13th CONFERENCE ON SUSTAINABLE DEVELOPMENT OF ENERGY, WATER AND ENVIRONMENT SYSTEMS

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Group of Energy COnversion Systems

PRELIMINARY SIMULATION STUDY AND HEAT INTEGRATION OF A HIGHLY INTENSIFIED AND FLEXIBLE PROCESS FOR BIO-DME AND ELECTRICITY PRODUCTION

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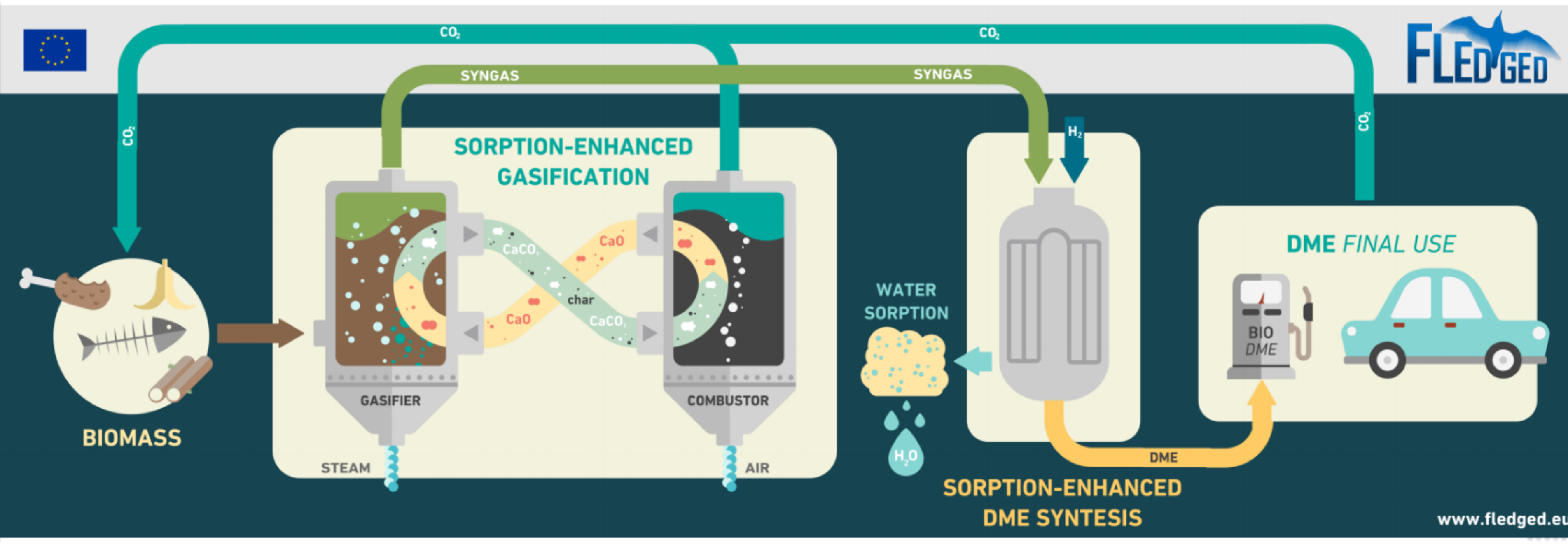
Introduction

Concept layout

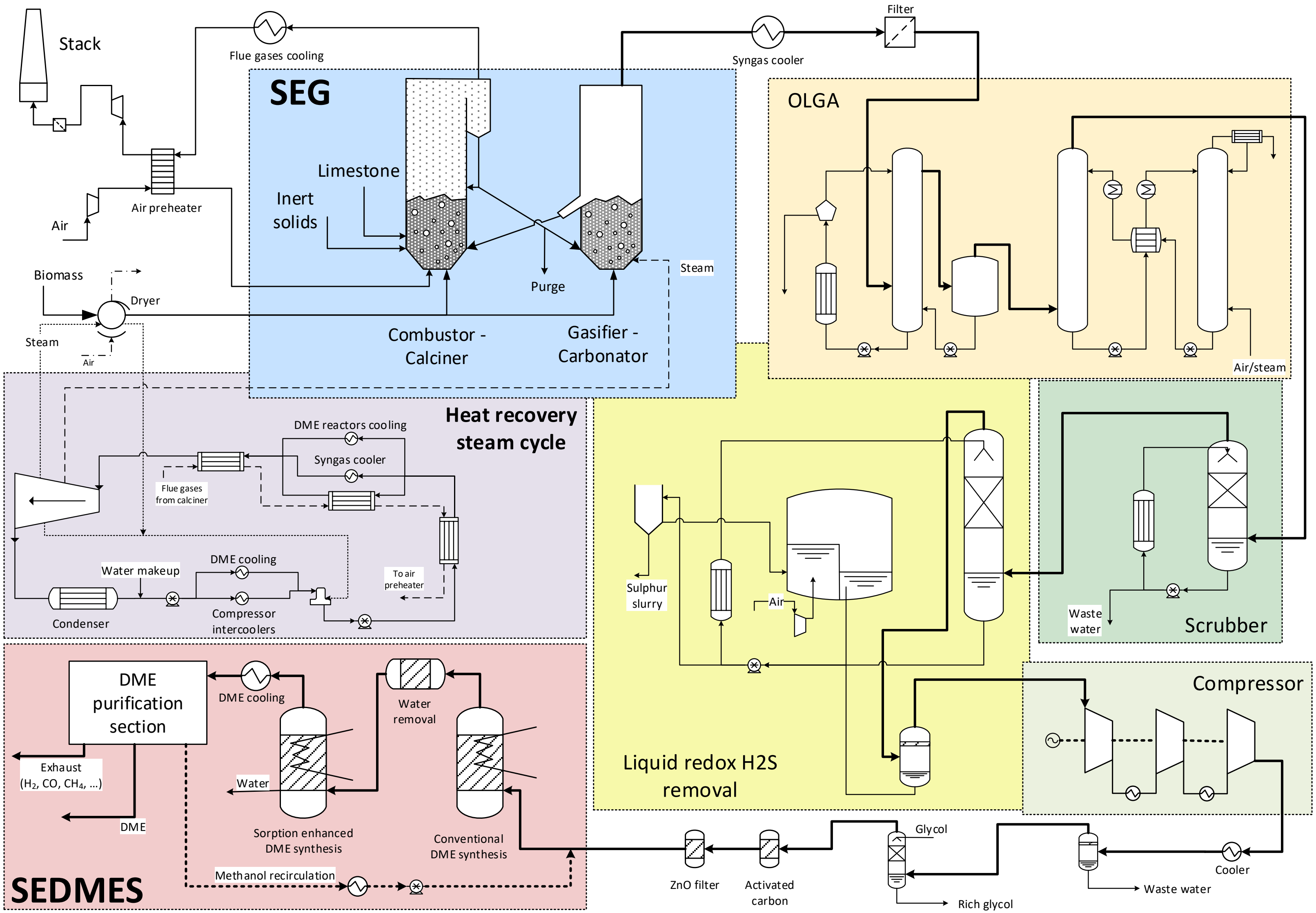


A novel highly intensified and flexible process for the **co-production** of **bio-DME** and **electricity** from biomass, coupling the indirect gasification with *in-situ* CO_2 separation

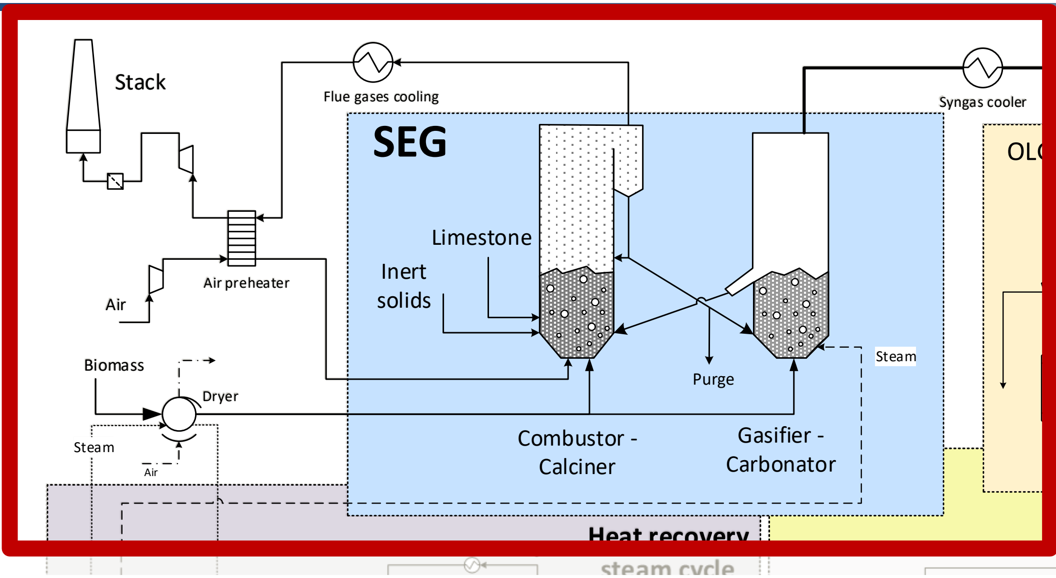
Preliminary simulation study

Preliminary heat integration study

FLEDGED reference plant layout



FLEDGED reference plant layout: SEG



Biomass pre-treatment:

Tube bundle dryer heated by LP steam (130-140 °C) - high efficiency, low air requirement

Sorption Enhanced Gasification (SEG):

- CO_2 is removed by CaO/CO_2 reaction (carbonation) yielding a **tailored syngas for downstream DME synthesis** (module = 2)
- A **bubbling fluidized bed gasifier/carbonator** and a **circulating fluidized bed combustor/calciner** are coupled to perform CO_2 capture from syngas and sorbent regeneration
- **Sensible heat from syngas and flue gases is recovered** in a bottoming steam cycle that provides also the steam for gasification
- Balances in the gasifier have been solved following the **0D model structure** in *Martínez & Romano, Energy, 2016*

