R&D activities on sCO_2 in Europe (and beyond)

Balance of Plant

Sixth episode – 14 February 2024

This webinar is in cooperation with 9 European R&D projects

ETN Global

COMPASsCO_2

SCARABEUS

iSOP

$CO_2OLHEAT$

sCO_2-4-NPP

CARBOSOLA

DESOLINATION

SOLAR sCO_2OL

sCO_2-Efekt

Webinar content & speakers

- **View of impacts on CAPEX and plant feasibility**
  (Matteo Baggiani – SIME)

- **Large scale CO_2 heat-pumps for decarbonizing heat and cold and for electricity storage (LDES)**
  (Raymond C. Decorvet – MAN Energy Solutions)

- **Transforming Natural Gas into Clean Power**
  (Xijia Lu – NET Power)

- **STEP Pilot Plant Inventory Management System**
  (Joshua Warren – Southwest Research Institute)

Webinar moderators

- **Marco Ruggiero** (Baker Hughes)

- **Jitka Špolcová** (ETN Global)

What is the first application that comes to your mind when you think about sCO2? (1-2 words)

High density electronics cooling
Efficiency
CPS
Turbomachinery
Waist Heat Recovery
Real lif application
Bottoming Cycles
Decarbonization
Heat Pumps
Waste heat
CSP
Nuclear
Storage
Extraction
Refrigeration
Power generation
Power Cycle
Heat recovery
Power plant
Waste heat recovery
Oxyfuel
Co2 storage
Heat pump
Tree food
WHR
Cryogenic
Aviation
Cheap energy
Oxy combustion
Full scale
Inconel
Replace steam
Fast response to the grid
Flexible Power Source
Carnot Batteries

What is the first item you think of when BoP is mentioned? (1-2 words)

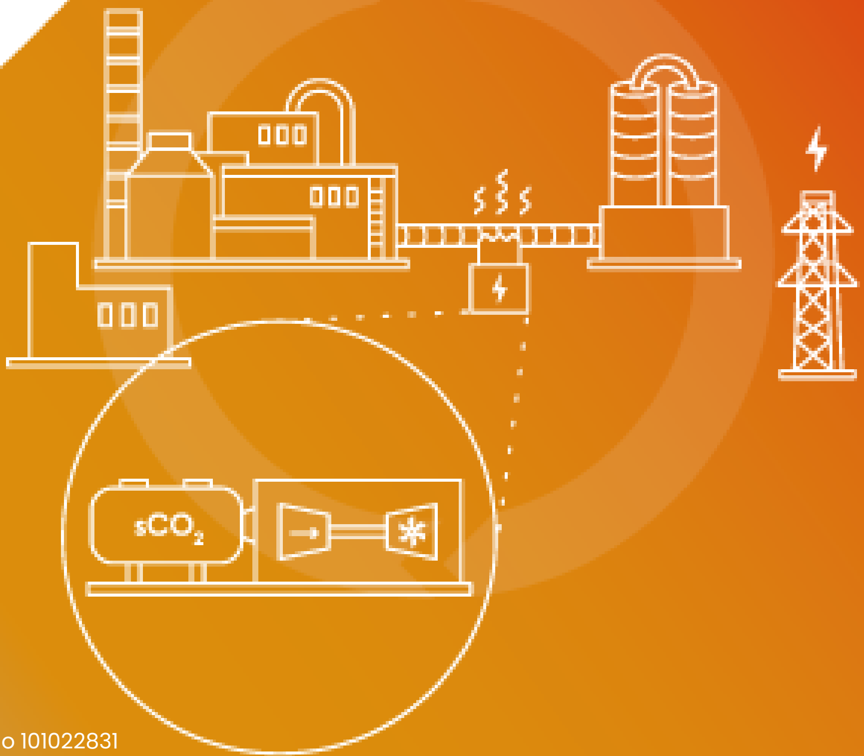
Electrical connection
Heat mass balance
Heay exchangers
Piping
Scope of Supply
Lube oil
Auxiliaries
Turbine
Auxiliary Systems
Systems integration
Inventory control
System integration
inventory system
Enthalpy
Entropy
Cooling
Heat exchangers
Work
Pipework
Dryer
Compressor
Heat exchanger
Recuperator
Cooler
Rotating equipment
Supporting components
Seal system
A lot of engineering
Cooling pump
Parcial load
Transient Response
Main piping
Cogeneration
Inventory management
Efficiency
Control system

ETN Global

CO2OLHEAT

*Supercritical **CO2** power cycles demonstration in **O**perational environment **L**ocally valorising industrial Waste **HEAT***

BALANCE OF THE PLANT: A VIEW OF IMPACTS ON CAPEX AND ON PLANT FEASIBILITY



Matteo Baggiani - 14/02/24

Sime

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101022831

Consortium

CO2OLHEAT brought together a consortium composed of **21 stakeholders** with complementary expertise from 10 European countries

- **Companies**: 13 Enterprises
- **Academia**: 3 research and technology organisations, 4 universities
- **Other**: 1 association

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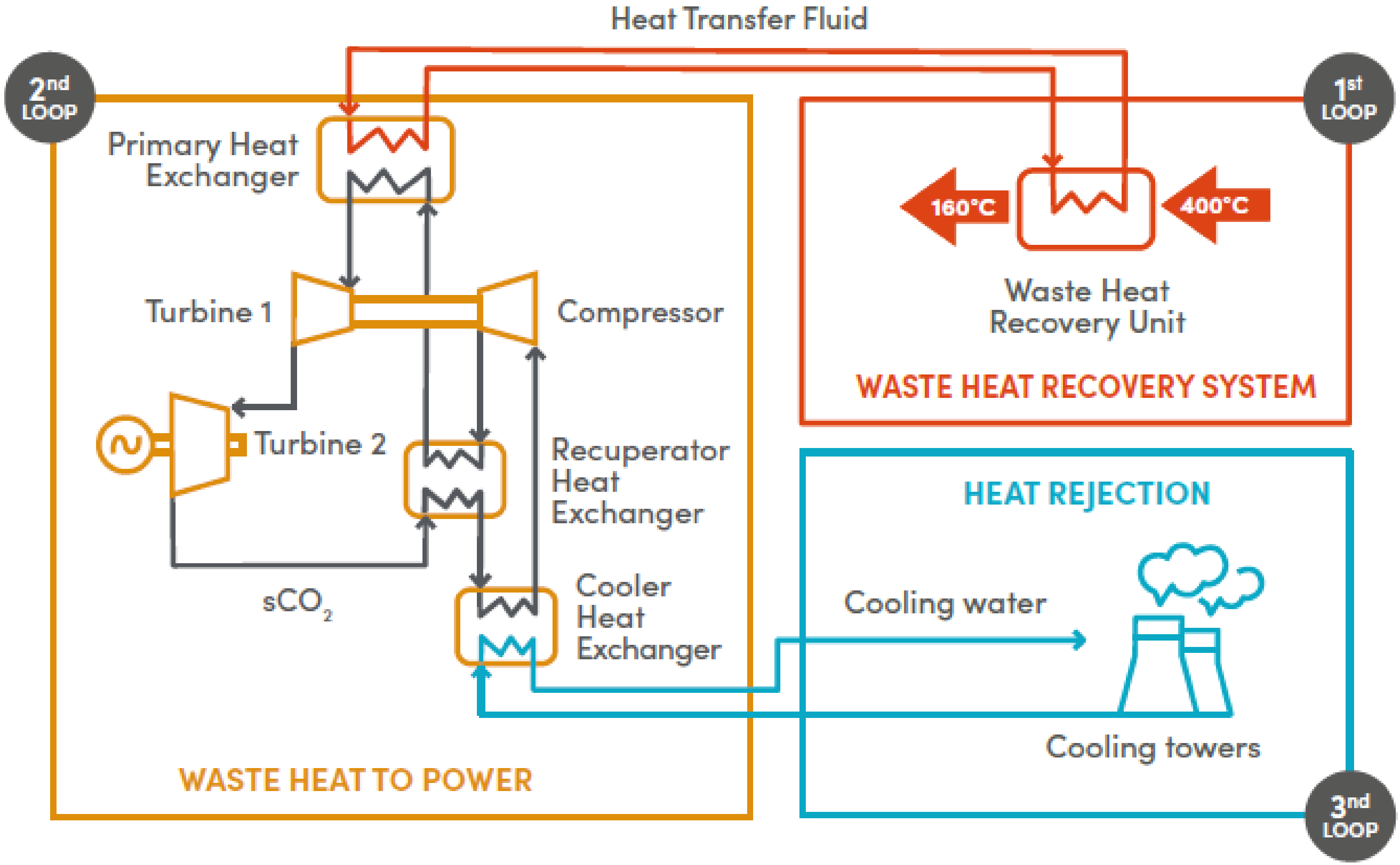
The Power Cycle



CO2OLHEAT's WH2P application based on a recuperated closed-loop Brayton cycle with sCO2 as a working fluid

