A New Concept to Designing a Combined Cycle Cogeneration Power Plant

Dr. Leonid Moroz – Presenter, Dr. Boris Frolov, Dr. Maksym Burlaka

PLAN

1. Introduction
2. Conventional Steam Cogeneration Plant
3. Synthesis of the S-CO2 Technology with CHP Principles
4. Study methodology

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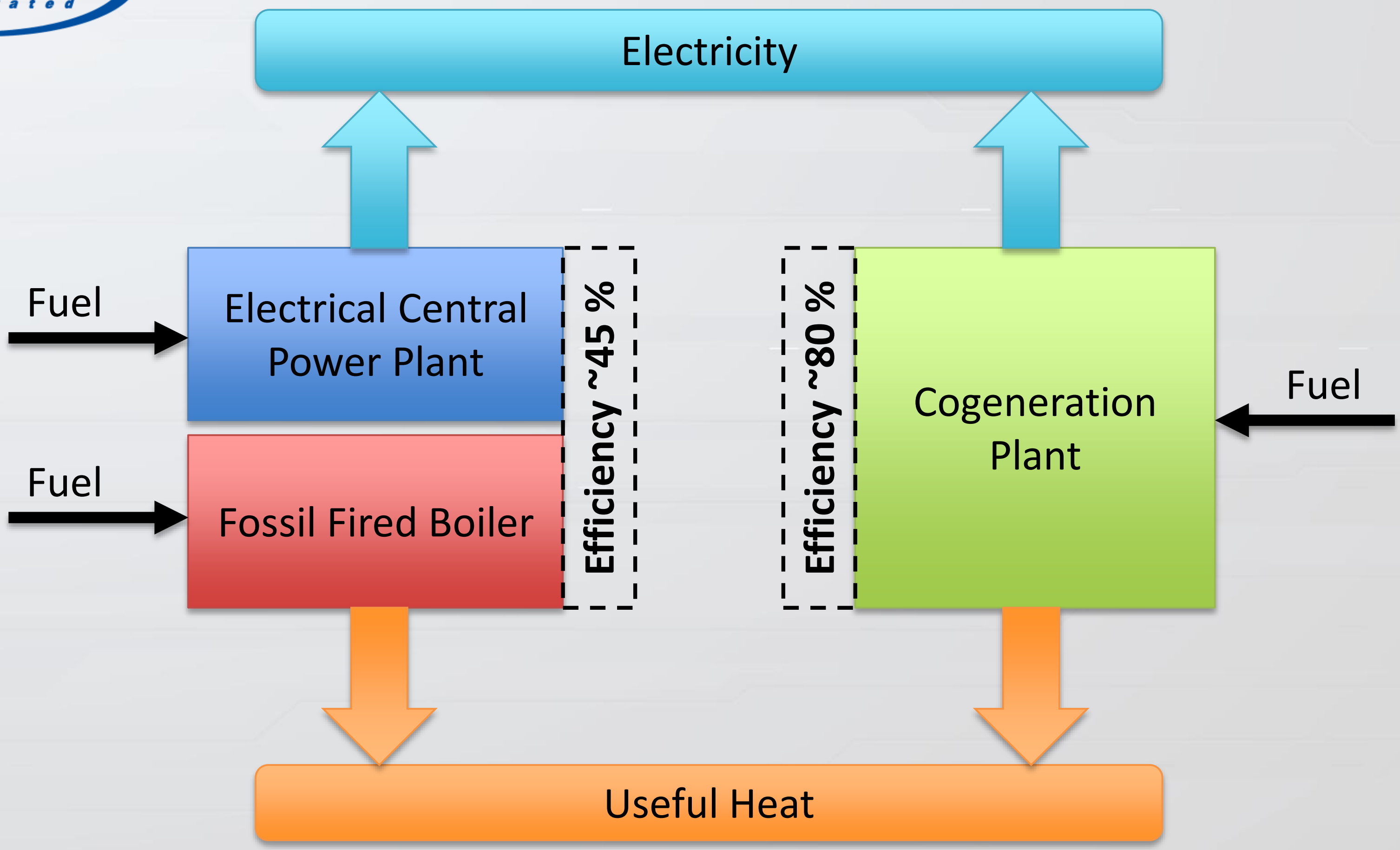
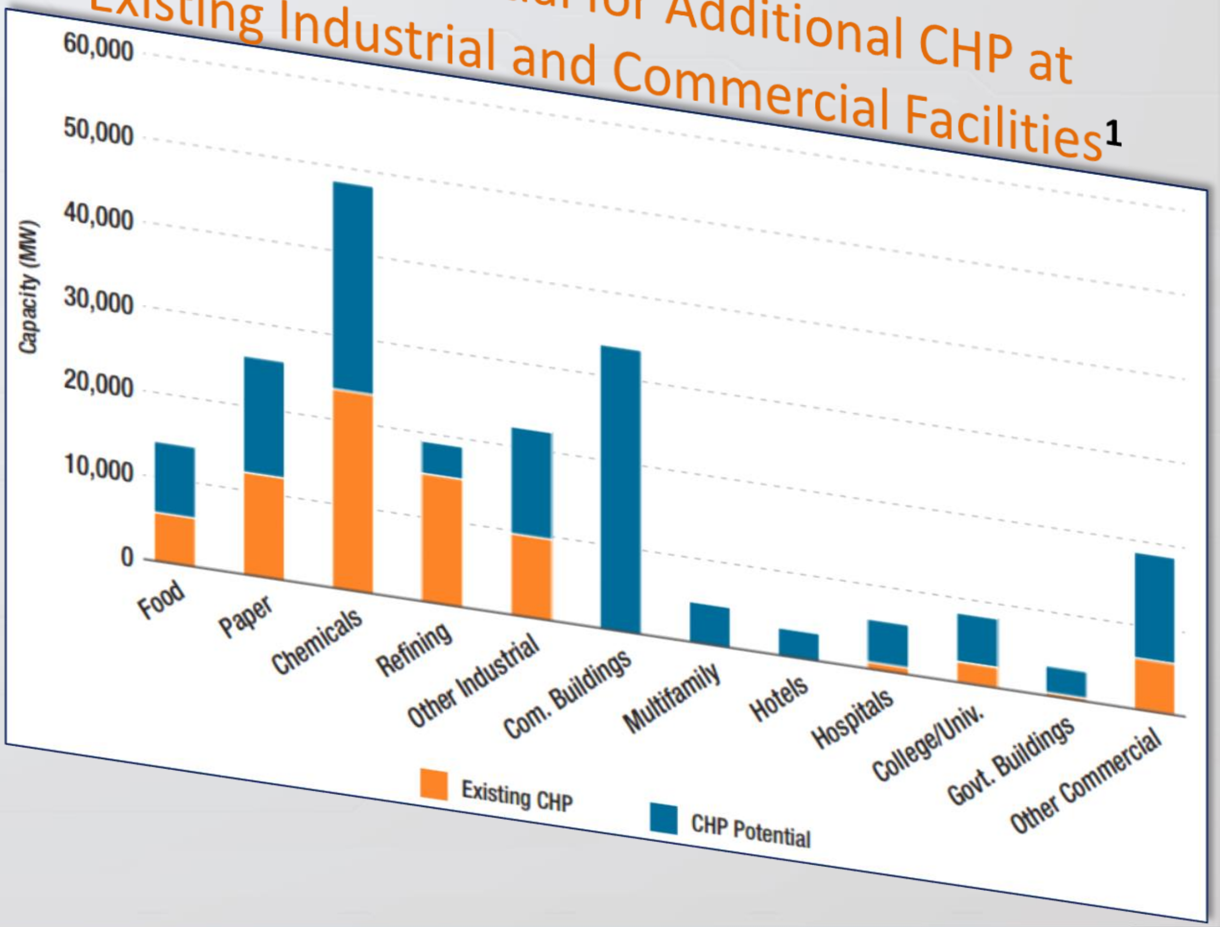
5. Combined Complex Steam-S-CO2 CHP Plant Analysis
6. Cascaded Supercritical CO2 CHP Plant Analysis
7. Total Dimensions Difference Comparison
8. Conclusions

