TOWARDS ENERGY INTENSIVE INDUSTRY DECARBONIZATION

HIGH TEMPERATURE LARGE SCALE HEAT PUMP

Industrial Processes Emissions Reduction (IPER)
January 30th 2024
SWRI- San Antonio, TX, USA

Gabriele Mariotti
Davide Rizzi
Heat Generation Business Unit

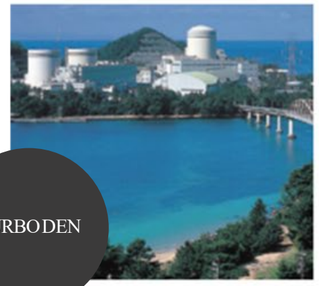
MORE HEAT OUT OF HEAT

TURBODEN IS A GROUP COMPANY OF MHI

MHI BUSINESS DOMAINS

TURBODEN

Energy Systems



Main Businesses
- Gas & steam power systems*
- Nuclear power systems
- Compressors
- Aero engines
- Marine machinery

* Includes GTCC, steam power and air quality control system

42,4%

Plants & Infrastructure Systems

Main Businesses
- Commercial ships
- Engineering
- Environmental systems
- Metals machinery
- Machinery systems

16.7%

REVENUE $32B

Logistics, Thermal & Drive Systems

Main Businesses
- Material handling systems
- Engines
- Turbochargers
- HVAC systems
- Automotive air conditioners

25.3%

Aircraft, Defense & Space

Main Businesses
- Commercial aircraft
- Defense aircraft
- Missile systems
- Naval ships
- Special vehicles (tanks)
- Maritime systems (torpedoes)
- Space systems

15.6%

Ca. 80,000 EMPLOYEES WORLDWIDE

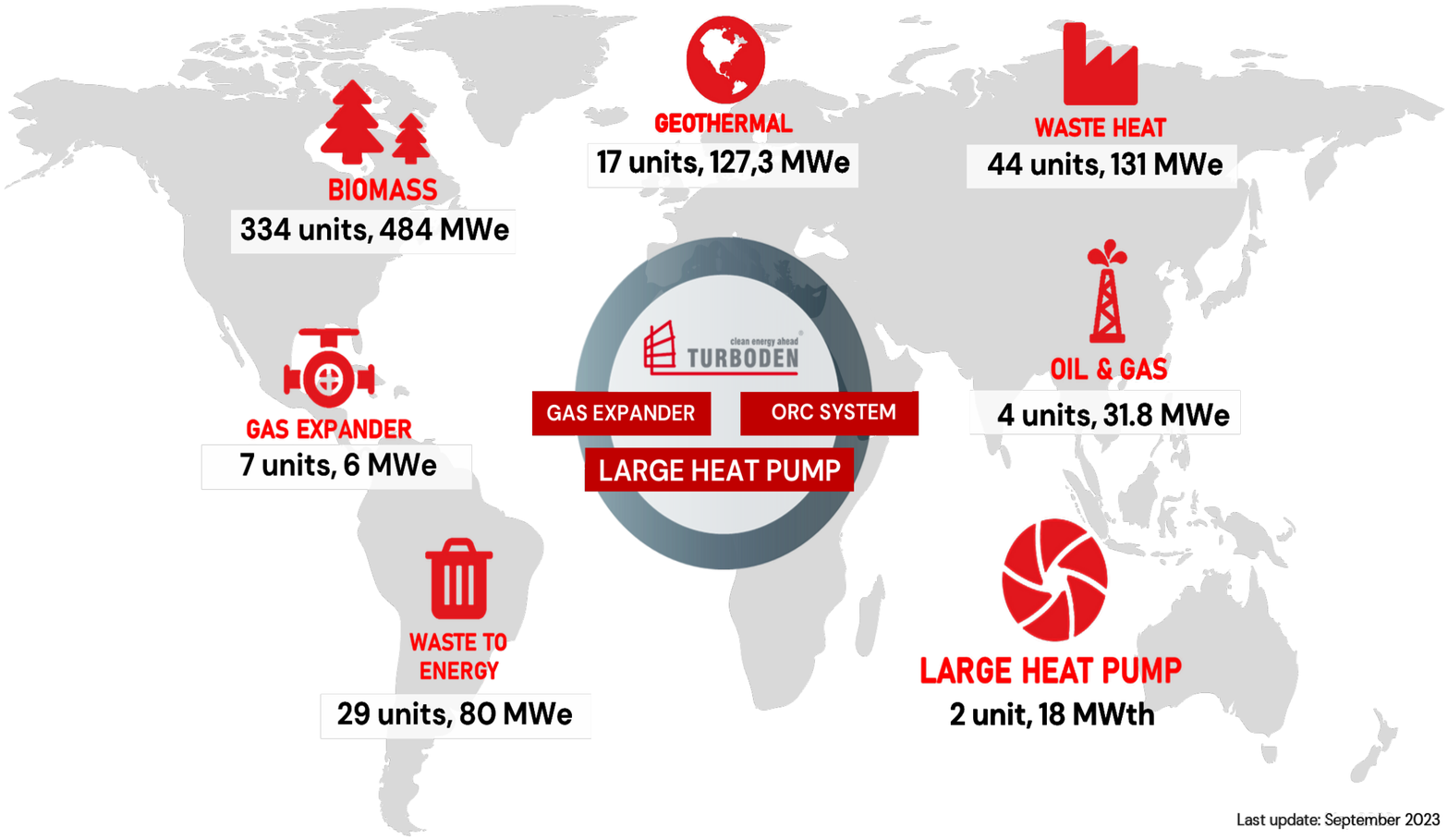
$32B ANNUAL REVENUE

300 COMPANIES WORLDWIDE

Ca. 26,000 PATENTS GLOBALLY

MITSUBISHI HEAVY INDUSTRIES GROUP

TURBODEN GLOBAL PRESENCE



Last update: September 2023

Experience in over
50
countries

With
430+
plants

Power generated
25 thousand
GWh

Cumulative operation time
20 million
hours

clean energy ahead
TURBODEN

TURBODEN LARGE HEAT PUMPS

Large Heat Pumps (LHP) are utility-scale heating plants that allow to transfer large quantities of heat from a colder source to a higher temperature heat user, like a district heating network or an industrial process.

Highly efficient
Electrically driven based on turbo compressor technology

Large-scale
Output from 5 MWth to 70 MWth per single unit

High lift
Up to more than 100 °C, possible thanks to custom design

High temperature
Steam output up to 200 °C

Heavy Duty
Designed and Engineered with Power Industry standards and best practises

Environment-friendly
Natural Refrigerants - Experience with 10+ different working fluids

