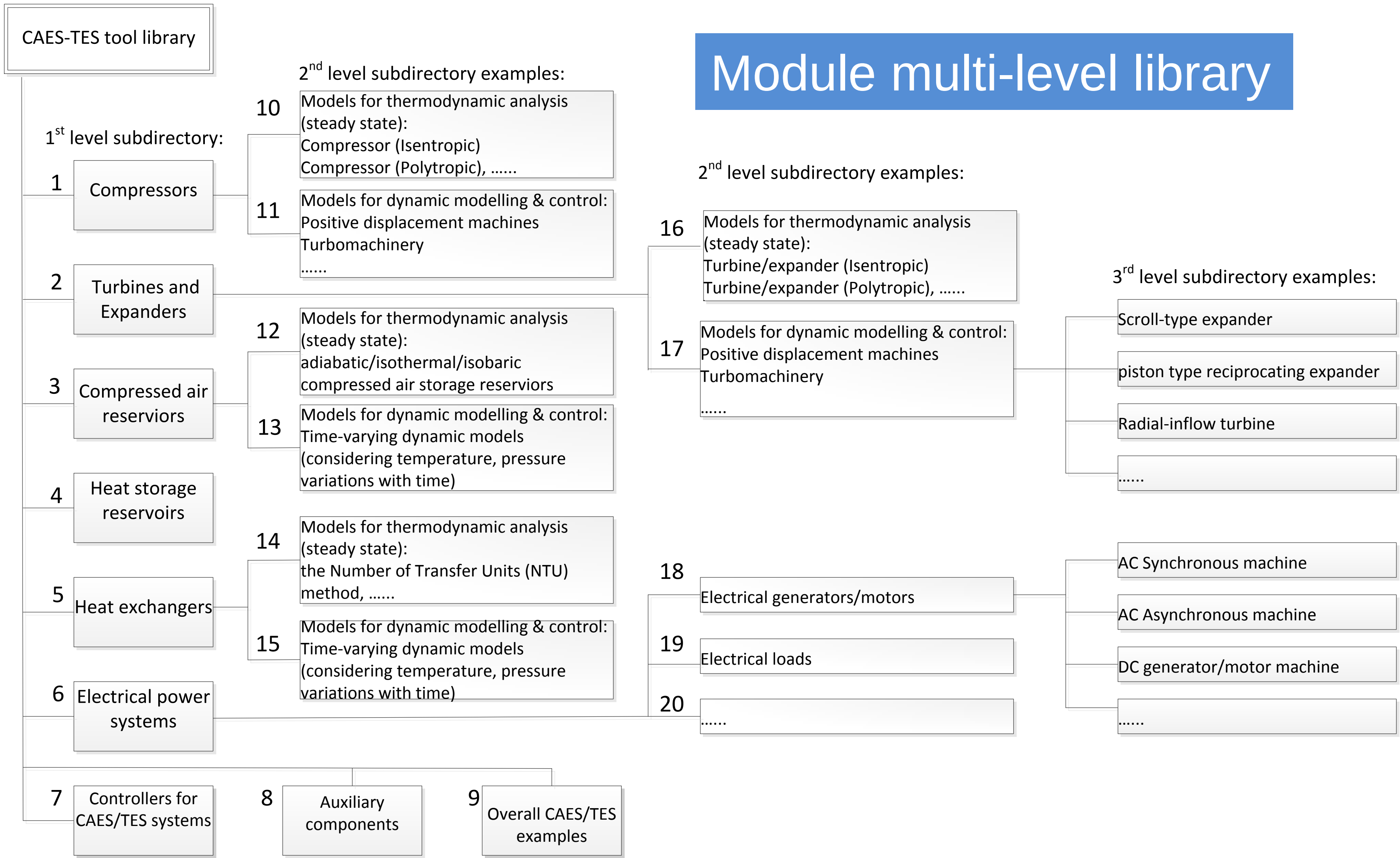
# 2.1 CAES-TES dynamic modelling & software

**Structure of standard module with its connections**

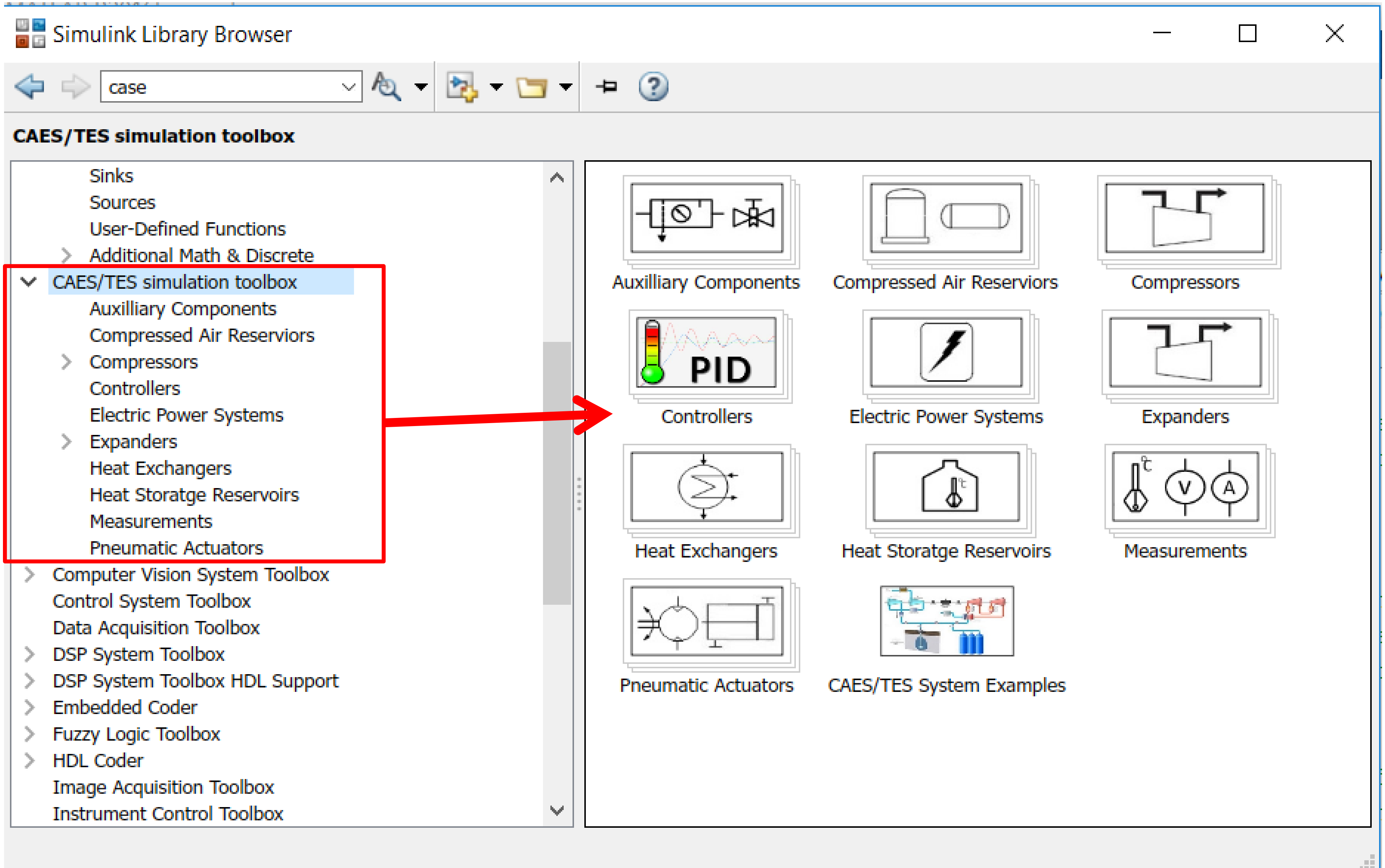


# 2.1 CAES-TES dynamic modelling & software

## Module multi-level library

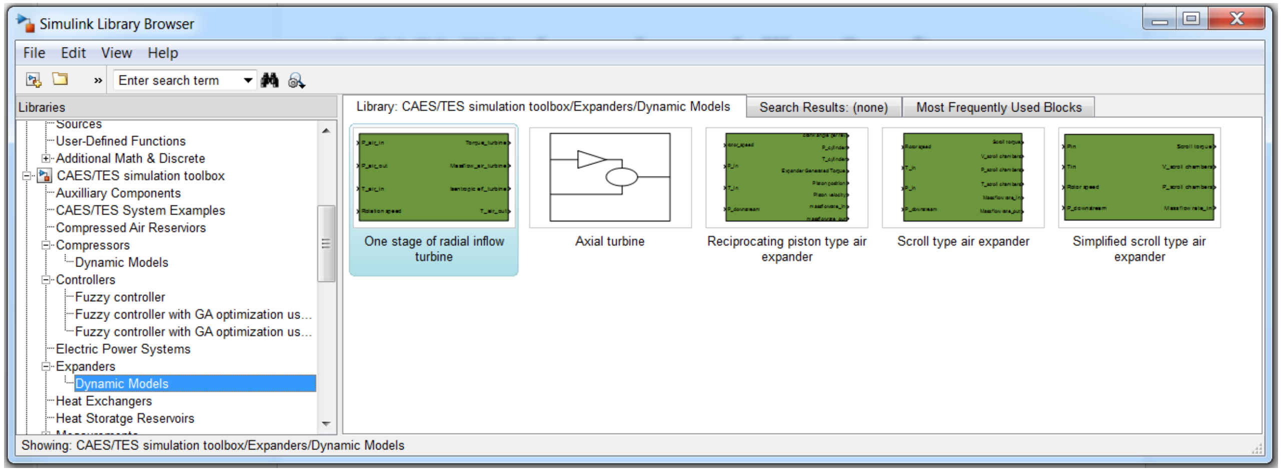


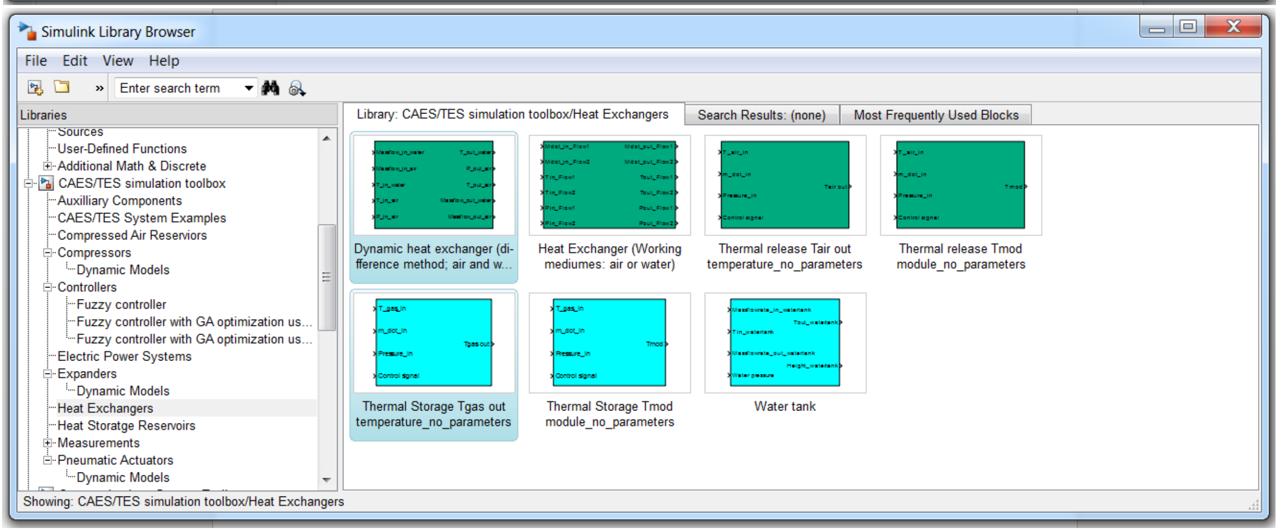
# 2.1 CAES-TES dynamic modelling & software



# 2.1 CAES-TES dynamic modelling & software

- Examples of dynamic expander and TES sub libraries:



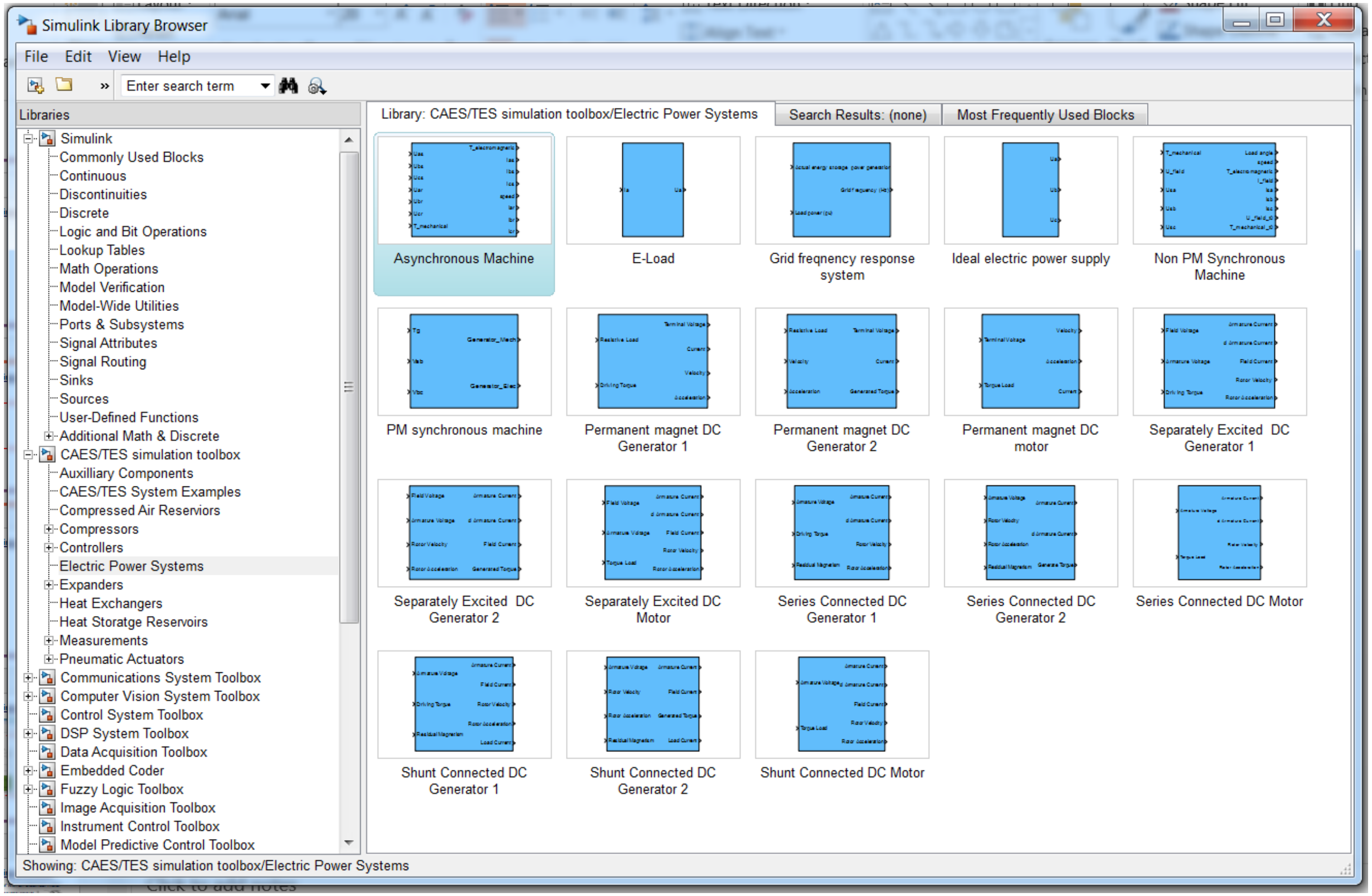




- Radial inflow turbine
- Axial turbine (under development)
- Piston expander
- Scroll expander

- NTU Heat exchanger
- Dynamic heat exchanger
- Hot/cold water storage tank
- Packed bed thermal energy storage

# 2.1 CAES-TES dynamic modelling & software

- An example of electrical power system sub library:




- AC generators
- AC motors (synchronous, asynchronous machines)
- DC generators
- DC motors
- Electrical loads
- Grid model (under development)
- Frequency converter

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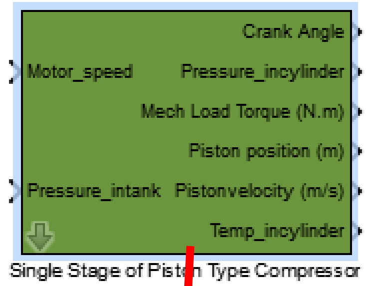
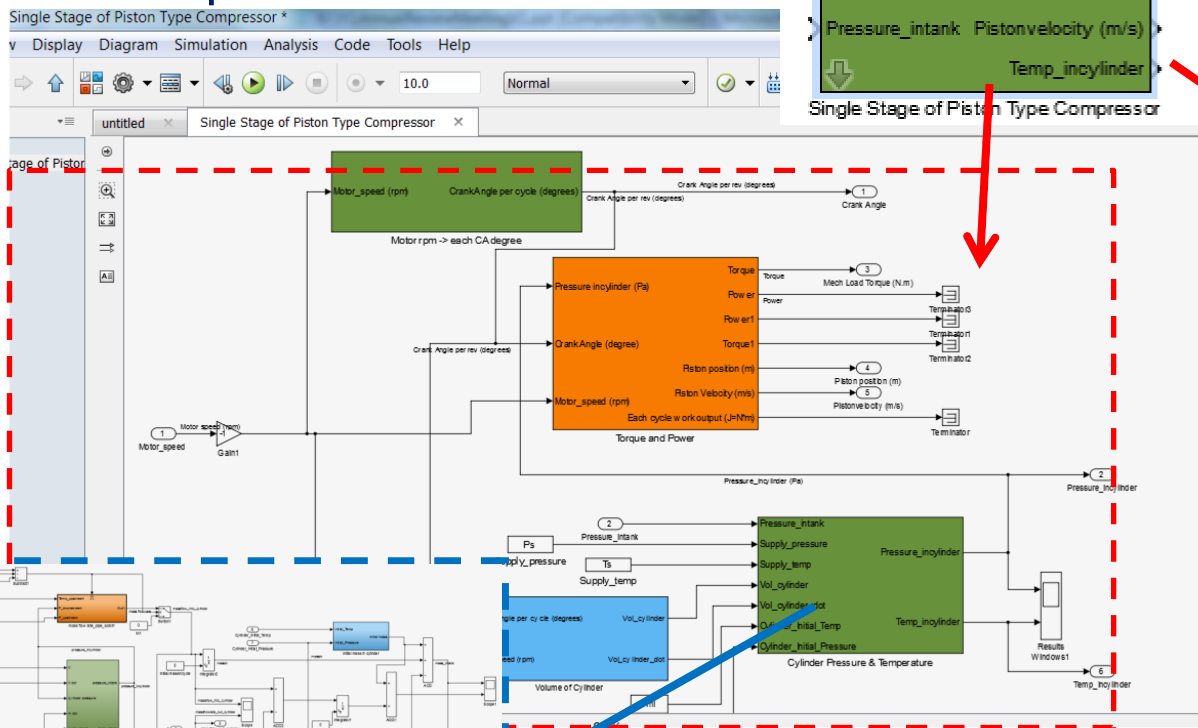
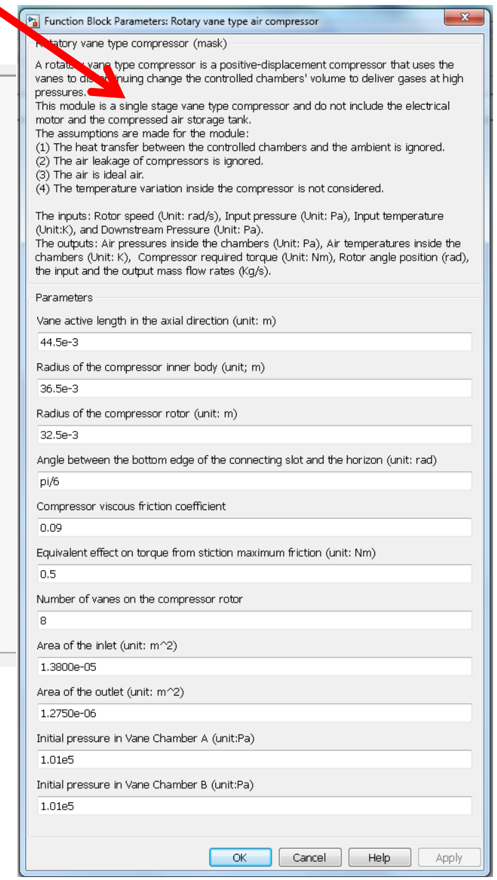
# 2.1 CAES-TES dynamic modelling & software