1. Introduction


Electricity
Fuel
Electrical Central Power Plant
Fuel
Fossil Fired Boiler
Efficiency ~45 %
Efficiency ~80 %
Cogeneration Plant
Fuel
Useful Heat

Technical Potential for Additional CHP at Existing Industrial and Commercial Facilities[1]



Internal estimates by ICF International and CHP Installation Database developed by ICF International for Oak Ridge National Laboratory and the DOE; 2012

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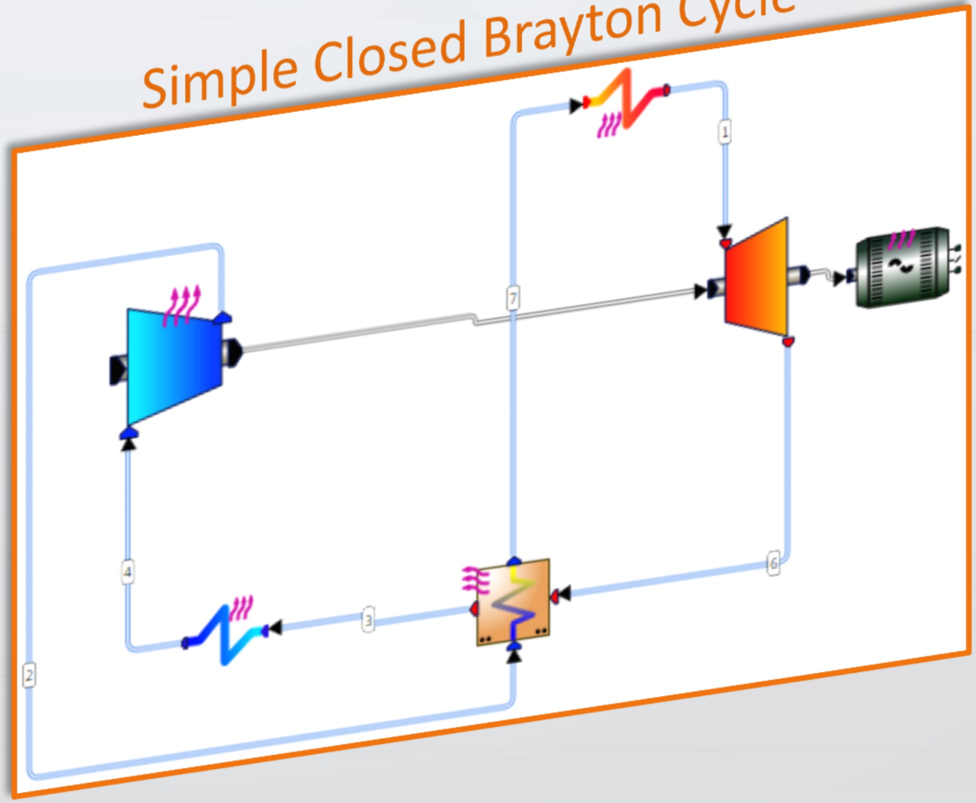
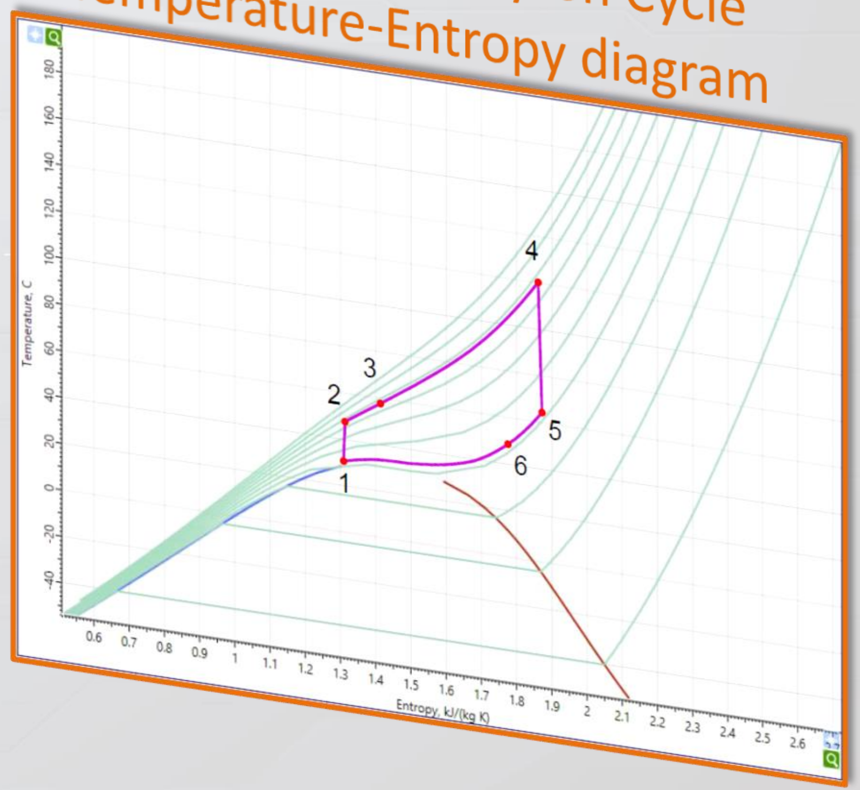
Simple Closed Brayton Cycle