FLEDGED reference plant layout: syngas purification

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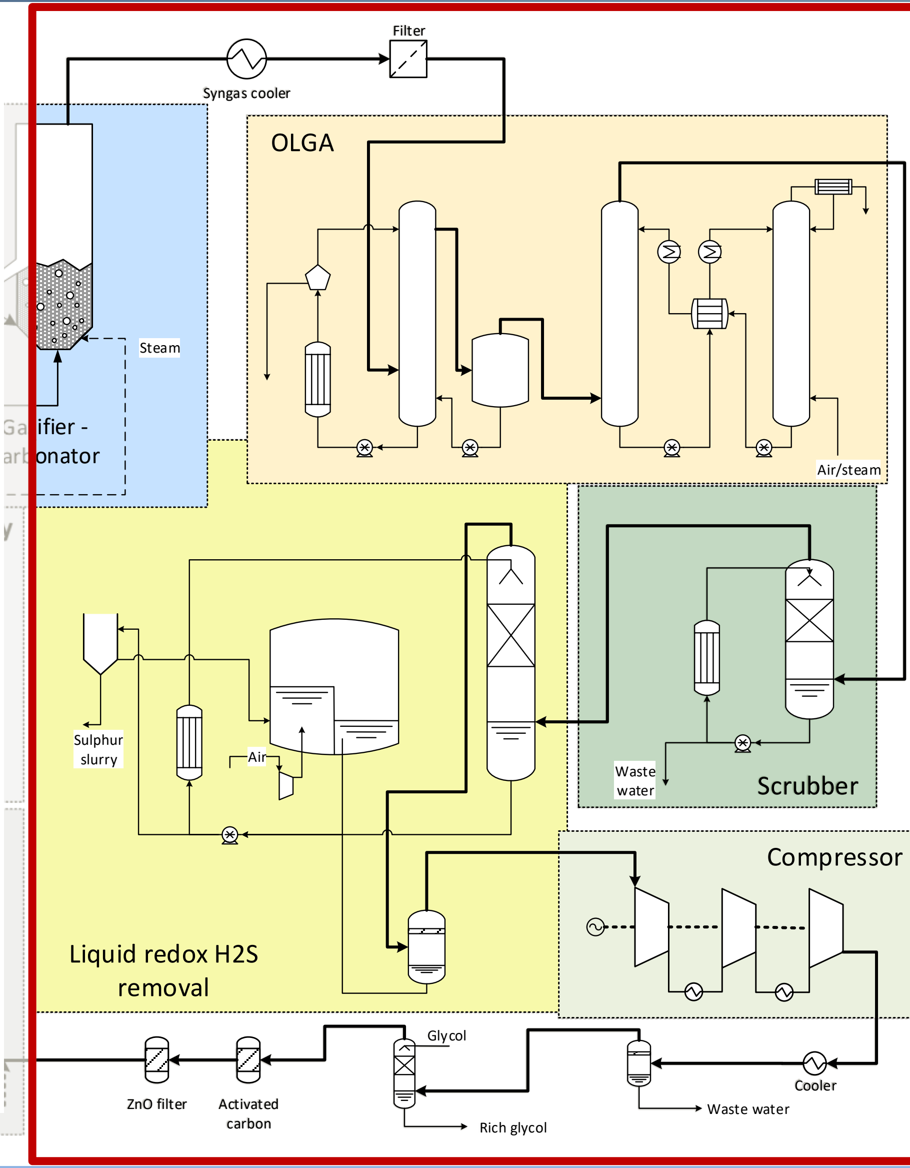
Syngas purification:

- **High temperature particulate removal** (350-400 °C) by ceramic candle filters
- **Tar removal** by oil scrubbing (e.g. regenerative OLGA process or non-regenerative process)
- **Caustic washing** to remove soluble contaminants (e.g. HCl, NH_3)
- **Sulphur removal** through a liquid Redox process (LO-CAT) by means of iron oxygen carrier

Three **stages intercooled syngas compressor** is required to reach the operating pressure of downstream SEDMES section (between 20 and 30 bar)

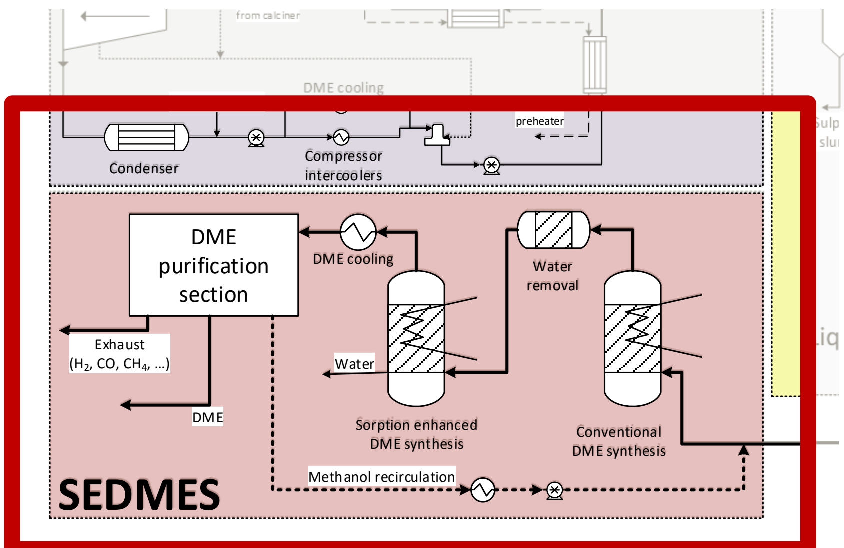
Final purification steps (glycol washing, activated carbon bed, ZnO filter) remove traces of pollutants and water



FLEDGED reference plant layout: SEDMES

Sorption enhanced DME synthesis (SEDMES):

- Adsorption material admixed to the catalyst will improve the conversion, removing water product inside the reactor circumventing the thermodynamic limitations
- A **conventional DME synthesis reactor** is included **upstream the SEDMES**
- Both DME reactors are assumed to operate at 25 bar and 240 °C
- SEDMES is modelled **lumped 0D SEDMES model** that considers three steps: Complete limiting reactant conversion → Water removal step → Conversion to equilibrium
- Fixed DME yield equal to 90% at SEDMES outlet



DME purification:

- **DME cooling and heat recovery**
- DME is separated from residual reactants (offgas), methanol and water by means of strippers and distillation columns in order to reach the required purity (ISO standard)

Preliminary simulation results

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Performances indexes

- **Gasifier island**

$$CGE_{gasif} = \frac{G_{syngas} \cdot LHV_{syngas}}{G_{bio,tot} \cdot LHV_{bio}}$$

- **DME synthesis island**

$$CGE_{DME} = \frac{G_{DME} \cdot LHV_{DME}}{G_{syngas} \cdot LHV_{syngas}}$$

Preliminary simulations of a **100 MW_{LHV}** plant

A reference woody biomass has been assumed with a moisture content of 45% and a LHV equal to 9.75 MJ/kg biomass as received

Dryer		
Biomass thermal input to the plant (LHV)	100.00	MW_{th}
Biomass thermal input after drying (LHV)	107.75	MW_{th}
Dryer heat input	9.45	MW_{th}
SEG		
Syngas production (dry)	3.14	kg/s
	5.298	Nm^3/s
Syngas heating value (LHV wet)	5.77	MJ/kg
Syngas heating value (LHV dry)	20.86	MJ/kg
Gasifier cold gas efficiency (CGE_{gasif})	**60.66**	**%**
Syngas compressors		
Compressor consumption	3.50	MW_{el}
Compressor net cooling duty	1.13	MW_{th}
SEDMES		
DME production rate	1.08	kg/s
DME chemical power (LHV basis)	31.14	MW
Syngas to DME conversion efficiency (CGE_{DME})	**53.86**	**%**
Syngas to DME conv. efficiency w/o CH_4	73.08	%
DME off-gas chemical power (LHV basis)	**22.68**	**MW**
Biomass to DME conversion efficiency	**31.14**	**%**

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Heat integration study

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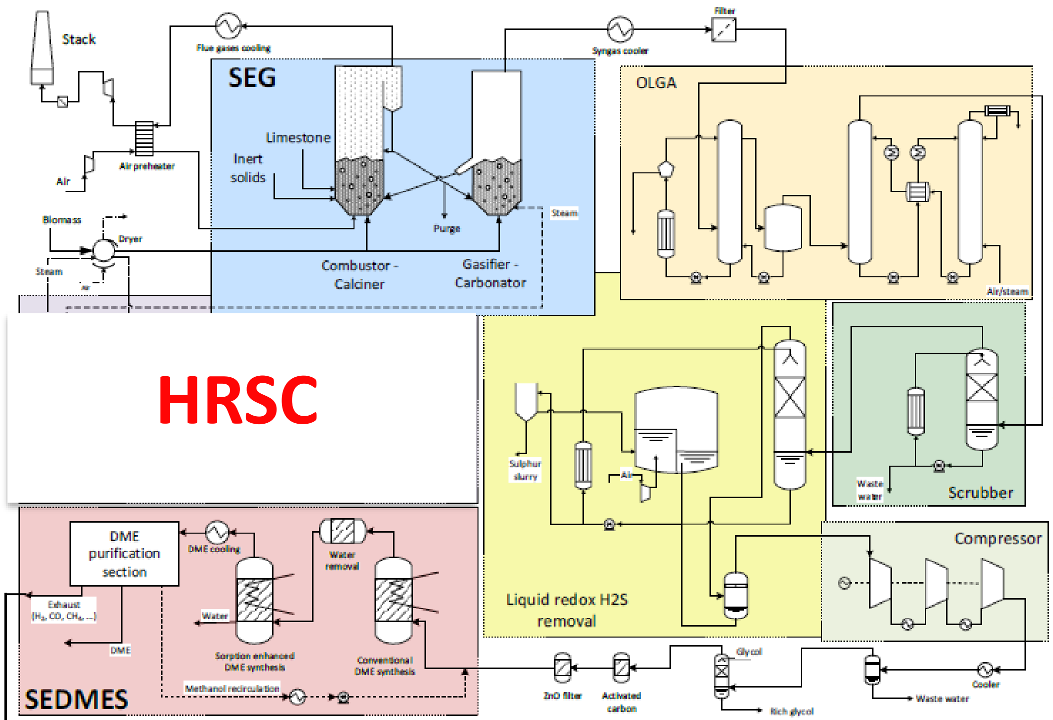

Process streams data

	T in [°C]	T out [°C]	Q [kW]
Calciner flue gases	910	300	16,131
Syngas cooler	720	340	9,548
Conv DME reactor cooling	240	240	496
SEDMES reactor cooling	240	240	3,115
DME cooling	240	53	787
Compr intercooler	170	40	1,487
Compr intercooler	178	40	1,441
Compr intercooler	179	40	1,326
Biomass dryer	20	80	-10,473

	m [kg/s]	LHV [MJ/kg]
Offgas DME	0.861	26.341

OFFGAS DME

GAS TURBINE?