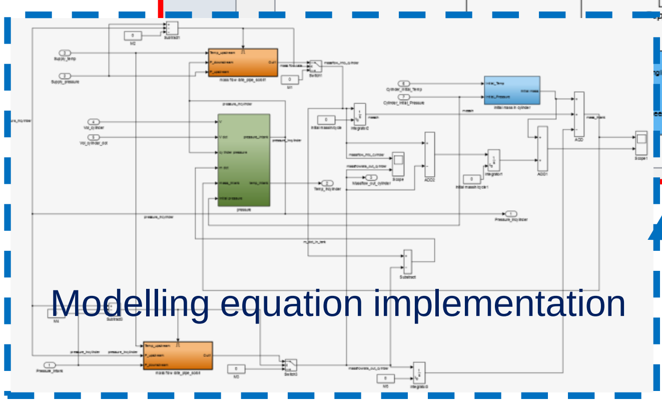
- An example: piston compressor code and panel




Module mask panel settings



Modelling equation implementation

$$\dot{P} = \frac{[\dot{X}_{air}]V\hat{h} + \dot{V}\hat{h}[X_{air}] + n_{mol} C_{p,air}(T)\dot{T} - \dot{m}_{in} h_{in} + \dot{m}_{out} h_{out}}{V}$$

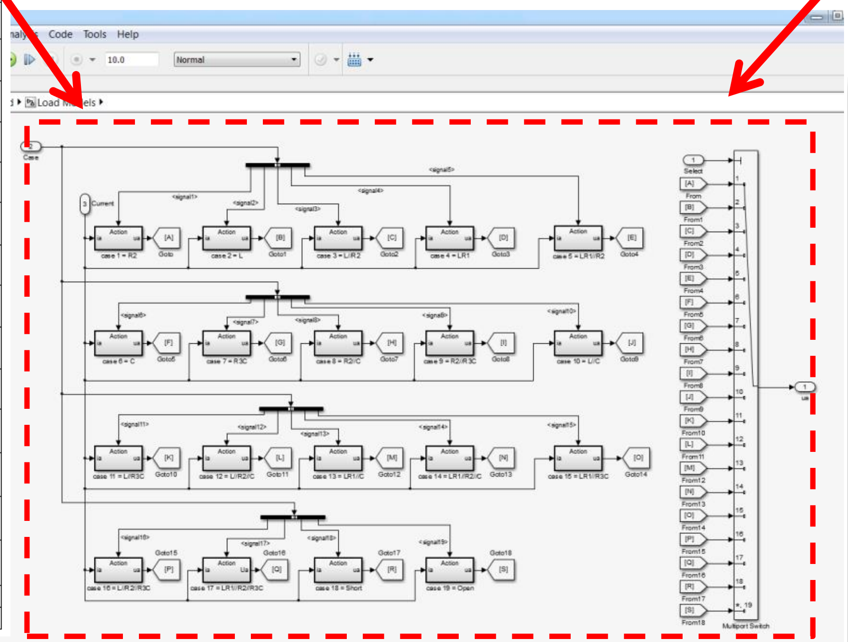
$$\dot{m}_{orifice} = C_d C_0 A_{ori} P_u f\left(\frac{P_d}{P_u}\right) / \sqrt{T_u}$$

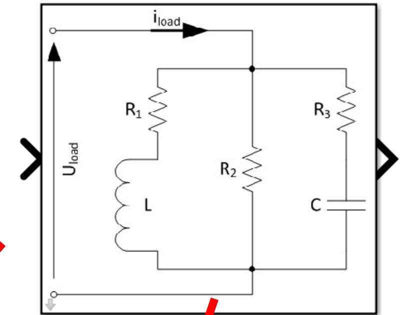
# 2.1 CAES-TES dynamic modelling & software

- An example: basic electrical load code and panel:

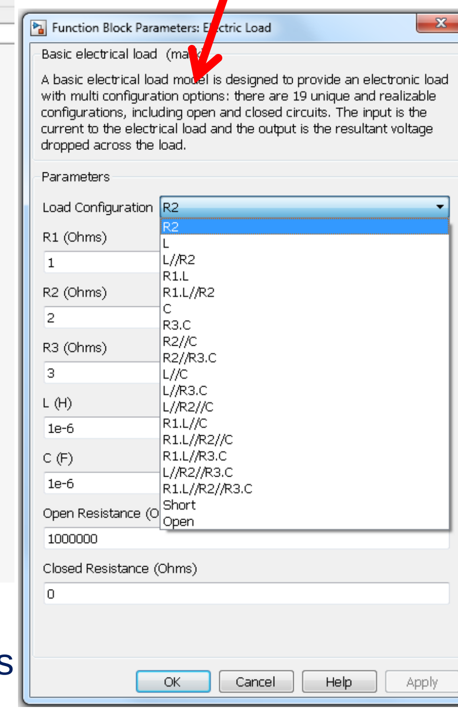
| State | Configuration | Equation |
|---|---|---|
| 1 | $R_2$ | $\frac{U_a}{I_a}=R_2$ |
| 2 | L | $U_a=L\frac{dI_a}{dt}$ |
| 3 | $L//R_2$ | $\frac{U_a}{I_a}=\frac{Ls}{(L/R_2)s+1}$ |
| 4 | $LR_1$ | $U_a=L\frac{dI_a}{dt}+R_2I_a$ |
| 5 | $LR_1//R_2$ | $\frac{U_a}{I_a}=\frac{Ls+R_1}{(L/R_2)s+((R_1/R_2)+1)}$ |
| 6 | C | $\frac{U_a}{I_a}=\frac{1}{Cs}$ |
| 7 | $R_3C$ | $\frac{U_a}{I_a}=\frac{CR_3s+1}{Cs}$ |
| 8 | $R_2//C$ | $\frac{U_a}{I_a}=\frac{R_2}{CR_2s+1}$ |
| 9 | $R_2//R_3C$ | $\frac{U_a}{I_a}=\frac{CR_3s+1}{C(1+(R_3/R_2))s+1/R_2}$ |
| 10 | L//C | $\frac{U_a}{I_a}=\frac{Ls}{LCs^2+1}$ |
| 11 | $L//R_3C$ | $\frac{U_a}{I_a}=\frac{R_3LCs^2+Ls}{LCs^2+R_3Cs+1}$ |
| 12 | $L//R_2//C$ | $\frac{U_a}{I_a}=\frac{Ls}{LCs^2+(L/R_2)s+1}$ |
| 13 | $LR_1//C$ | $\frac{U_a}{I_a}=\frac{Ls+R_1}{LCs^2+R_1Cs+1}$ |
| 14 | $LR_1//R_2//C$ | $\frac{U_a}{I_a}=\frac{R_2s+(R_1R_2)}{R_2LCs^2+(R_1R_2C+L)s+(R_1+R_2)}$ |
| 15 | $LR_1//R_3C$ | $\frac{U_a}{I_a}=\frac{(R_1R_3C+R_1L+L)s+R_1}{-LCs^2+C(R_1+R_3)s+1}$ |
| 16 | $L//R_2/R_3C$ | $\frac{U_a}{I_a}=LR_2\frac{R_3Cs^2+s}{LC(R_3-R_2)s^2+(R_2R_3C+L)s+R_2}$ |
| 17 | $LR_1//R_2//R_3C$ | $\frac{U_a}{I_a}=R_2\frac{R_3LCs^2+(R_1R_3C+L)s+R_1}{LC(R_2+R_3)s^2+(C(R_1R_2+R_2R_3+R_1R_3)+L)s+(R_1+R_2)}$ |
| 18 | Short | $U_a=R_cI_a$ |
| 19 | Open | $U_a=R_oI_a$ |

Modelling equation implementation






Electric Load




Module mask panel settings

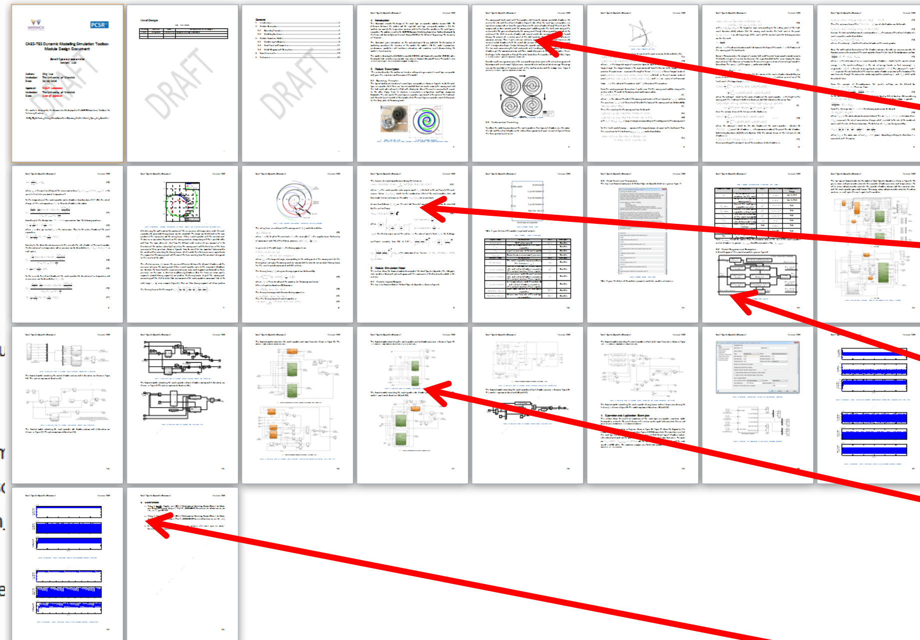
# 2. CAES-TES dynamic modelling → software

| Groups | Refining the modules developed last year | New modules |
|---|---|---|
| Compressors & Expanders | Vane expanders/compressors, Radial inflow turbines, piston expanders | Axial compressors |
| TES (Heat exchanger & Heat storage) | Air-water HEX steady and dynamic state models, Heat/cold storage (water) | Phase Change Materials (PCM) |
| Electrical machines, load and grid | Four different types of DC machines (shunt/ series connected, separately excited, PM), AC machines (synchronous, asynchronous, PMSM), Electrical load, controlled electrical power source | Non-PM synchronous machine, electrical machine model simplification |
| Compressed air storage | Salt cavern, adiabatic tank with documentations | Isothermal storage |
| Pneumatic accessories | Pressure regulator, non-return flow valve | |
| System controllers | PID controller, two types of bang-bang controller | Advanced controllers |
| CAES-TES subsystem / system relevant examples | Four CAES-TES subsystem/system demos: CAES whole system, CAES-TES charging, 1.2 MW CAES-TES discharging, CAES charging with control | Packed-bed TES |
| Module development documentations | This is a new task to the last year: each developed module added a corresponding documentation. | Update with the developing modules |

# 2.1 CAES-TES dynamic modelling & software

- Software module development documentation

Name
- CAES_Tool_Update
- CAES_Tool_Update1March2016
- CAES_Tool_Update02Nov2016
- CAES_Tool_Update12Feb2016
- CAES_Tool_Update19Sept2016
- Structure
- 130304_PMDC_Generator_Design_Doc
- 160105_DC_Motor_Module_Example_Older_Version
- 160108_Module_template_draft
- 160210_Simplified_scroll air expander_software_docu
- 160226_Water-Water_Shell_Tube_HEX_Module
- 160304_PMDC_Motor_Design_doc
- 160309_HeatExchanger_SteadyState_software_docum
- 160315_Reciprocating_piston_type_air_compressor_sc
- 160323_Scroll air expander_software_documentation_
- 160324_Asynchronous motor_v1.1
- 160331_Vane_type_air_compressor_software_docume
- 160404_SEDC_Motor_Design_doc
- 160404_ShCDC_Motor_Design_doc
- 160405_SEDC_Generator_Design_doc
- 160405_ShCDC_Generator_Design_doc
- 160406_SCDC_Generator_Design_doc
- 160406_SCDC_Motor_Design_doc
- 160408_Asynchronous motor_v1.1_final_version
- 160504_Simplified_scroll air expander_software_documentation_final
- 160511_ELoad
- 270315_Adiabatic_air_tank_software_documentation_V1.1
- 310315_Salt_ dome_cavern_documentation_V1.1



Background

Modelling equations

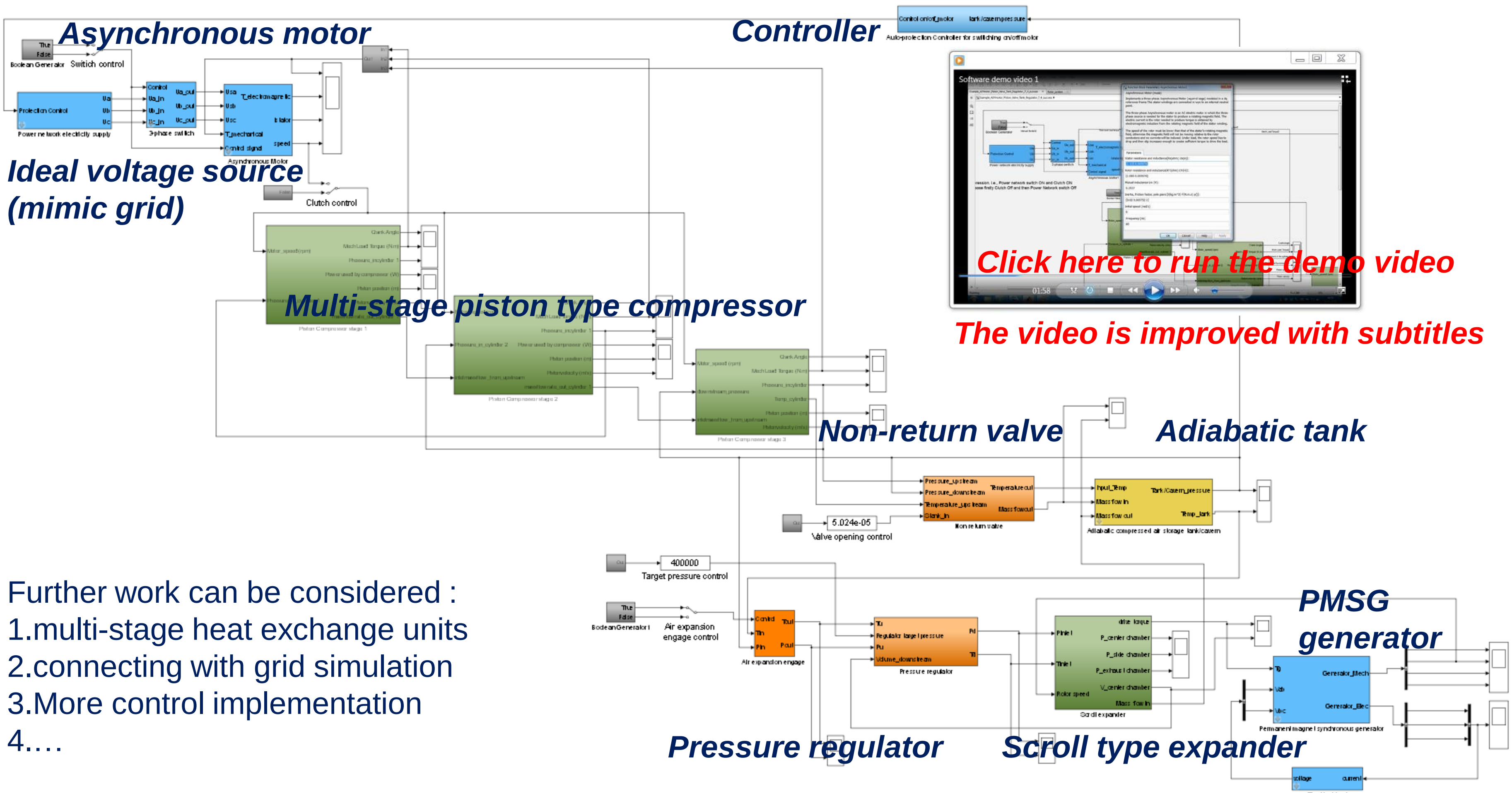
Standard settings (inputs, outputs, parameters, etc.)

Matlab/Simulink Code explanation

Simulation study and application examples

# 2.1 CAES-TES dynamic modelling & software

- Dynamic simulation of a whole CAES system (e-to-e)

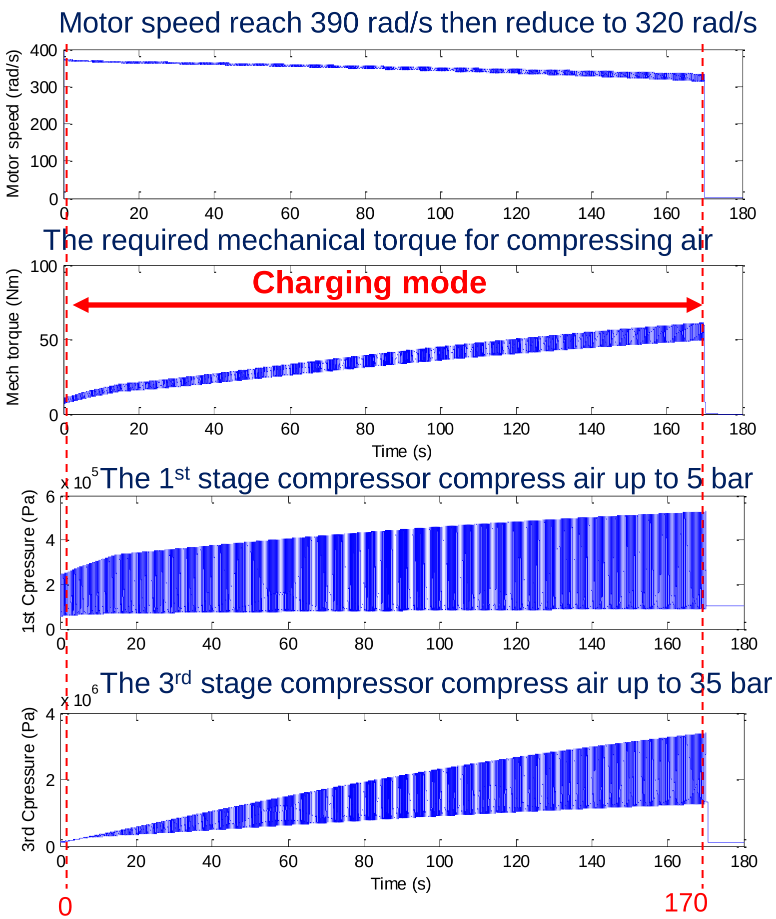


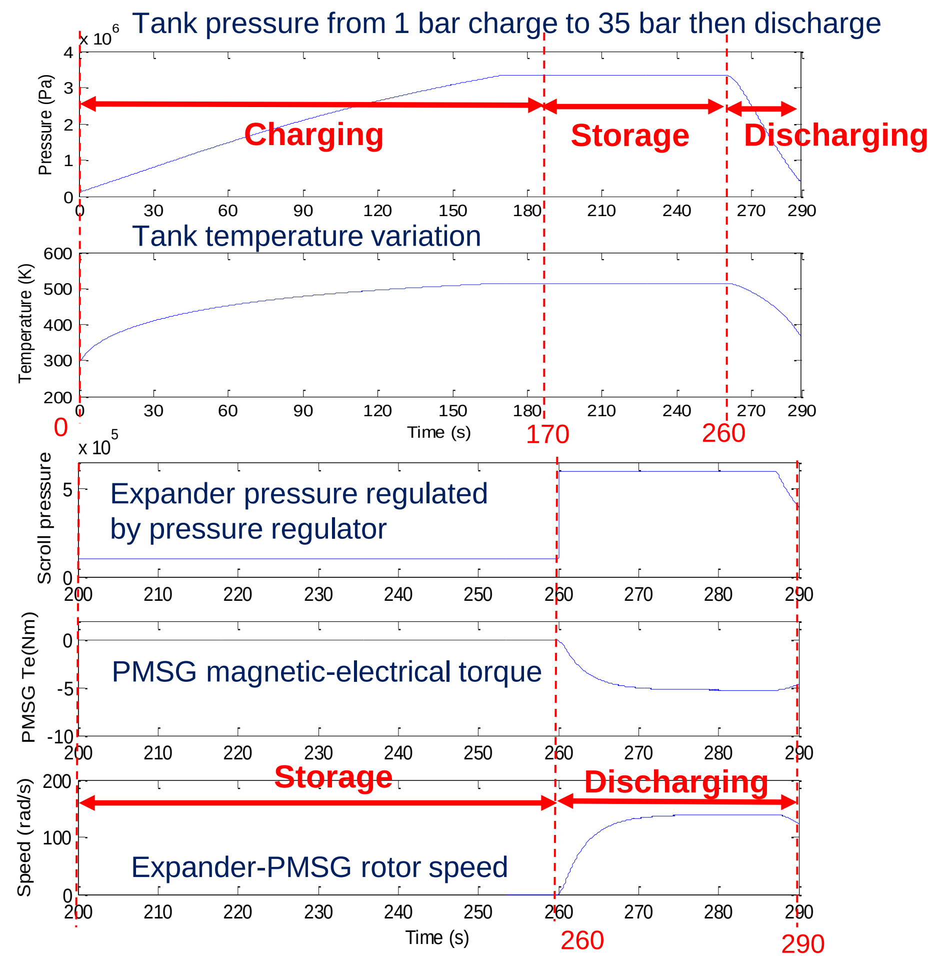

The video is improved with subtitles

Further work can be considered :
1.multi-stage heat exchange units
2.connecting with grid simulation
3.More control implementation
4.…