Simple Closed Brayton Cycle Temperature-Entropy diagram



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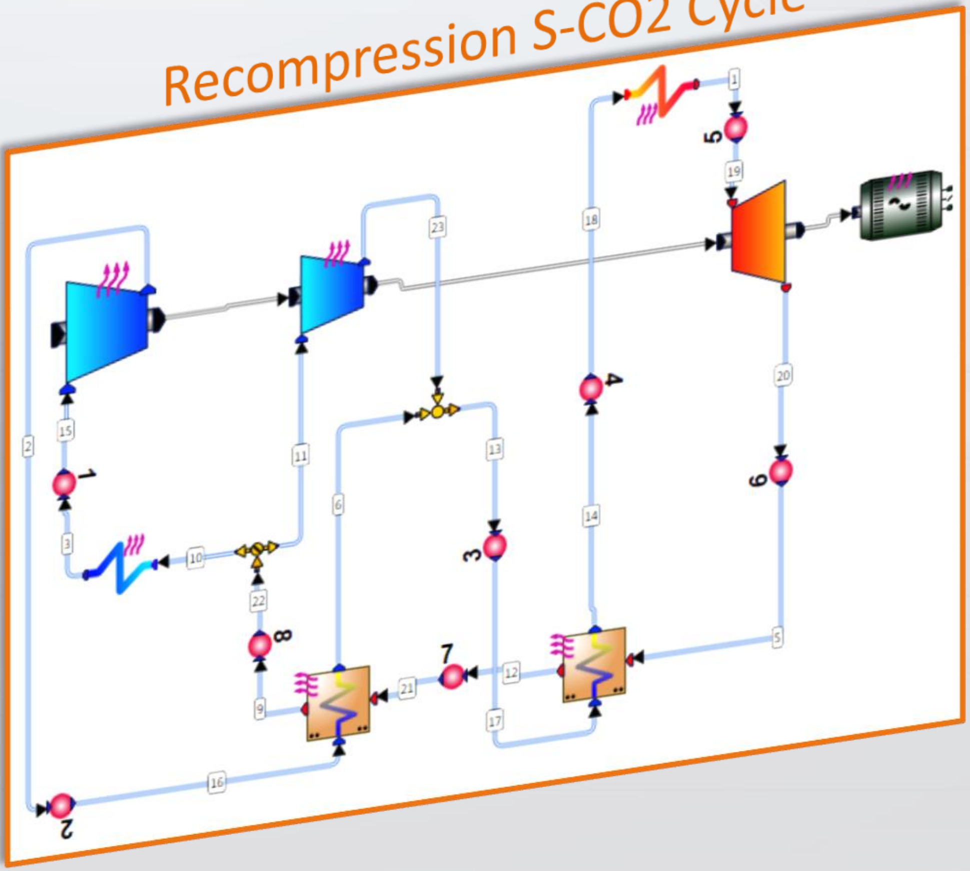
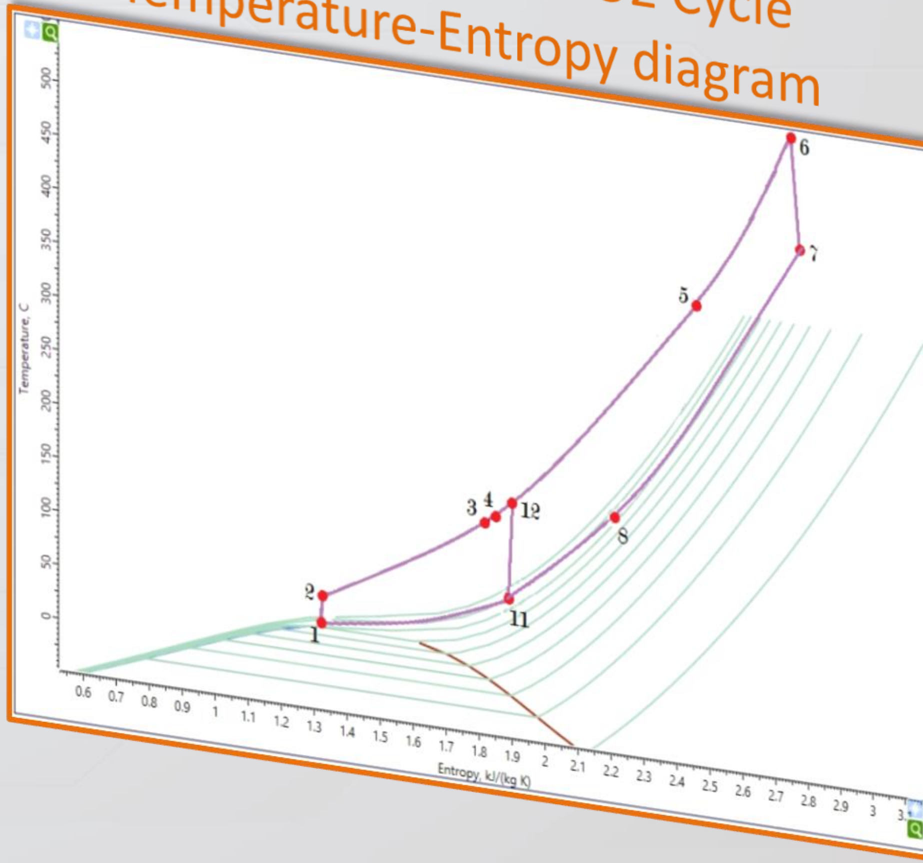
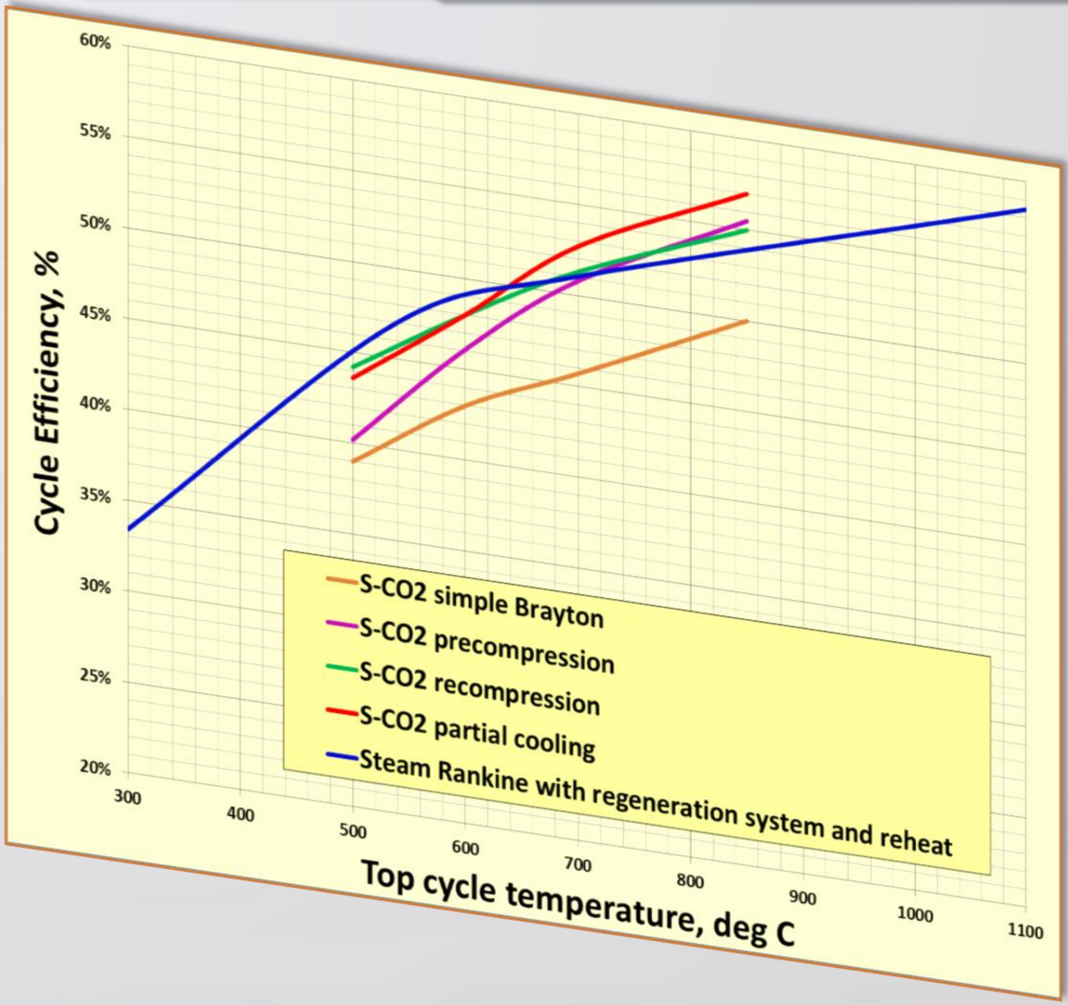
Recompression S-CO2 Cycle