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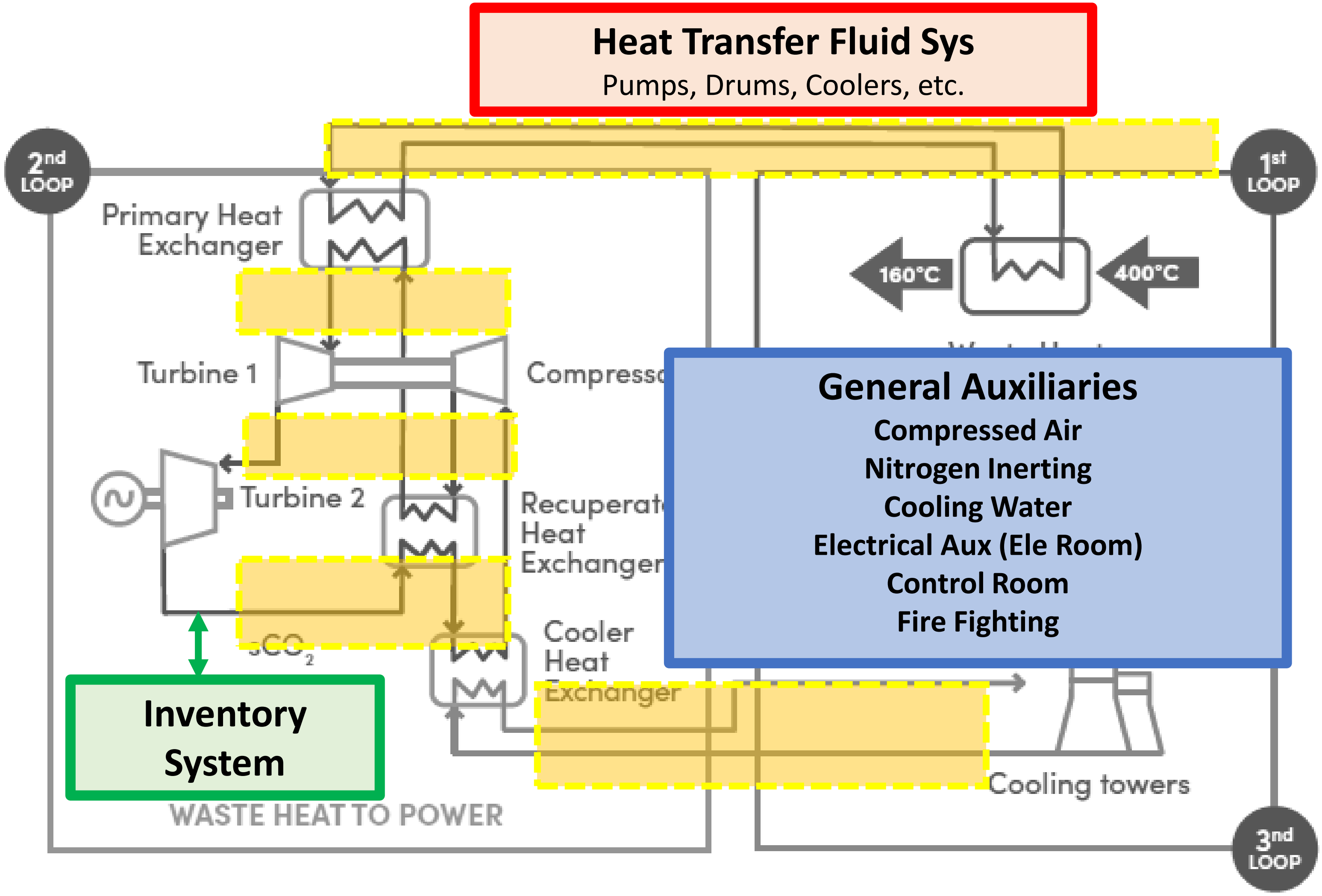
CO2OLHEAT

The Balance of the Plant



1. HTF System
2. Inventory System
3. General Auxiliaries
4. Interconnections

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The Installation Plant – tipically a brown field…

All of potential installation site of technology are existing Plants having some heat to be recovered…

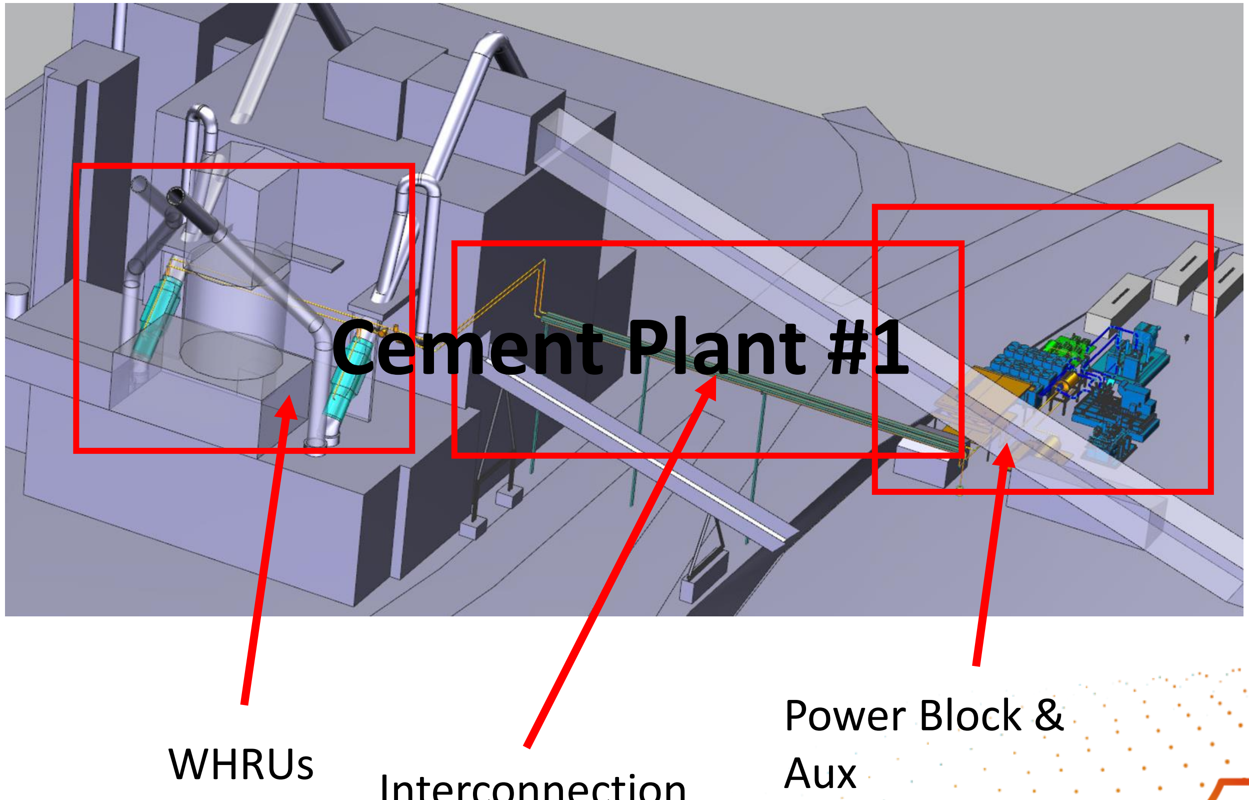
BROWN FIELD

- Congested footprint
- Old infrastructures (specifically electrical & tech gas distribution)
- Lack of Water Availability (for cooling)
- Difficulties in Tie-In location