ICE?

The gross energy (waste heat + offgas) is approximately 57% of the biomass thermal power (LHV)!
28% must be provided to dryer and gasification steam

Methodologies for heat integration

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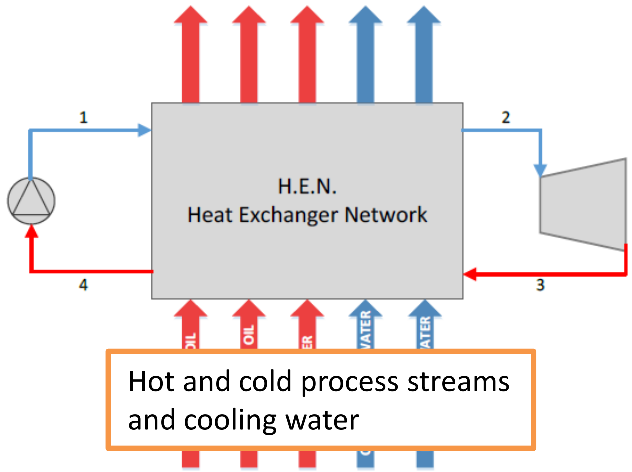
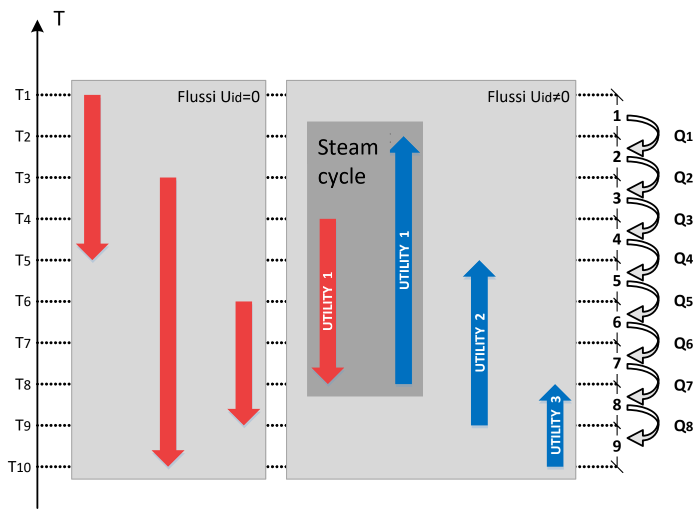
Objectives:

- Optimize the **heat integration** between hot and cold process streams as well as heat recovery steam cycle
- Determine the optimal use of the **offgas**
- Optimize the layout of the **heat recovery steam cycle** considering:
  - Multiple heat sources available
  - Different steam users (gasifier, biomass dryer)
  - Technical limits (metal dusting, required DME reactor cooling steam, etc.)

1. **Energy targeting methods (e.g. Pinch Analysis)** → Preliminary screening of possible solutions
2. **HEN Synthesis methods**
3. **Utility optimization**
4. **Simultaneous HEN + Utility optimization** → Most rigorous methodology, but the problem is extremely challenging to solve

Energy Targeting methodology





Problem statement:

Given hot/cold process streams and steam cycle superstructure, determine the selection of the components and the mass flow rates of the steam cycle, maximizing the heat recovery (without designing the heat exchanger network)
→ TARGETING METHOD

Methodology[1,2]:

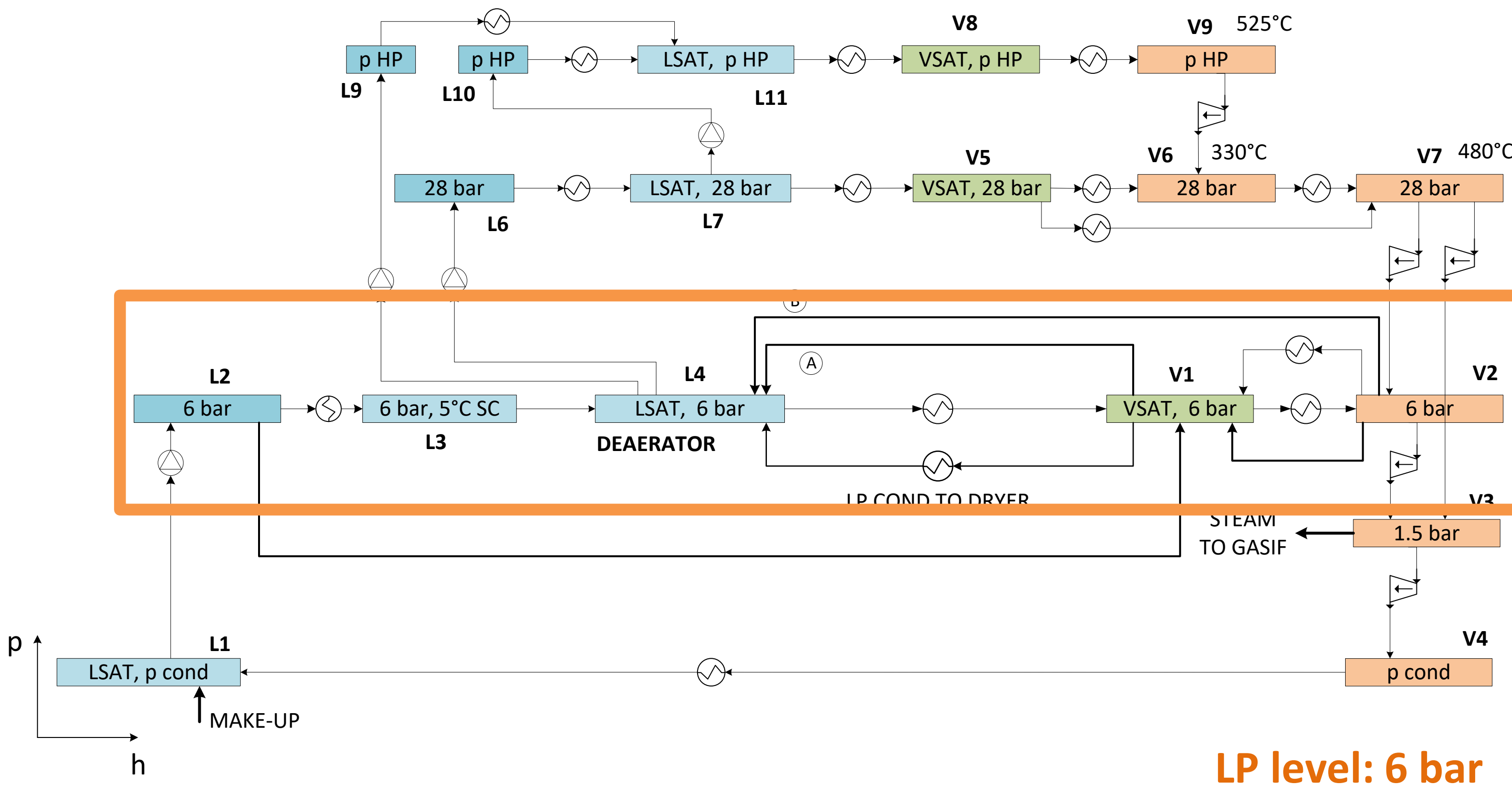
«Heat cascade»:

- Discretization and shift of the streams on the axis of temperatures
- Definition of temperature intervals
- Energy balances in each interval
- Subject to minimum temperature differences

Maximize: *Net Electric Power*

1. Papoulias, S. A., & Grossmann, I. E. (1983). Computers & Chemical Engineering, 7(6), 707–721
2. Marechal, F., & Kalitventzeff, B. (1998). Computers & Chemical Engineering, 22, S149–S156

Steam cycle superstructure



LP level: 6 bar

- Deaerator
- Biomass dryer

- Possible alternative steam cycle configurations
- Need of a general steam cycle superstructure[1]

1. Elsido C, Mian A, Marechal F & Martelli E. A general superstructure for the optimal synthesis and design of power and inverse Rankine cycles. Computer Aided Chemical Engineering, 2017, 140, 2407-2412