Recompression S-CO2 Cycle Temperature-Entropy diagram

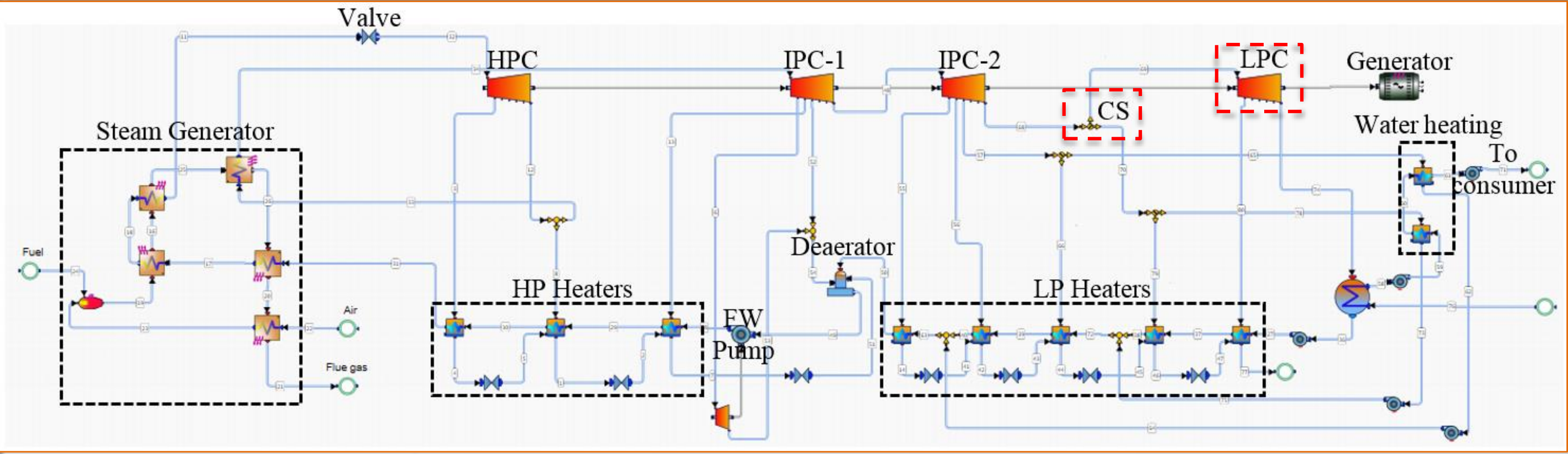


Cycle Efficiency Dependencies of different S-CO2 cycles and Steam Rankine cycle from live fluid temperature



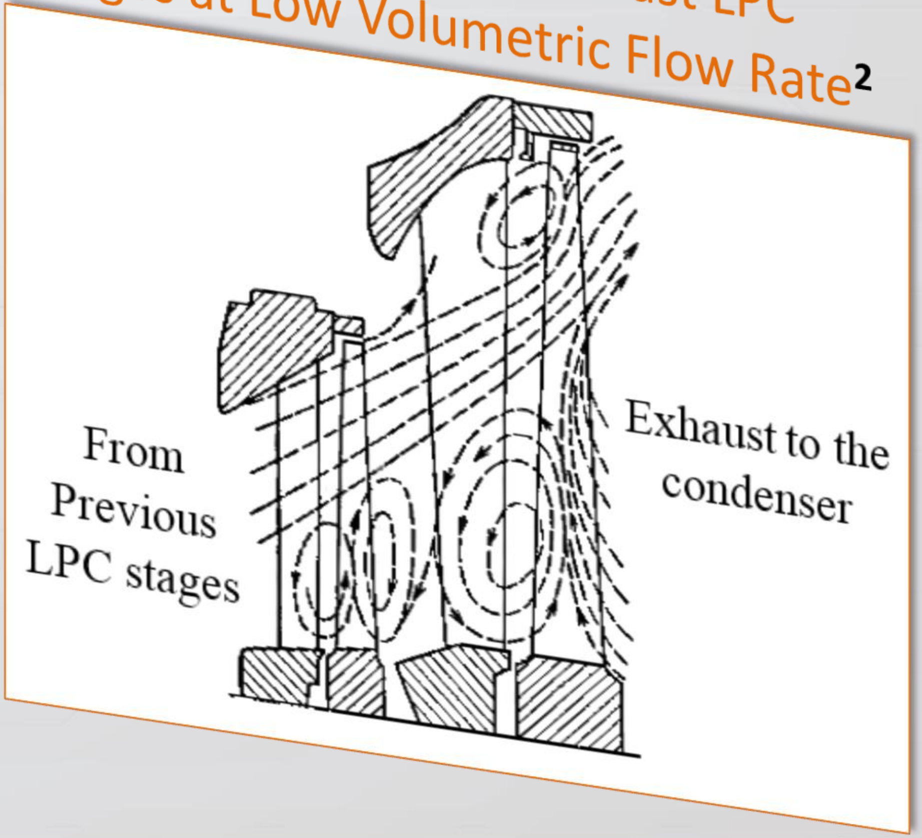
2. Conventional Steam Cogeneration Plant

Schematic Flow Diagram of T-250/300-23.5 CHP unit



Flow Structure in the Last LPC Stages at Low Volumetric Flow Rate[2]

- Flow separations near hub and tip at low mass flow rate
- Part of the main flow energy is lost
- Captured energy dissipates into the heat, which, in turn, increases the temperature of the LPC flow path



3. Synthesis of the S-CO2 Technology with CHP Principles

1

Steam Rankine cycle CHP plant with bottoming supercritical CO2 cycle

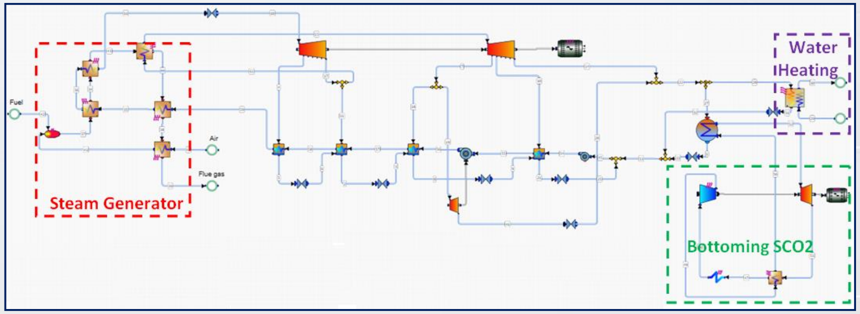
- **Embodiment a.** Combined Complex Steam-S-CO2 CHP Plant
- **Embodiment b.** Combined Simple Steam-S-CO2 CHP Plant

2

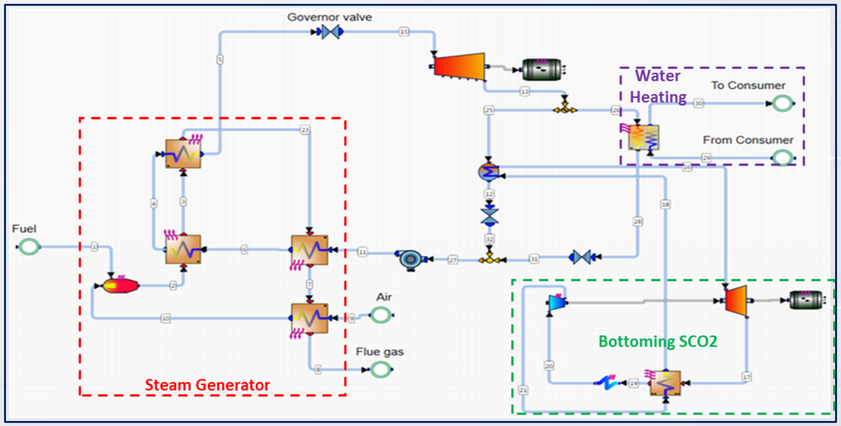
CHP plant with single supercritical CO2 working fluid

- **Embodiment a.** Cascaded Supercritical CO2 CHP Plant
- **Embodiment b.** Single Supercritical CO2 CHP Plant

Embodiment 1a
Combined Complex
Steam-SCO2 CHP Plant

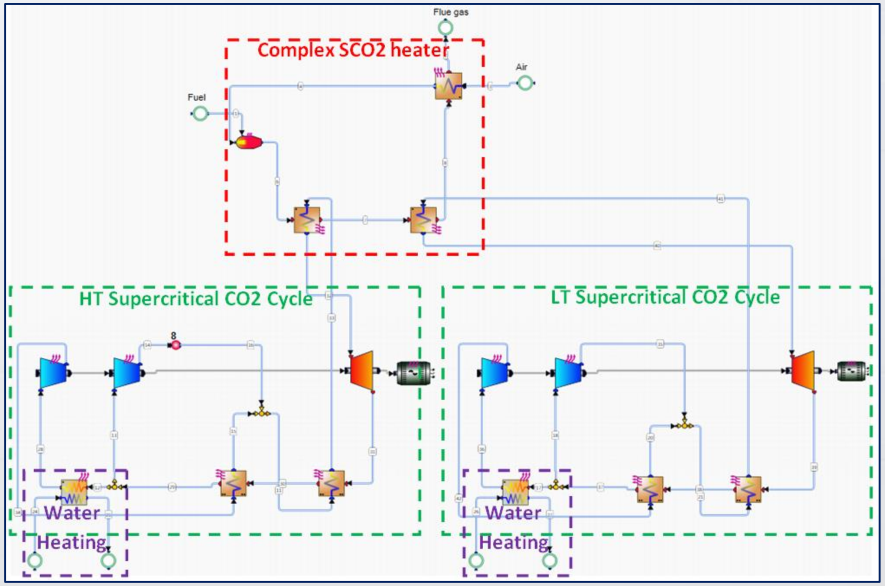


	Parameter	Value
Steam part		
1	Live steam pressure, MPa	23.5
2	Live steam temperature, °C	540
3	Back pressure, MPa	0.2
4	Constant net electrical power production, MW	252.3
Bottoming SCO2 part		
5	Compressor outlet pressure, MPa	15
6	Maximum supercritical CO2 temperature , °C	120
7	CO2 cycle lower pressure, MPa	7.7
8	CO2 temperature after the cooler, °C	32