# 2.1 CAES-TES dynamic modelling & software

## dynamic simulation of a whole CAES system (e-to-e)

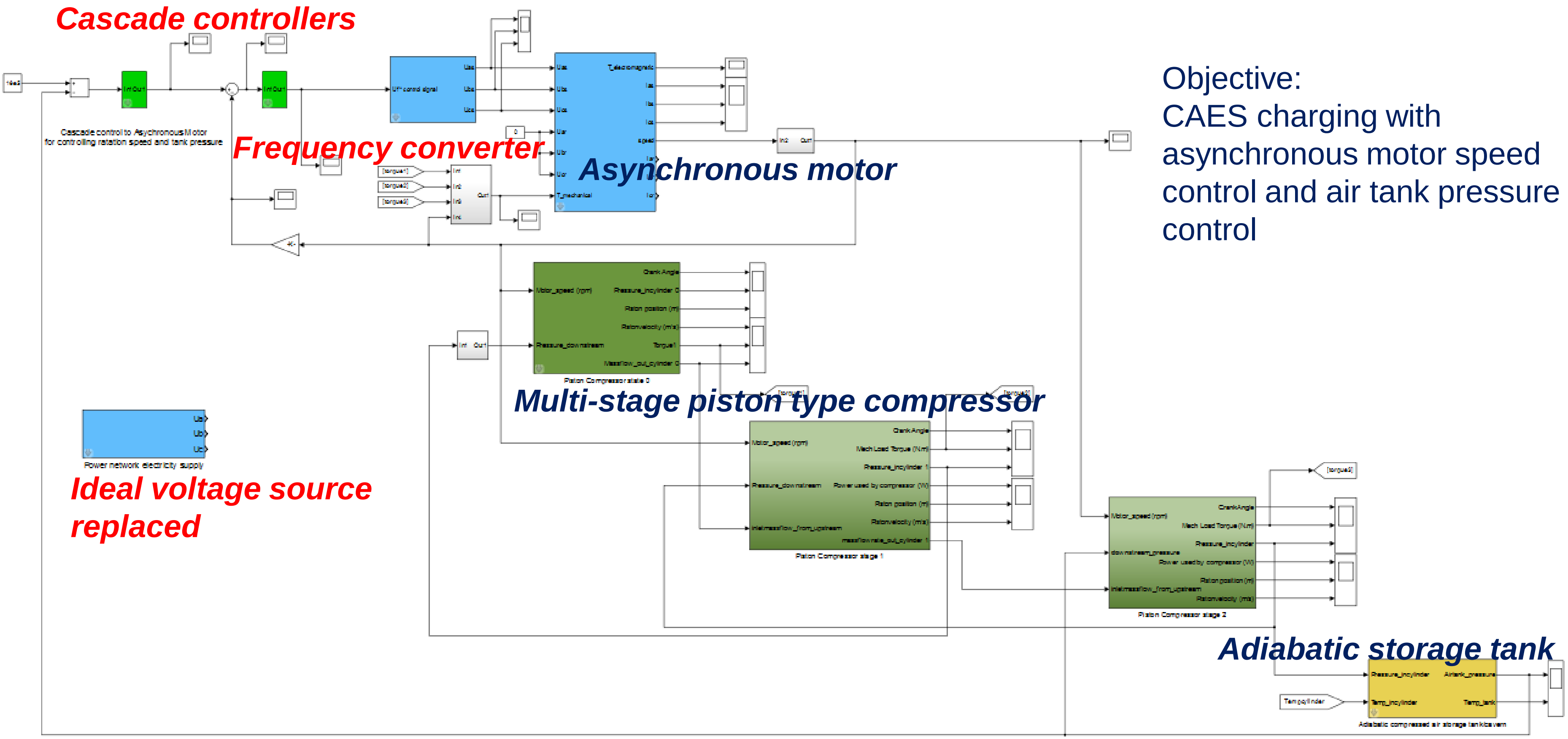



**Simulation: Charging mode 0 to 170s; Storage mode 170 to 260s; Discharging mode 260s to 290s.**

# 2.1 CAES-TES dynamic modelling & software

## CAES charging with cascade control

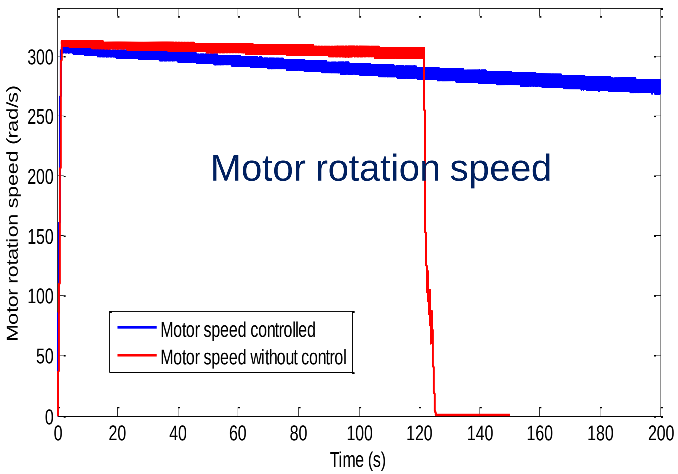


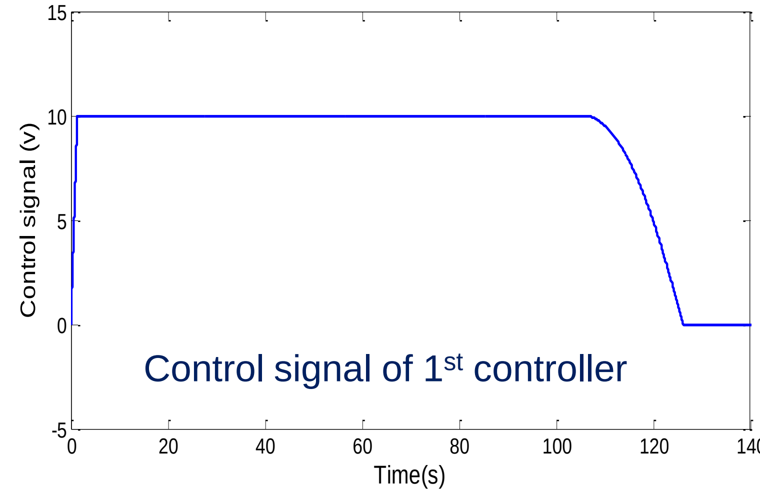

Objective:
CAES charging with asynchronous motor speed control and air tank pressure control

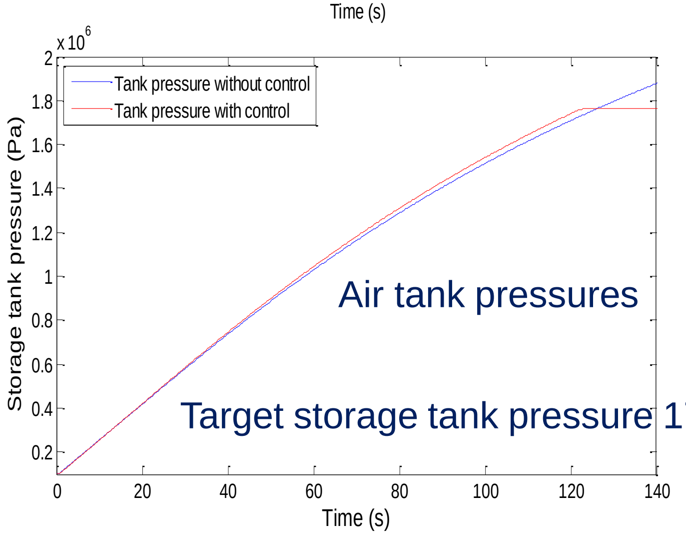
# 2.1 CAES-TES dynamic modelling & software

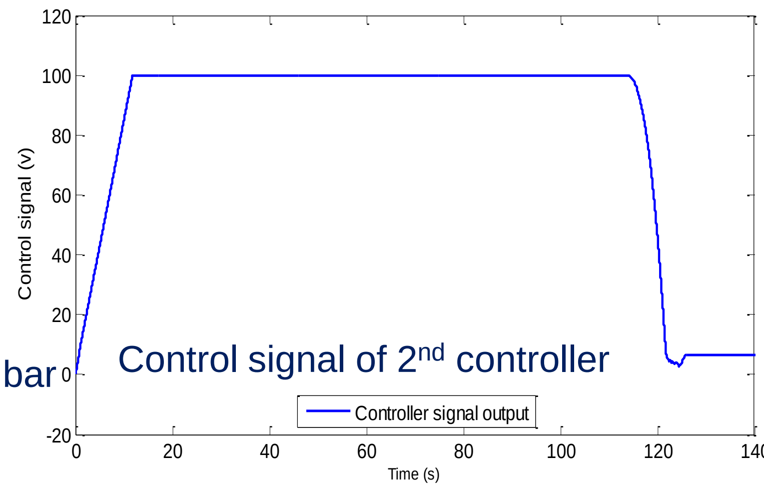
## CAES charging with cascade control

With the target tank pressure increase, the difference of motor speed and the system efficiency can be more clearer!



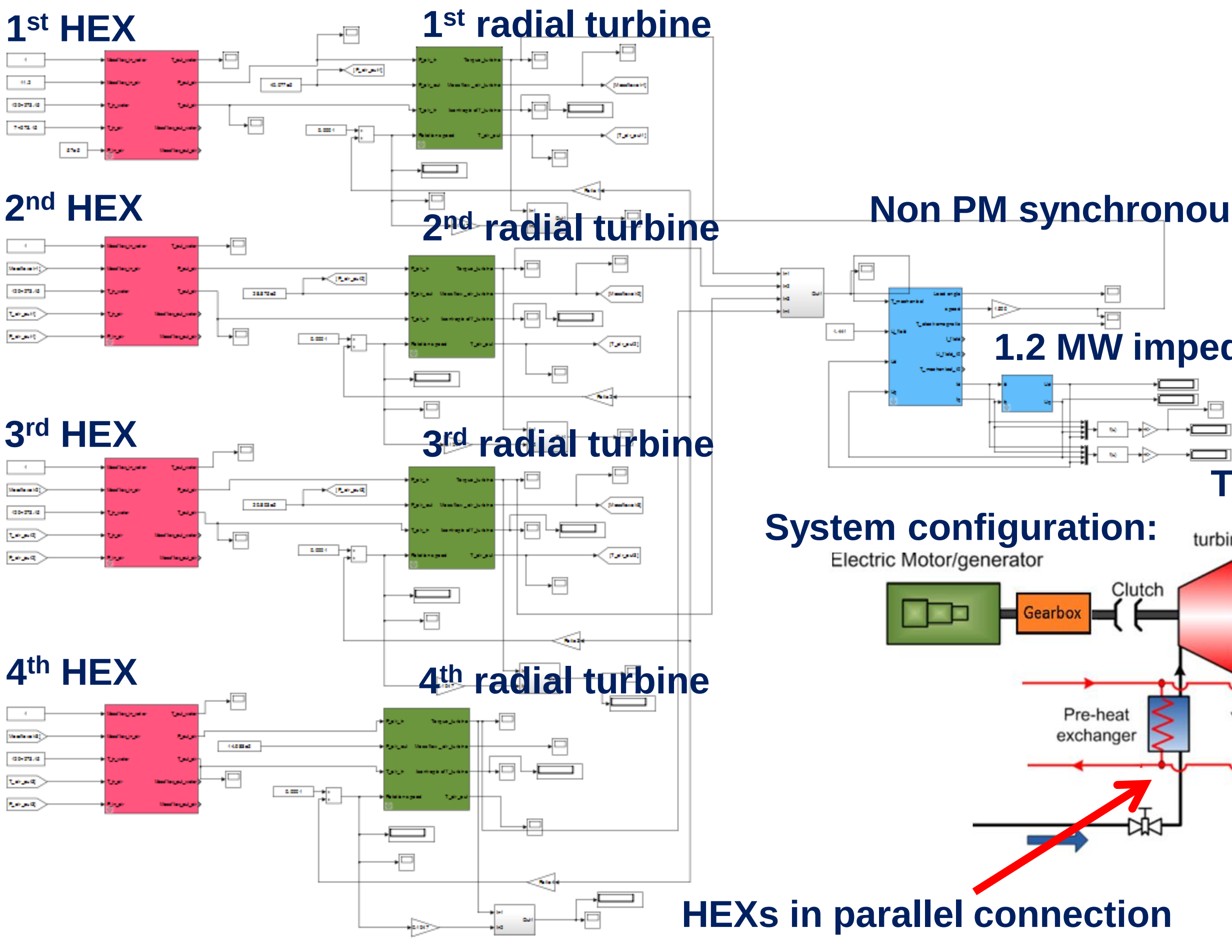



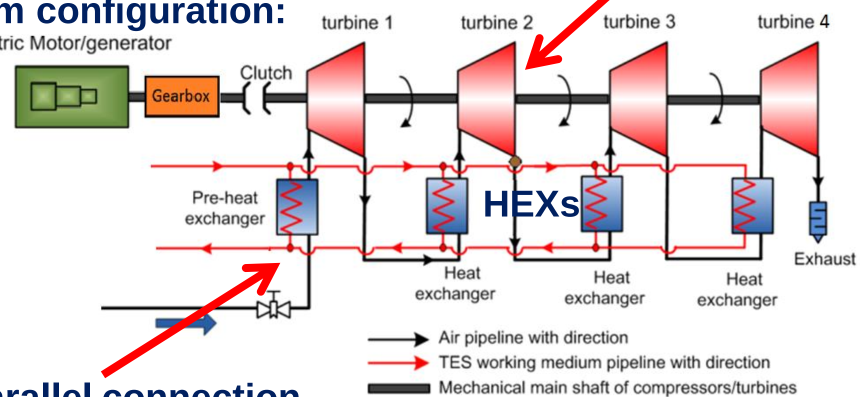



# 2.1 CAES-TES dynamic modelling & software

1.2 MW CAES discharging
(multi-stage turbine with HEXs + non PM synchronous generator)




System configuration:

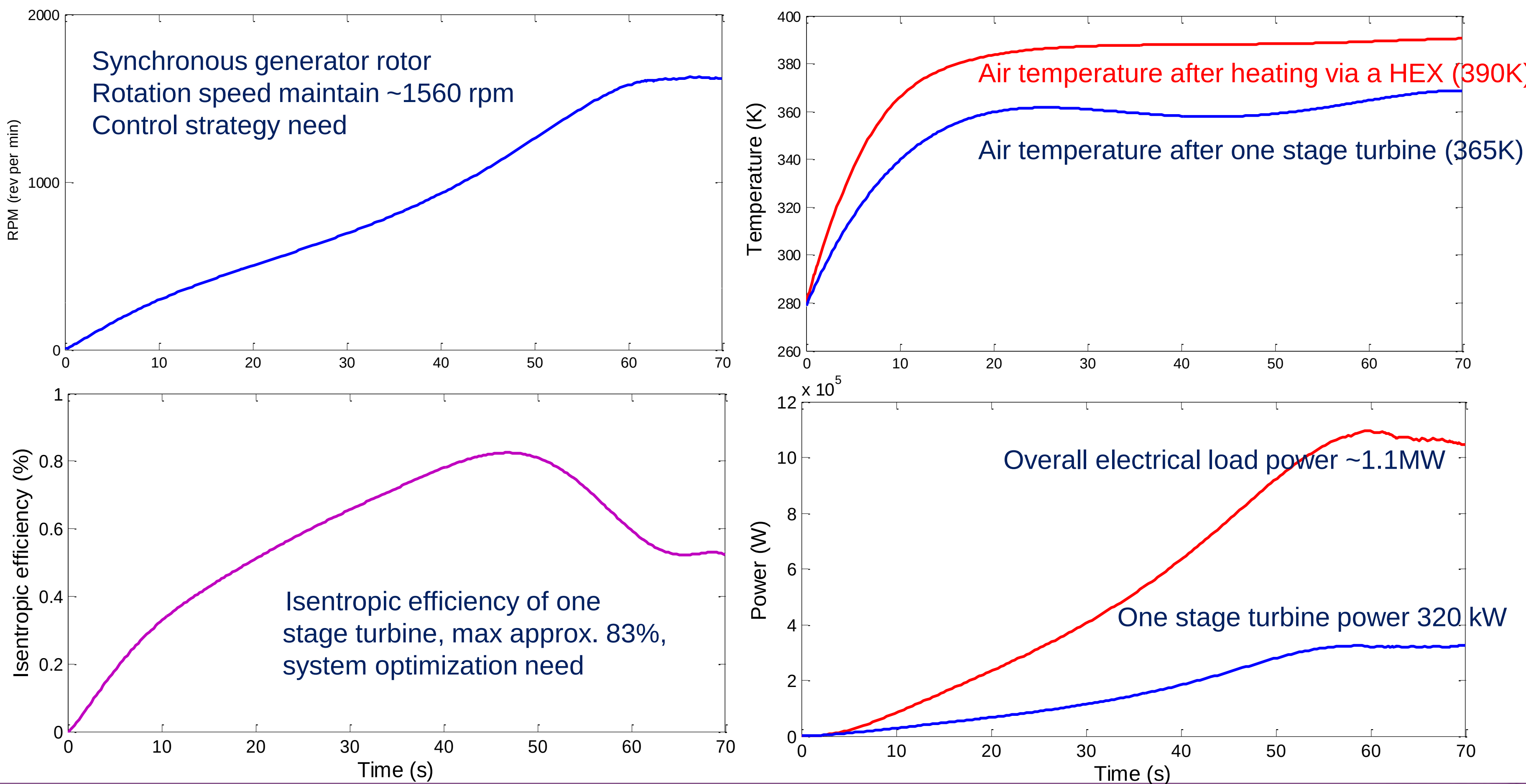



HEXs in parallel connection

# 2. CAES-TES dynamic modelling & software

- Software example 4: 1.2MW CAES discharging

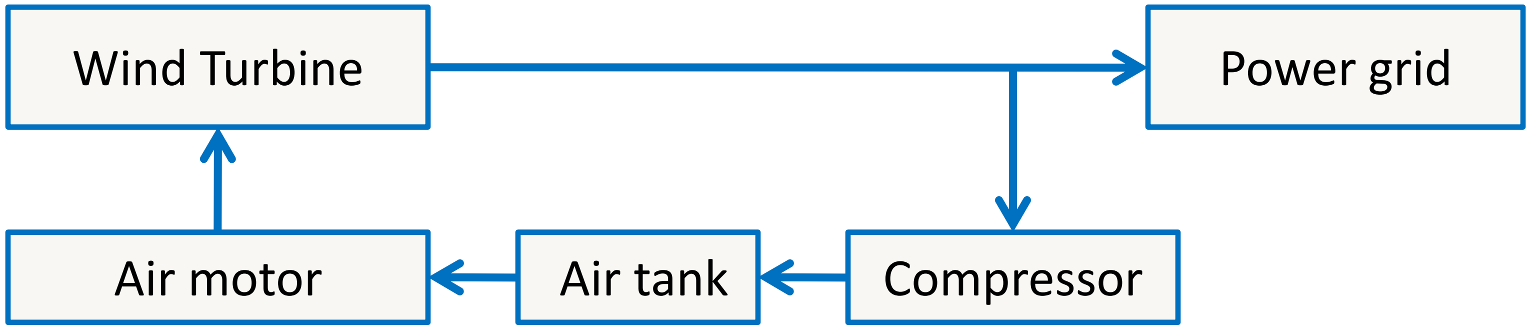
Compressed air discharge from 57bar; initial mass flow rate of air 11.2 kg/s



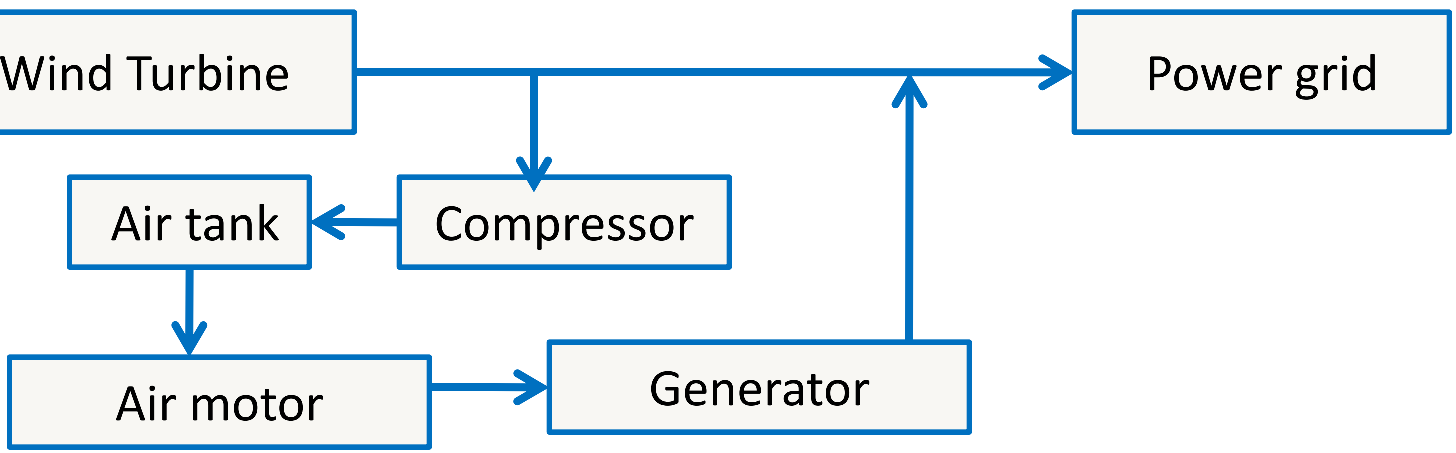
# 2.2 Hybrid wind turbine



1.