Steam cycle superstructure

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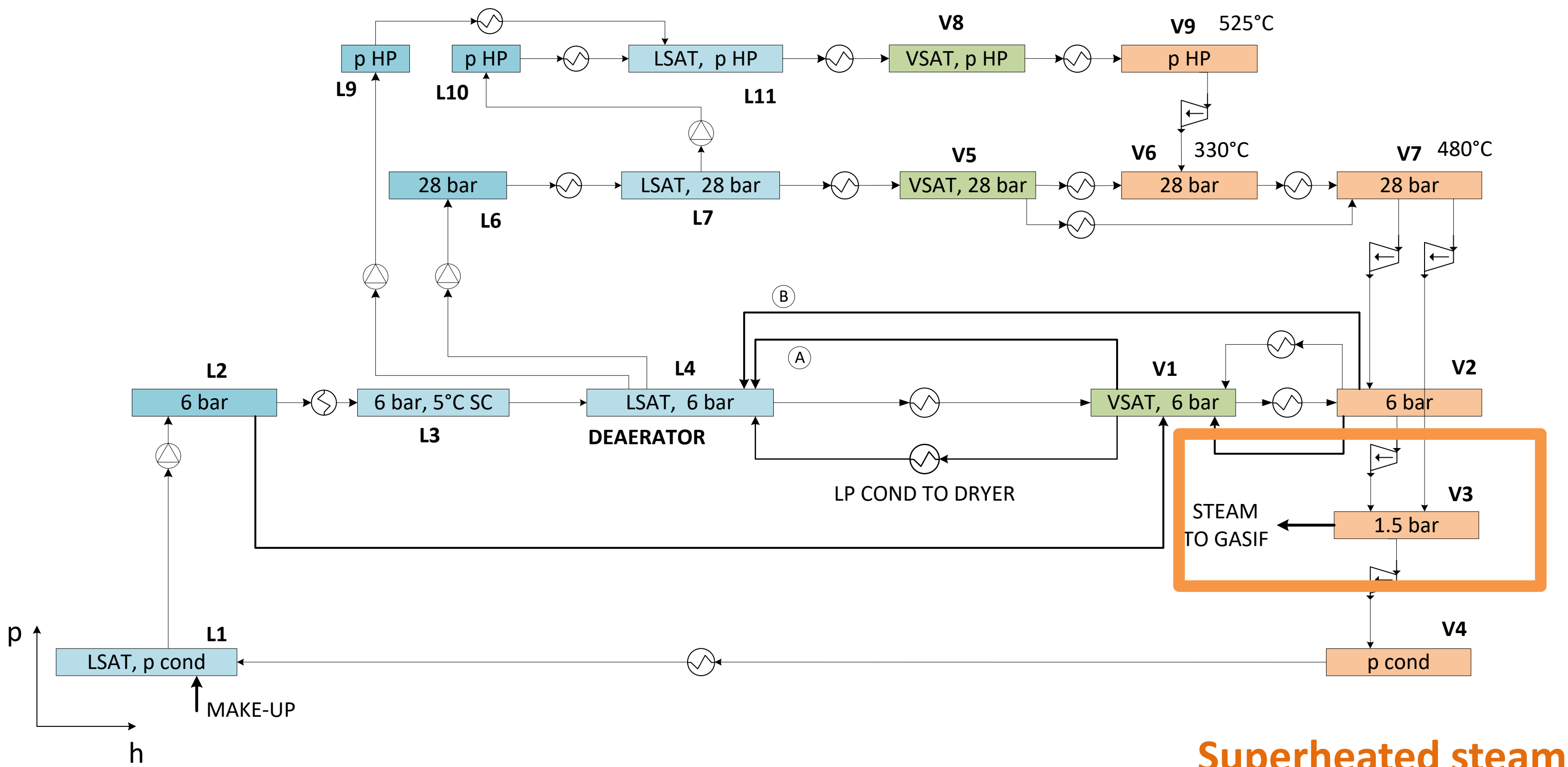

Superheated steam at 1.5 bar required by gasifier

- Possible alternative steam cycle configurations
- Need of a general steam cycle superstructure[1]

1. Elsido C, Mian A, Marechal F & Martelli E. A general superstructure for the optimal synthesis and design of power and inverse Rankine cycles. Computer Aided Chemical Engineering, 2017, 140, 2407-2412

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Steam cycle superstructure

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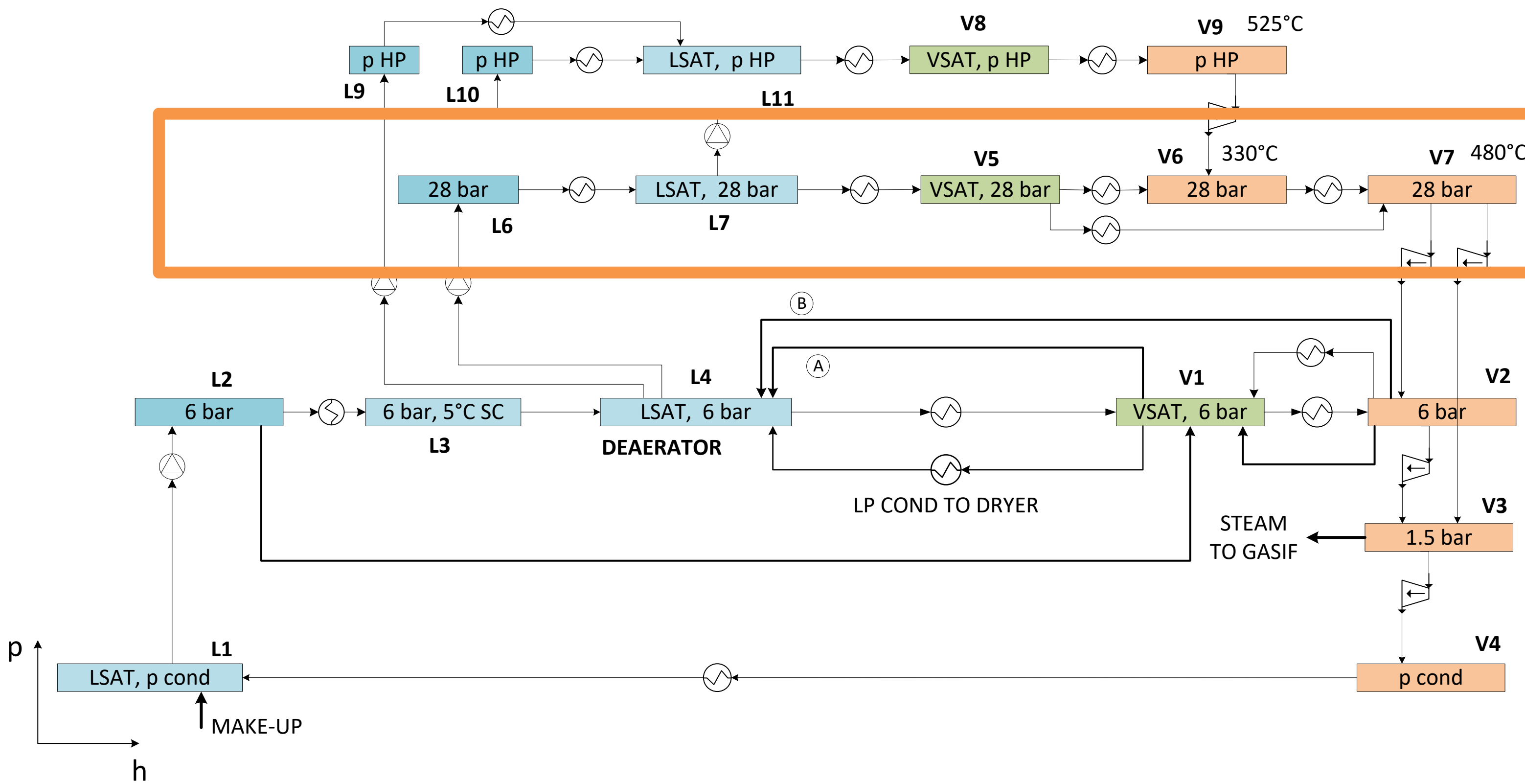

MP level: 28 bar

- **DME reactor at 240°C**

- Possible alternative steam cycle configurations
- Need of a general steam cycle superstructure[1]

Steam cycle superstructure

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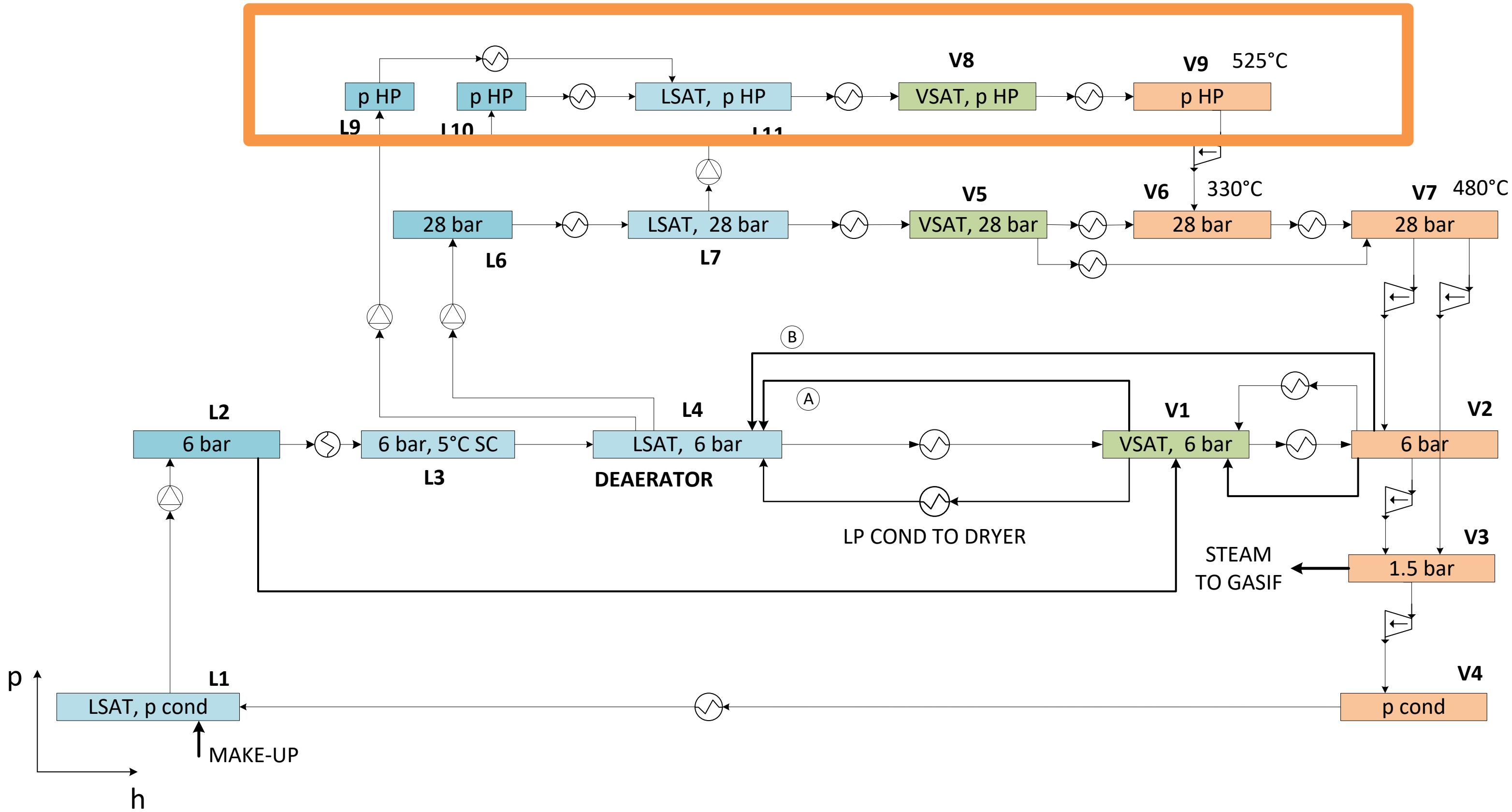