Design of the BOP can make the difference

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101022831

First Example: The Plant & The Layout



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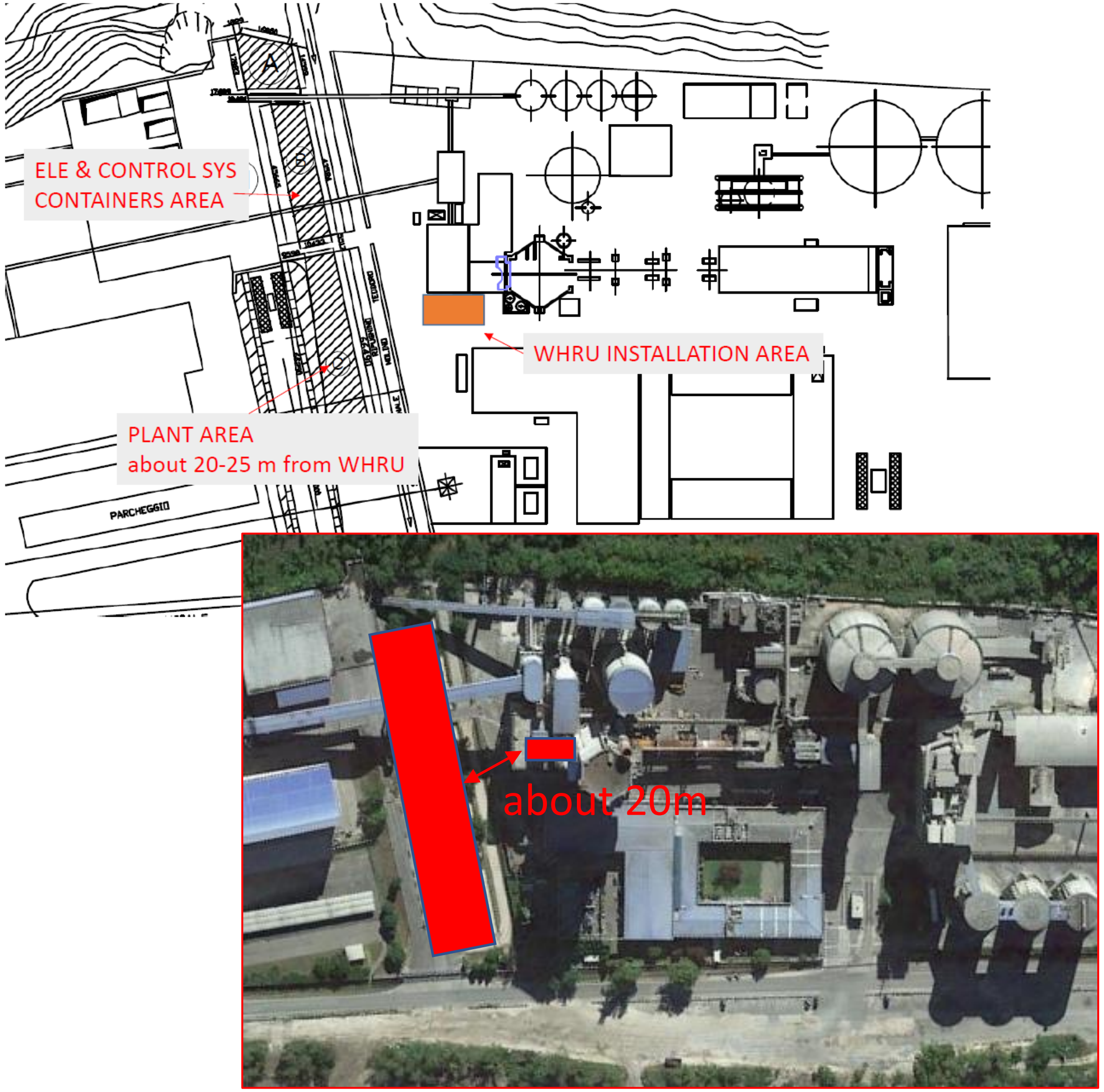
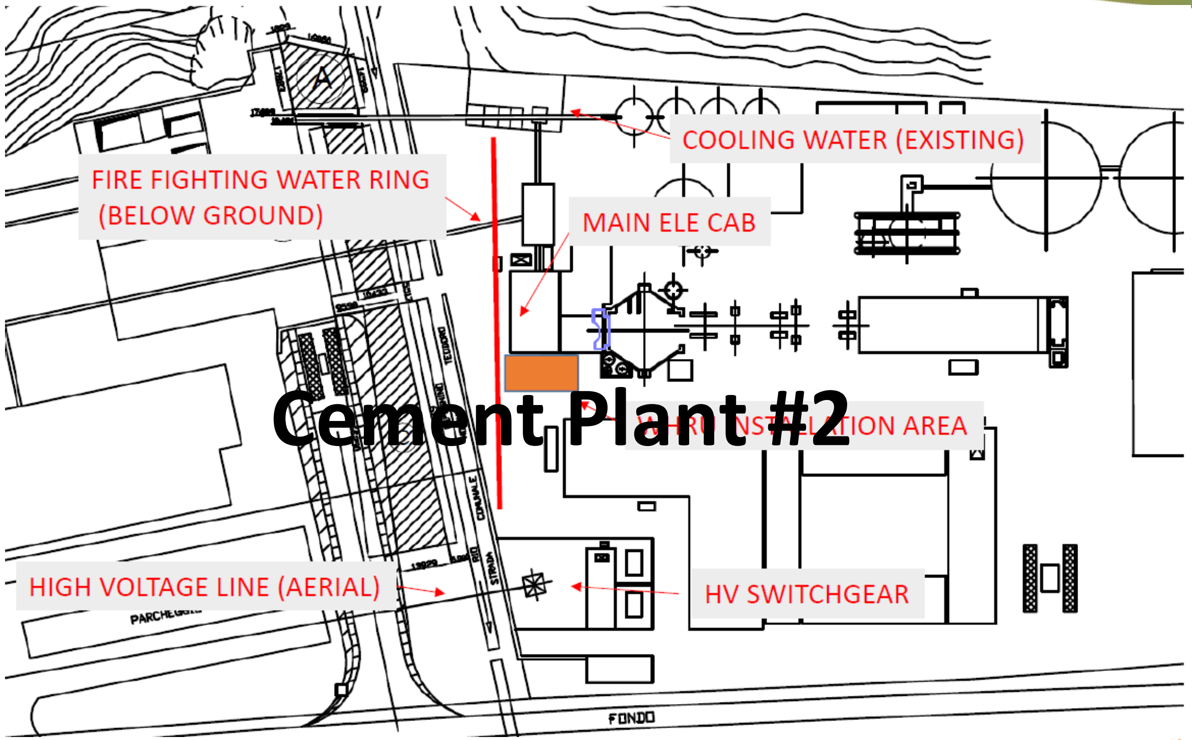
Second Example: The Plant & The Layout





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Examples Comparisons

Topic/Detail	Plant #1	Plant #2
Layout		
Distance between WHRU & Plant+Aux	60m	20m
Space for Plant+ Aux	1200 m^2	1000 m^2
Utilities @ Plant Area		
Compressed Air availability	No	No
Nitrogen availability	No	No
Fire Fighting System availability	No	Yes
Cooling Water availability	No	No
Electrical BOP		
Electrical Room Space availability	No	No
Control Room Space availability	No	Yes
BOP CAPEX IMPACT*	**1**	**0,7**

Calculates as: BOP IMPACT = Plant x % of CAPEX / Plan #1 % of CAPEX

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CO2OLHEAT

Other potential Issues and Tips…

Issues	Tips
1. Connection to the Grid (Production vs Use of Generated Power)	Is there needs to have Inventory? How is the status of the electrical grid around the plant?
2. Safety/Environmental Constraints: Venting CO_2 + High Pressure Pipes	Existing Cold Flare? / Existing HP Gas systems in the plant?
3. Installation Time vs Plant planned shutdown 4. Access and Logistic	Modular Pre-Assemble & Pre-Tested Plant Design

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Conclusions: An Advices List…

1. Prepare a check list when visiting the plant
2. Cooperate with the Client to gain the most from existing structures
3. Maximize Modularization and Footprint flexibility
4. Keep everything close by
5. Include in the evaluation what's beyond the fence (Electrical Grid, Road Access, etc.)

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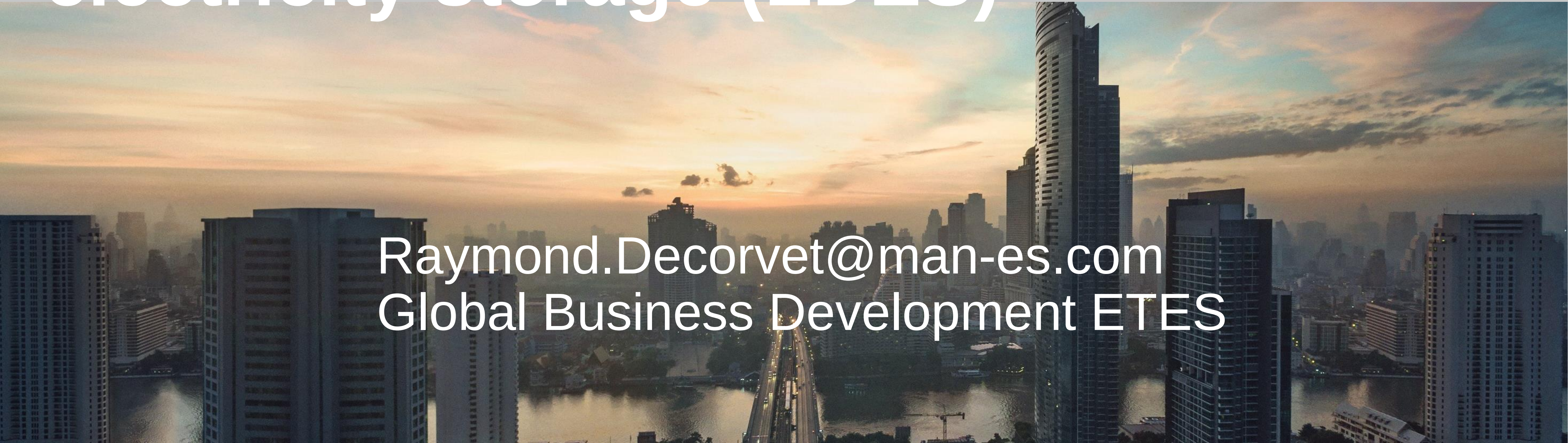
MAN Energy Solutions
Future in the making

Large scale CO_2 heat-pumps for decarbonizing heat and cold and for electricity storage (LDES)