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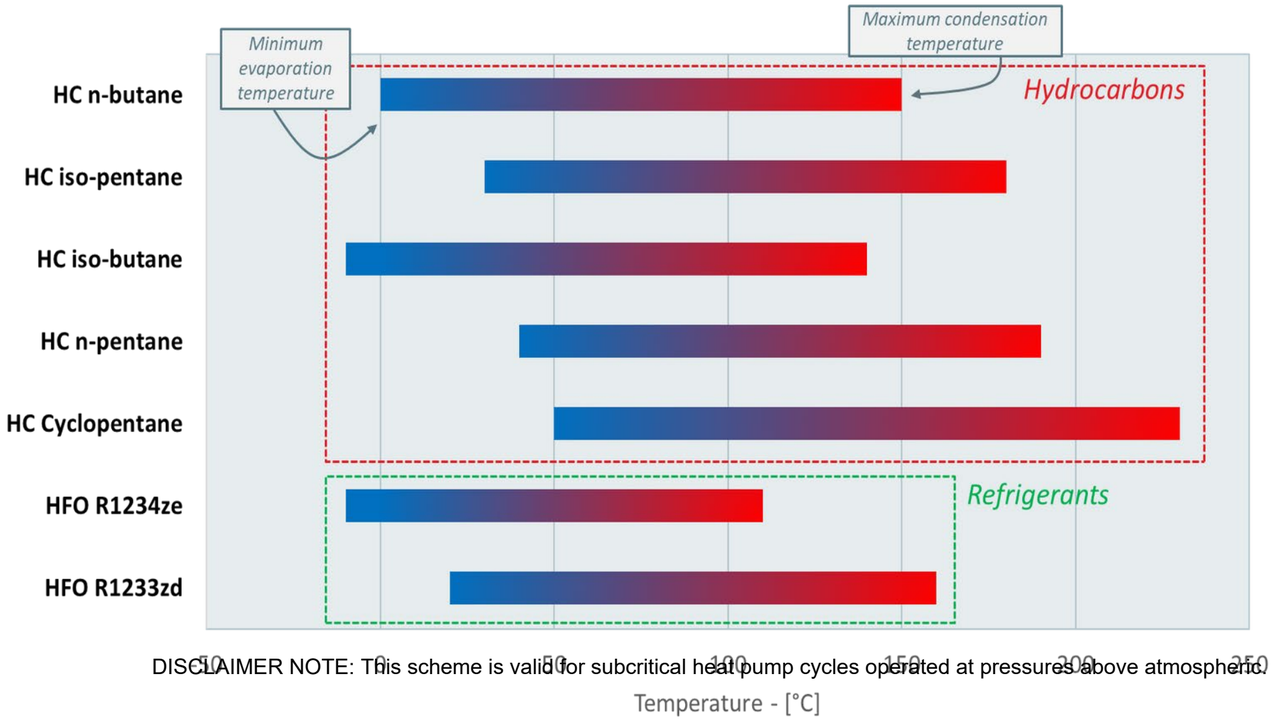
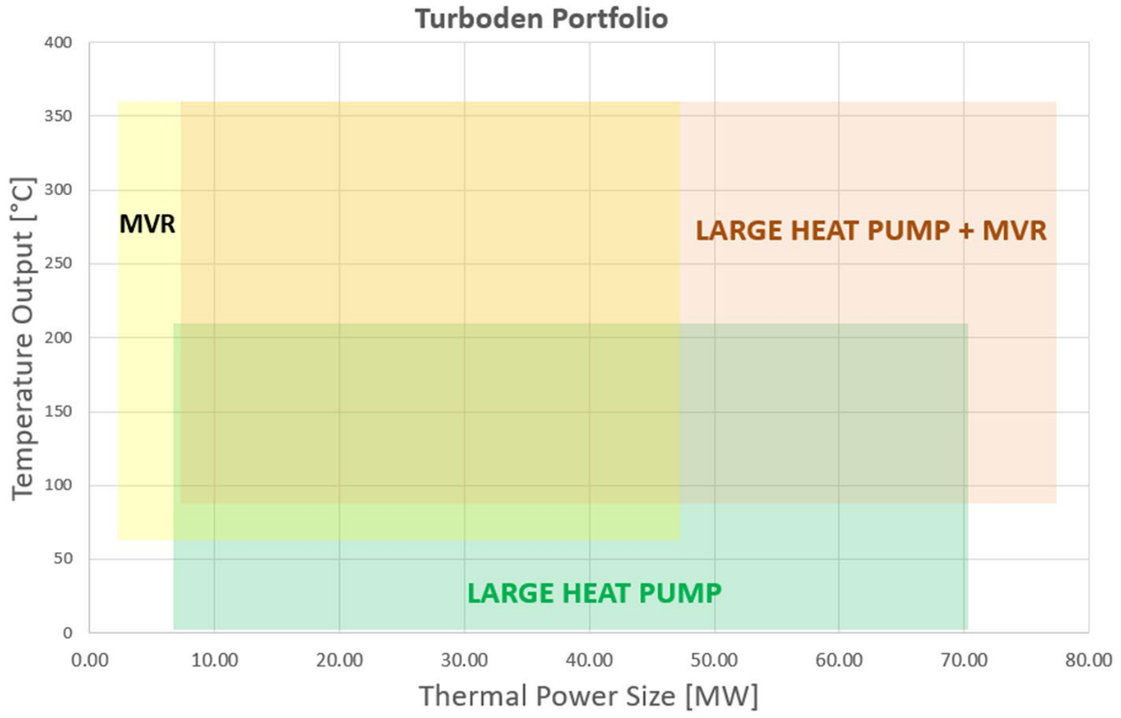
WORKING FLUIDS AND APPLICATION RANGE



DISCLAIMER NOTE: This scheme is valid for subcritical heat pump cycles operated at pressures above atmospheric.



TURBODEN REFERENCES LARGE HEAT PUMPS

Steel Mill

IN OPERATION

- **CUSTOMER**: ORI Martin SpA
- **LOCATION**: Italy
- **CONFIGURATION**: Thermal power generation from furnace cooling water to produce hot water for district heating
- **LHP THERMAL POWER OUTPUT**: 6 MW
- **FEATURES**:
- Heat source: 75-70°C
- Heat Sink: 65→120°C
- Thermal power delivered: 6MWt
- COP: 8,2-5 (depending on the operation)

Pulp&Paper

UNDER CONSTRUCTION

- **CUSTOMER**: Undisclosed
- **LOCATION**: Europe, Nordic
- **CONFIGURATION**: Steam generation generation from cold water cooling water to produce steam for process. Sinergy of LHP with MVR. Sinergy with MCO for compressor implementation.
- **LHP THERMAL POWER OUTPUT**: 12 MW
- **FEATURES**:
- Heat source: 17-8°C
- Heat Sink: 100→175°C
- Thermal power delivered: 12 MWt superheated steam
- COP: 2

FEED / Studies / R&D

ONGOING FOCUS

- **Several project in different industrial fields are under discussion.**
- CCUS
- Refineries
- Petrochemical
- Chemical
- Pulp&paper
- Process industry
- District heating
- Diaries
- Food&beverage
- Pharma
- Etc…

COMPRESSOR OVERVIEW FOR TD LHP

SINERGICCOMPRESSOR OPTIONS TOADDRESSHEAT PUMP MARKET:

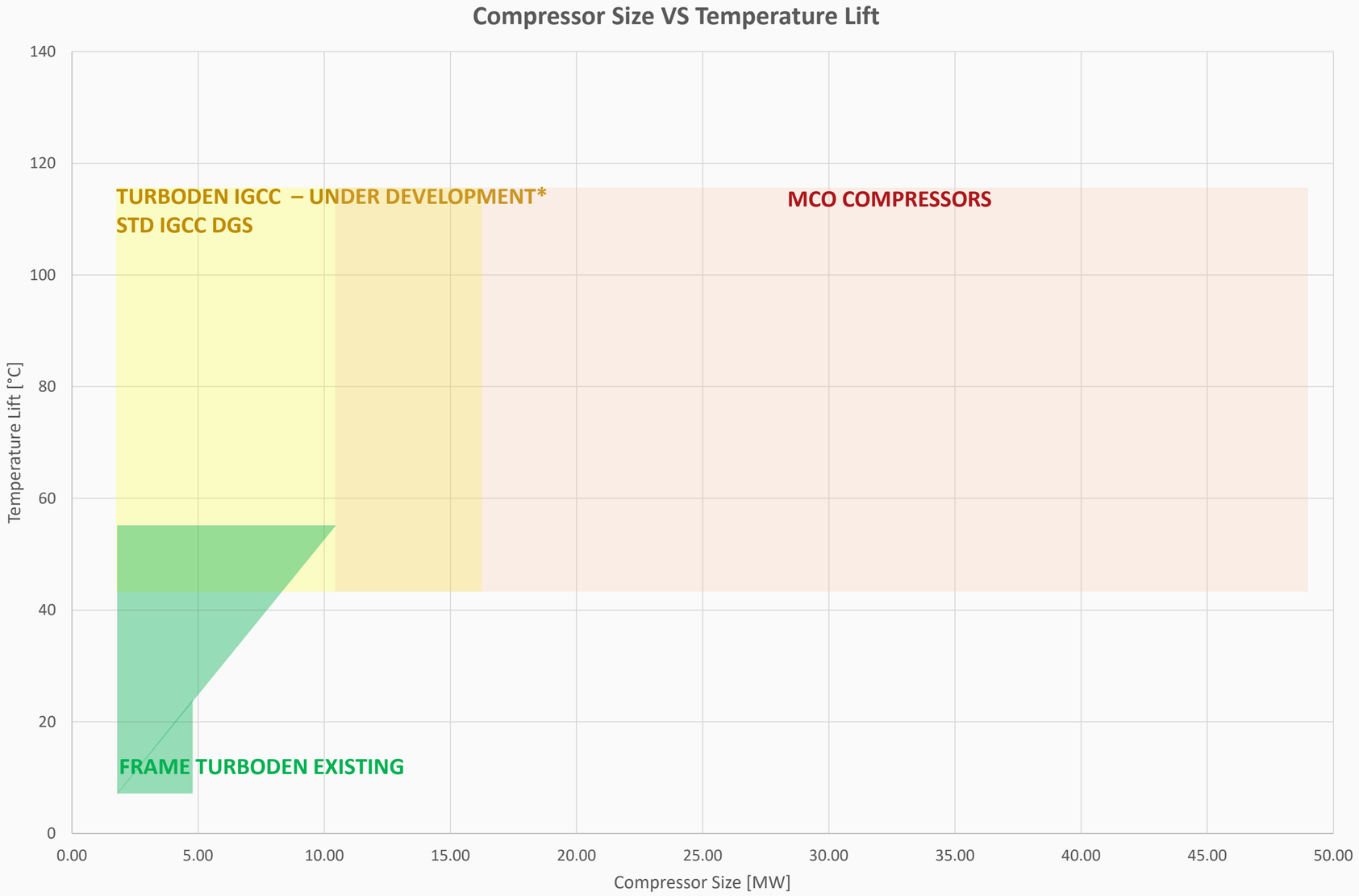
- MCO technology jointly selected for large compressors
- Turboden technology developed in house leveraging turbine experience with external collaborations / hiring