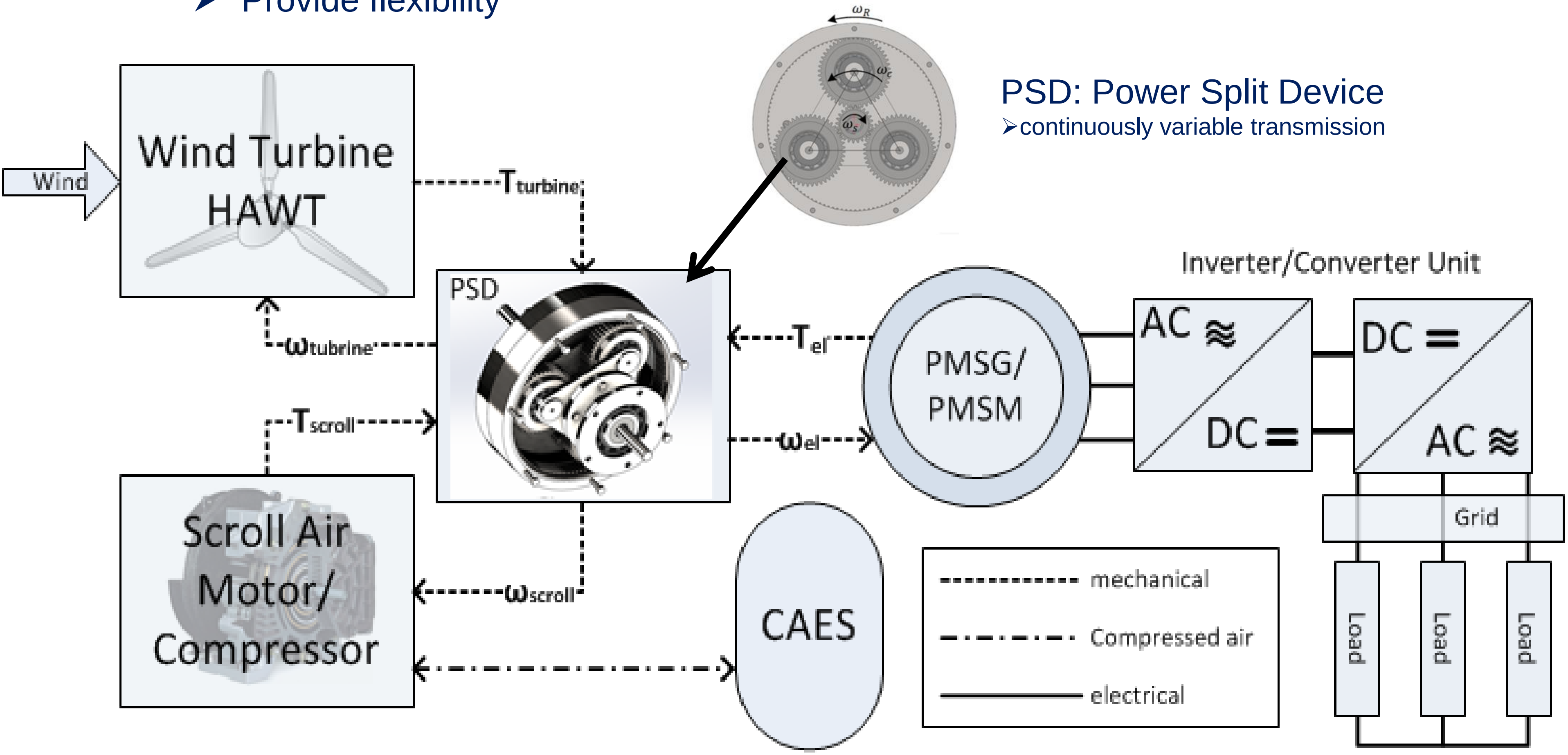

2.



# 2.2 Hybrid wind turbine

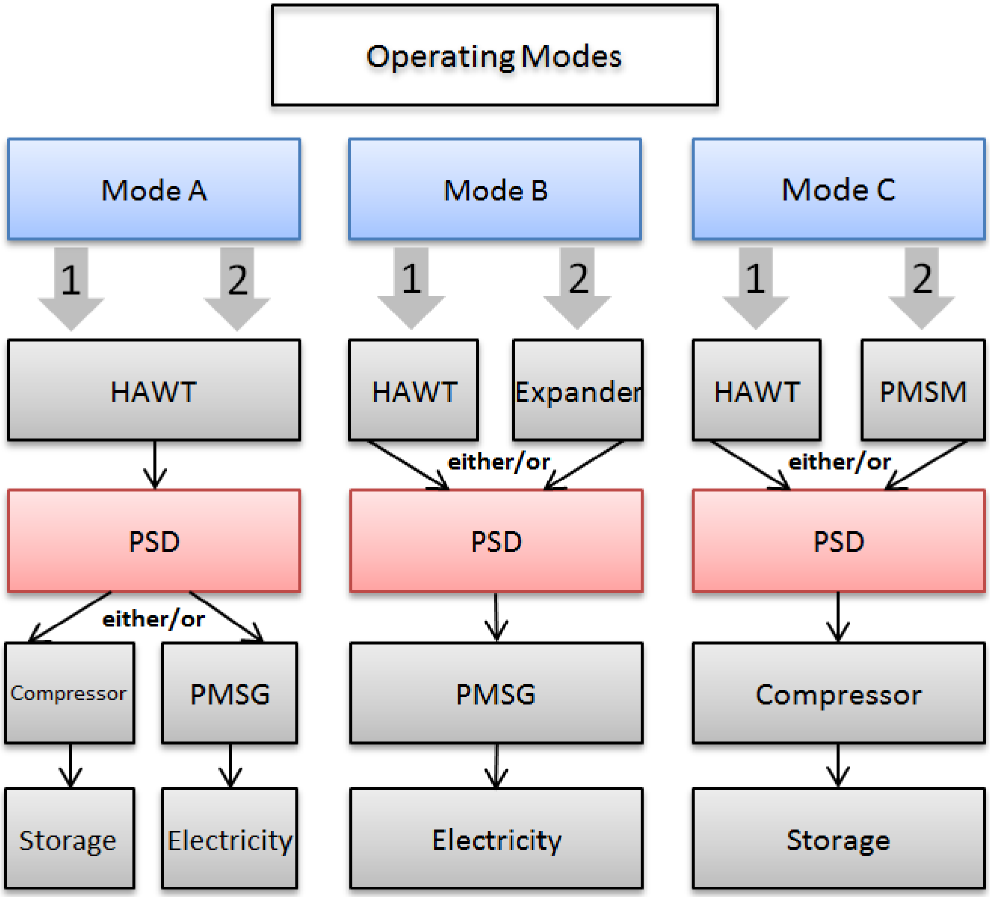
**Aim:**
- To augment a wind turbine with CAES on the turbine level with a flexible mechanical transmission device
- Control generator power output under fluctuating wind speed and enable CAES provision
  - Provide flexibility

PSD: Power Split Device
- continuously variable transmission



# 2.2 Hybrid wind turbine

- Flexibility in operation: 3 operating modes identified

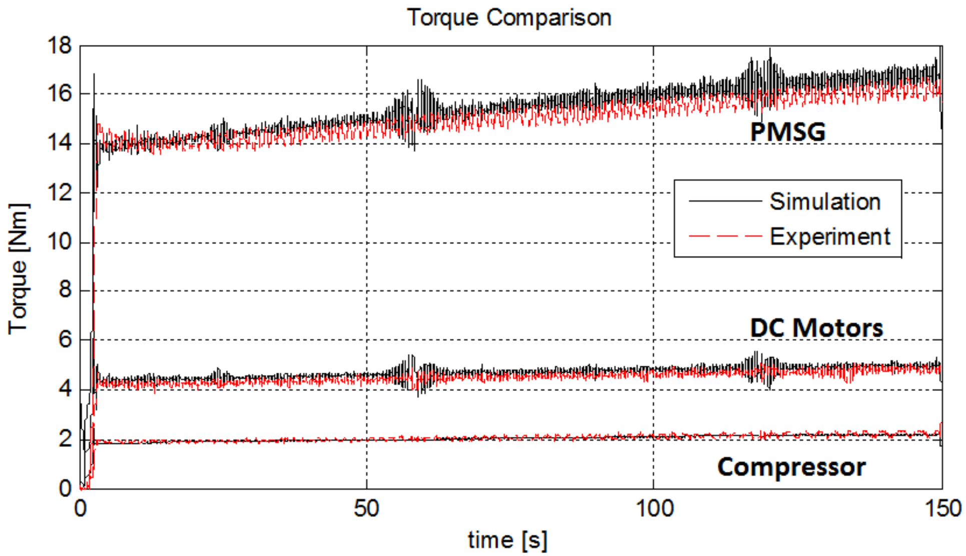



**Mode A:** HAWT drives
- Compressor
- PMSG
- Compressor & PMSG

**Mode B:** PMSG driven by
- Expander
- HAWT
- Expander & HAWT

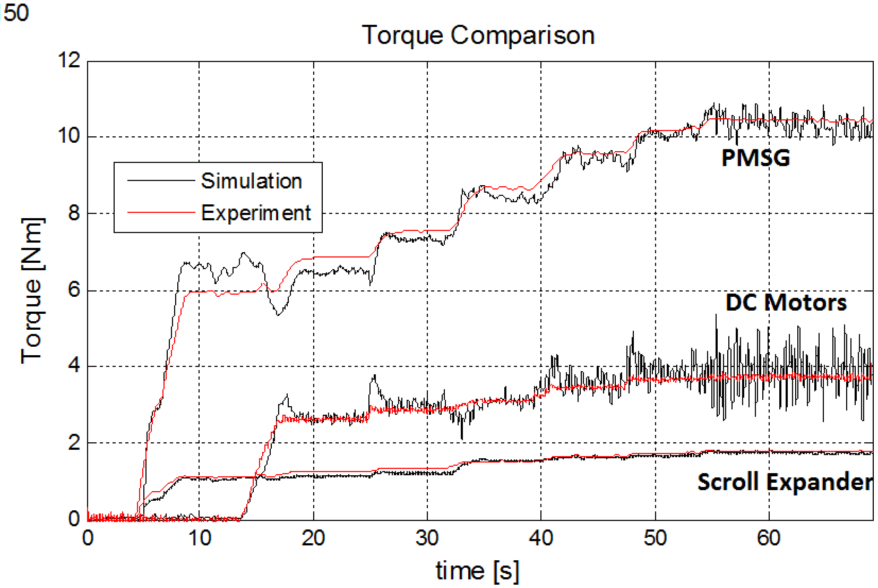
**Mode C:** Compressor drive by
- PMSM
- HAWT
- PMSM& HAWT

# 2.2 Hybrid wind turbine

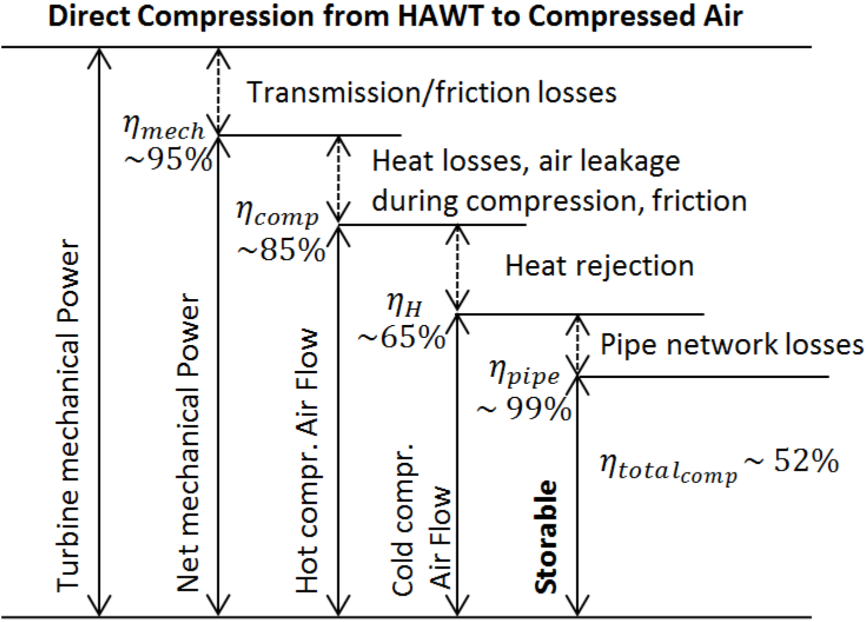


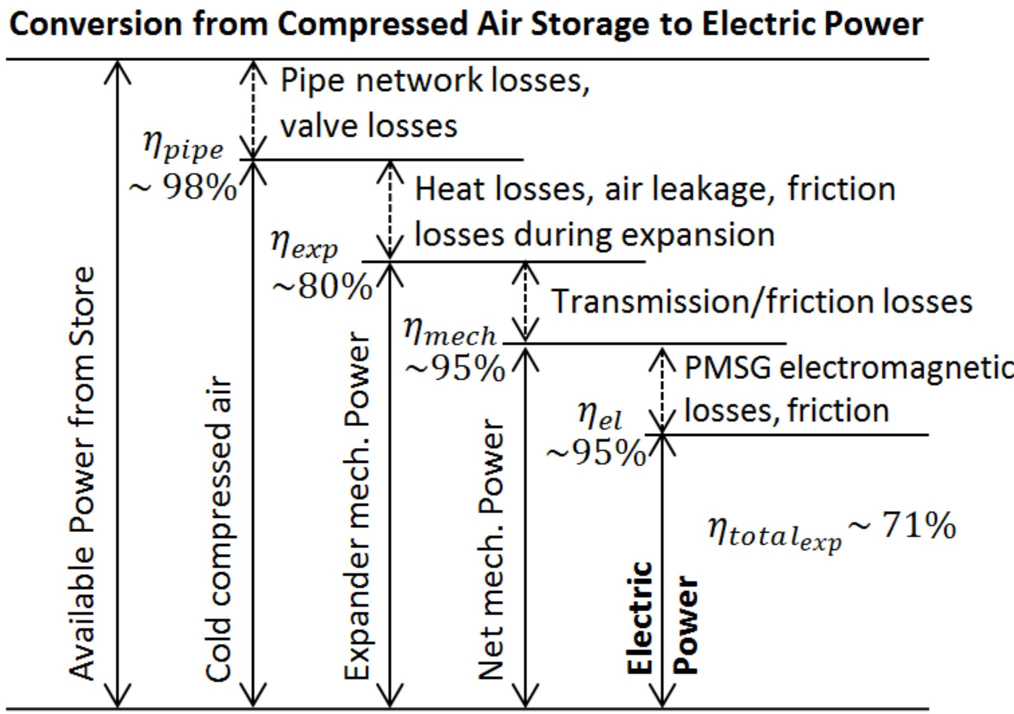

Model validation for **Mode A**: HAWT drives compressor and PMSG

Model validation for **Mode B**: PMSG driven by HAWT and Scroll expander



# 2.2 Hybrid wind turbine



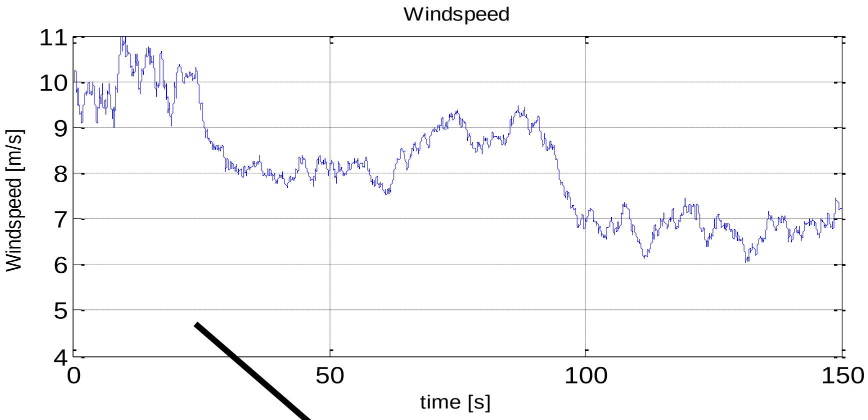




Turnaround efficiency:

Ratio of electrical energy to turbine mechanical energy after all energy has passed through storage

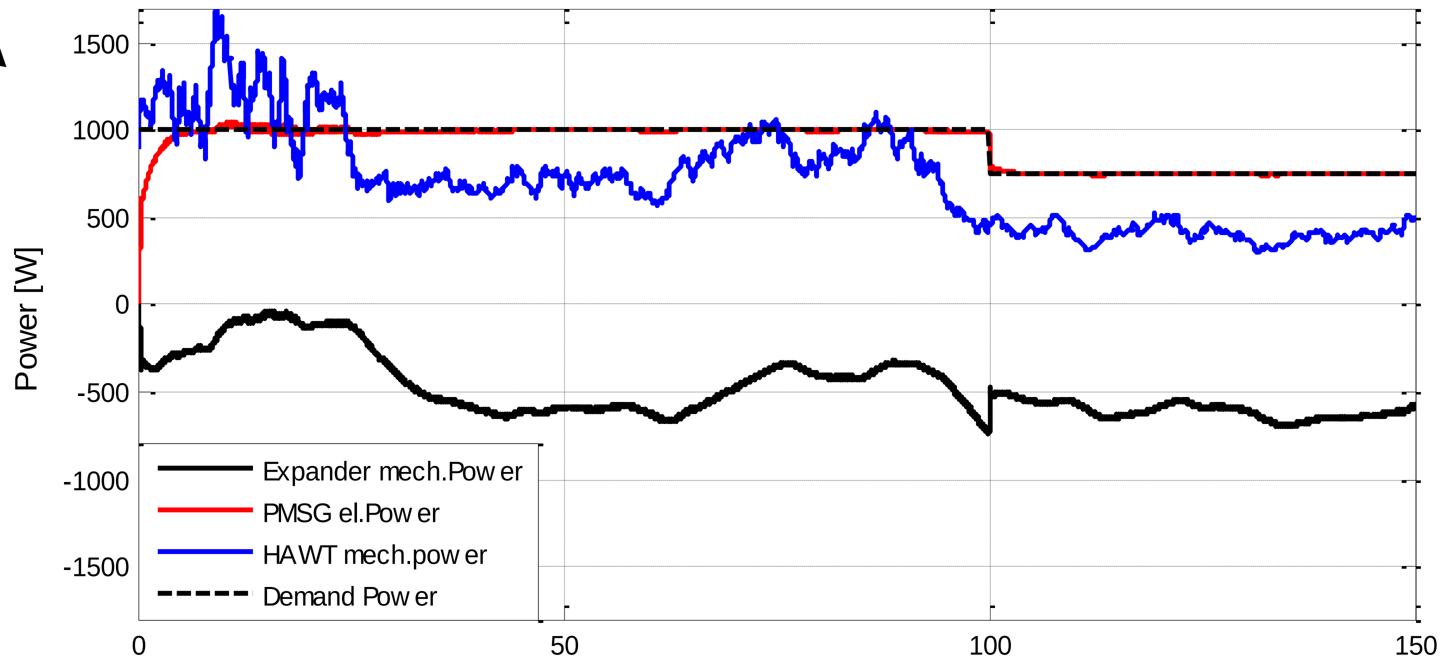
~37%

# 2.2 Hybrid wind turbine




Example Mode B:

- Generator power can be controlled
- Scroll expander compensates for lack of power



# 2.2 Hybrid wind turbine

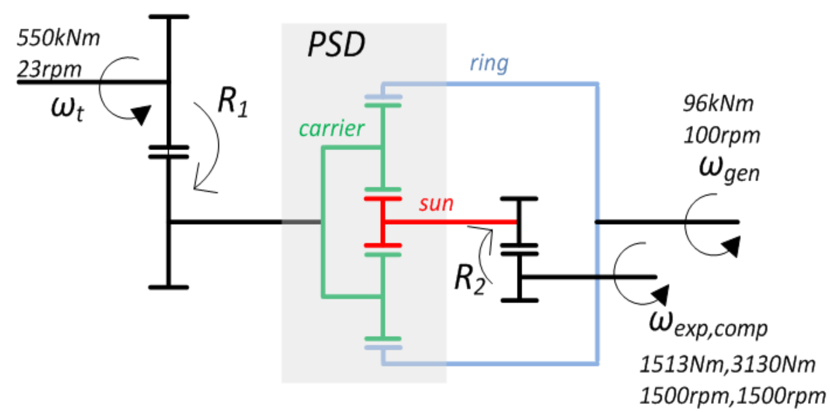
## Extension to 1MW wind turbine:

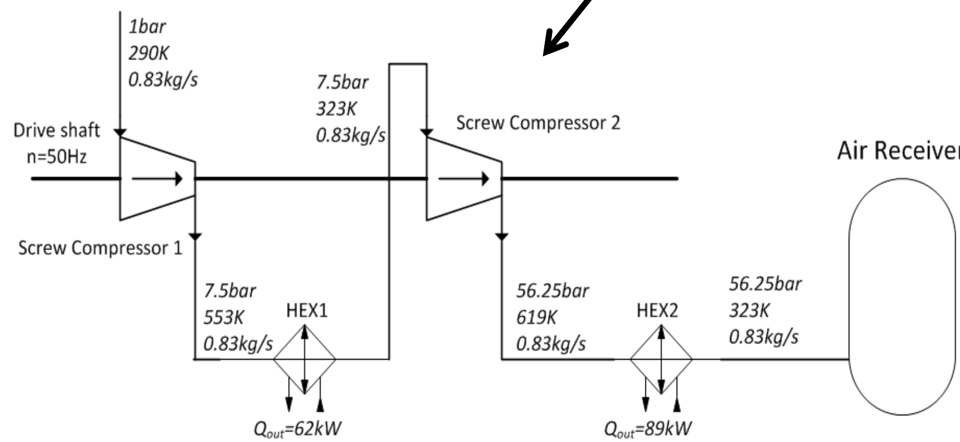
1MW hybrid wind turbine specifications

| | HAWT (at 12.5m/s) | PMSG | Expander | Compressor |
|---|---|---|---|---|
| Rated Power | 1.3$MW$ | 1$MW$ | 240$kW$ | 490$kW$ |
| Rated Speed | 23$rpm$ | 100$rpm$ | 1500$rpm$ | 1500$rpm$ |
| Rated Torque | 550$kNm$ | 96$kNm$ | 1513$Nm$ | 3130$Nm$ |
| Vessel size | 500$m^3$ | | | |
| Storage Capacity | 3$MWh$ | | | |
| Time Charging | ≈ 11$hrs$ (at 1500$rpm$, 626 $l/s$ FAD) | | | |
| Time Discharge | ≈ 5$hrs$ (at 1500$rpm$, 626 $l/s$ FAD per expander) | | | |

2 screw compressors in series (to increase air pressure in air receiver)

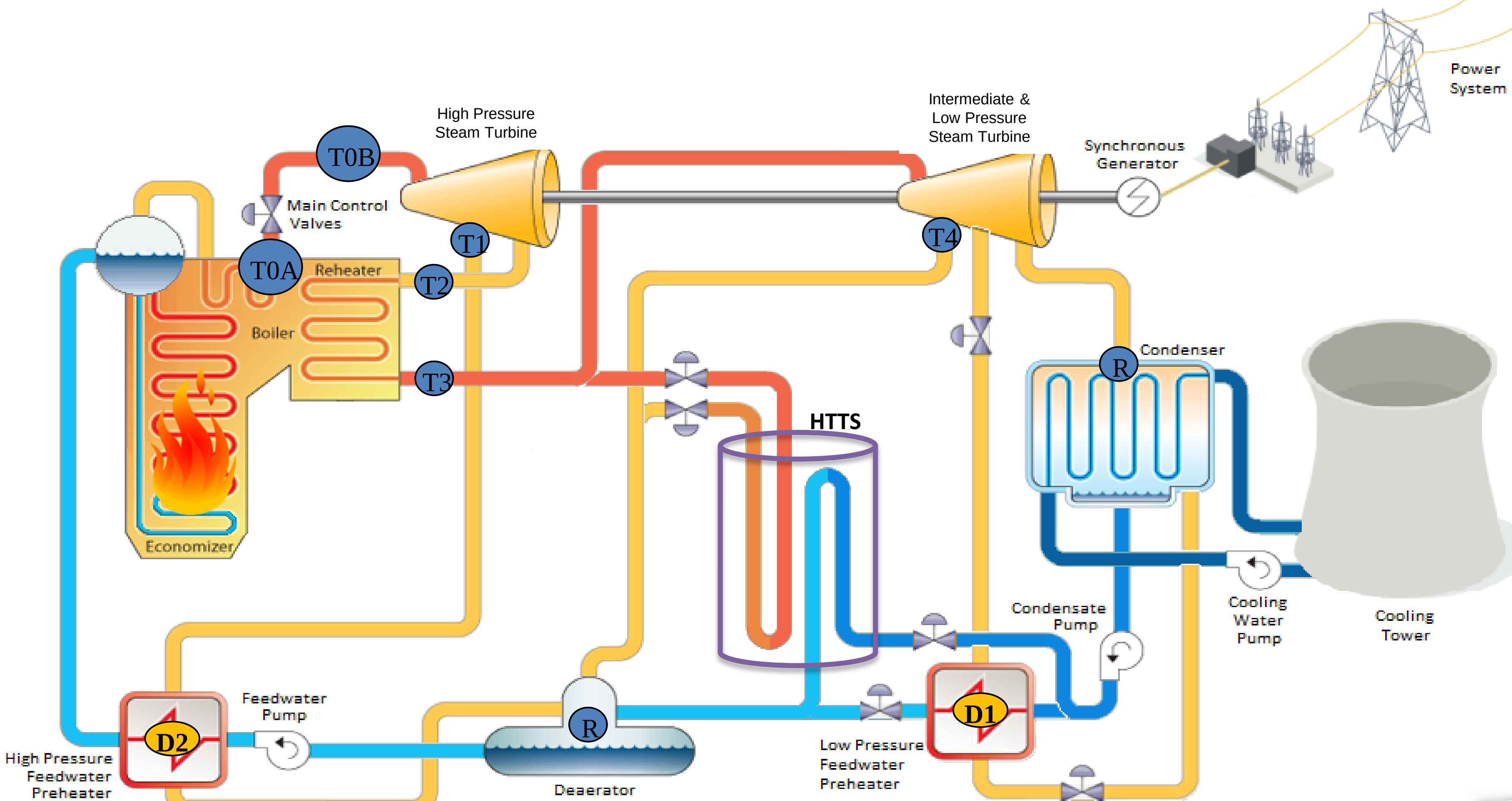
## Mechanical Transmission:



# 2.3 Further investigation on HTTS integration

## *Progress – HTTS concept*



# 3. Work Plan

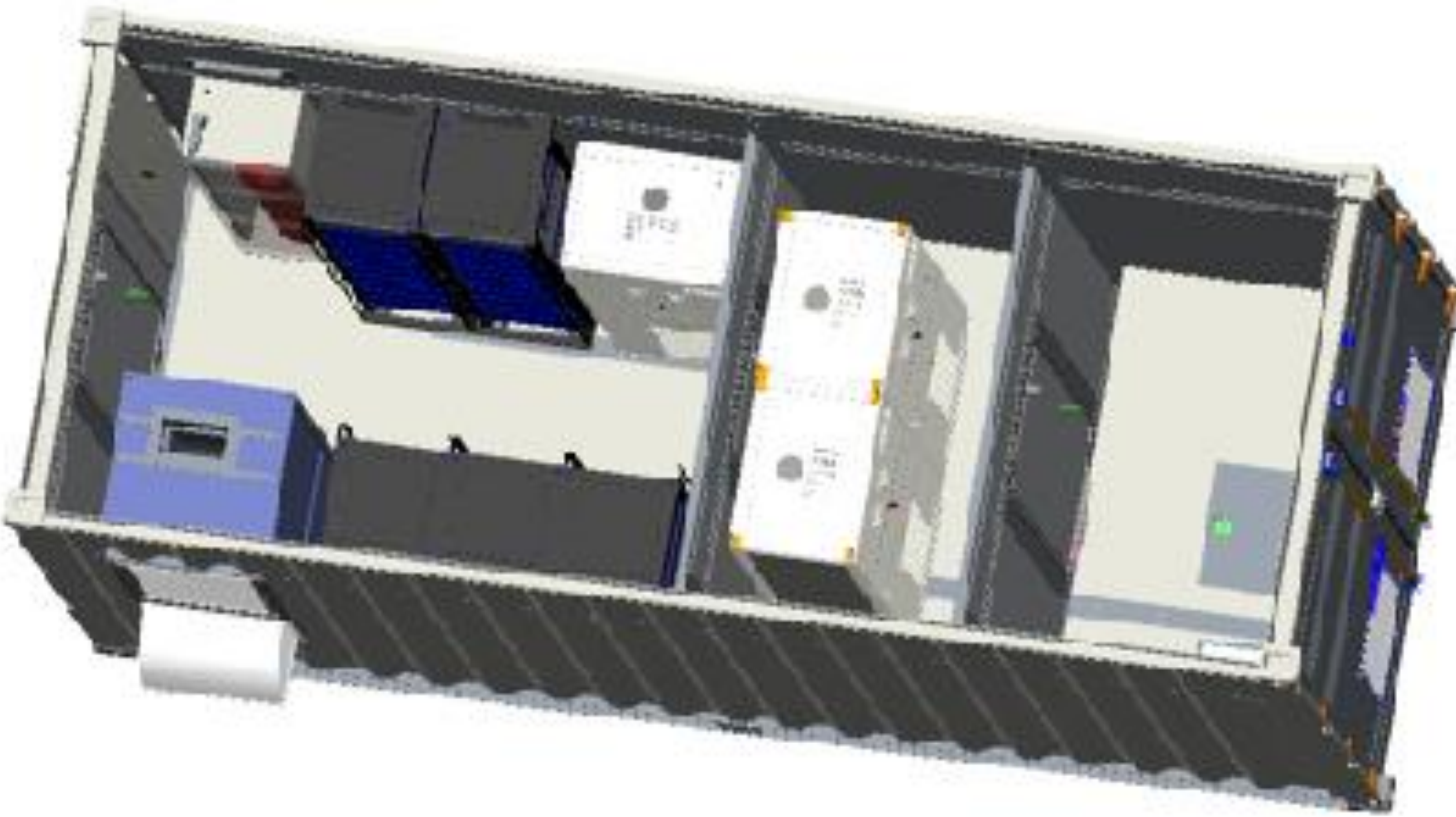
- Continue development of CAES-TES simulation tool
- Complete the joint work between Warwick, BGS and Nottingham on energy capacity calculation
- With the TE material parameters from Loughborough University, HTTS integration with thermal power plant can be simulated and optimised
- Increase impact activities

# 3. Work Plan

-Study of energy storage integration with micro grid or grid

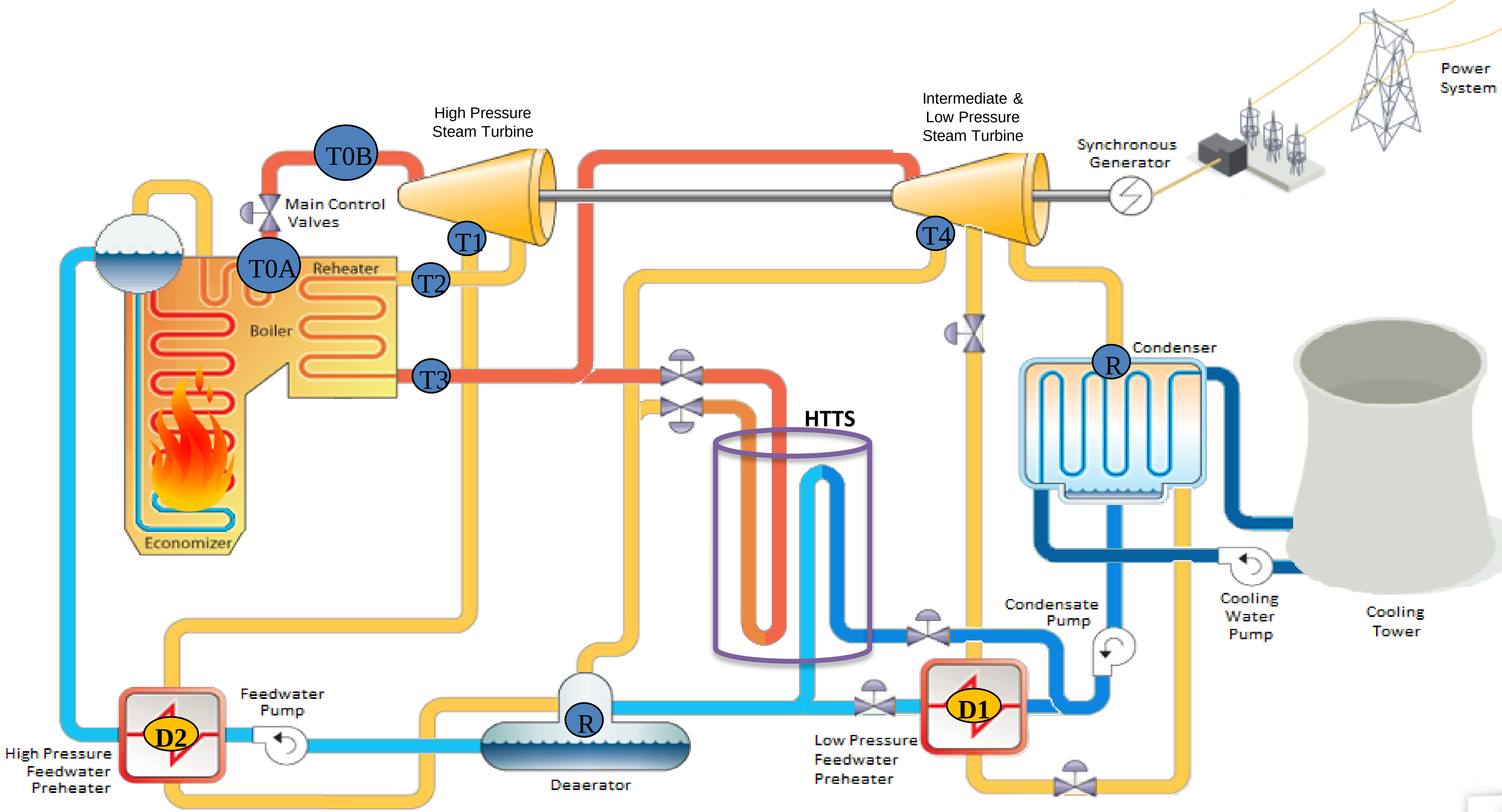
# 3. Work Plan

-Study of energy storage role in VPP



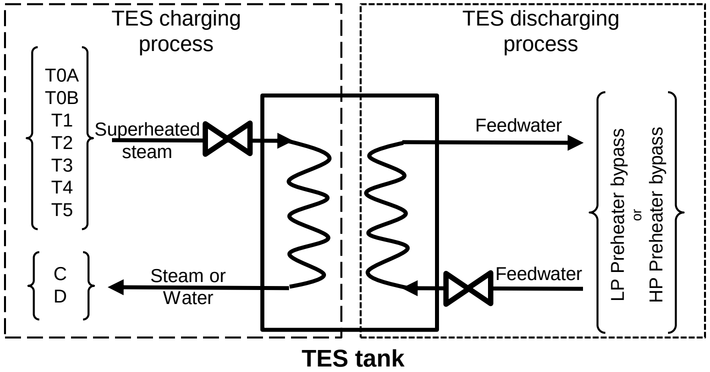
# 2.3 Further investigation on HTTS integration

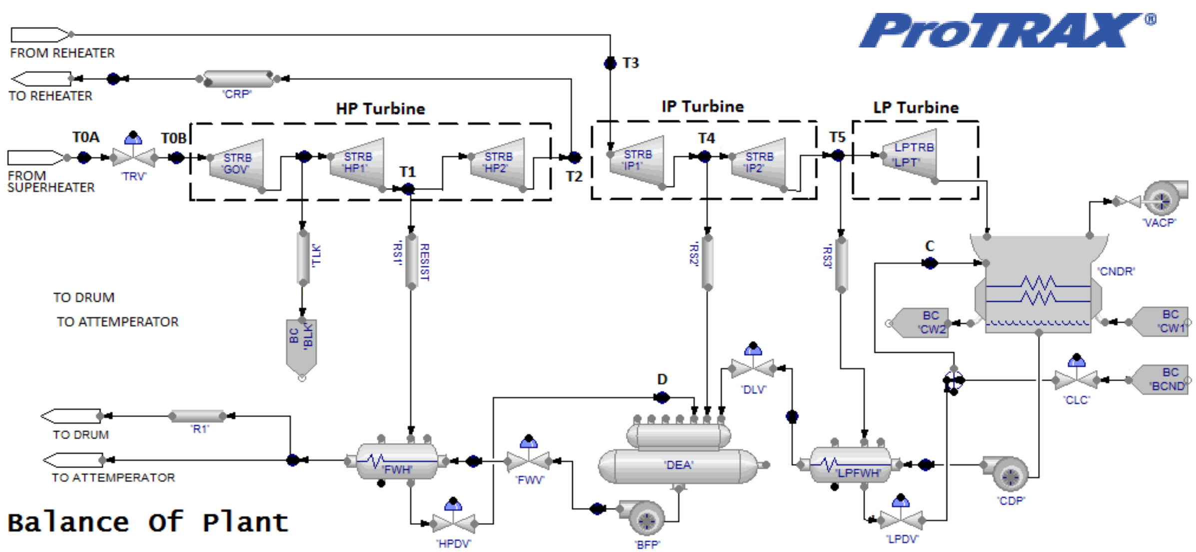
## *Progress – HTTS concept*



## *Progress – modelling*

1. Modelling work in ProTRAX



## *Progress – modelling*

1. Modelling work in ProTRAX

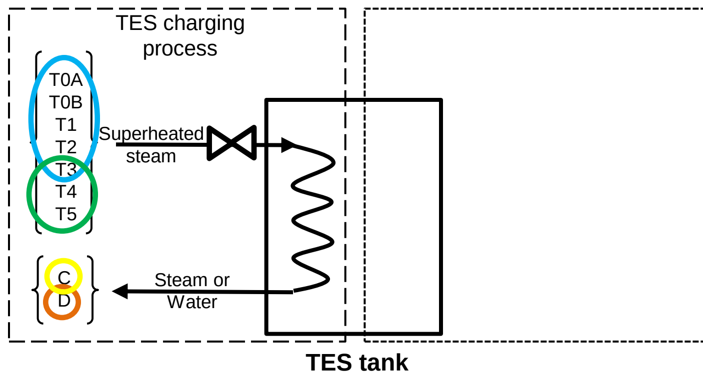
**HTTS Charging process**

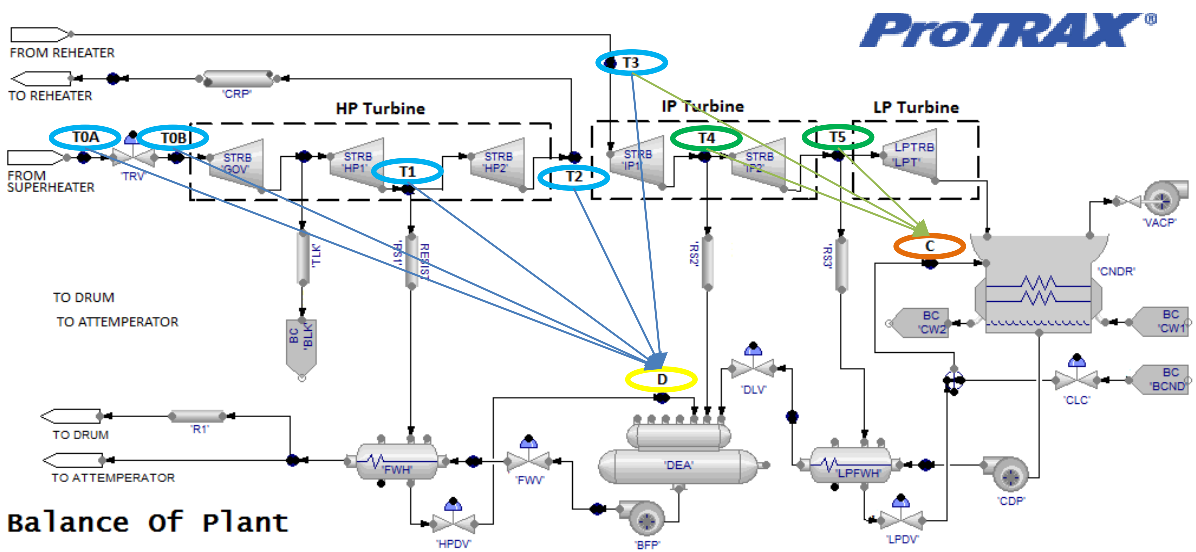
- 7 steam extraction points (T0A-T5)
- 2 return points (C & D)

c) **Fixed Pressure/Sliding Pressure** control system mode.

d) **Steam/Water** from HTTS HX in HTTS charging mode.