Raymond.Decorvet@man-es.com
Global Business Development ETES

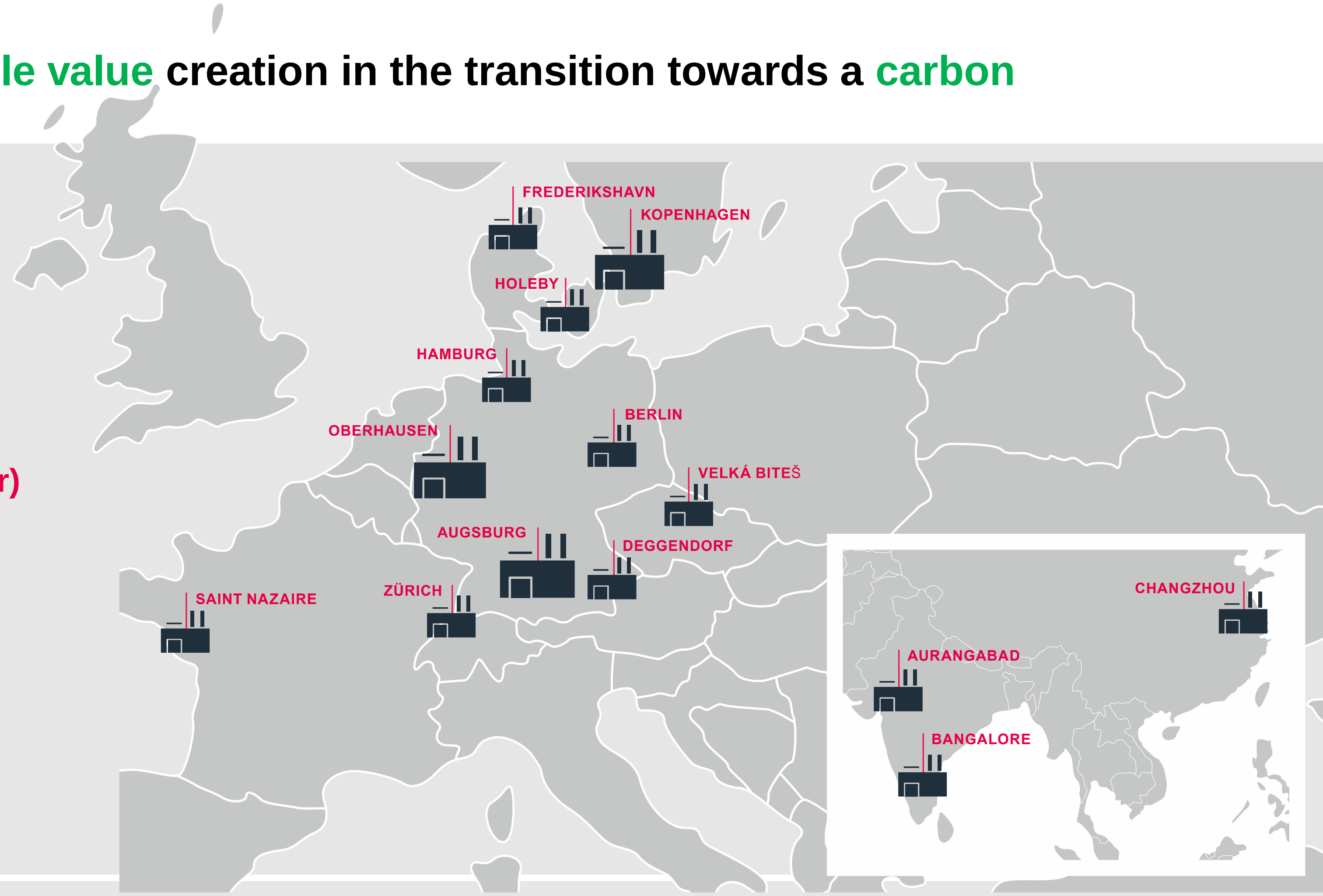
MAN Energy Solutions @ a Glance

Vision:

Building on our unique range of capabilities, we create pioneering solutions to master the business, technical, and operational challenges of decarbonization.

We enable customers to achieve sustainable value creation in the transition towards a carbon neutral future.

11	Production sites in Europe
3	Production sites in Asia
30	Licensees in 7 countries (two- and 4-stroke, turbocharger)
+14’000	Employees worldwide
3.8bn €	Revenue 2022
HQ	Augsburg / Germany



New forward strategy

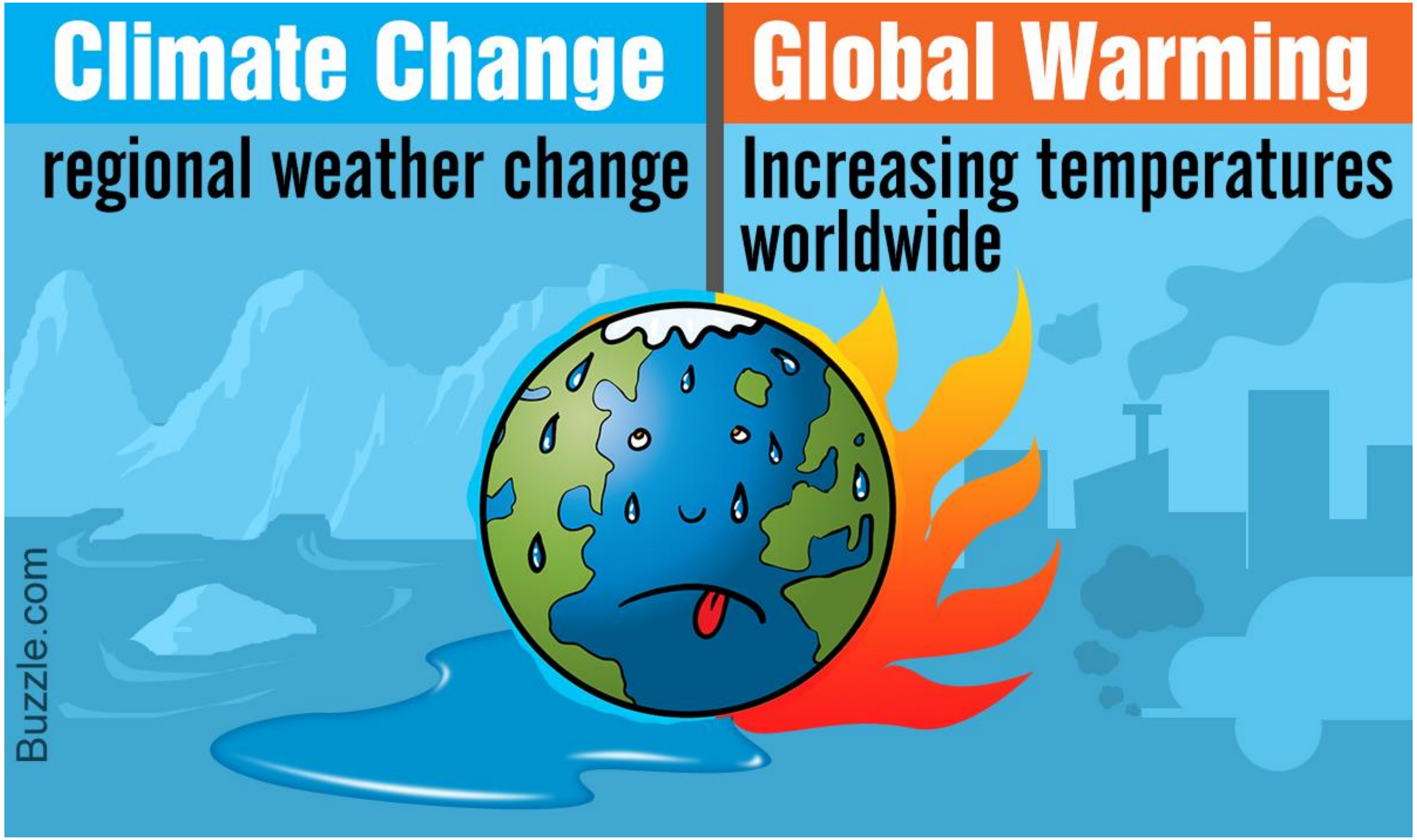
Large HT Heat-Pumps

Carbon Capture (CCS)

Hydrogen (H2)

Global MAN Service Organisation PrimeServ

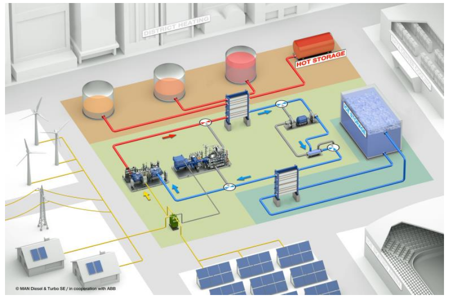
Climate Change & Global Warming is happening!



Decarbonisation & CO_2 reduction is <u>THE</u> option !