POLITECNICO MILANO 1863

NTNU Norwegian University of Science and Technology

UNIVERSITÀ DI PISA

- ✓ Universities collaboration for centrifugal stages design / CFD
- ✓ aeromechanics
- ✓ Wet gas compression
- ✓ Low cost country third party design companies for package design / drafting

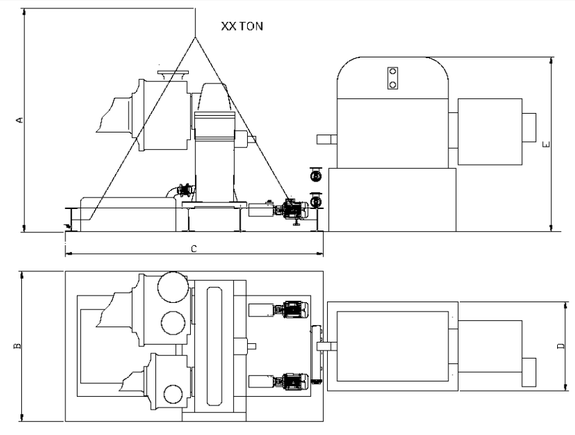


TECHNICAL SOLUTIONS

Product Range

Compressors for closed loop refrigeration fluids

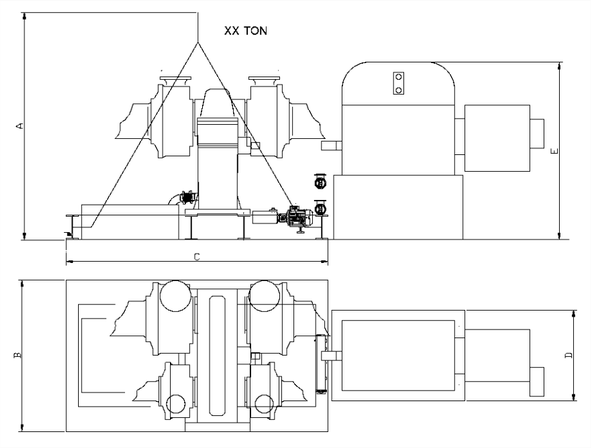
- Type: multistage integral gear
- Power range : 300 kW to 15 MW
- Max number of stages: 5
- Electric Motor 2 or 4 poles
- Pinion speed range 8000 – 32000 rpm
- Impeller Diameter : 150 - 1000 mm
- Impeller type : 3D closed (by brazing / full milled)
- Lubrication system: pressurized with process fluid
- Sealing system: double mechanical seal



Refrigerant compressor design

Compressors for water steam or water steam + incondensable gases

- Type: multistage integral gear
- Power range : 100 kW to 15 MW
- Max number of stages: 8
- Electric Motor: 2 or 4 poles
- Control: IGV + speed variation
- Pinion speed range: 5000 – 55000 rpm
- Impeller Diameter : 150 - 1500 mm
- Impeller type : 3D open
- Lubrication system: atmospheric
- Sealing system: air buffered double carbon seal

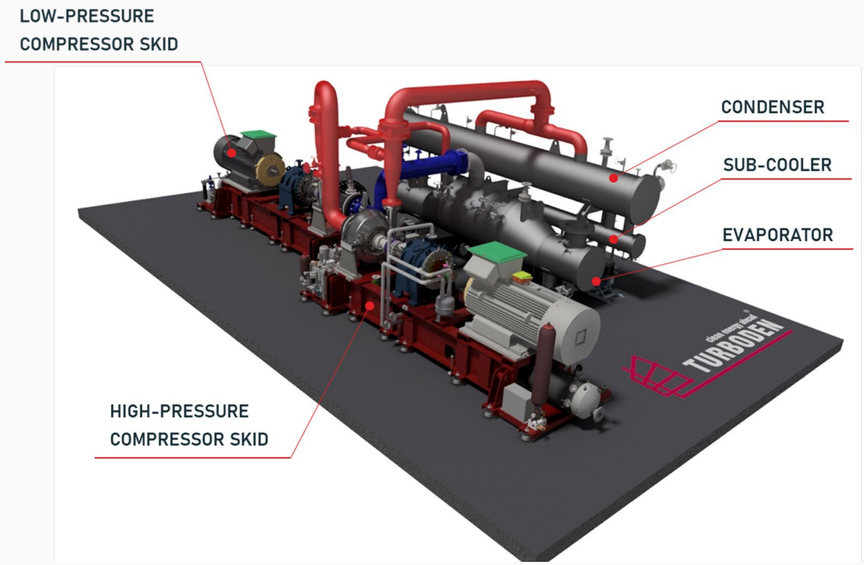


MVR

TECHNICAL SOLUTIONS

Small frame compressor

ORI MARTIN PROJECT



3D impeller with HIRTH coupling from solid forging

Materials

- X12Cr13 SS
- 17/4 PH SS
- Inconel

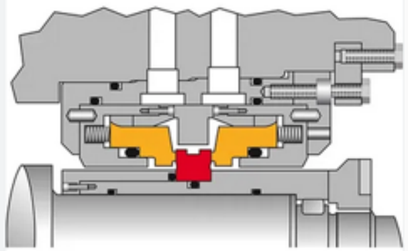
Gear design by others

RENK-MAAG
Integral Gear Unit MULTICOM®

*for compressors with pressurized oil system the gear is designed by Turboden according to DIN/AGMA std.

Air buffered Espey seals or labyrinth for MVR

Mechanical seal for Heat Pump compressor



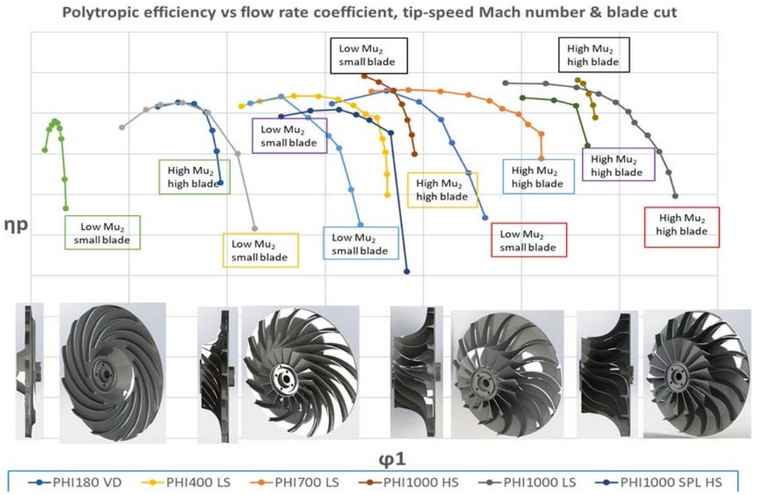
TECHNICAL SOLUTIONS

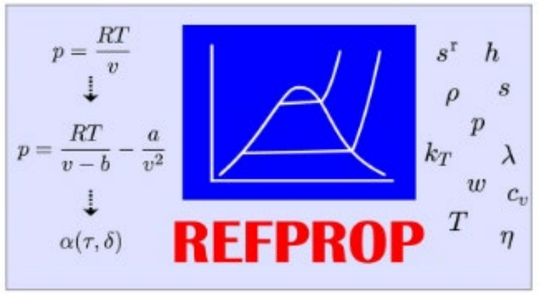
Compressor performances

Compressors are selected using a thermodinamic package with most suitable EOS and leveraging from a pre-designed impeller family verified by CFD

- Impellers for high MW gases
- Impellers for high head (H2O , light gases)

Impeller family





ANSYS CFX

MRT + PTC10 test bench in Brescia (Italy)

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SYSTEM INTEGRATION

DYNAMIC ANALYSIS SIMULATION

Turboden applies state of art design tools to assess system integration (Dynamic modeling and simulation , Hazops, Reliability assesment etc..) in order to:

- Obtain **flowless startup** and **commissioning activities**
- Support **customer operation** and plant **throughput maximization**
- Support **life cycle assessment** via **digital twin techniques**

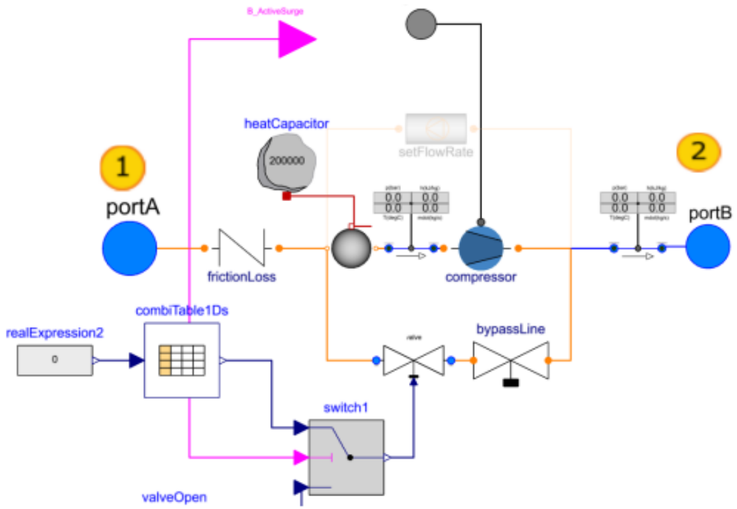


Figure 7: Insight into compressor stage model (stage 1), including the actual compressor model, as well as a bypass (HGB) for surge control.