Embodiment 1b
Combined Simple Steam-SCO2 CHP Plant

	Parameter	Value
	Steam part	
1	Live steam pressure, MPa	23.5
2	Live steam temperature, °C	540
3	Pressure at steam turbine outlet, MPa	3
4	Constant net electrical power production, MW	140.4
	Bottoming SCO2 part	
5	Compressor outlet pressure, MPa	25
6	Maximum supercritical CO2 temperature , °C	225
7	CO2 cycle lower pressure, MPa	7.7
8	CO2 temperature after the cooler, °C	32



Embodiment 2a
Cascaded SCO2 CHP Plant

	Parameter	HT cycle	LT cycle
1	Live CO2 temperature, °C	540	300
2	Maximum cycle pressure, MPa	21	20
3	Lower cycle pressure, MPa	7.7	7.7
4	CO2 temperature at LT recuperator outlet, °C	115	110
5	Temperature at CO2 cooler (water heater) outlet, °C	37	37
6	Net electrical power production, MW	297.7	13.9
7	Hot water temperature, °C	100	

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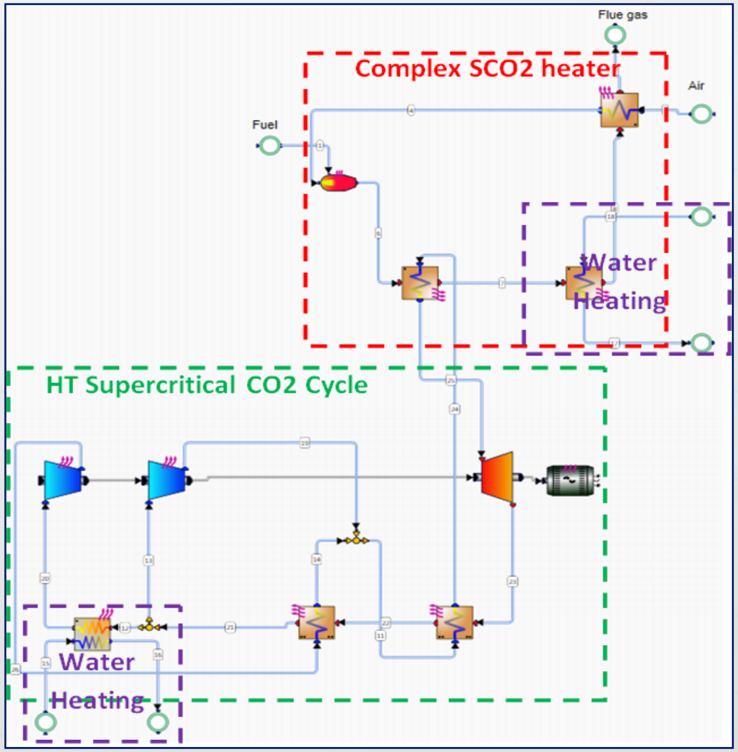


Embodiment 2b
Single SCO2 CHP Plant

	Parameter	HT cycle
1	Live CO2 temperature, °C	540
2	Maximum cycle pressure, MPa	21
3	Lower cycle pressure, MPa	7.7
4	CO2 temperature at LT recuperator outlet, °C	115
5	Temperature at CO2 cooler (water heater) outlet, °C	37
6	Net electrical power production, MW	297.7
7	Hot water temperature, °C	100

Performances of the considered CHP plants

Parameter	Embodiment 1.a		Embodiment 1.b		Embodiment 2.a		Embodiment 2.b		T-250/300	
Heat load, %	0	100	0	100	0	100	0	100	0	100
Heat consumption, MW	789.998									
Net electrical power, MW	304.4	252.2	266.6	140.4	311.6	311.6	297.7	297.7	300	250
Useful heat, MW	-	494.6	-	607.6	-	421.0	-	436.2	-	384.1
Electrical efficiency, %	38.53	31.93	33.76	17.77	39.44	39.4	37.68	37.68	37.97	31.65
Heat utilization factor	0.385	0.945	0.338	0.947	0.394	0.927	0.364	0.929	0.380	0.803
Potential of Useful heat, MW	-	-	-	-	421.0	-	436.2	-	-	-

- $S\text{-}CO_2$ CHP plants have an advantage at moderate live fluid temperature – 540 °C
- The synthesis of the $S\text{-}CO_2$ and CHP technologies gives more benefit than pure electricity production $S\text{-}CO_2$ embodiments

4. Study methodology

Study methodology

Combined Complex Steam-SCO2 CHP Plant

Cascaded SCO2 CHP Plant

T-250/300-23.5 CHP unit

Evaluation of turbines and compressors, thermo/aerodynamic and structural analyses
- AxSTREAM™

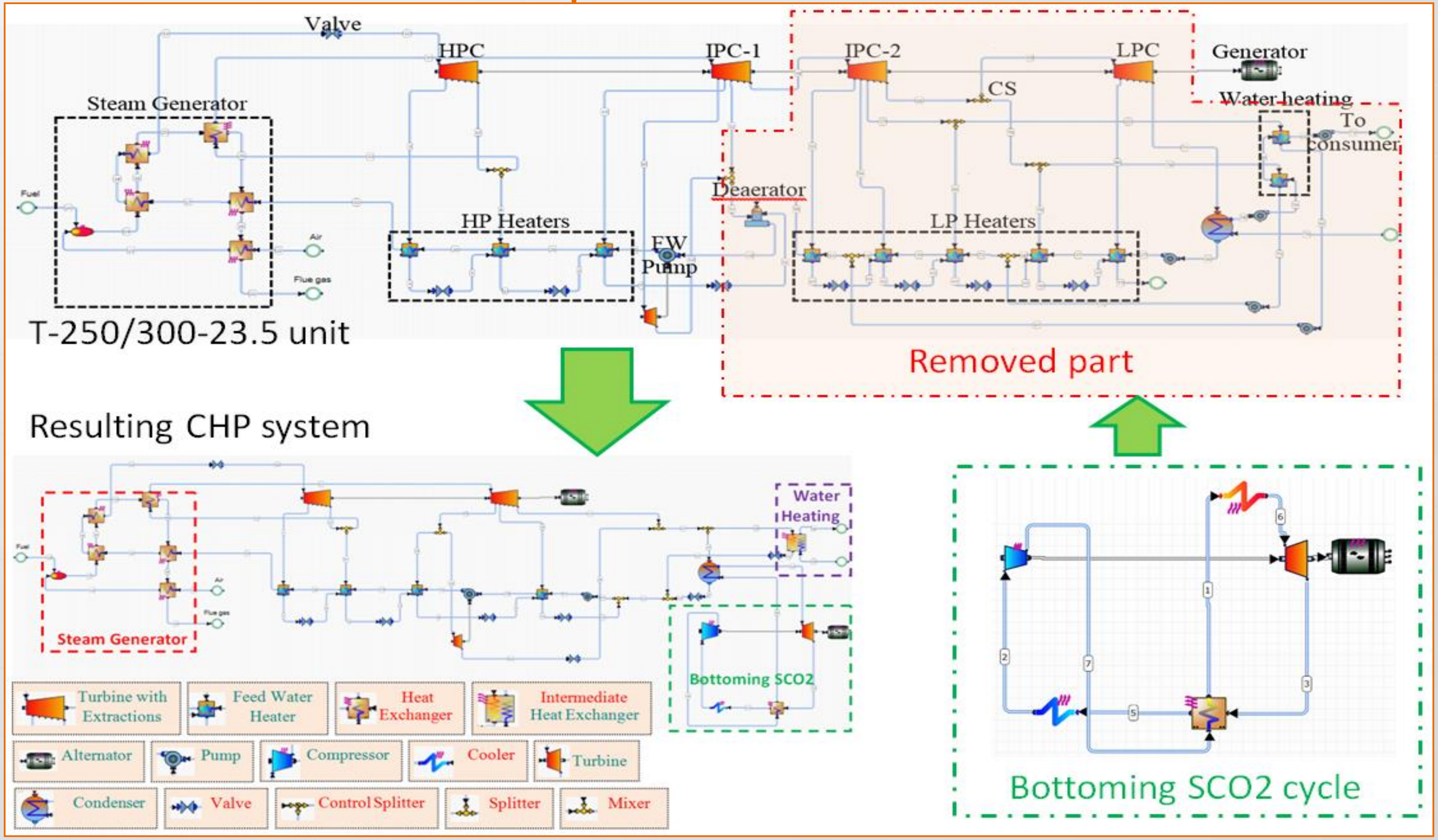
Thermodynamic analysis, heat balance calculations
- AxCYCLE™
- RefProp