Ways forward towards decarbonisation

- Reduce energy consumption
- Increase energy efficiency
- Sector Coupling
- Invest in proven and mature technologies now that support climate goals
    - ➢ renewables
    - ➢ heat-pumps
    - ➢ energy storage (LDES)



ETES

Heat-Pump technology is relevant for the power sector

- **Energy Transition** ➡ Decarbonize heat & cold production (Power-to-H&C)
- **Energy Crisis**
  - ➢ Renewable integration ➡ Efficient, proven and reliable technology (COP >5)
  - ➢ Thermal storage (LDES) ➡ Flexibility and peak recovery
  - ➢ Grid balancing ➡ Primary Reserve (+/- >8MWel in <30 sec.)
- **Sector Coupling** ➡ exploiting synergies among different business sectors
- **Electricity Storage** ➡ MAN ETES (**E**lectro **T**hermal **E**lectricity **S**torage / Carnot Battery)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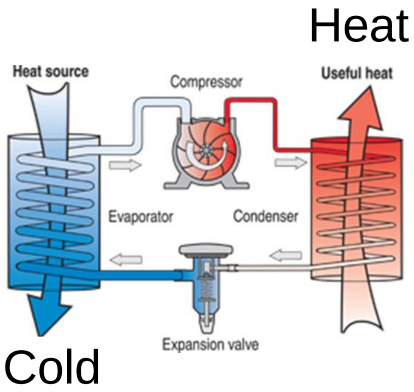

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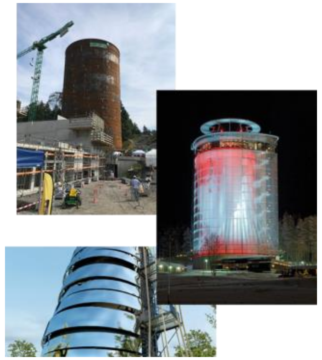
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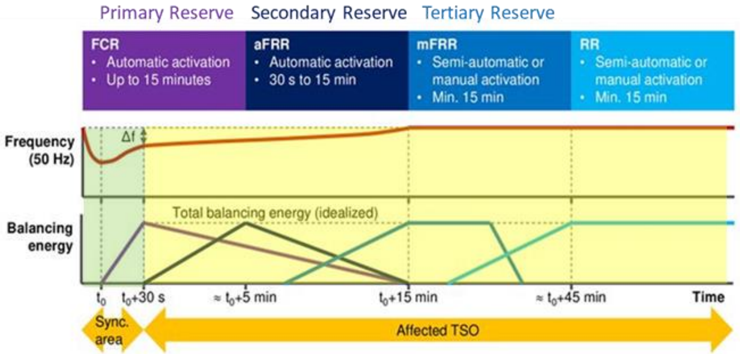
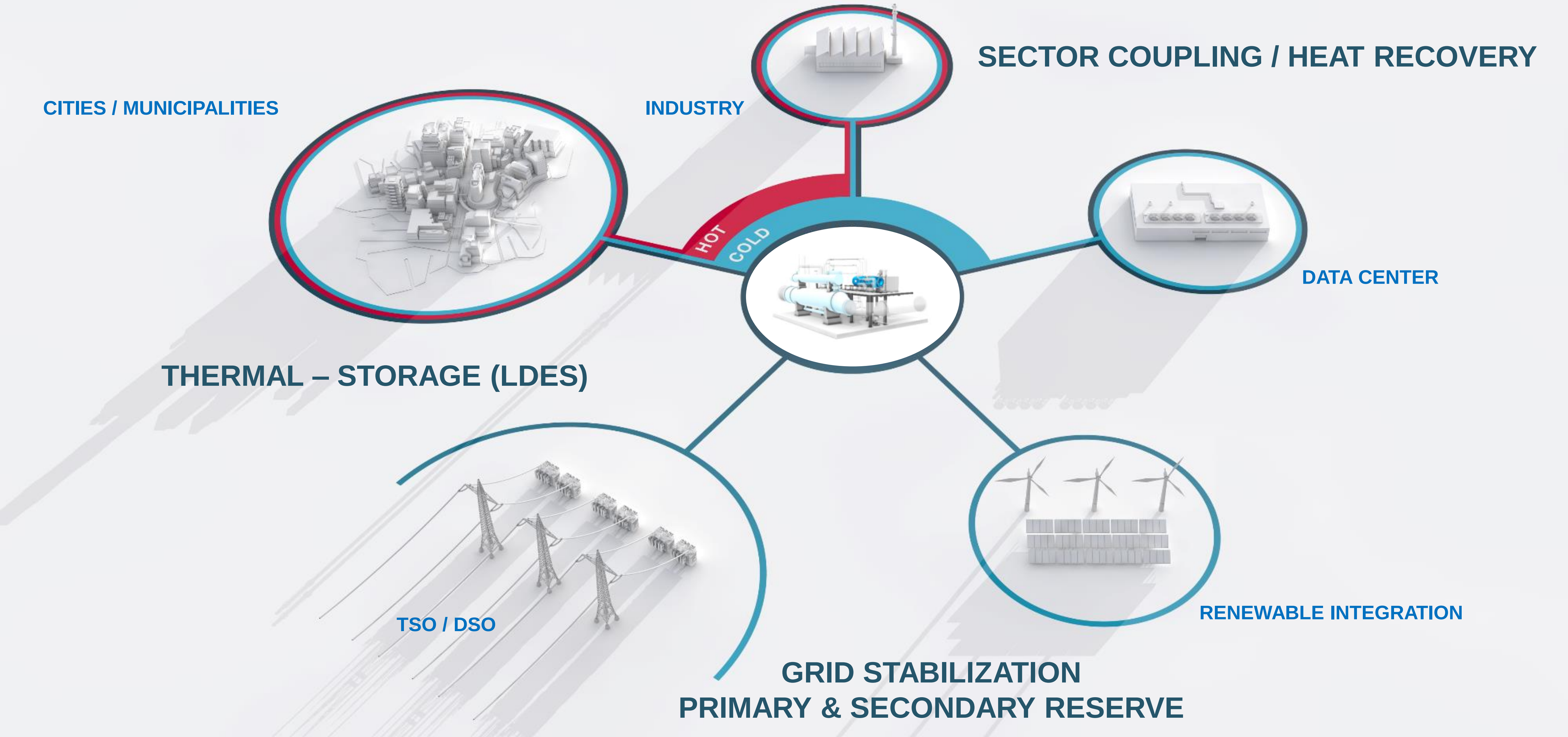
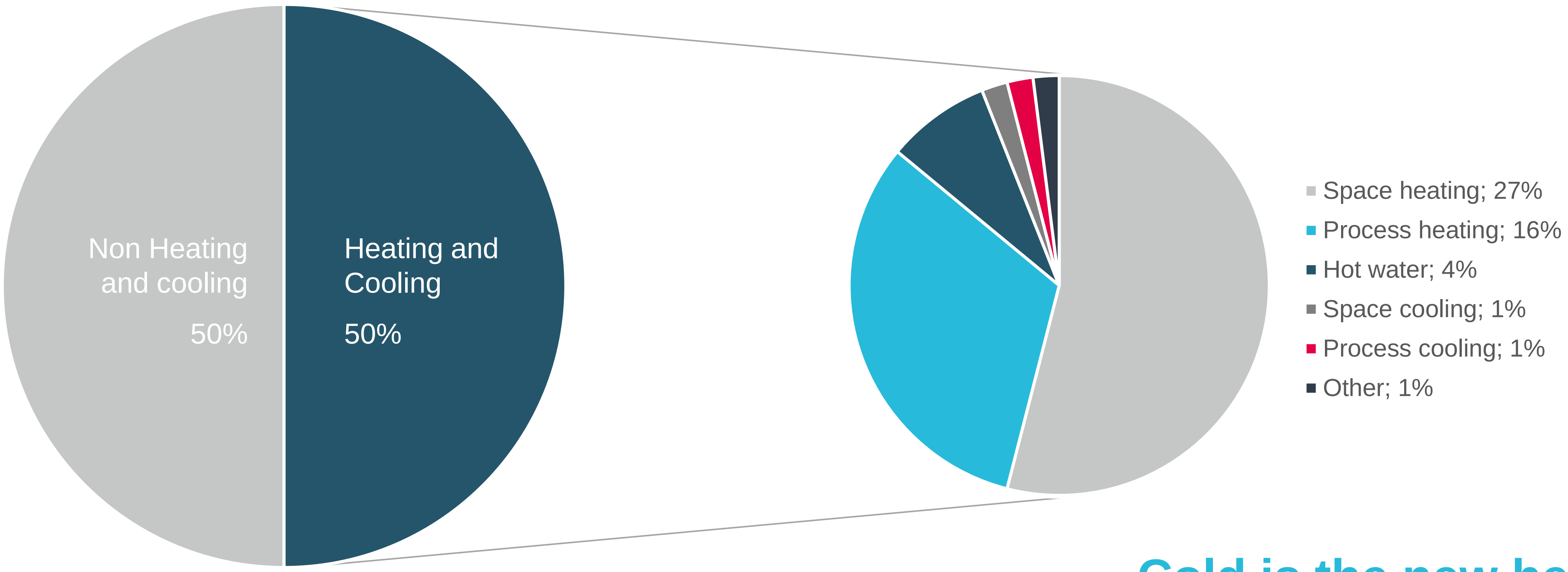