HP level: 120 bar, 525°C

- Possible alternative steam cycle configurations
- Need of a general steam cycle superstructure[1]

1. Elsido C, Mian A, Marechal F & Martelli E. A general superstructure for the optimal synthesis and design of power and inverse Rankine cycles. Computer Aided Chemical Engineering, 2017, 140, 2407-2412

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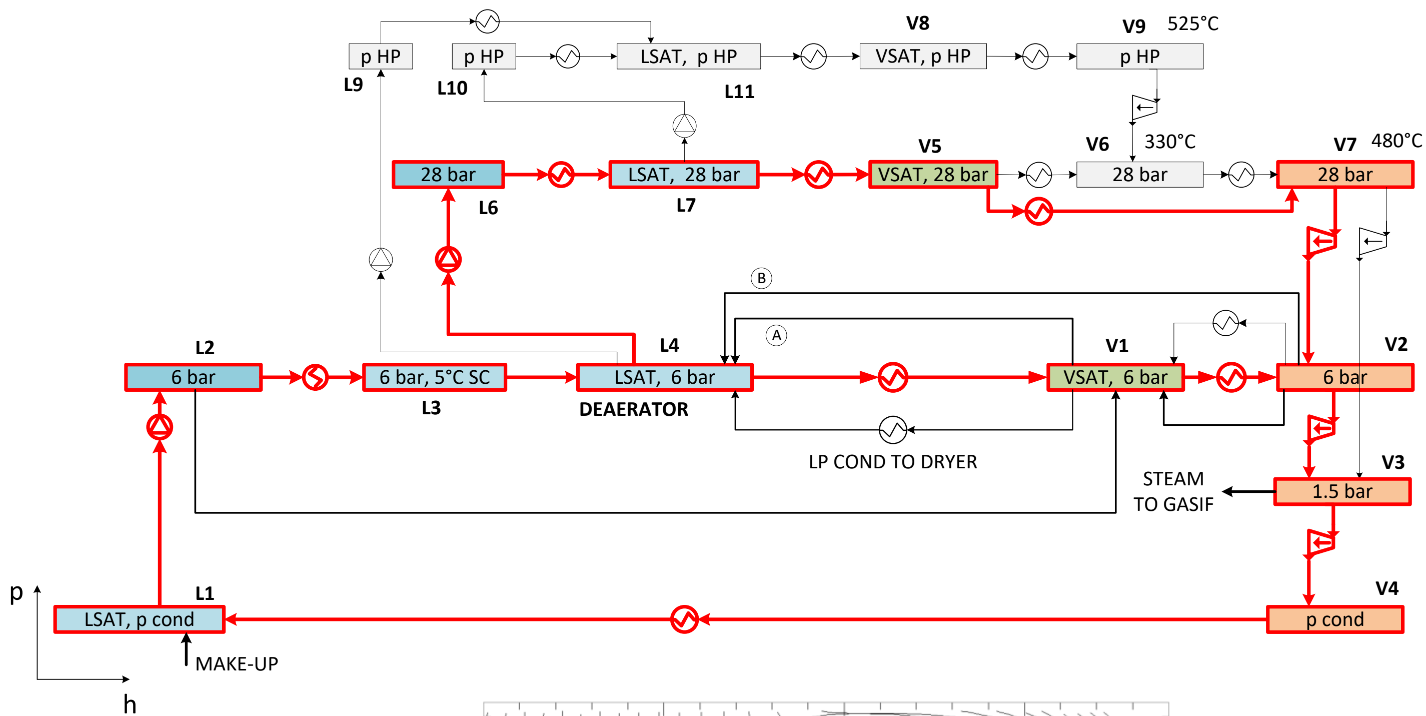
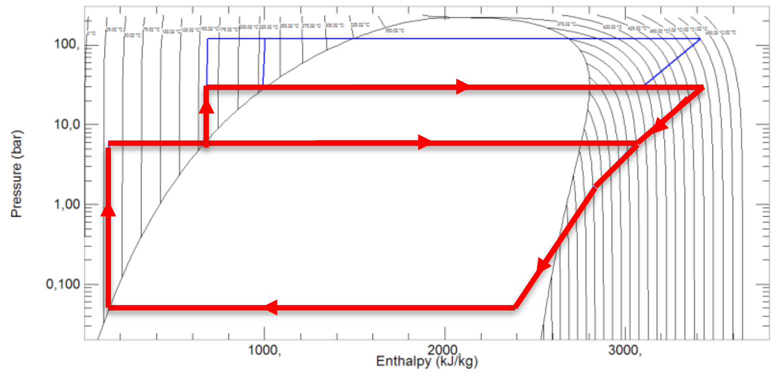
Steam cycle superstructure