4.1.2. COLD STARTUP RESULTS AND DISCUSSION

The cold startup process starts from consistent cycle temperature cycle at around 10° (winter) or 31°C (summer), the filling levels are applied according to Table 4. The initial state of the system in starting conditions and its evolution during the startup process is shown in Figure 11. Initially, all components are at around 10°C, the working fluid pressure corresponds to the equilibrium pressure, which is around 2bar.

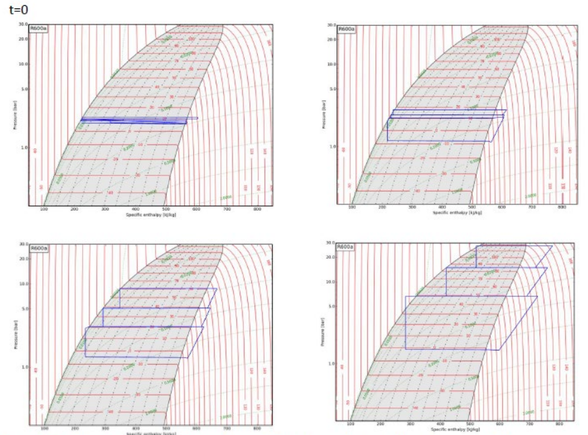


Figure 11: Evolution of the pressure-enthalpy diagram of the heat pump during cold startup process (winter)

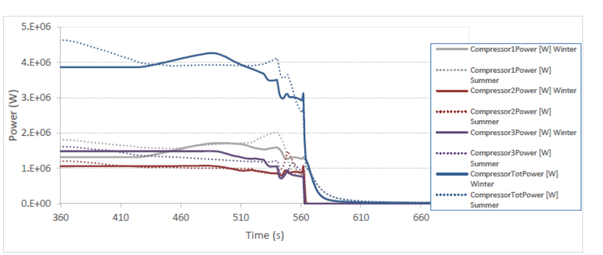


Figure 28: compressor power during normal stop procedure

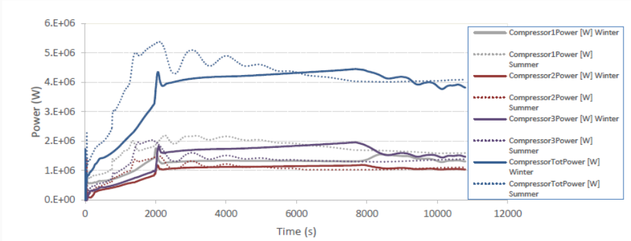


Figure 12: Compressor power during cold startup

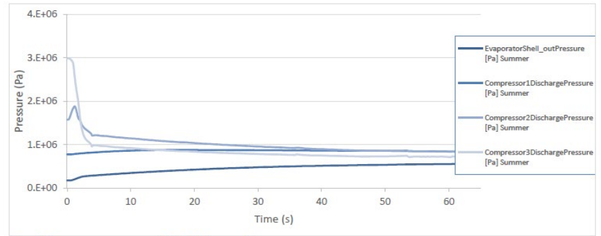


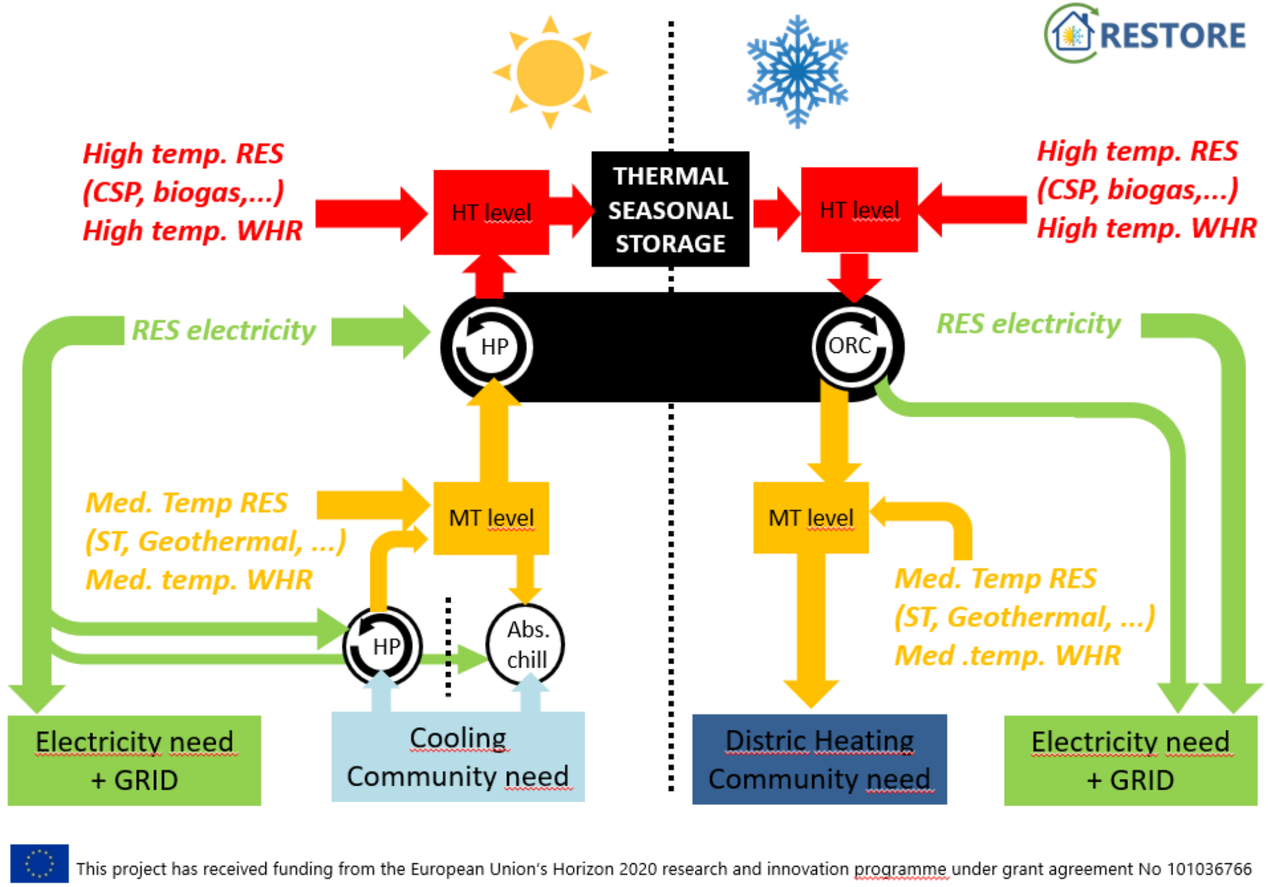
Figure 34: compressor pressures during trip (summer)

Figures refers to dynamic simulation carried out during a FEED regarding LHP integration in refinery process

INTEGRATION WITH ORC / ENERGY STORAGE

Turboden is working to develop affordable energy storage solution leveraging propertary turbomachinery design (Compressor and Turbines) which includes a combination of the following technologies :

- **Thermochemical storage** solution
- Phase change materials **Carnot battery**
- **Integra tion** of third party **storage system** within Turboden **Large Heat Pumps**



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101036766

clean energy ahead
TURBODEN

THANK YOU!

THE FUTURE IS ELECTRIFIED, GET READY!