Large heat-pumps are highly relevant to the energy system



Energy transition – Decarbonizing heat & cold production

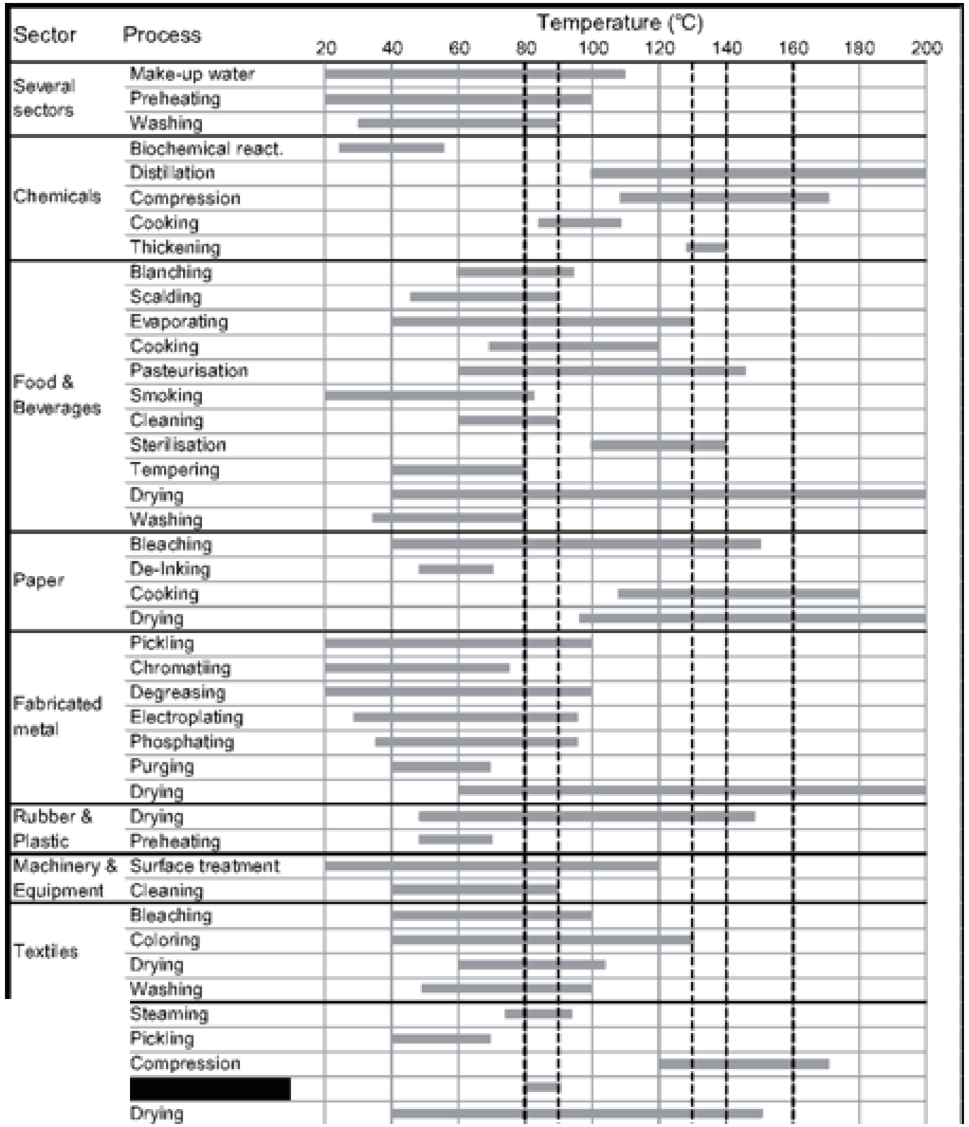
Power-to-Heat and Power-to-Cold



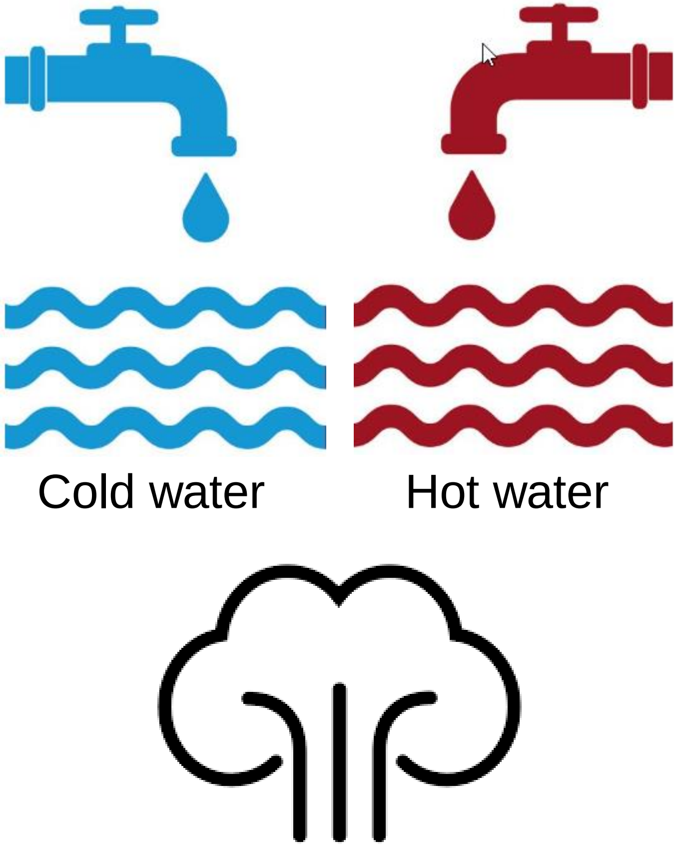
Cold is the new heat !

Process industry – Yes, heat-pumps can !