Evaluation of heat exchangers design
- General approaches and methodic

Plant Total Volume Comparison

5. Combined Complex Steam-S-CO2 CHP Plant Analysis

Combined Complex Steam-SCO2 CHP Plant



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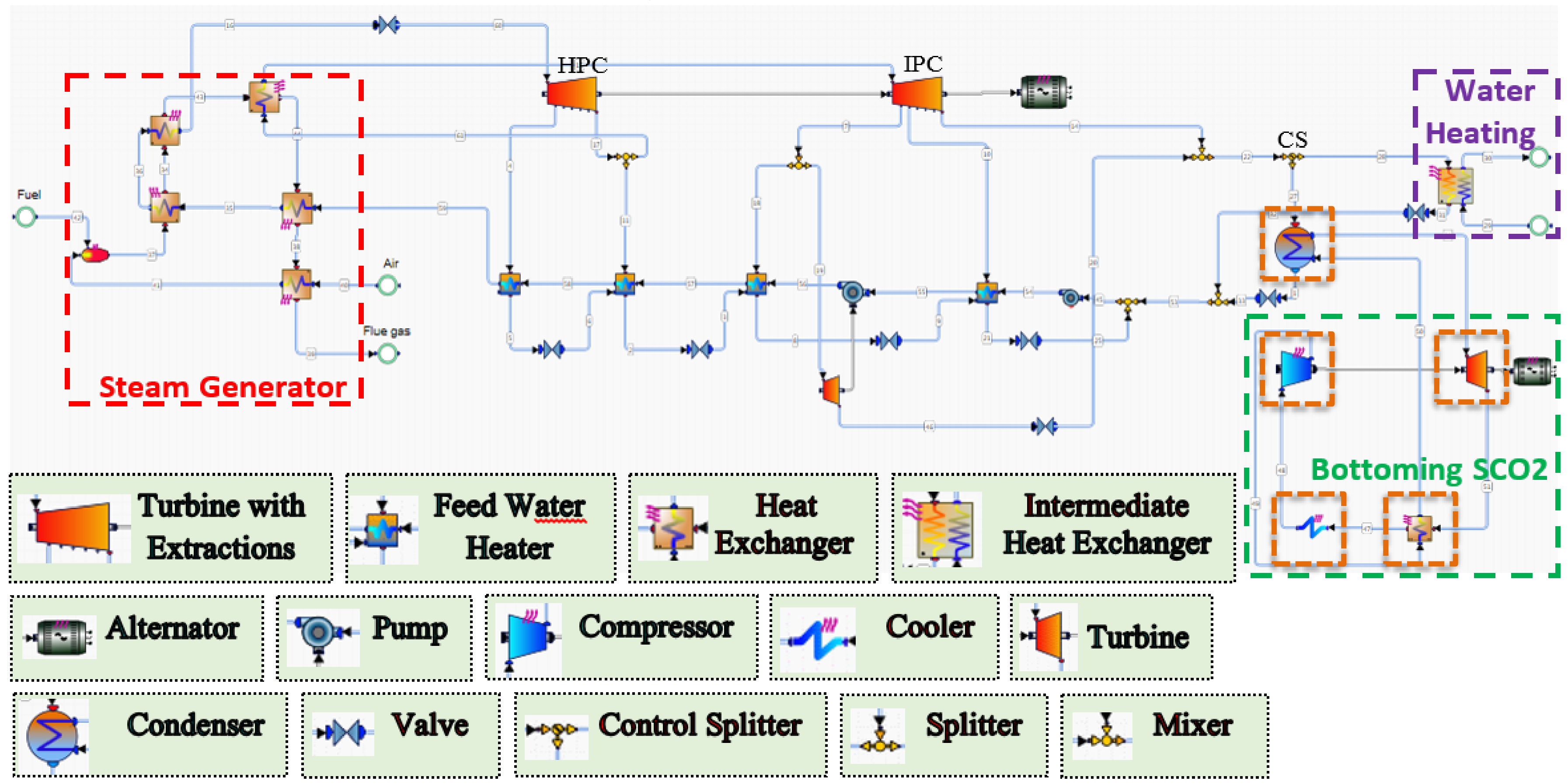
Combined Complex Steam-SCO2 CHP Plant