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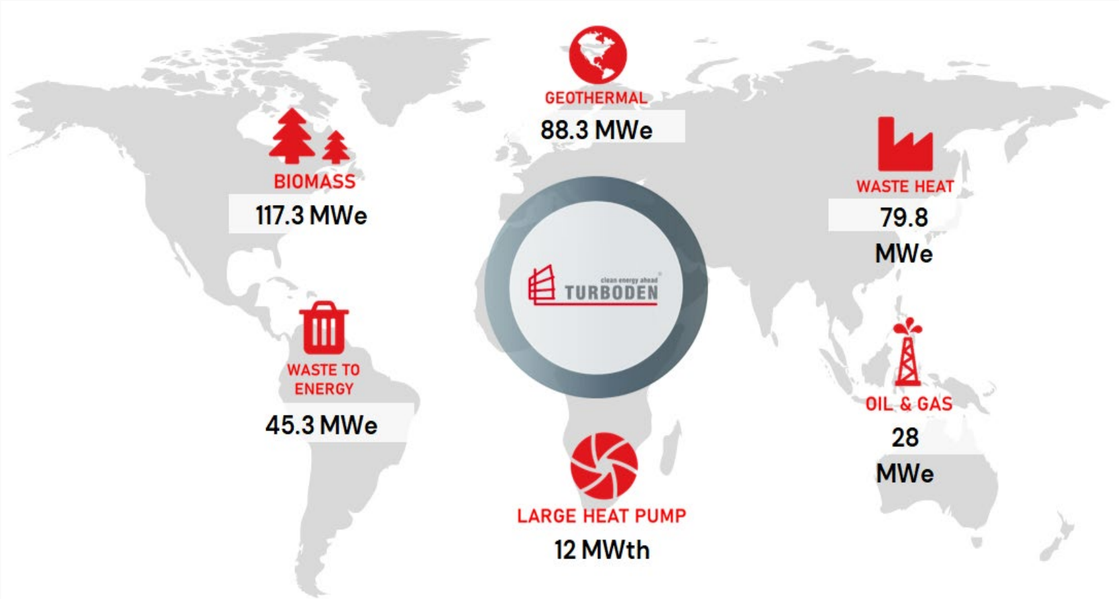
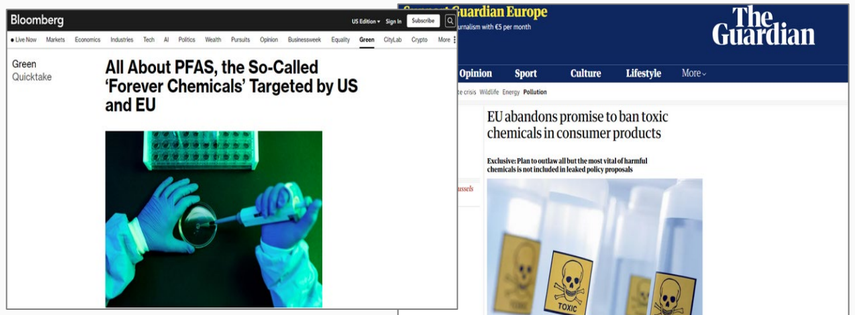
BACKUP

WORKING FLUID: NATURAL REFRIGERANTS




Bloomberg

Green
Quicktake

All About PFAS, the So-Called 'Forever Chemicals' Targeted by US and EU

The Guardian

Opinion Sport Culture Lifestyle

EU abandons promise to ban toxic chemicals in consumer products

Exclusive: Plan to outlaw all but the most vital of harmful chemicals is not included in leaked policy proposals

Working fluids

- Fluid selection according to process requirement
- Butanes (R600 – R600a)
- Pentanes (R601- R601a)
- Cyclopentane (C5H10)

Company Experience

- Turboden pioneering company in HC implementation for power plants
- More than 45 units installed with HC working fluid
- Worldwide experience in over 20 countries*
- Installed capacity 355+ MWe, 12 MWth

*Canada, Croatia, Egypt, El Salvador, France, Germany, Greece, Italy, Japan, Netherlands, Philippines, Portugal, Romania, Serbia, Slovakia, Taiwan, Turkey, UAE, UK, US

Hydrocarbon as Winning choiche

- Natural refrigerants with low ODP and GWP [1]
- Cost effectiveness (~10 – 15 times lower than equal HFOs)
- HFOs within possible PFAS ban [2]
- High temperature suitability
- Flammability handled as usual best practice in industrial plants [3]

[2] *Council of the EU and the European Council, https://www.consilium.europa.eu/en/press/press-releases/2023/10/05/fluorinated-gases-and-ozone-depleting-substances-council-and-parliament-reach-agreement/*

[3] *HEX construction according to ASME and international standard*
ATEX requirements: IEAC 600079-10 as ZONE 2
Ventilation according to EN378
Turboden experience with 40+ reference plants in operations adopting hydrocarbons

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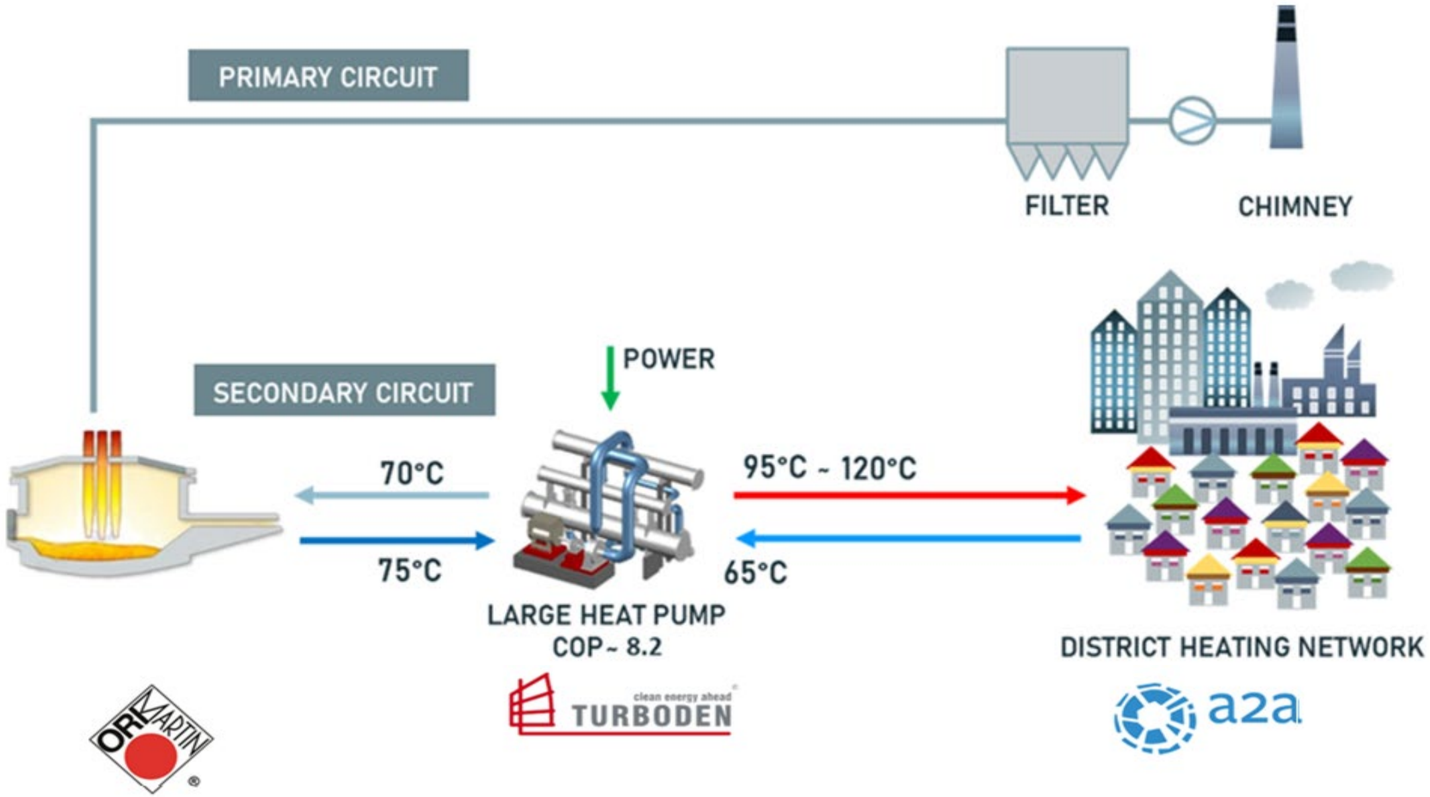
REFERENCE PROJECT: STEEL MILL PRODUCTION

Heat from the cooling of the steelmaking process can be upgraded through a LHP and used for district heating instead of being wasted, i.e. dissipated through cooling towers.