### *Charging process*

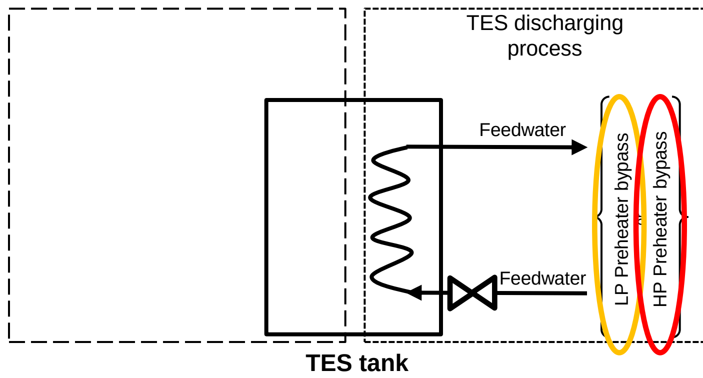


## *Progress – modelling*

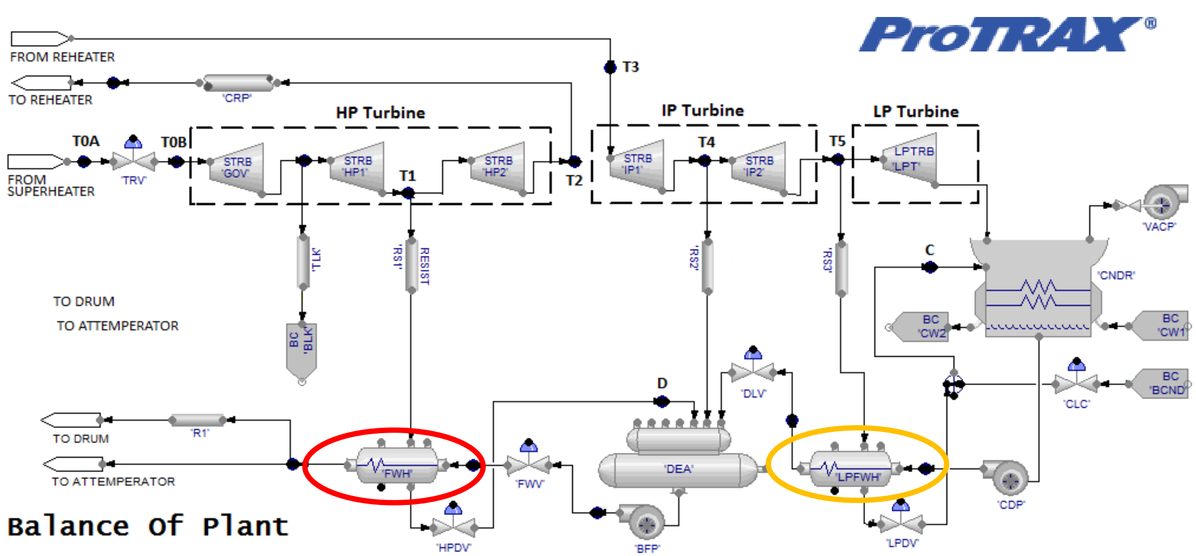
1. Modelling work in ProTRAX

## ***Discharging process***




**HTTS Discharging process**

- LP feedwater preheater bypass
- HP feedwater preheater bypass



# *Progress – modelling*

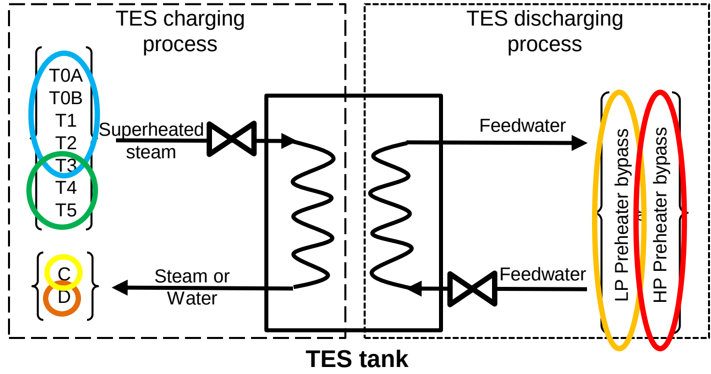
1. Modelling work in ProTRAX

**HTTS Charging process**

- 7 steam extraction points (T0A-T5)
- 2 return points (C & D)

**c) Fixed Pressure/Sliding Pressure** control system mode.

**d) Steam/Water** from HTTS HX in HTTS charging mode.




**HTTS Discharging process**

- LP feedwater preheater bypass
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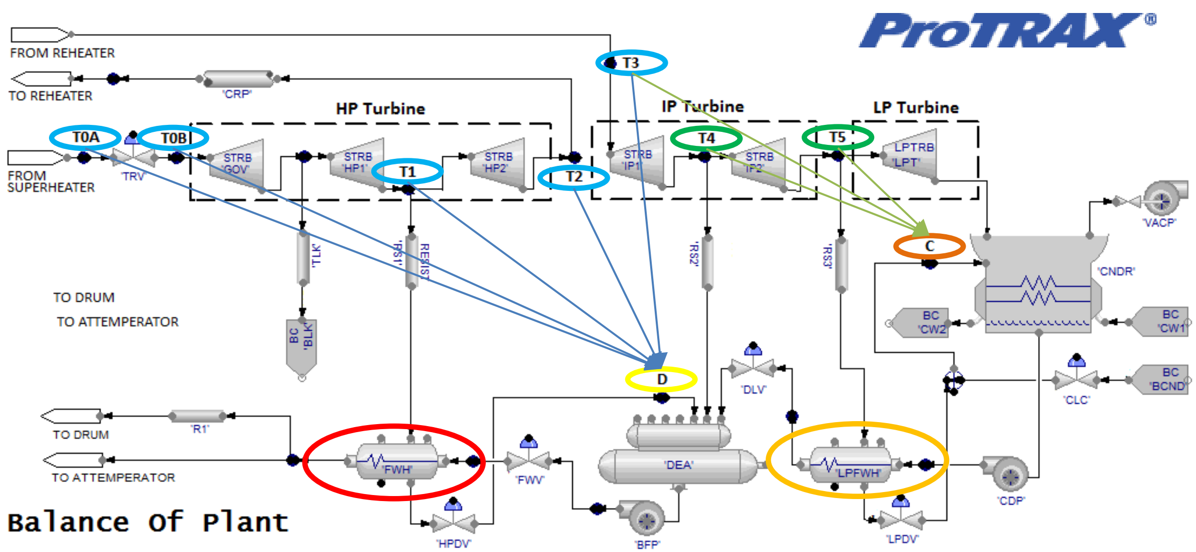
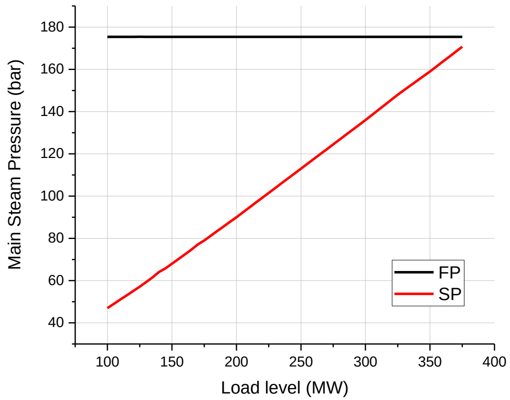
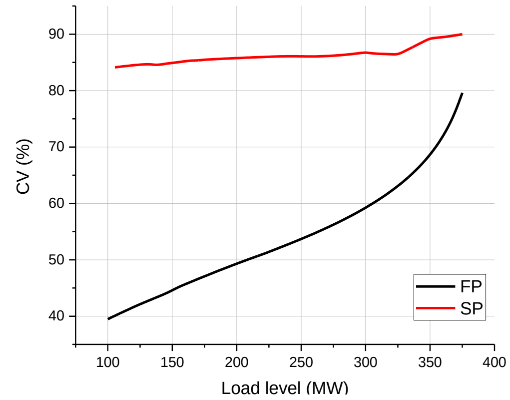
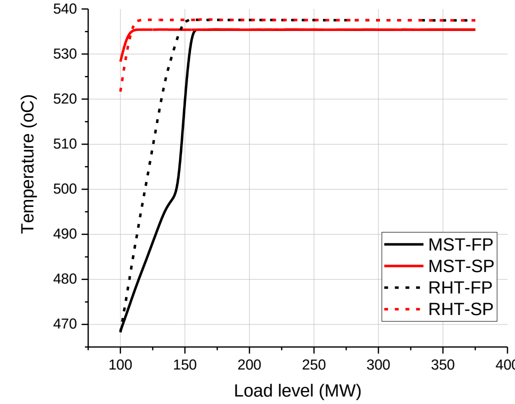


# *Progress – Results*

The main control system modes: **Fixed Pressure** vs **Sliding Pressure** mode

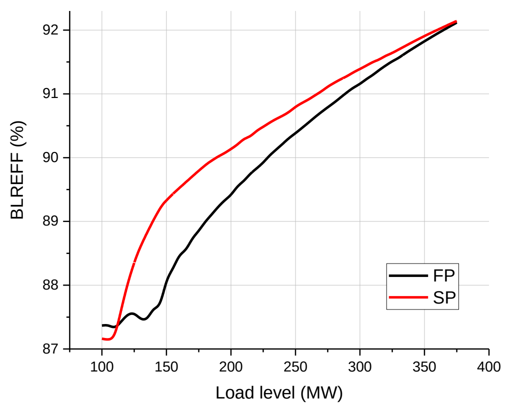


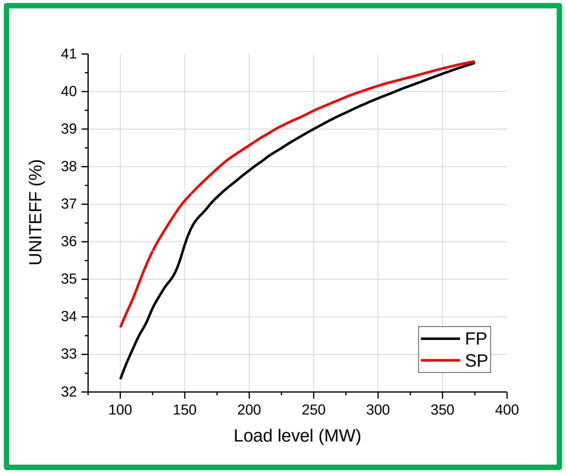




**FP – Fixed Pressure mode**

**SP – Sliding Pressure mode**

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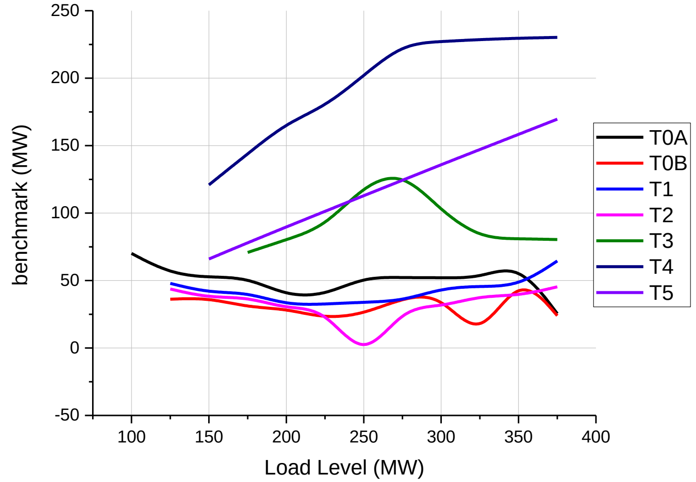
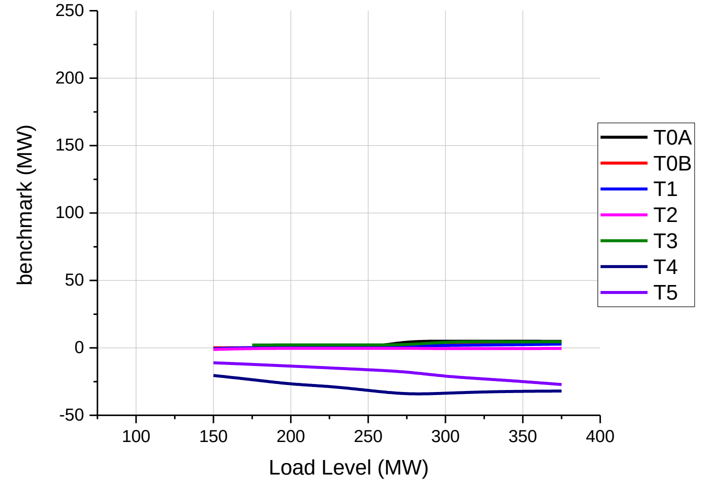
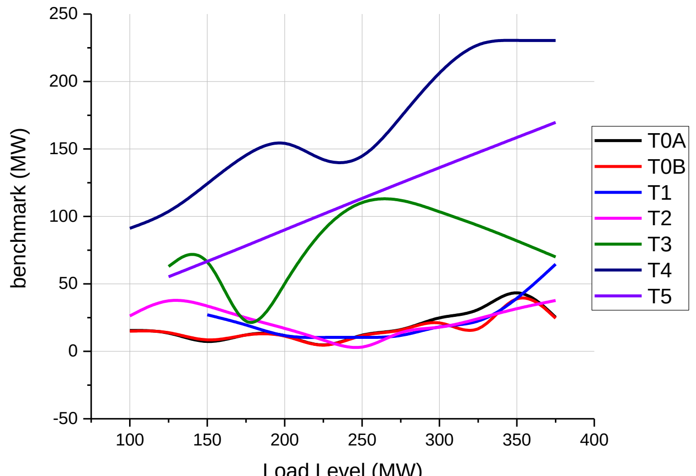
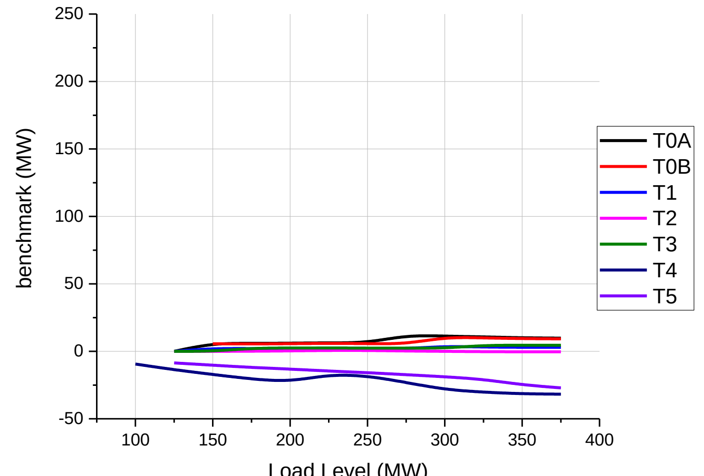
# *Progress – HTTS Charging*

$P_{HTTS} = W*(h_{in}-h_{out})$

**Bench**$=P_{HTTS} - dP$ [MW]

## HTTS charging results

| | Condensation | ~~Non-Condensation~~ |
|---|---|---|
| **Fixed Pressure** |  |  |
| **Sliding Pressure** |  |  |