Example:
LP + MP level

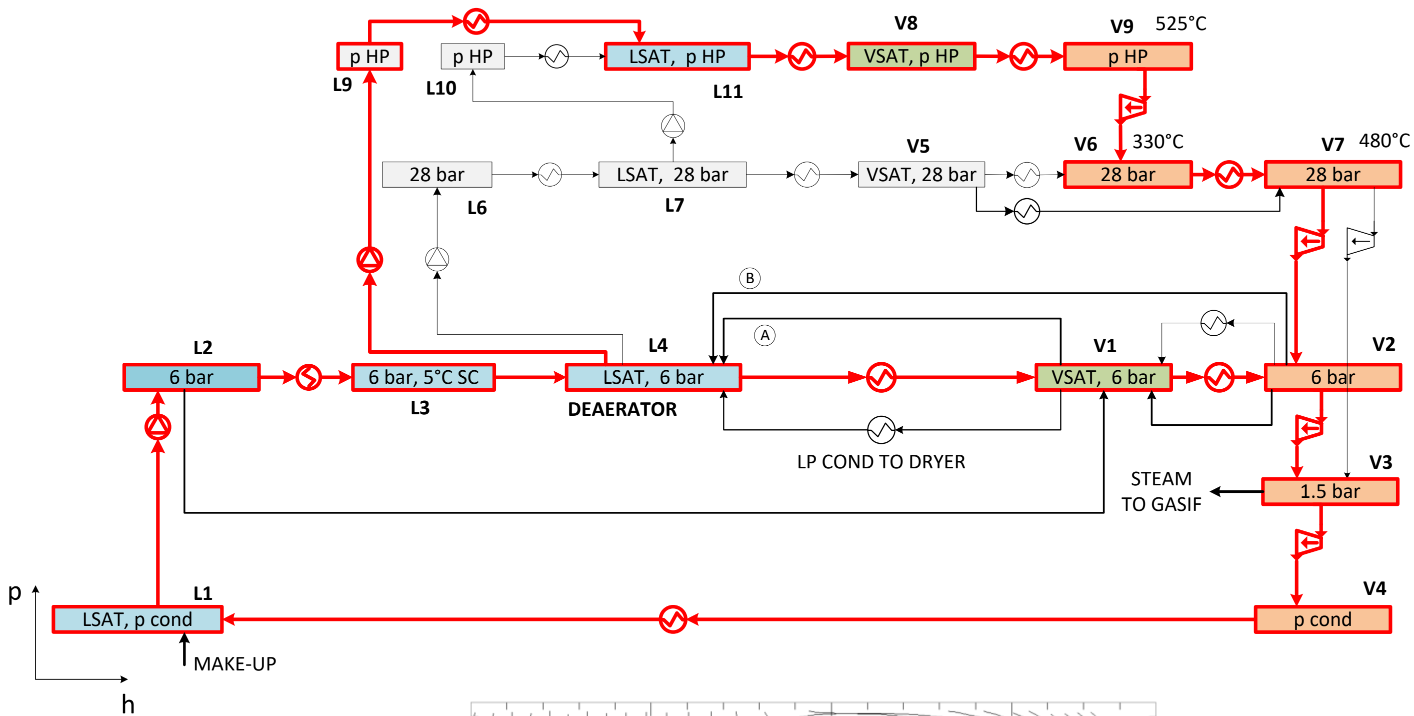


***p-h* diagram**

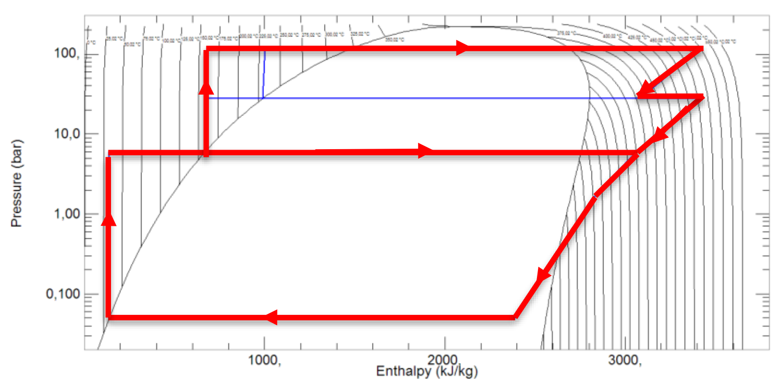


Steam cycle superstructure

Example:
LP + HP level,
with RH

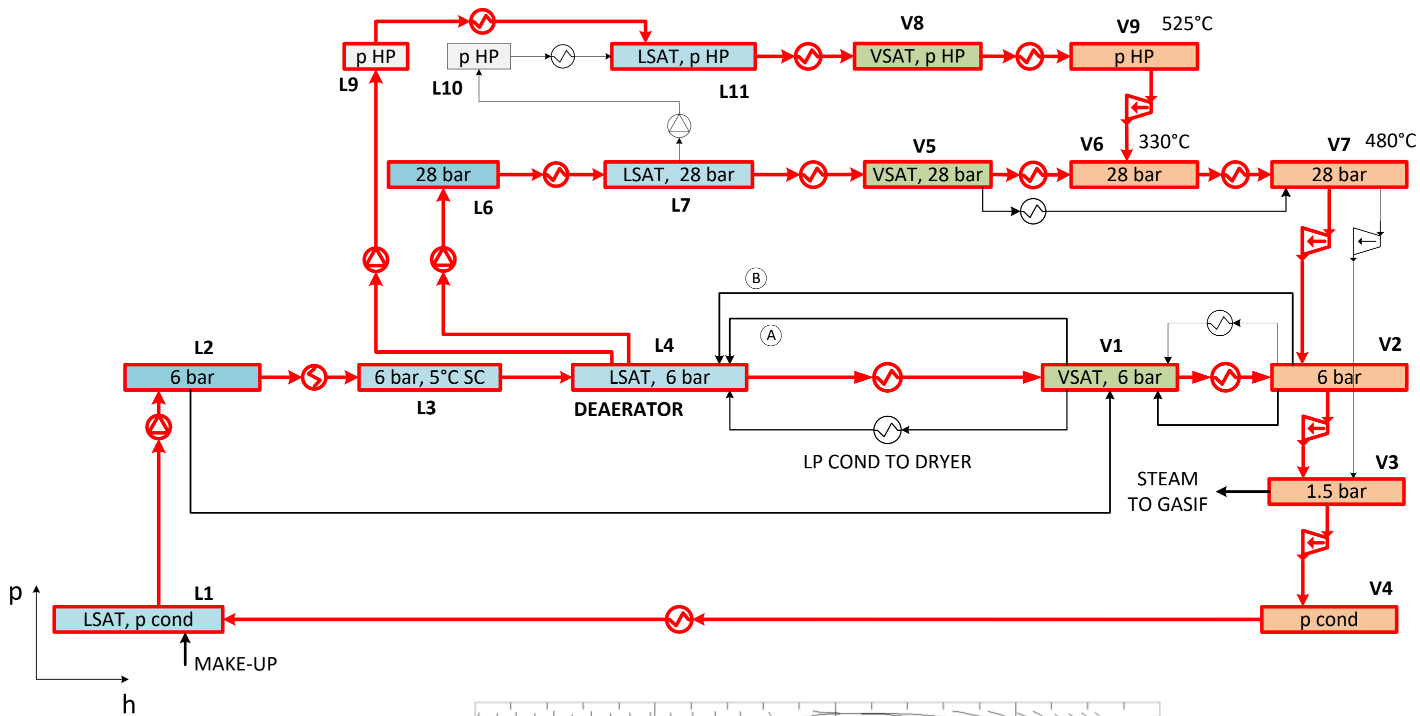


***p-h* diagram**

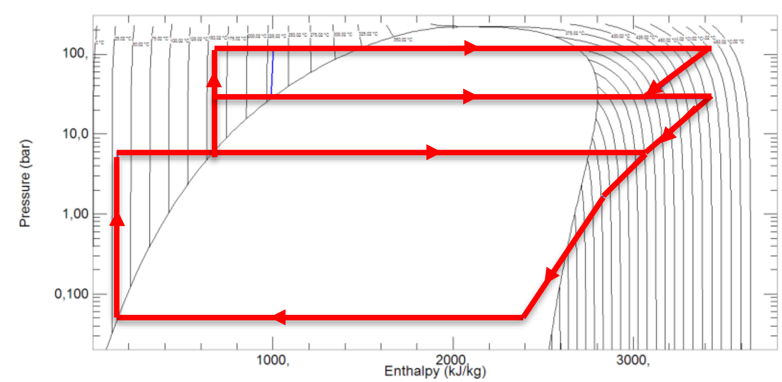


Steam cycle superstructure

Example:
LP + MP + HP level, with RH

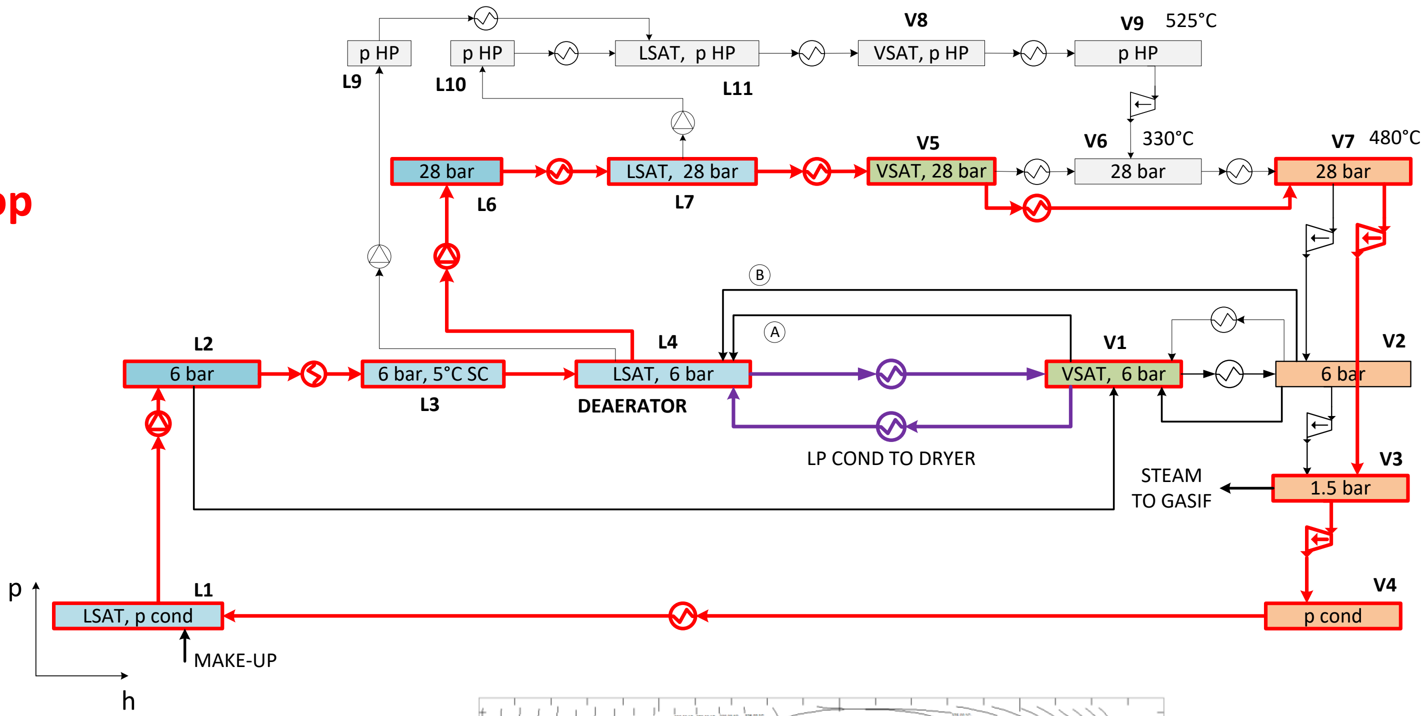


***p-h* diagram**

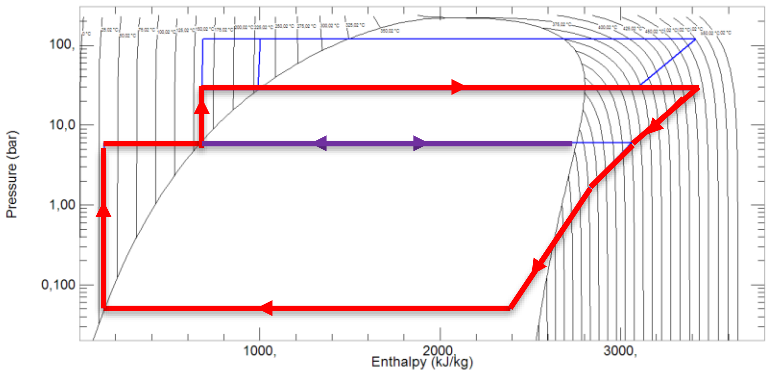


Steam cycle superstructure

Example:
MP level, with
LP EVA-COND loop

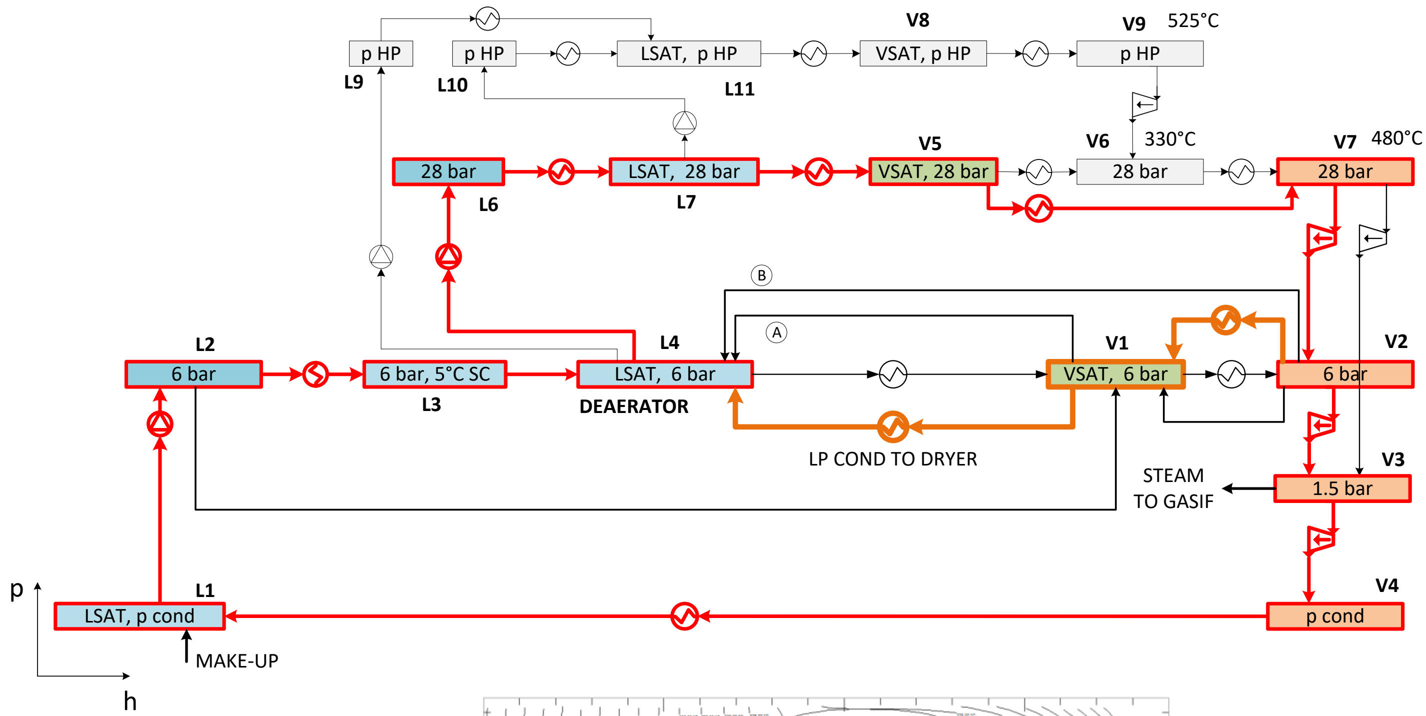


***p-h* diagram**

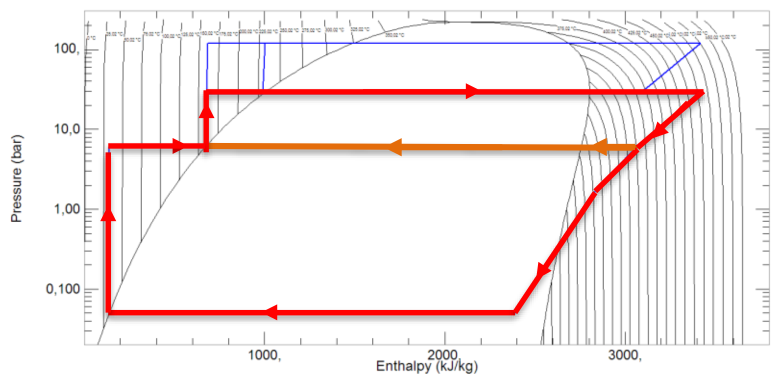


Steam cycle superstructure

Example: MP level, extraction-condensing

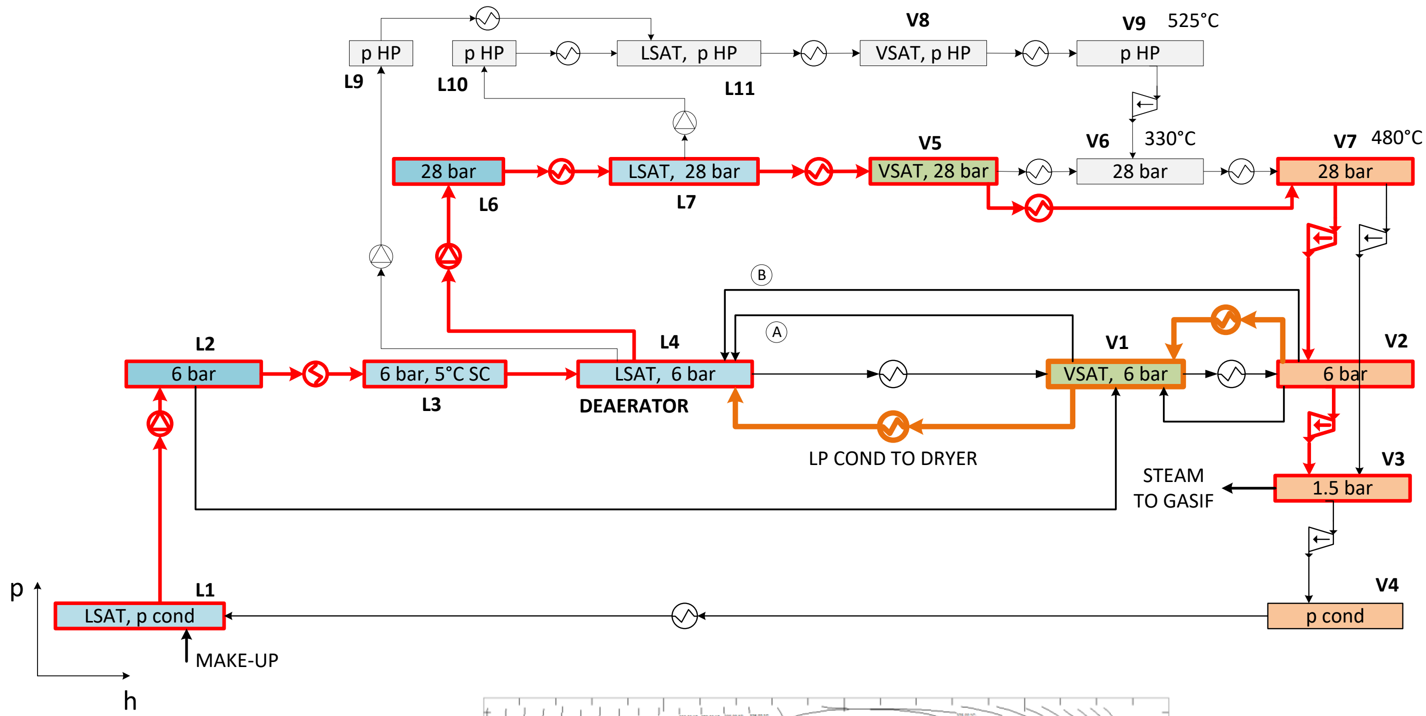


***p-h* diagram**

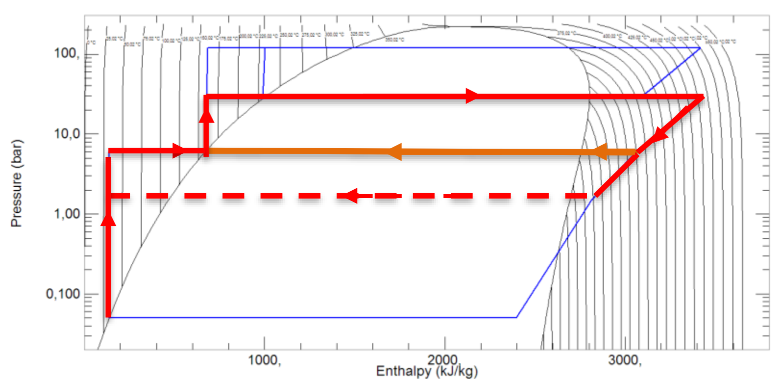