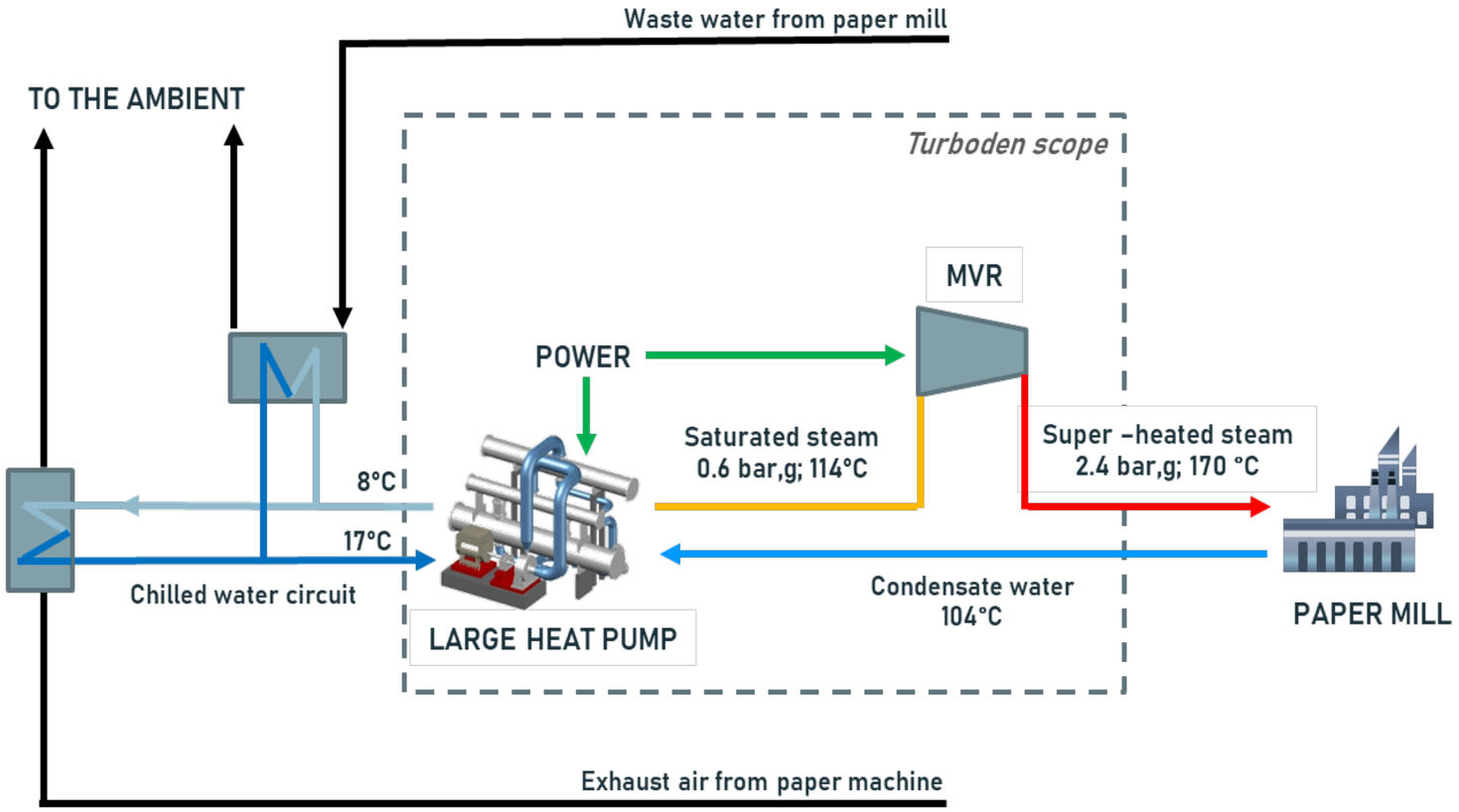
PROJECT FEATURES

- Industrial application: Steel Mill plant
- Country: Italy
- Status: in operation since 2023
- Size: 6 MWth
- Output Temperature: 120 °C

TECHNICAL FEATURES

- Turboden scope: EP
- Delivery: pressurized water 120 °C to District Heating
- Centrifugal compressor from Turboden
- LHP working fluid: R1233zd
- Fully automated operation

REFERENCE PROJECT: PAPER MILL INDUSTRY



PROJECT FEATURES

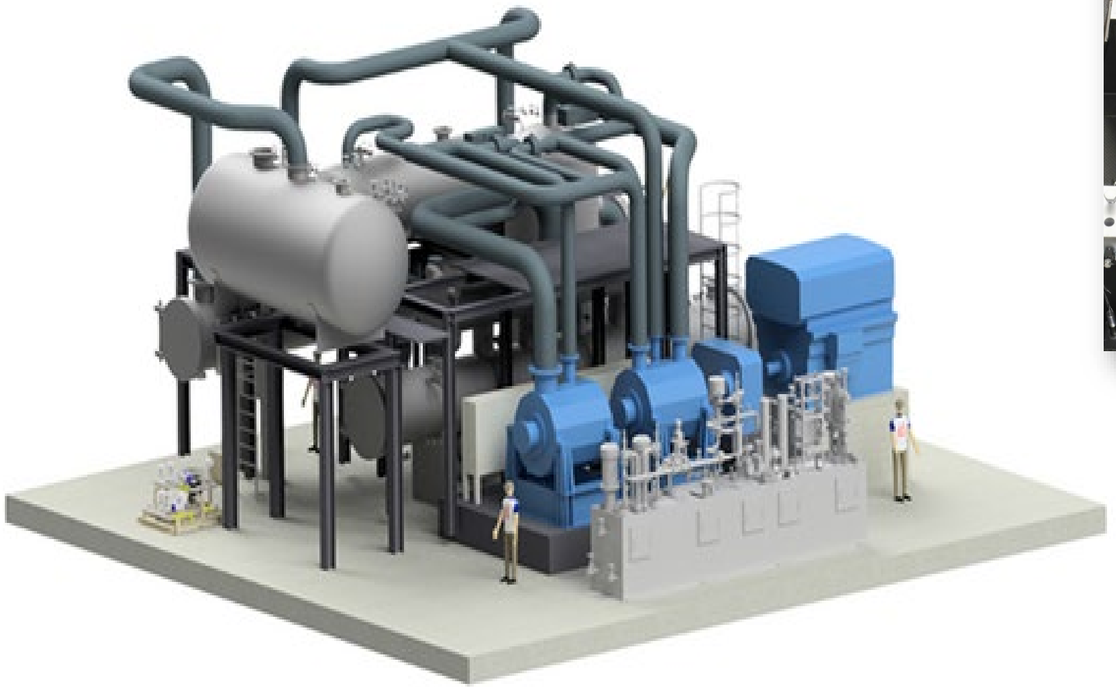
- Industrial application: Paper Mill
- Country: Northern Europe
- Status: under erection – start up 2024
- Size: 12MWth
- Output temperature: 170 °C

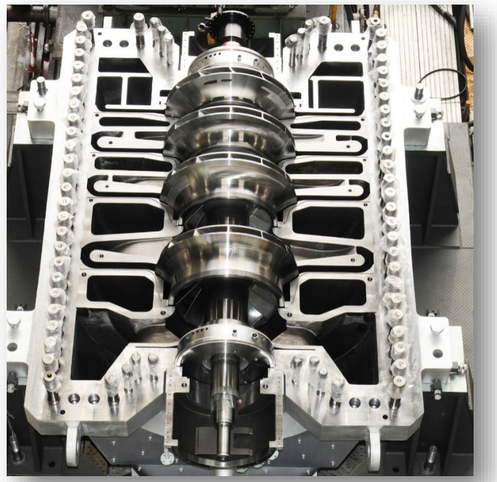
TECHNICAL FEATURES

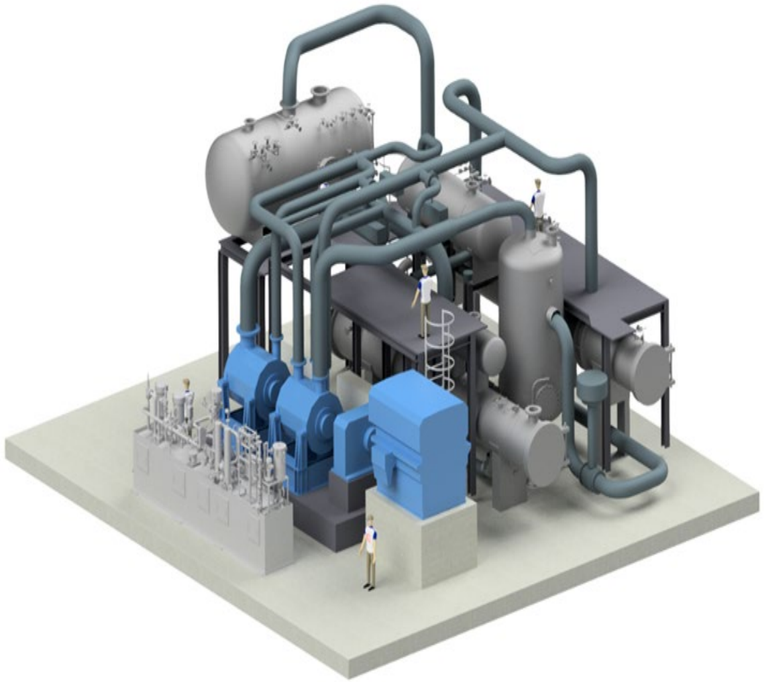
- Turboden scope: EPC (LHP + MVR)
- Delivery: Steam @2.4 bar.g (superheated at 170 °C)
- Centrifugal compressor from MCO
- LHP working fluid: Natural refrigerant Isobutane