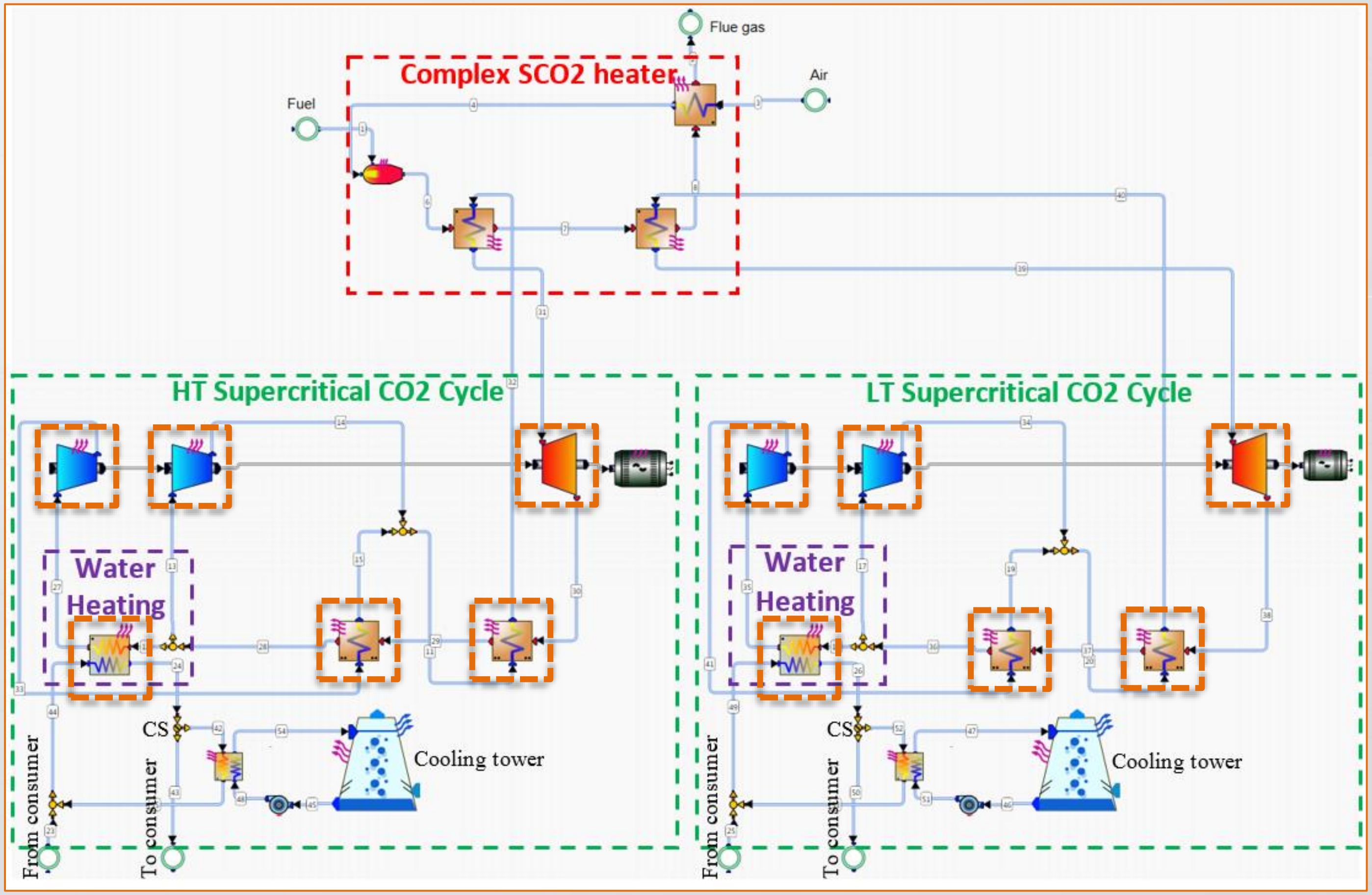


Combined Complex Steam-SCO2 CHP Plant Dimensions: Bottoming S-CO2 cycle components

Parameter	Turbine	Compressor	Recuperator	Cooler	Condenser
Type	Reaction	Centrifugal	Shell&tube	Shell&tube	Shell&tube
Estimated dimensions, m	D1.4*L1.4	D2.4*L0.5	D3.3*L12.8	D2.7*L11.9	D2.5*L9.3
Volume, m3	2.2	2.3	109.5	68.1	45.7
Total volume, m3	227.7				

6. Cascaded Supercritical CO2 CHP Plant Analysis

Cascaded Supercritical CO2 CHP Plant



HT Cycle of the Cascaded Supercritical CO2 CHP Plant Dimensions

Parameter	Turbine	Main Compressor	Recompressor	High temperature recuperator	Low temperature recuperator	Water heater
Type	Reaction type	Centrifugal	Centrifugal	Shell&tube	Shell&tube	Shell&tube
Estimated dimensions, m	D1.6*L4.0	D2.5*L0.5	D5.0*L0.8	D3.5*L13.2	D3.3*L11.9	D2.2 *L10.9
Volume, m3	8.0	2.5	15.7	127.0	101.8	41.4
Total volume, m3	296.4					

LT Cycle of the Cascaded Supercritical CO2 CHP Plant Dimensions

Parameter	Turbine	Main Compressor	Recompressor	High temperature recuperator	Low temperature recuperator	Water heater
Type	Impulse type	Axial	Axial	Shell&tube	Shell&tube	Shell&tube
Estimated dimensions, m	D0.7*L1.6	D0.5*L0.5	D0.8*L0.8	D1.3*L8.5	D1.9*L9.1	D1.3 *L9.3
Volume, m3	0.6	0.1	0.3	11.3	25.8	12.2
Total volume, m3	50.5					