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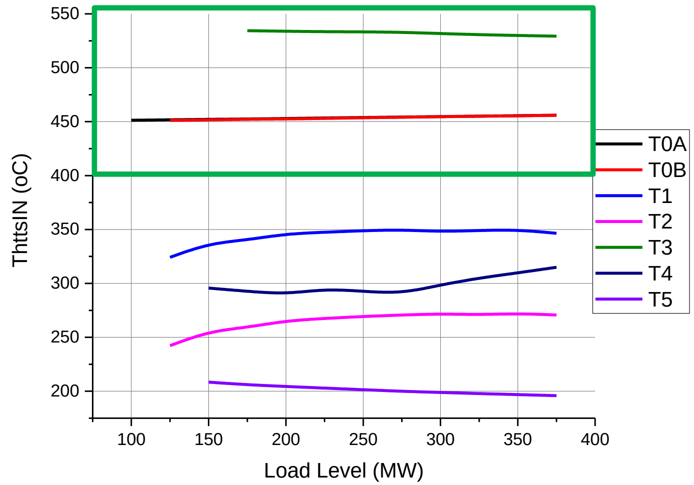
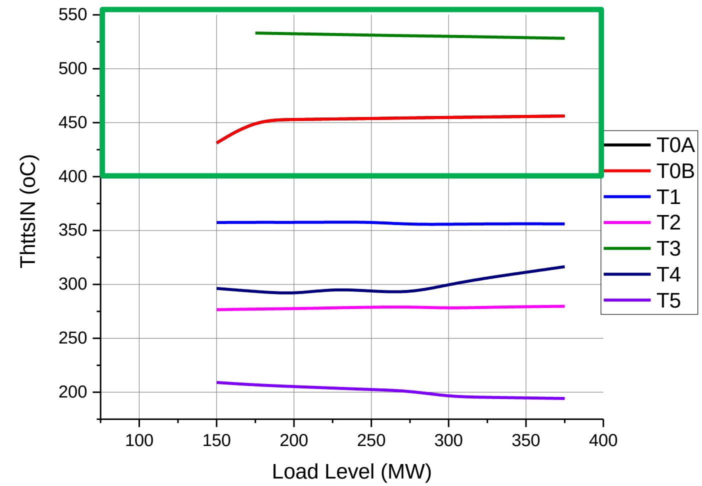
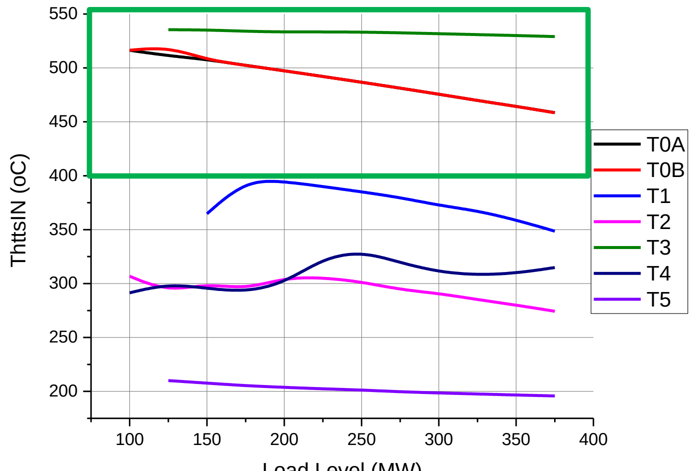
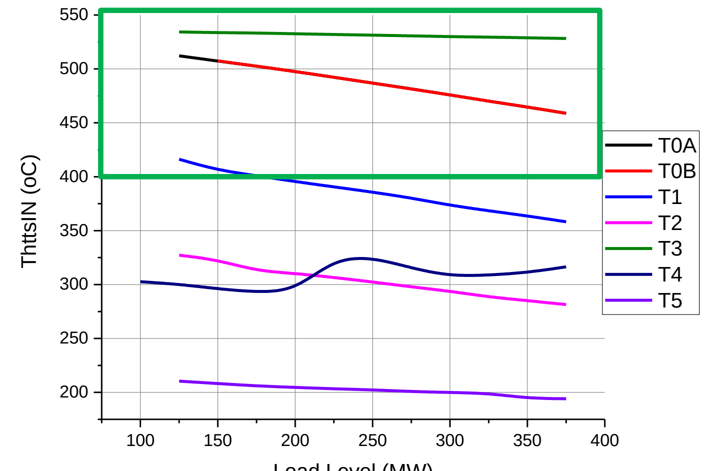
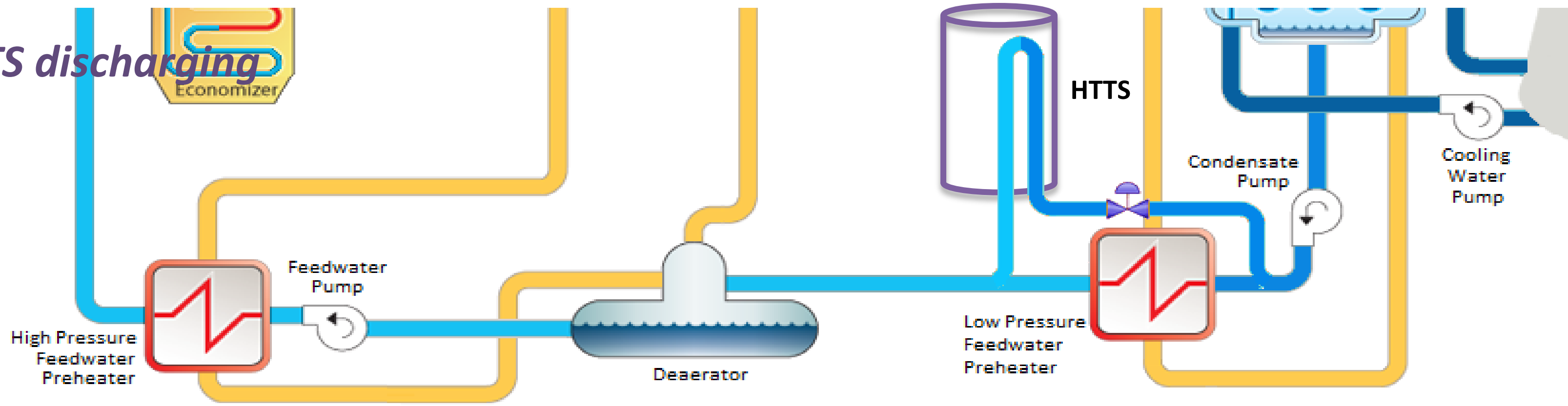
# *Progress – HTTS Charging*

## HTTS charging results

**$T_{HTTSin}$ [°C]**

| | Condensation | Non-Condensation |
|---|---|---|
| **Fixed Pressure** |  |  |
| **Sliding Pressure** |  |  |

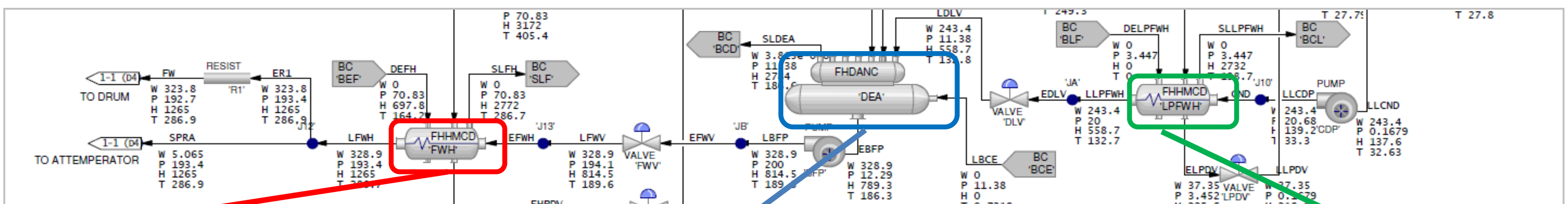
# *Progress – HTTS discharging*

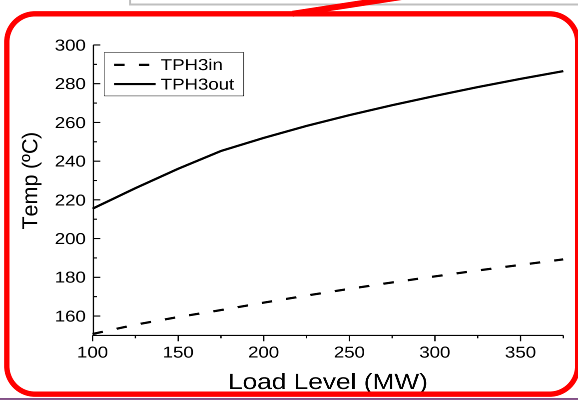


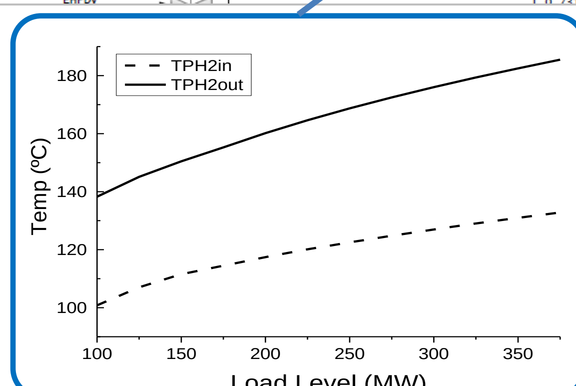

**High Pressure Preheater**

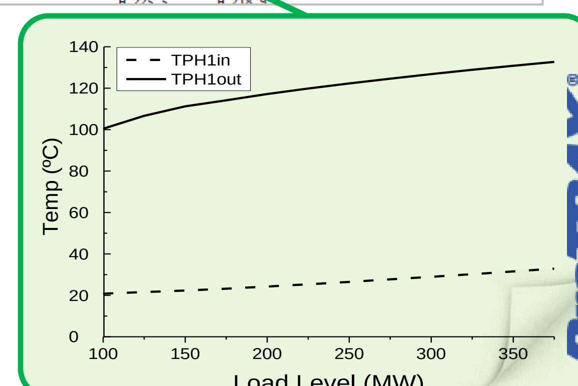
**Deaerator**

**Low Pressure Preheater**

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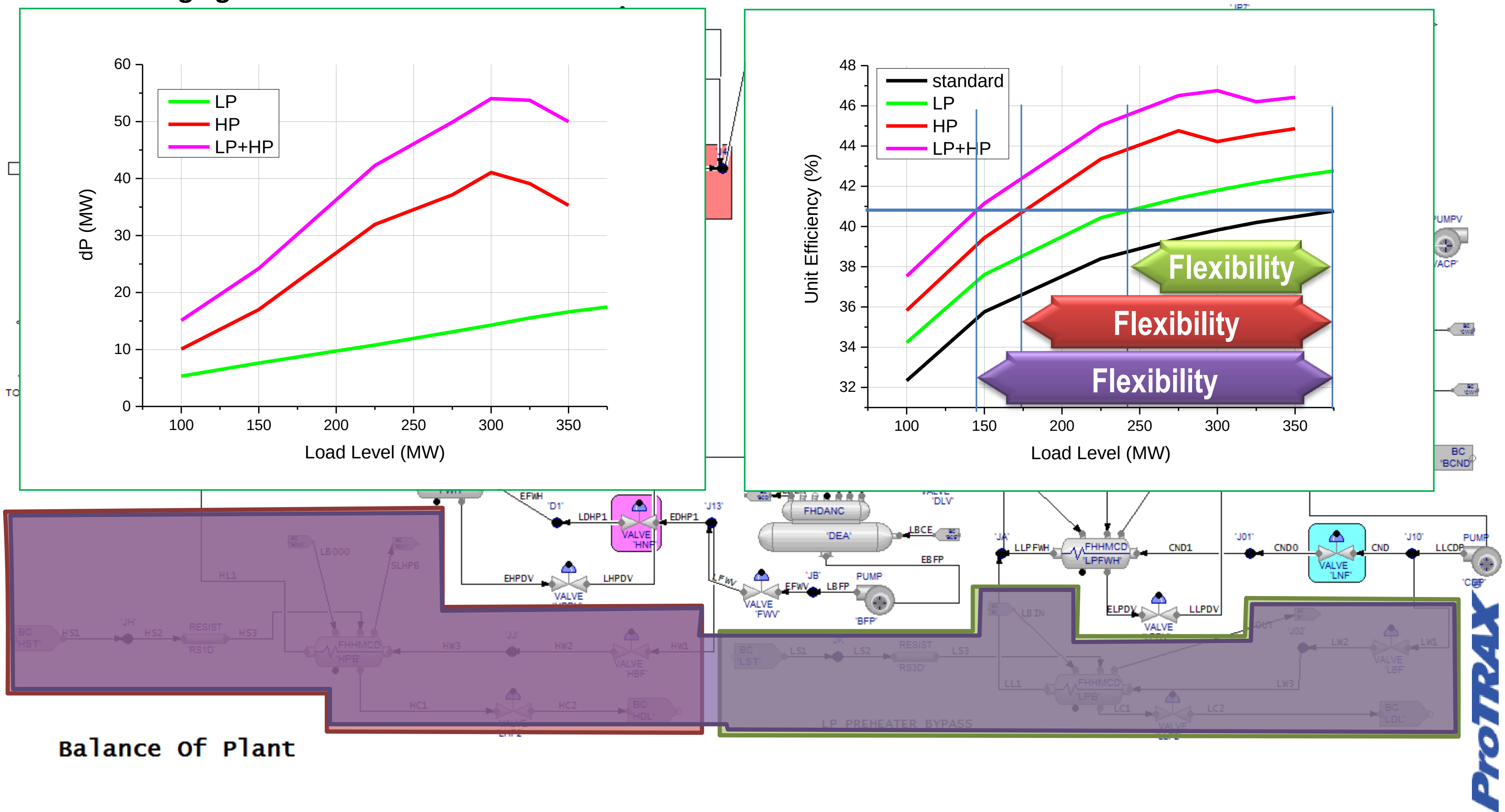
# *Progress – HTTS discharging*

## HTTS discharging results

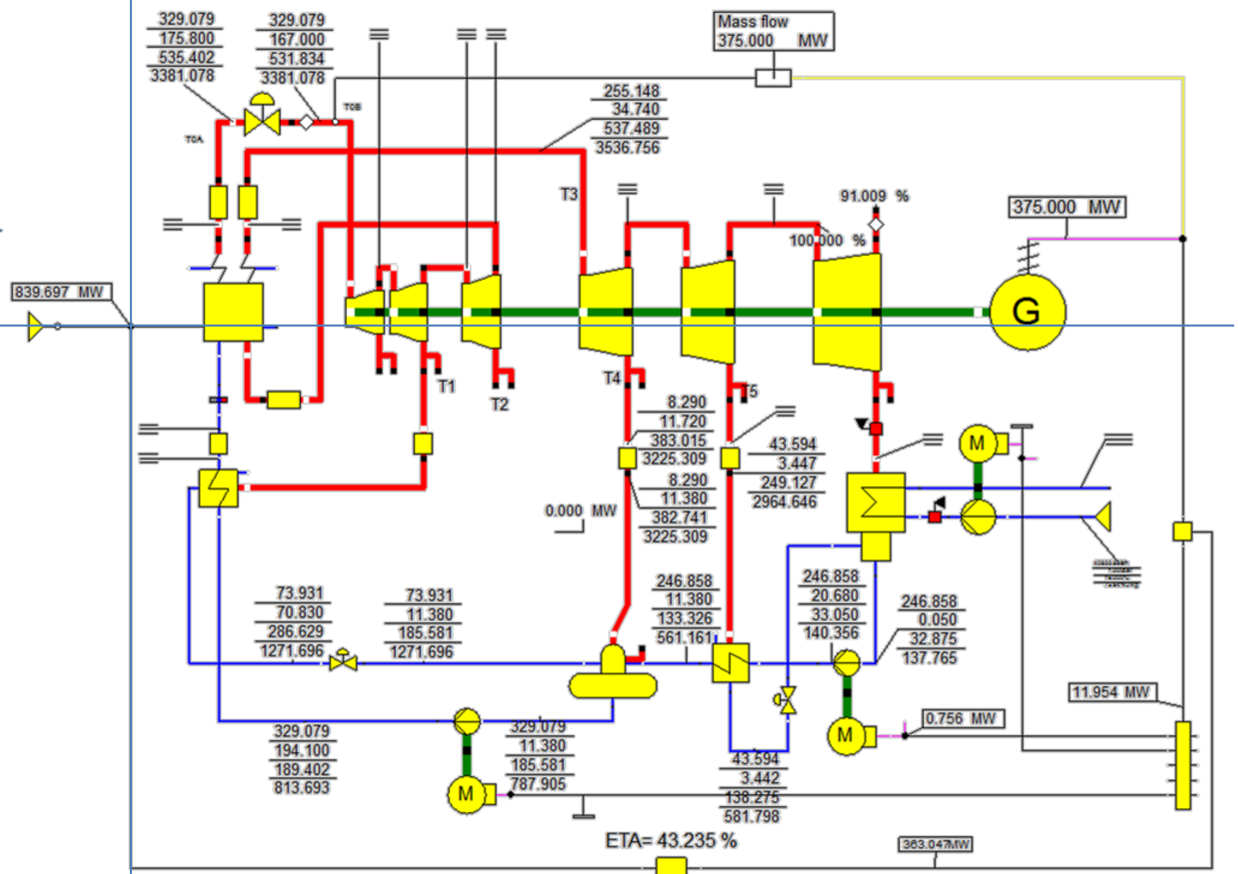


# *Progress – Modelling*


Pset 375.00 MW
Pgen 375.00 MW
dP -0.00 MW
eff 43.24 %
Pfuel 839.70 MW
Ptot 363.05 MW

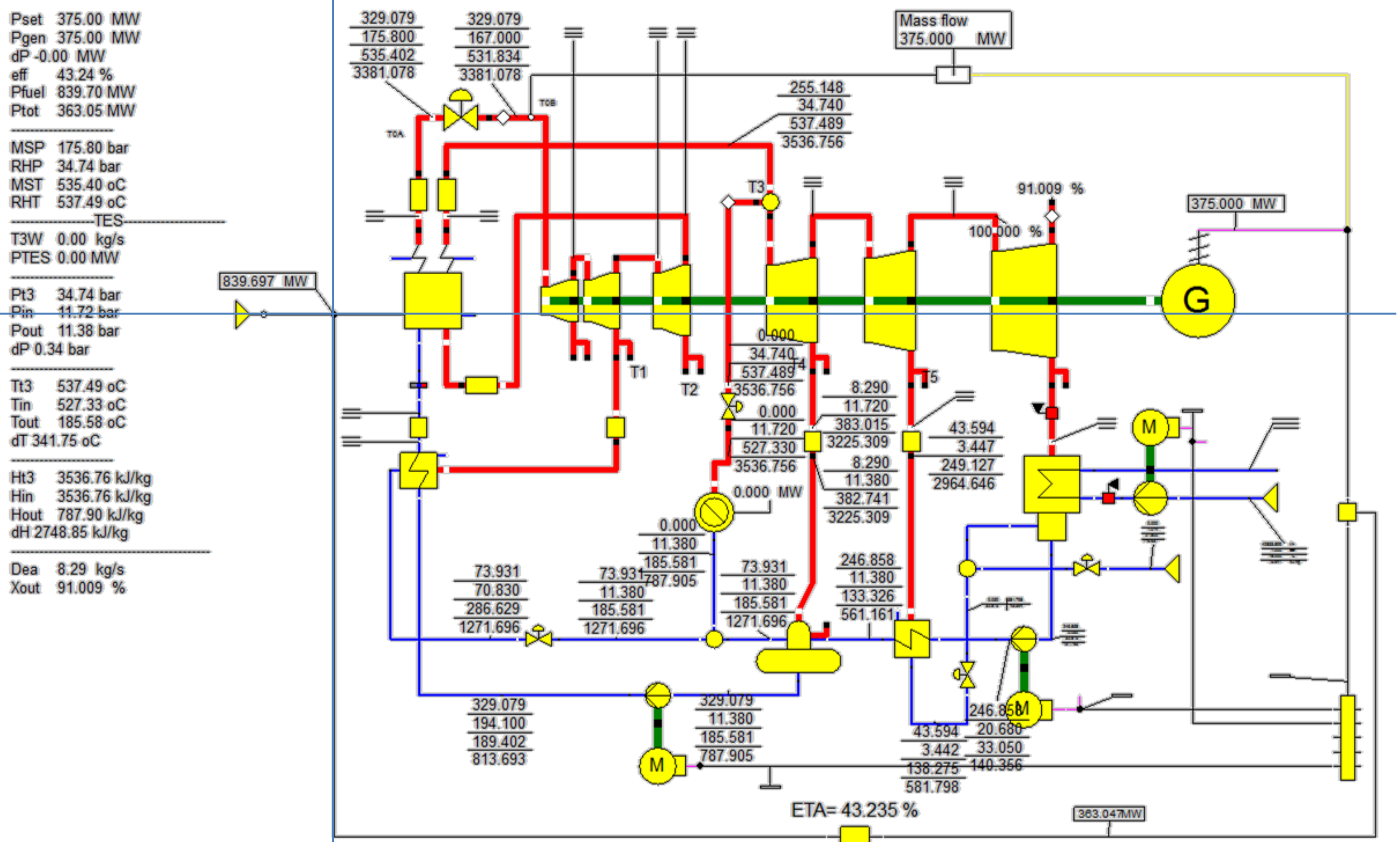
MSP 175.80 bar
RHP 34.74 bar
MST 535.40 oC
RHT 537.49 oC

Dea 8.29 kg/s
Xout 91.009 %



# *Progress – Modelling*

1. HTTS Charging (T3 – DEAE)

## *Progress – Modelling*

2. HTTS Charging (T3 – COND)


Pset 375.00 MW
Pgen 375.00 MW
dP -0.00 MW
eff 43.24 %
Pfuel 839.70 MW
Ptot 363.05 MW