Steam cycle superstructure

Example:
MP level,
Back-pressure



***p-h* diagram**



Options for DME offgas fuel

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A. INTERNAL COMBUSTION ENGINE

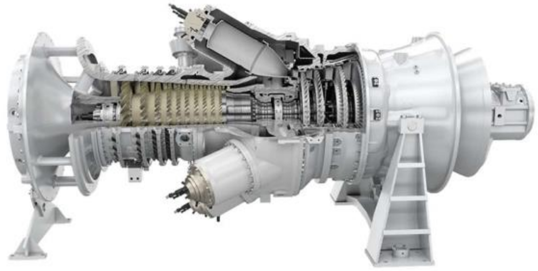
Wärtsilä 20V34SG

Q_{in} [kW]	η_{el}	W [kW]
22667.8	0.445	10093.2

	m [kg/s]	C_p [kJ/kgK]	T_{in} [°C]	T_{out} [°C]	Q [kW]
Flue gases	16.63	1.114	360.5	110	4,642.58
Hot water	50.15	4.2	93.86	86.86	1,474.46

B. GAS TURBINE

Siemens SGT300



Q_{in} [kW]	η_{el}	W [kW]
22,667.8	0.306	6,936.34

	m [kg/s]	C_p [kJ/kgK]	T_{in} [°C]	T_{out} [°C]	Q [kW]
Flue gases	26.516	1.095	542	110	12,543.2

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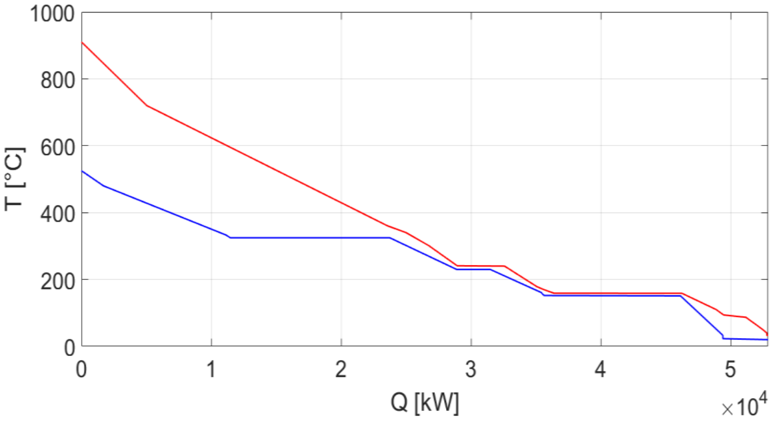
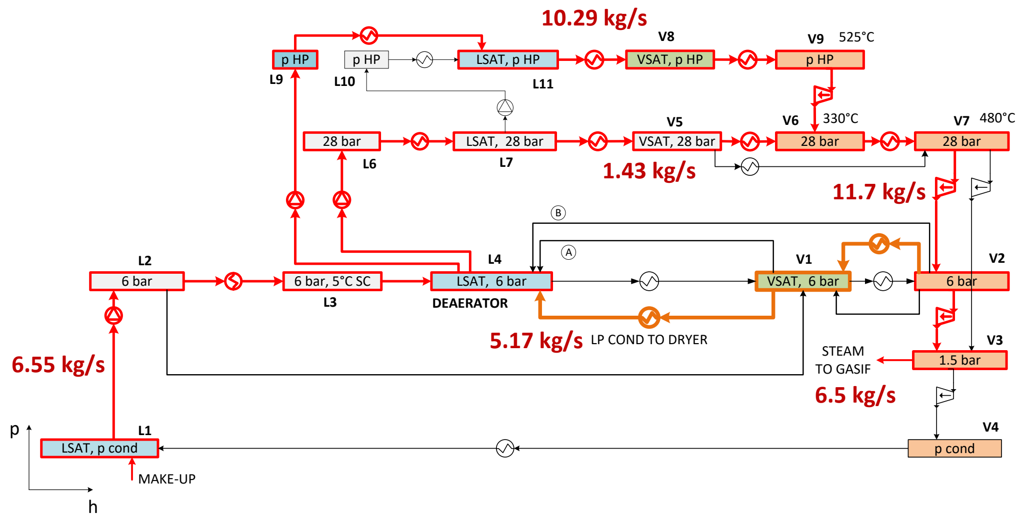
A. INTERNAL COMBUSTION ENGINE