7. Total Dimensions Difference Comparison

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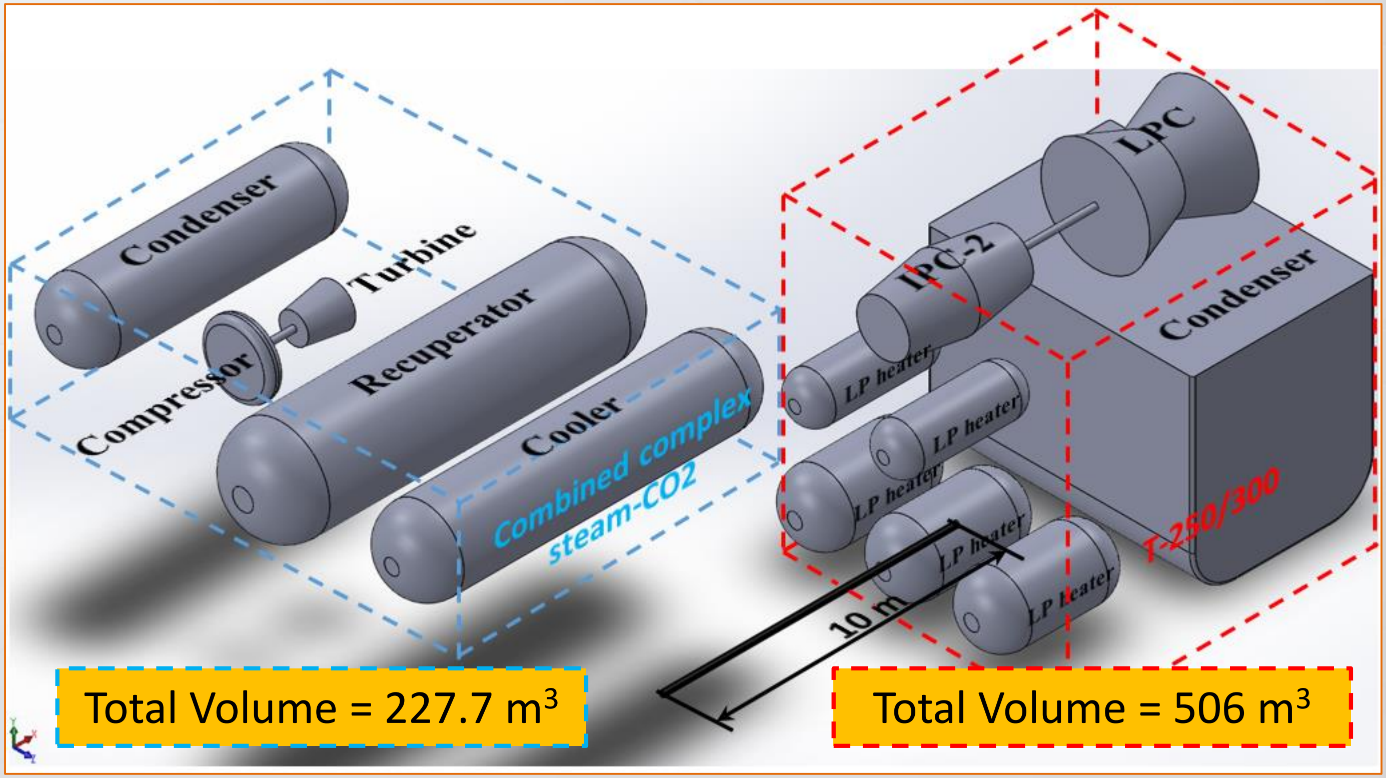
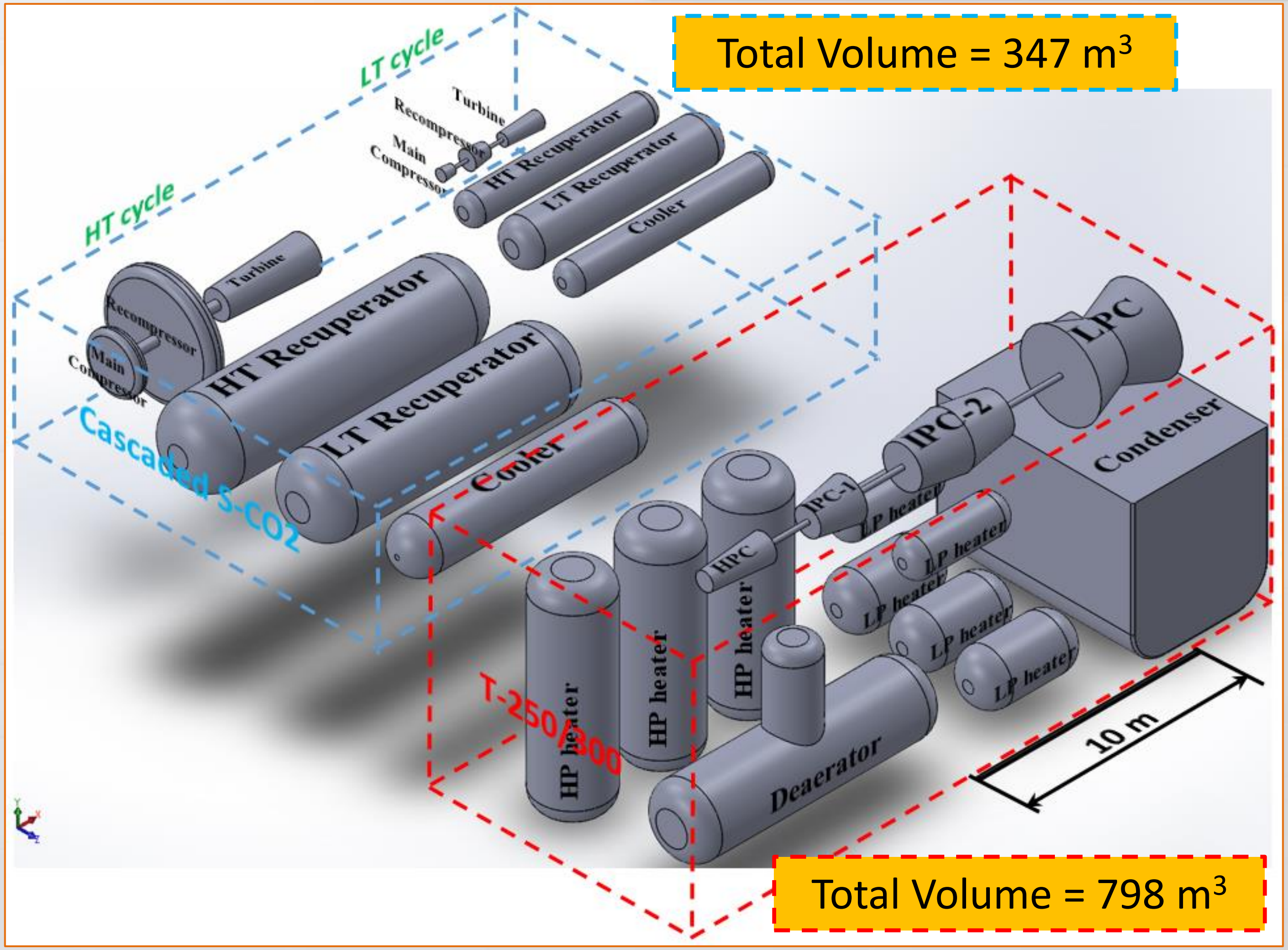
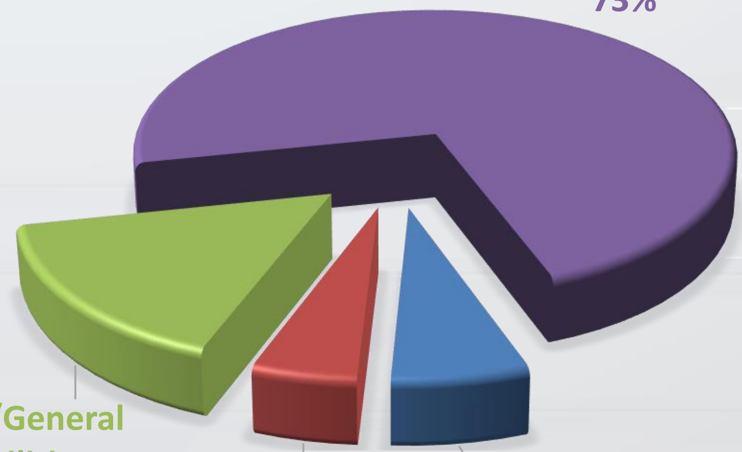
Comparison of the interchangeable components dimensions between the Combined Complex Steam-SCO2 and the T-250/300



Comparison of the Cascaded S-CO2 CHP plant 3D layout with the T-250/300 CHP plant 3D layout



Costs for 300 MW Pulverized Coal Power Plant[3]



Conceptual Cost Estimate Summary Coal ->	U.S. PRB (thousands $)
Earthwork/Civil	52,600
Structural Steel	29,400
Mechanical Equipment	
Boiler	113,400
Steam Turbine	40,200
Coal Handling	38,200
Ash Handling	13,400
Particulate Removal System	17,800
Wet Flue Gas Desulfurization (FGD) System	61,800
Selective Catalytic Reduction	26,400
Total Mechanical Equipment	311,200
Electrical	47,200
Piping	32,000
BOP/General Facilities	130,400
Direct Field Cost	602,800
Indirect Costs[1]	46,000
Engineering and Home Office Costs[2]	62,600
Process Contingency	0
Project Contingency	106,700
Total Plant Cost	818,100

8. Conclusions

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Conclusions

1. Taking into account the benefits of CHP plants and the high potential of the Supercritical CO2 technology, the latter should also be considered as the basis for future CHP plants. The comparison with traditional Steam based CHP plants should be performed.

Conclusions

2. The most significant drawback of the convenient steam CHP plants scheme is that at a high heat load, the LPC operates at low mass flow rates. At partial mass flow rate modes the LPC may consume the power from the shaft which may lead to an unwanted flow path temperature increase and all the consequent problems.

Conclusions

3. Two new embodiments of the S-CO2 CHP plant (Combined Complex Steam-S-CO2 CHP Plant and Cascaded Supercritical CO2 CHP Plant) are considered and compared with the conventional steam CHP plant in terms of components total sizes.

Conclusions

4. Comparisons of the total volumes of the Combined Complex Steam-SCO2 and the T-250/300 of the interchangeable components showed that new CO2 components have in 2.2 times less total volume (506 m3/ 227.7 m3).

Conclusions

5. Cascaded S-CO2 CHP unit has a total volume 347 m3. This is 2.3 times less than T-250/300-23.5 unit total volume.

Conclusions

6. Taking into account the high effectiveness of Cascaded S-CO2 CHP plant (311.6 MW of net electrical power and 421 MW of useful heat) at any heat load mode and relatively small total volume, it must be considered a promising CHP plant concept.

Conclusions

7. The embodiment with the bottoming S-CO2 cycle also may be reasonable in terms of effectiveness and footprint but partial modes of operation remain to be studied.

Sources of the borrowed pictures

1. Combined Heat and Power. A Clean Energy Solution // U.S. Department of Energy, U. S. Environmental Protection Agency, August 2012.
2. Truhnij A., Lomakin B., Cogeneration steam turbines and units: manual for University, MPEI press, 2002. ISBN 5-7046-0722-5
3. Dirk Pauschert, Study of Equipment Prices in the Power Sector, ESMAP Techincal Paper 122/09, December 2009.

Authors

Dr. Leonid Moroz - Presenter

Dr. Boris Frolov

Dr. Maksym Burlaka

SoftInWay Inc.
15 New England Executive Park Burlington, MA
01803, USA

Email:

l.moroz@softinway.com,
boris.frolov@softinway.com,
m.burlaka@softinway.com,