20 – 200°C



Source: ResearchGate



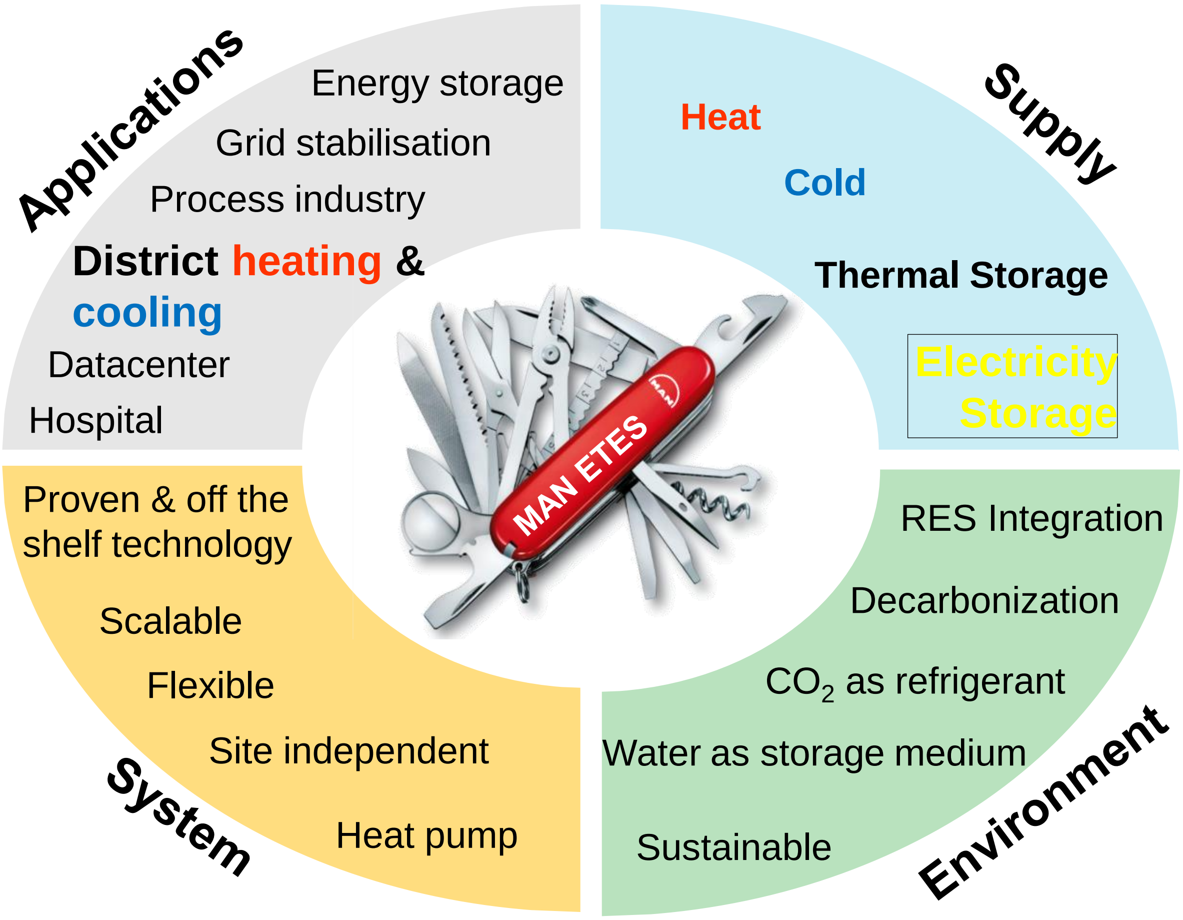
Cold water

Hot water

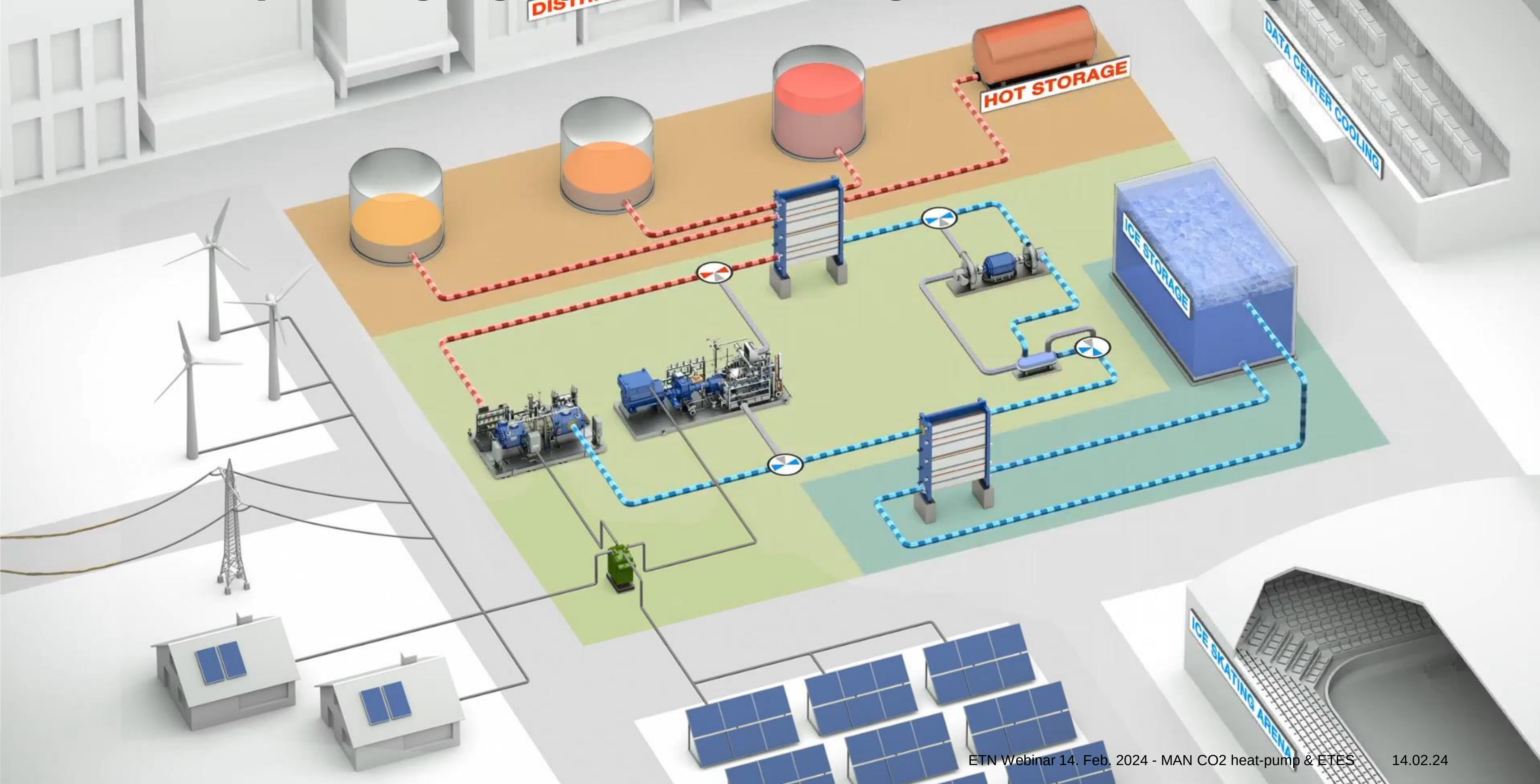
Steam

MAN-ES CO_2 heat-pump / ETES at a glance

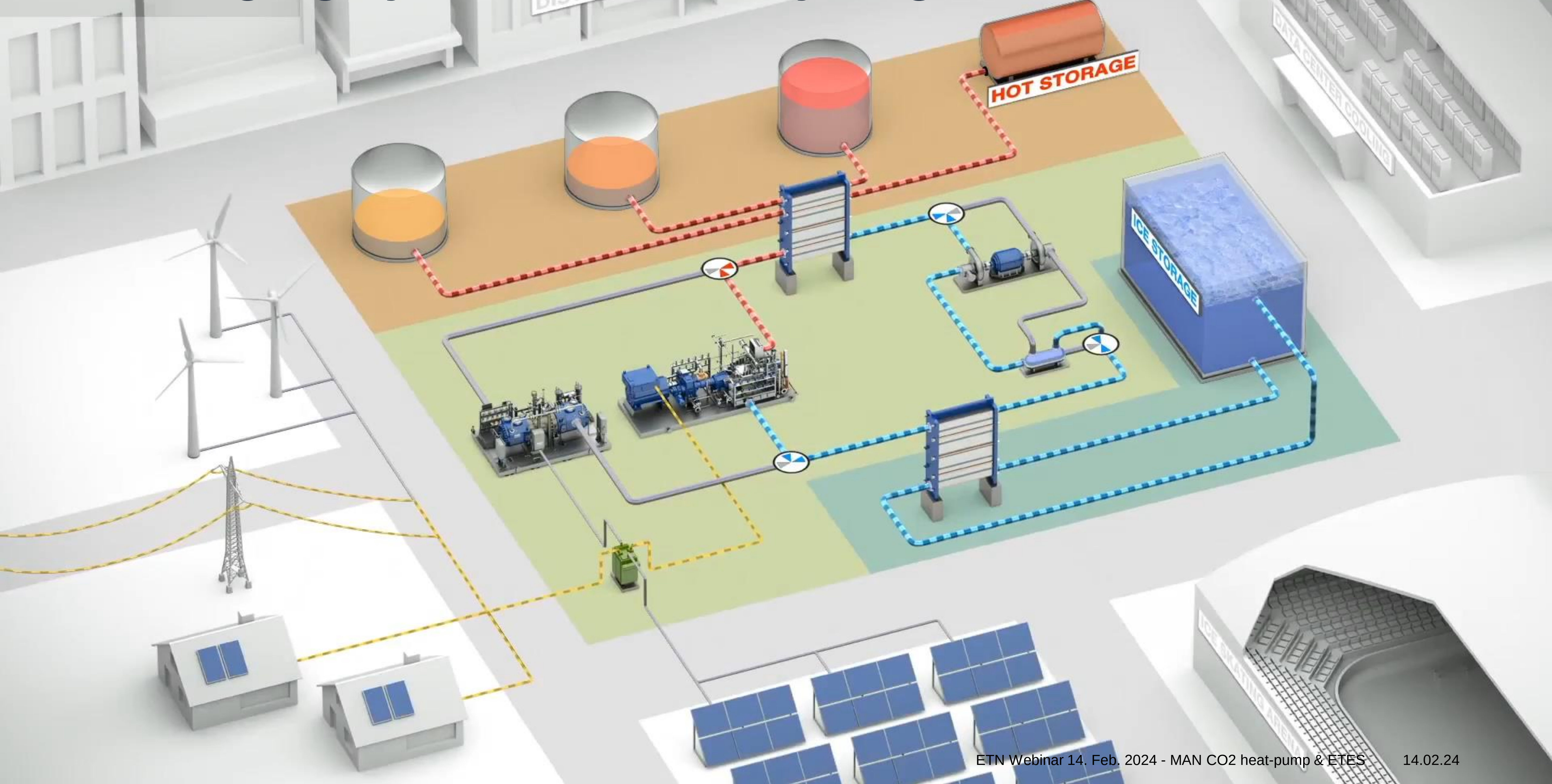
- **Thermal output: 50 MW_{th} heat + 30 MW_{th} cold /** per day with one Heat-Pump-Unit (HPU)
- **ETES** power Storage (LDES): up to 200MWh/day
- **Thermal storage** for more flexibility
- **Cost savings: Charging / Discharging** (arbitrage)
- Temperature levels **0° - 150+ °C** → ideal for **sector coupling** (e.g. district heating & process industry)
- **COP >5 - 7** (heat + cold)
- **Lifetime:** +35 years
- **NO** efficiency degradation during lifetime