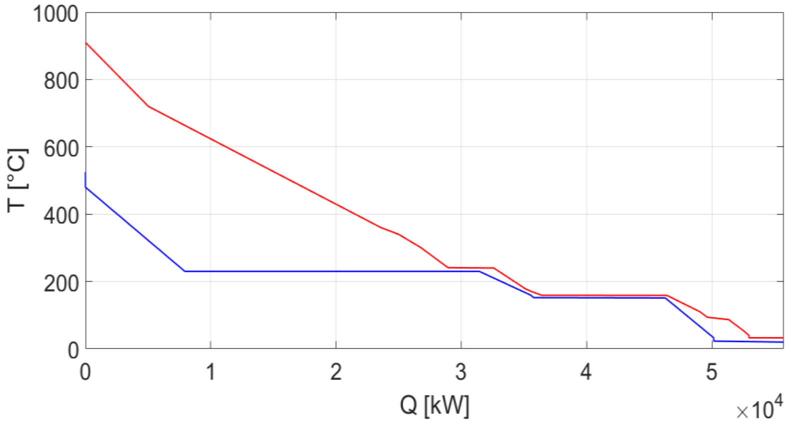
HRSC Power Output (target) = 9.2 MW

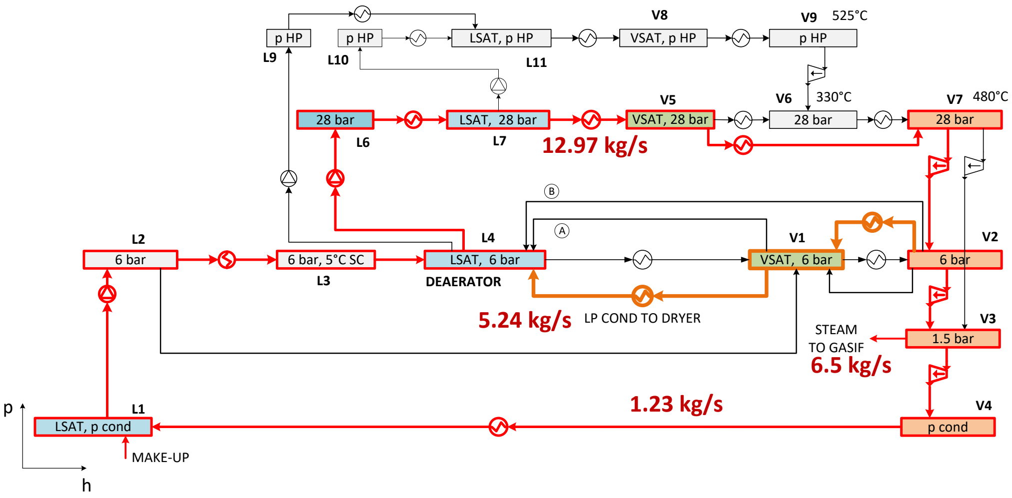
ICE Power Output = 10.1 MW

Total Power Output (target) = 19.3 MW

Energy Targeting results

A. INTERNAL COMBUSTION ENGINE/ no HP level





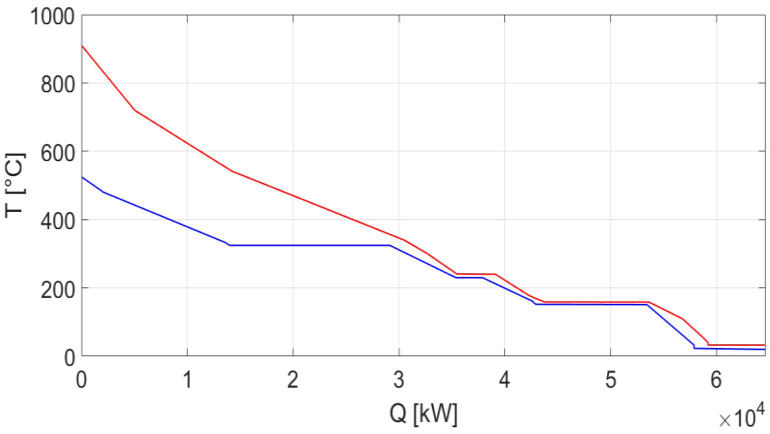
HRSC Power Output (target) = 7.0 MW

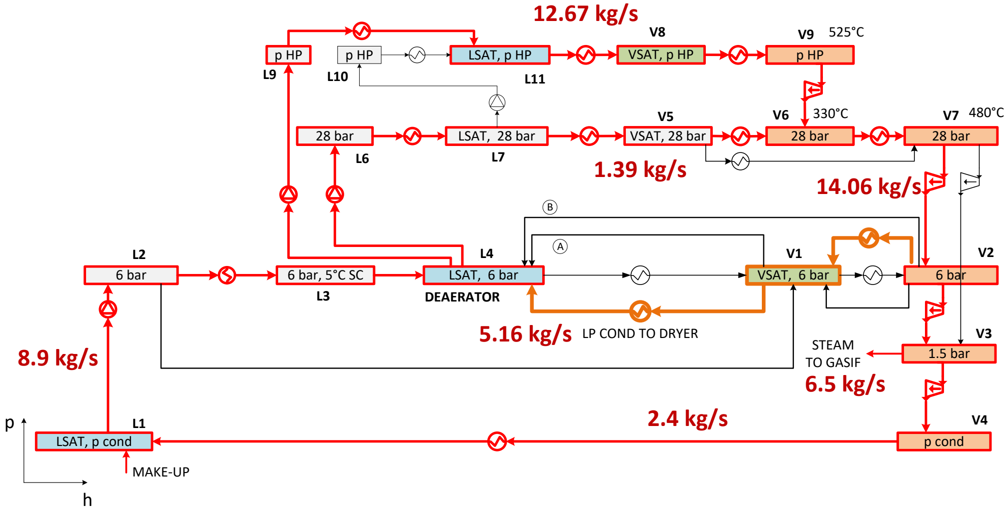
ICE Power Output = 10.1 MW

Total Power Output (target) = 17.1 MW

Energy Targeting results

B. GAS TURBINE



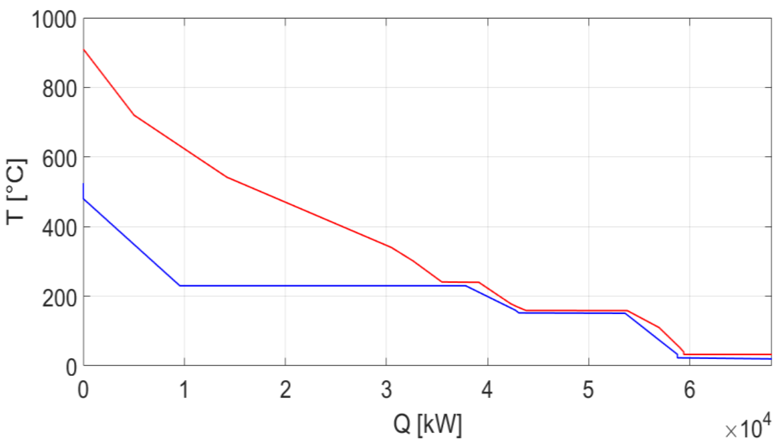


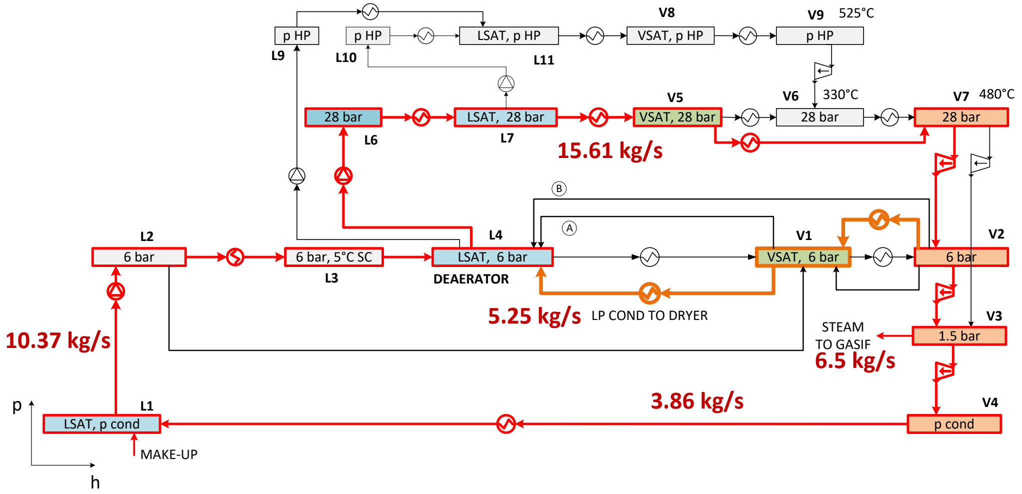
HRSC Power Output (target) = 12.4 MW

GT Power Output = 6.9 MW

Total Power Output (target) = 19.3 MW

B. GAS TURBINE/ no HP level





HRSC Power Output (target) = 9.7 MW

GT Power Output = 6.9 MW

Total Power Output (target) = 16.6 MW

CONCLUSIONS

Purification off-gases use	ICE	ICE	GT	GT
Steam cycle levels	HP+MP	MP	HP+MP	MP
Biomass-to-DME conversion efficiency	31.14 %	31.14 %	31.14 %	31.14 %
Biomass-to-electricity efficiency (target)	19.3 %	17.1 %	19.3 %	16.6 %

1. A detailed preliminary process simulation study and heat integration for a novel highly intensified and flexible polygeneration plant for the co-production of bio-DME and electricity from biomass
2. The simulated non-optimized reference plant achieves a global **biomass-to-DME conversion efficiency of 31.14 %**, penalized by the high fraction of CH_4 produced by the gasifier (unsuitable for DME synthesis) → **CH_4 reforming (option under study)**
3. The optimization algorithm for the heat recovery power generation plant leads to a **biomass-to-electricity efficiency of 16.6-19.3 %** depending on the off-gas use and steam cycle configuration → **techno-economic optimization (future work)**

THANK YOU FOR YOUR ATTENTION!

ANY QUESTIONS?

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