R600a

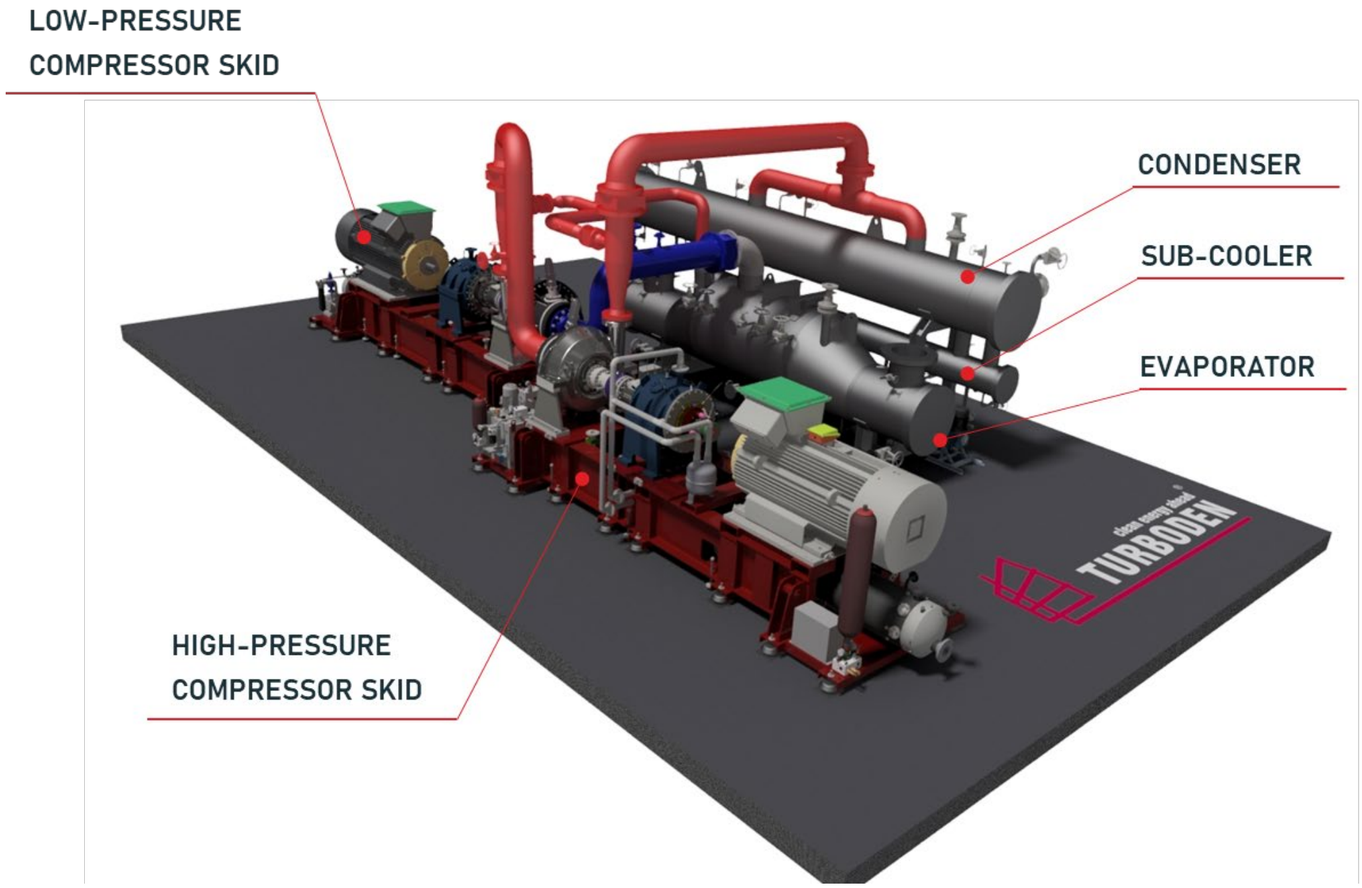
REFERENCE PROJECT: PAPER MILL INDUSTRY

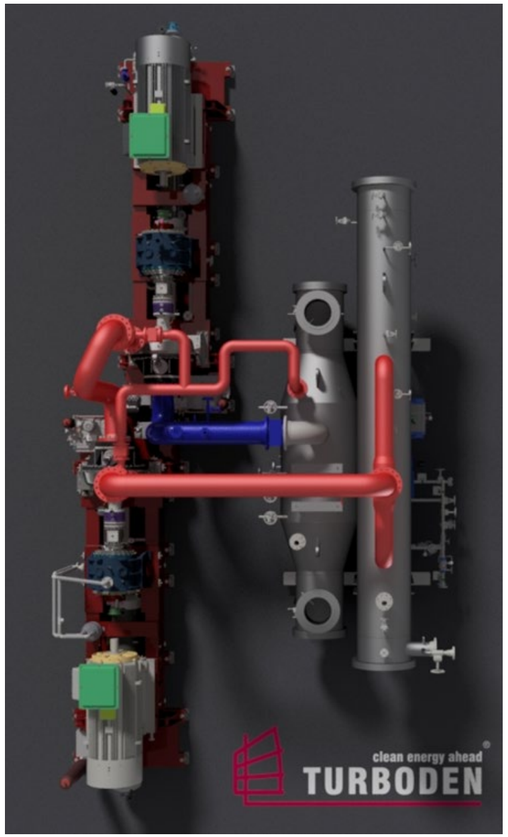






REFERENCE PROJECT: STEEL MILL PRODUCTION





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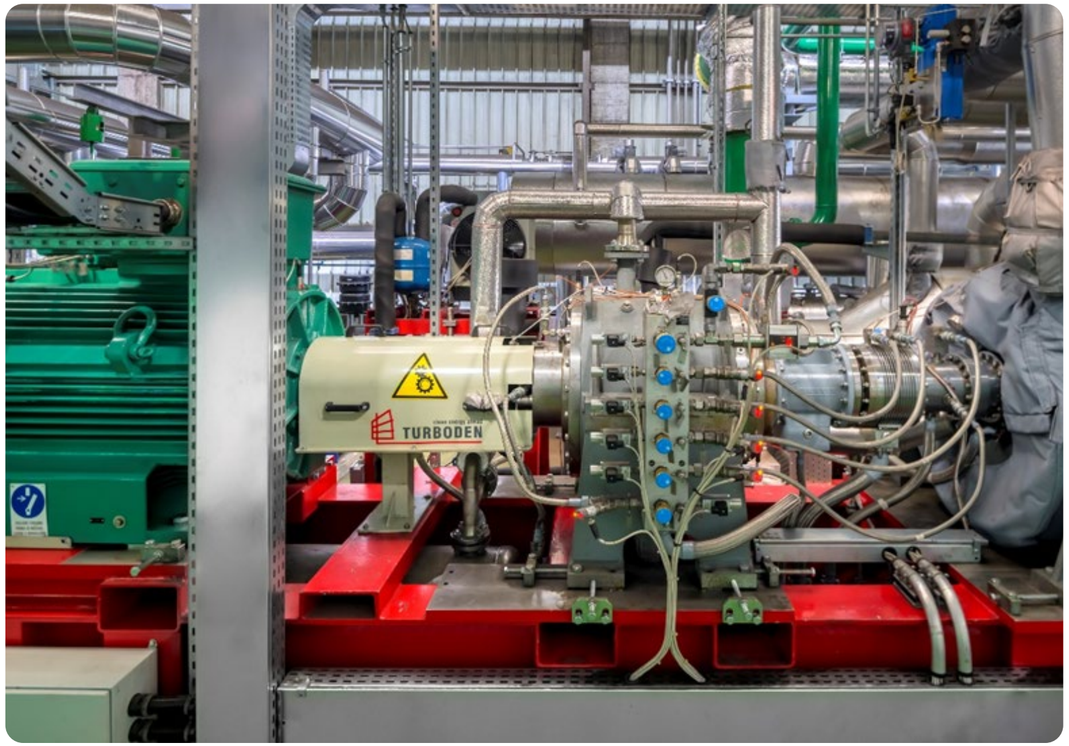
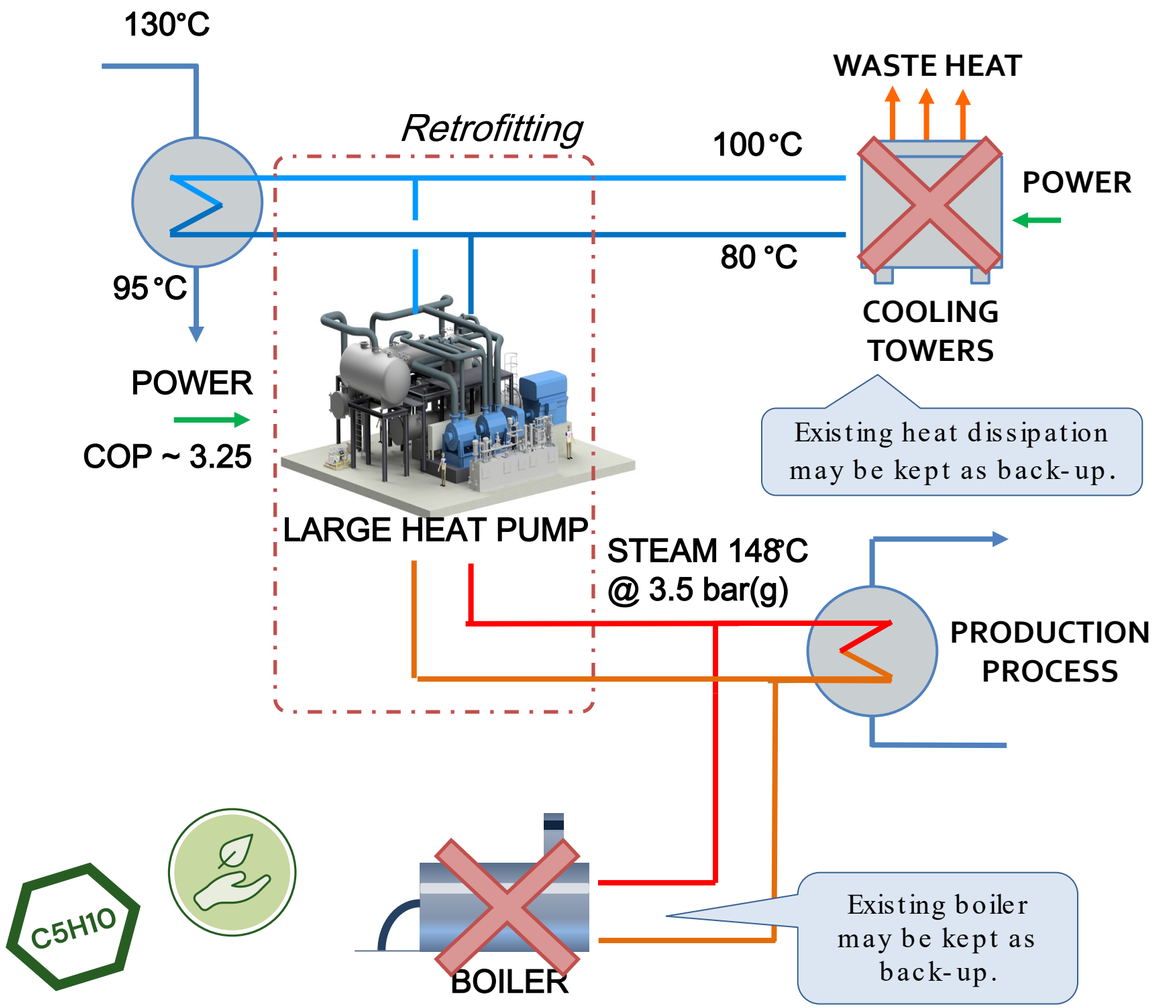
REFERENCE PROJECT: STEEL MILL PRODUCTION

REFERENCE CASE: STEEL MILL PRODUCTION



CASE STUDY: FEED in REFINERY PLANT



OUTLINE OF CASE STUDY

Large heat pump can be applied in the refinery sector to provide widely used steam via heat recovery from available waste heat sources. There are many potential applications for heat pump technology; here only one of them is presented.

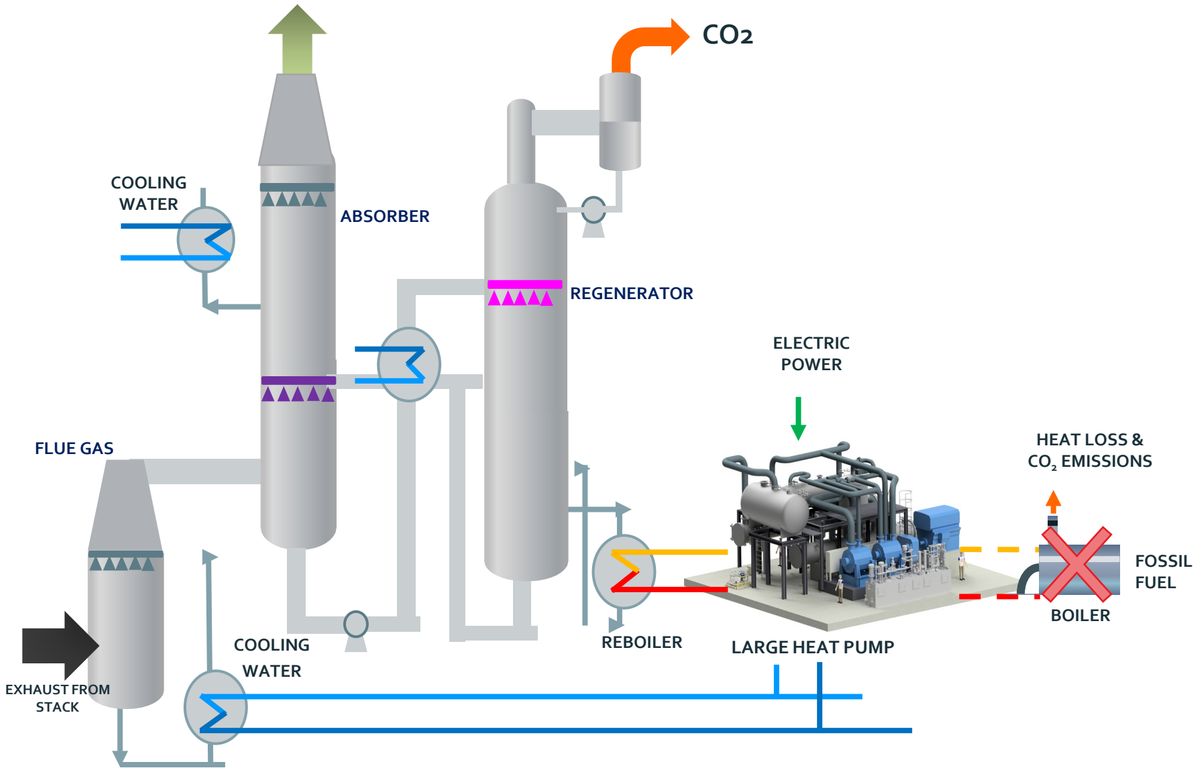
PROJECT BENEFITS

- Avoided consumption of fossil fuel for heat generation, significant carbon footprint reduction
- Avoided waste heat, cooling system' consumptions from existing systems

PROJECT FEASIBILITY

Heat output: 20 MWth
Electric input: 6.2 MWe
COP: 3.25
Natural gas saving: 18.9 MSmc/yr
CO2 saving: 36.900 tonCO2/yr
Operating hours: 8.300 hrs_eq/yr
Expected PBT: 3.5 years

CASE STUDY: FEED for Post-Combustion CO_2 capture



OUTLINE OF CASE STUDY

Large heat pump can be applied in Carbon Capture plant in order to provide both cooling capacity and the thermal power needed from the process. There are several cooling water stream that can be used as heat source for the heat pump. The heat pump can be applied to produce steam for the process or to directly heat the chemical solvent for CCS.

PROJECT BENEFITS

- Major voices of OPEX: Heating energy for regenerator & Cooling energy for process
- Heat pump system: OPEX improve by utilizing waste heat energy for regenerator
- Avoid additional CO2 emissions (gas steam boiler) and water consumption (cooling circuit)

PROJECT FEASIBILITY

Heat output: 46 MWth

Electric input: 15 MWe

COP: 4.1

Higher CO2 sequestration capacity (+10/+16%)

Reduced cooling water consumption (-40/-60 %)

R601