MSP 175.80 bar
RHP 34.74 bar
MST 535.40 oC
RHT 537.49 oC

TES

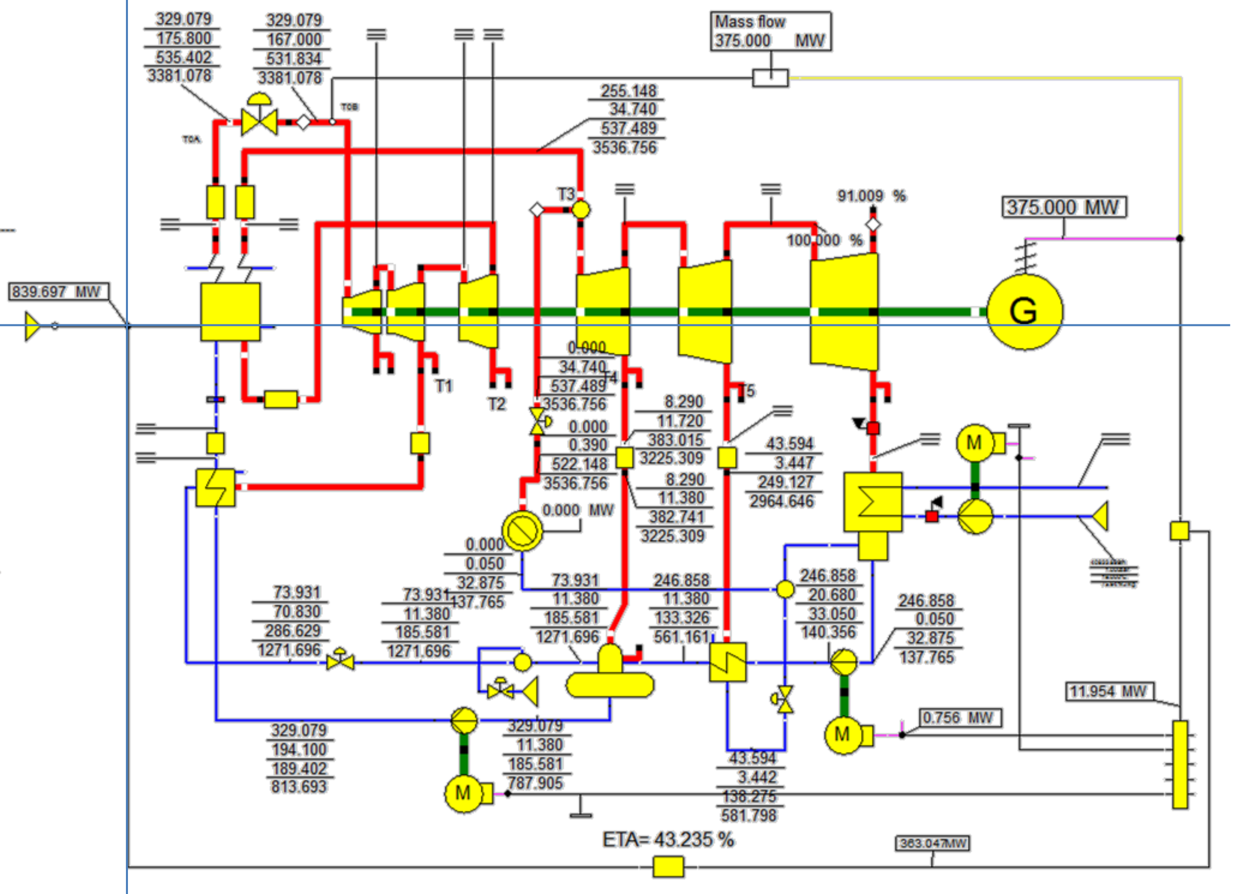
T3W 0.00 kg/s
PTES 0.00 MW

Pt3 34.74 bar
Pin 0.39 bar
Pout 0.05 bar
dP 0.34 bar

Tt3 537.49 oC
Tin 522.15 oC
Tout 32.88 oC
dT 489.27 oC

Ht3 3536.76 kJ/kg
Hin 3536.76 kJ/kg
Hout 137.77 kJ/kg
dH 3398.99 kJ/kg

Dea 8.29 kg/s
Xout 91.009 %

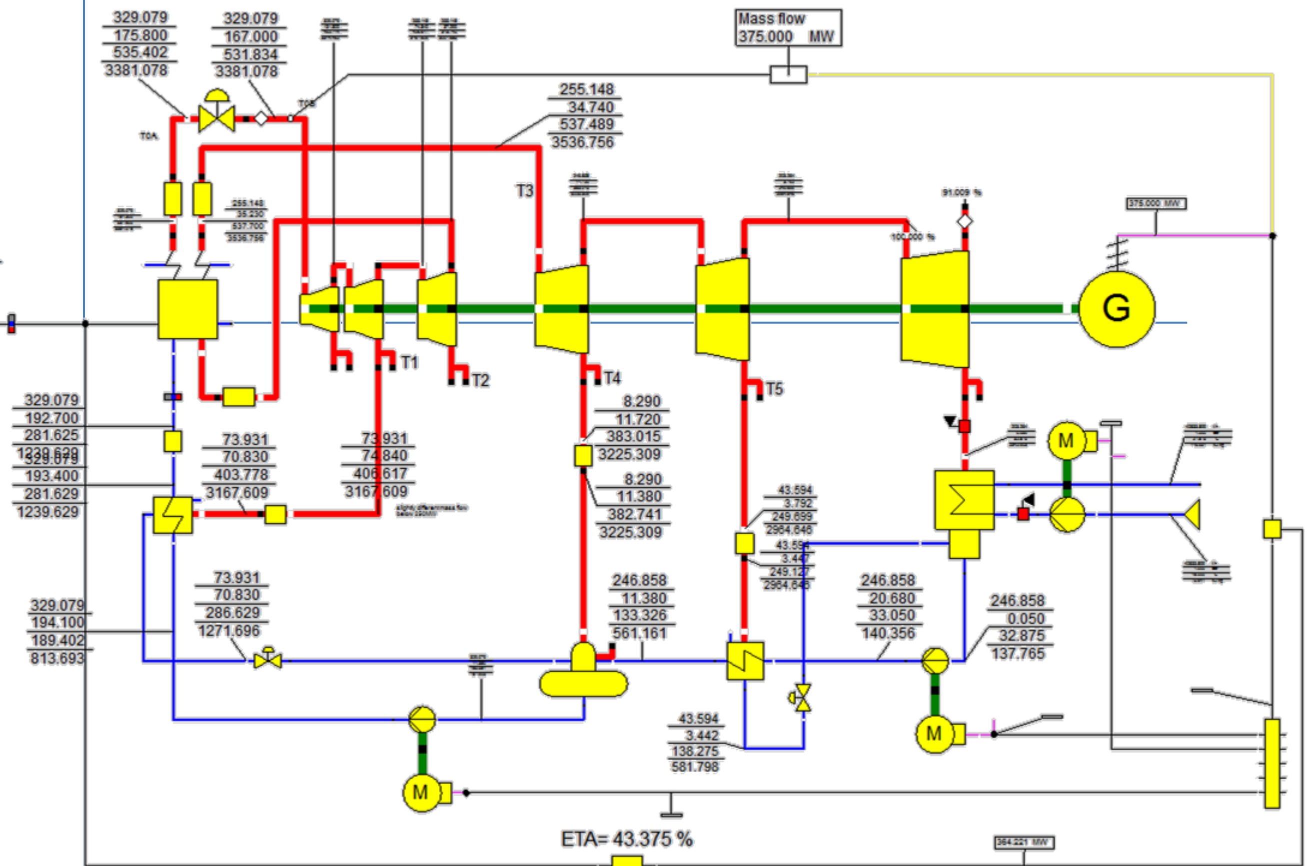


3. HTTS Discharging


Pset 375.00 MW
Pgen 375.00 MW
dP -0.00 MW
eff 43.38 %
Pfuel 839.70 MW
Ptot 364.22 MW

MSP 175.80 bar
RHP 34.74 bar
MST 535.40 oC
RHT 537.49 oC

Dea 8.29 kg/s
Xout 91.009 %



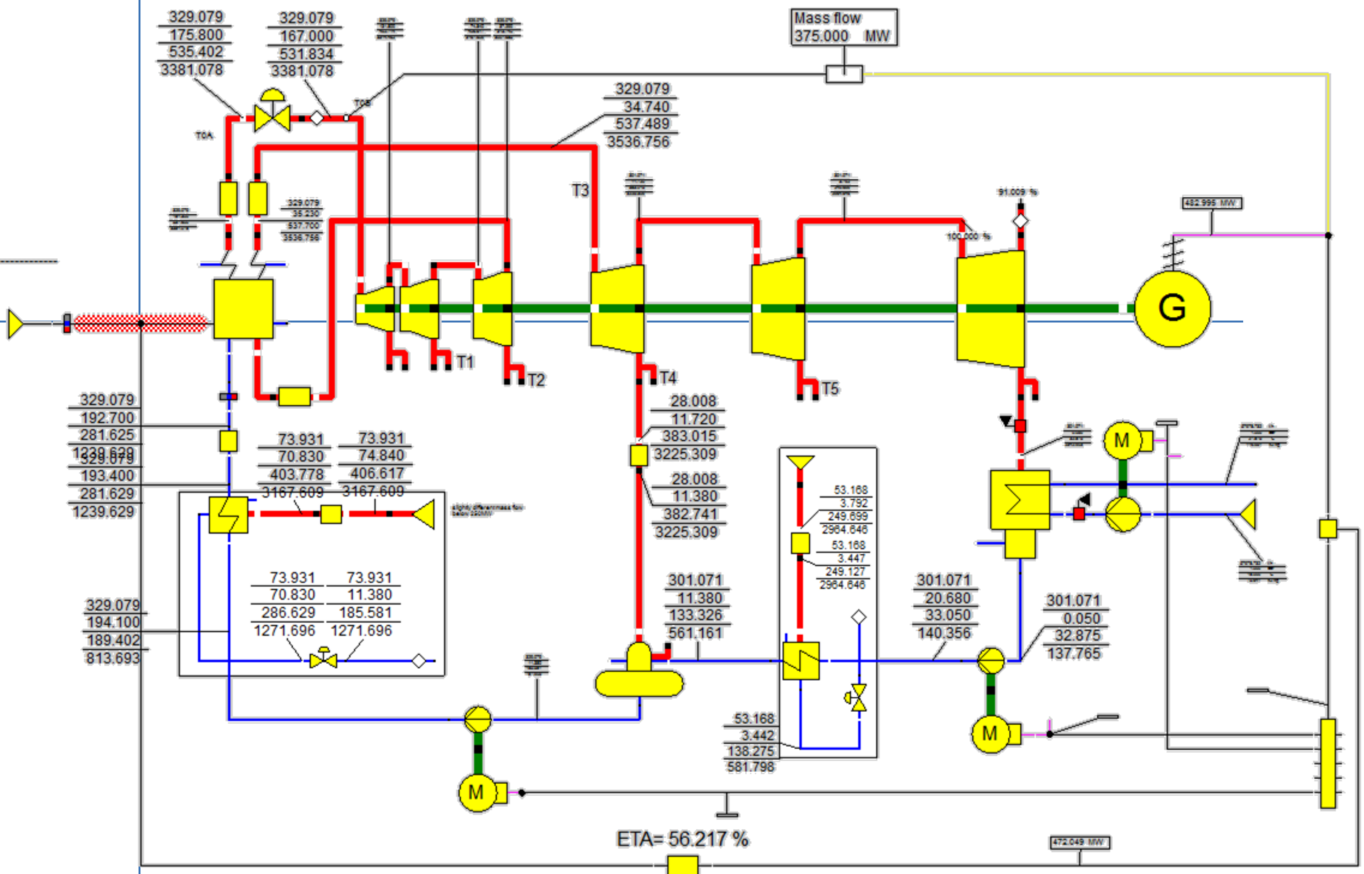
## *Progress – Modelling*

3. HTTS Discharging


Pset 375.00 MW
Pgen 482.99 MW
dP -107.99 MW
eff 56.22 %
Pfuel 839.70 MW
Ptot 472.05 MW

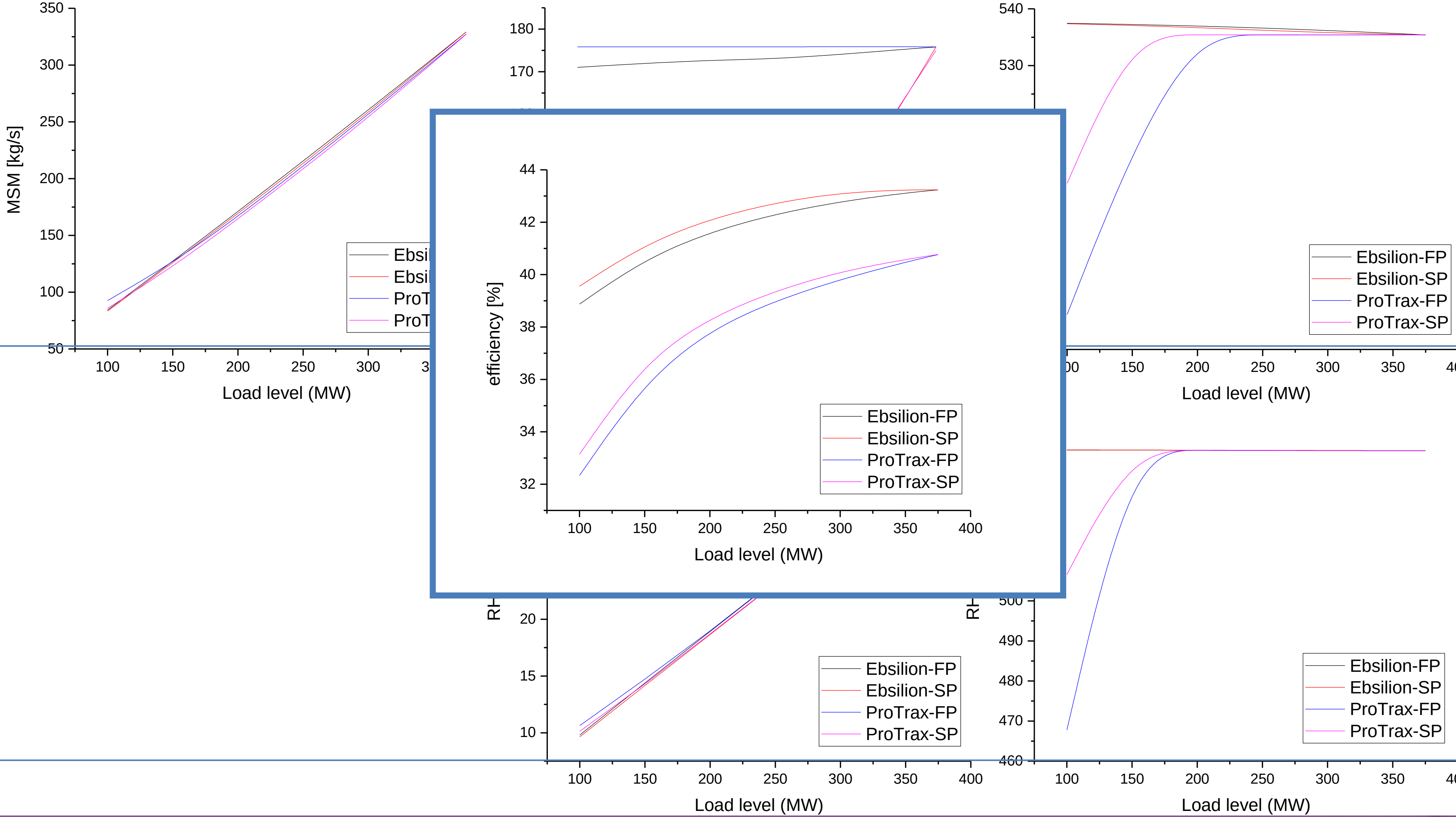
MSP 175.80 bar
RHP 34.74 bar
MST 535.40 oC
RHT 537.49 oC

Dea 28.01 kg/s
Xout 91.009 %



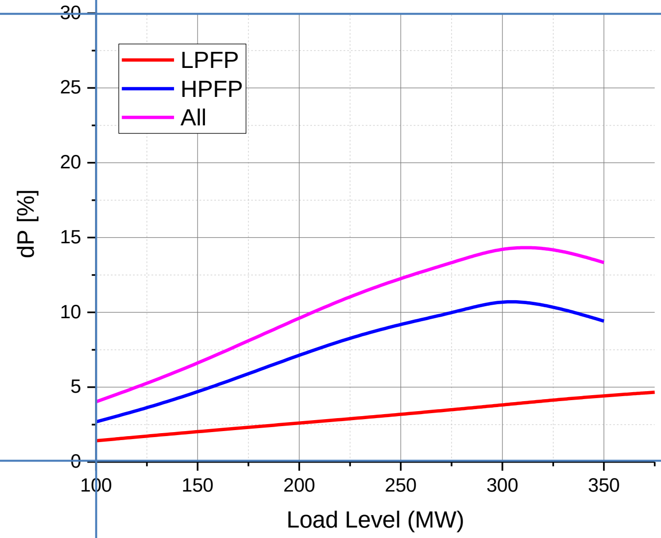
# *Progress – Modelling*

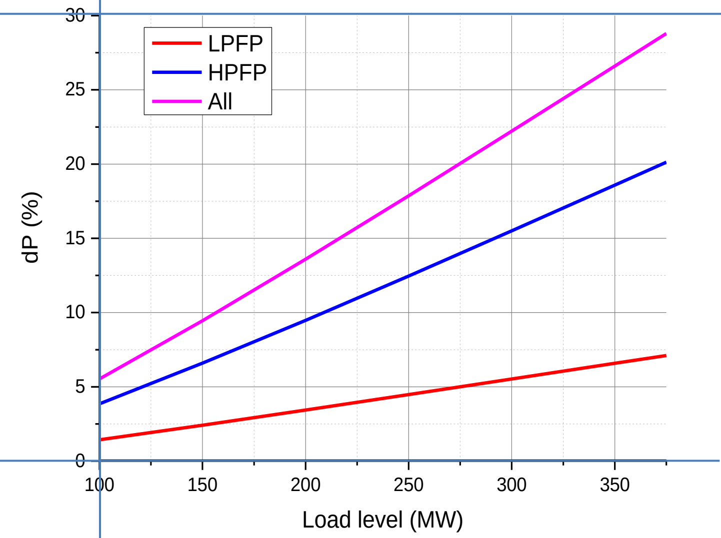
**ProTRAX® vs EBSILON®Professional** Plant engineering and design

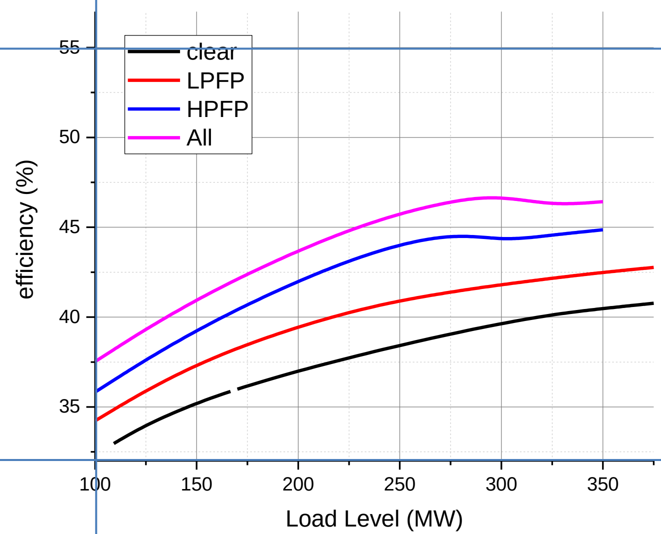


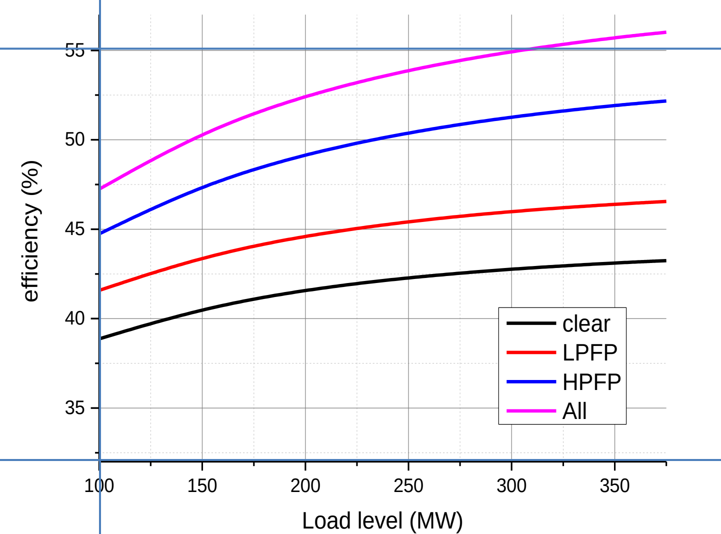
# Progress – Modelling ProTRAX® vs EBSILON®Professional

Plant engineering and design



## *Conclusions & Future plans*

**Conclusions:**

•It is feasible to integrate HTTS into power plant steam cycle with no request of changing the steam cycle.
•The steam taken to HTTS charging process should be quickly returned back to the process loop.
•There is a limit for how much heat can be extracted from the steam cycle and depends on the extraction point.
•**Power plant control system mode has influence on HTF parameters to HTTS system**
•**Steam condensation in HTTS heat exchangers highly increase efficiency in HTTS charging process**
•The main restrictions in operating range are the results of:

- MST and RHT temperature variations
- Negative steam flow from deaerator to turbine
- Maximum flow through HTTS valve (max valve conductivity)

•The size and scale requirements for thermal energy storage systems have been initially assessed
•Simulations are being developed for the different storage approaches.

**Future plans:**

- ❑ **HTTS integration article submission**
- ❑ HTTS tank model implementation (ProTRAX / Ebsilon / MATLAB software)
- ❑ Entire power plant cycle efficiency with HTTS
- ❑ Dynamic HTTS simulations
- ❑ HTTS feasibility study for existing power plants
- ❑ Comparison between subcritical and supercritical power plant with HTTS