Heat-Pump charging cycle for storage, heat & cold generation



Discharging cycle for electricity re-generation

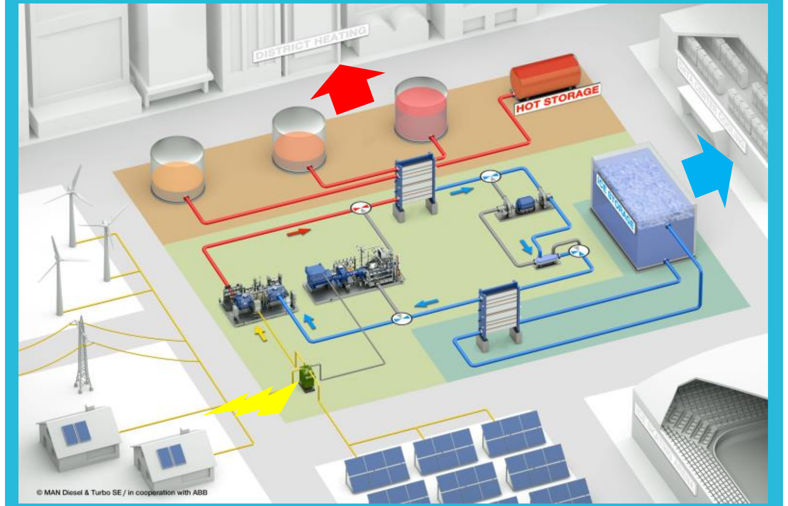


System Flexibility & Scalability

Base System Configuration Options **(3 Compressor sizes: 2 – 16MW electrical input)**

MAN ETES

- Heat pump
- Storage
- Re-electrification

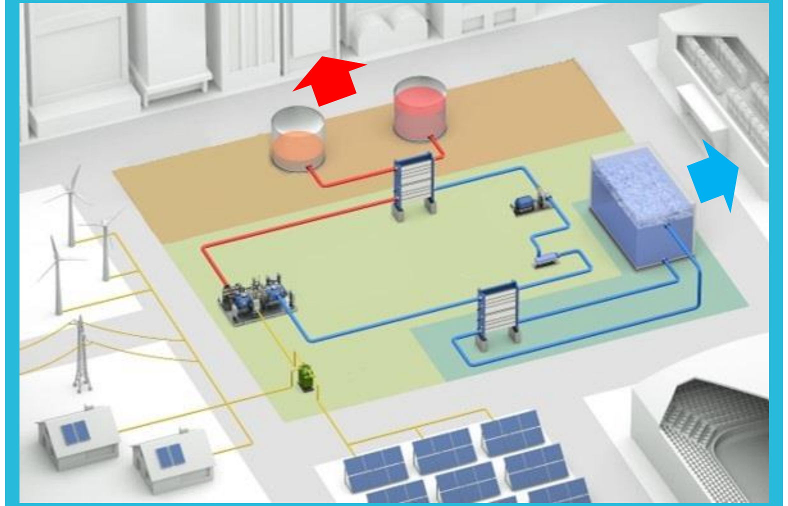


Supply:

- Electricity (primary)
- Heat & cold **(0° - 150°C)**
- Heat & cold storage **(0° - 150°C)**

MAN ETES "light"

- Heat pump
- Storage

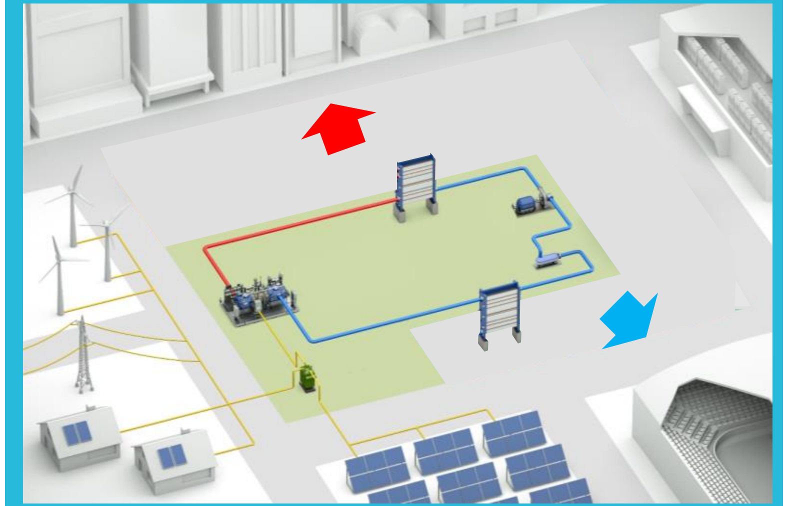


Supply:

- Heat & cold **(0° - 150°C)**
- Heat & cold storage **(0° - 150°C)**

MAN Heat Pump

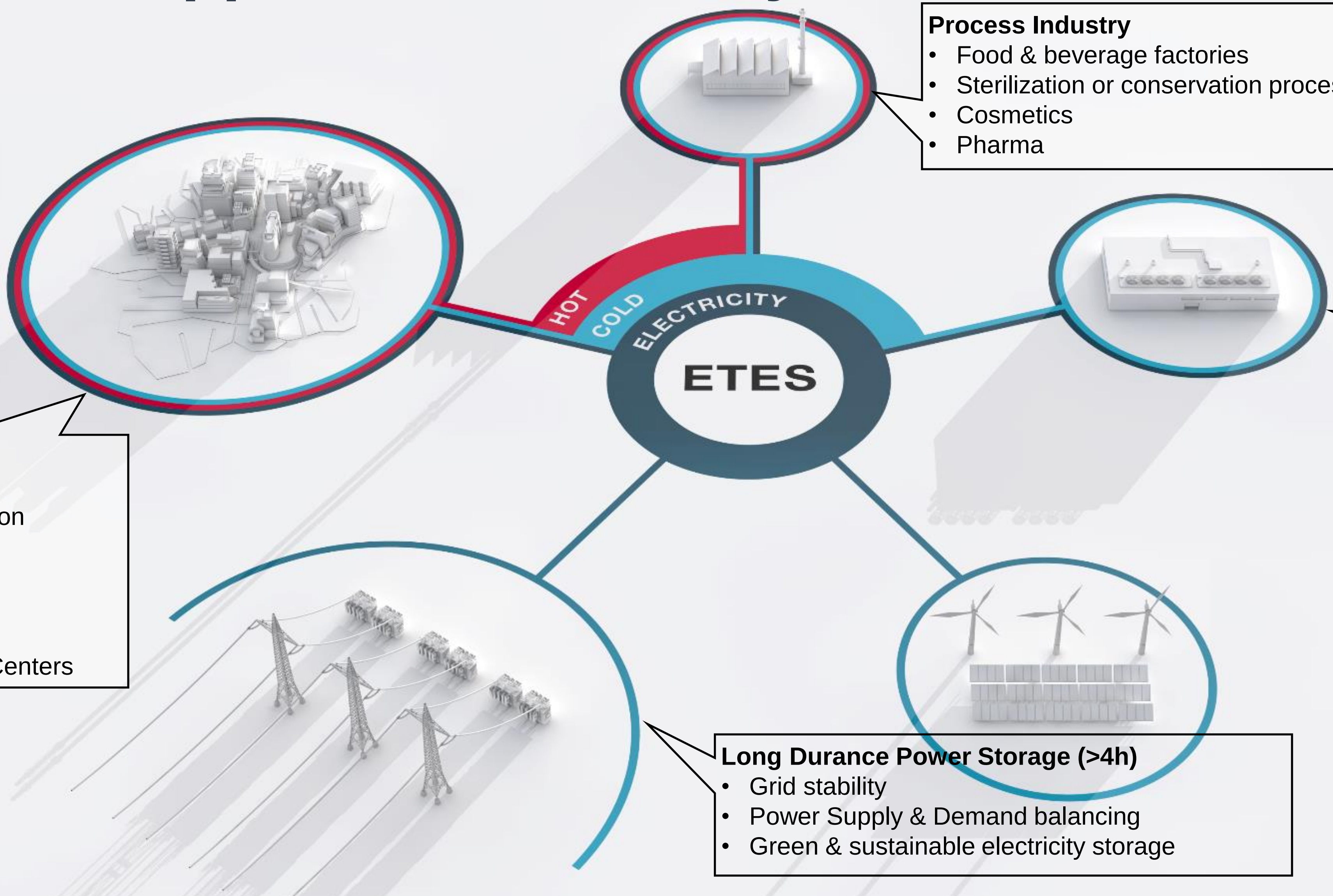
- Heat pump



Supply: **(7x24)**

- Heat & cold **(0° - 150°C)**

MAN ETES – Application flexibility



Process Industry
- Food & beverage factories
- Sterilization or conservation processes
- Cosmetics
- Pharma

Data Centers
Cooling houses

- District heating
- District cooling
- Waste heat regeneration
- Hospitals
- Airports
- University Campus
- Shopping malls
- Hotels & Convention Centers

Long Durance Power Storage (>4h)
- Grid stability
- Power Supply & Demand balancing
- Green & sustainable electricity storage

How much time it takes to bring the water of a Olympic sized swimming pool to boiling point?

- Length: 50m
- Width: 25m
- Depth: 2m
- Water: 2.5 million litres
- 20°C

< 4 hours

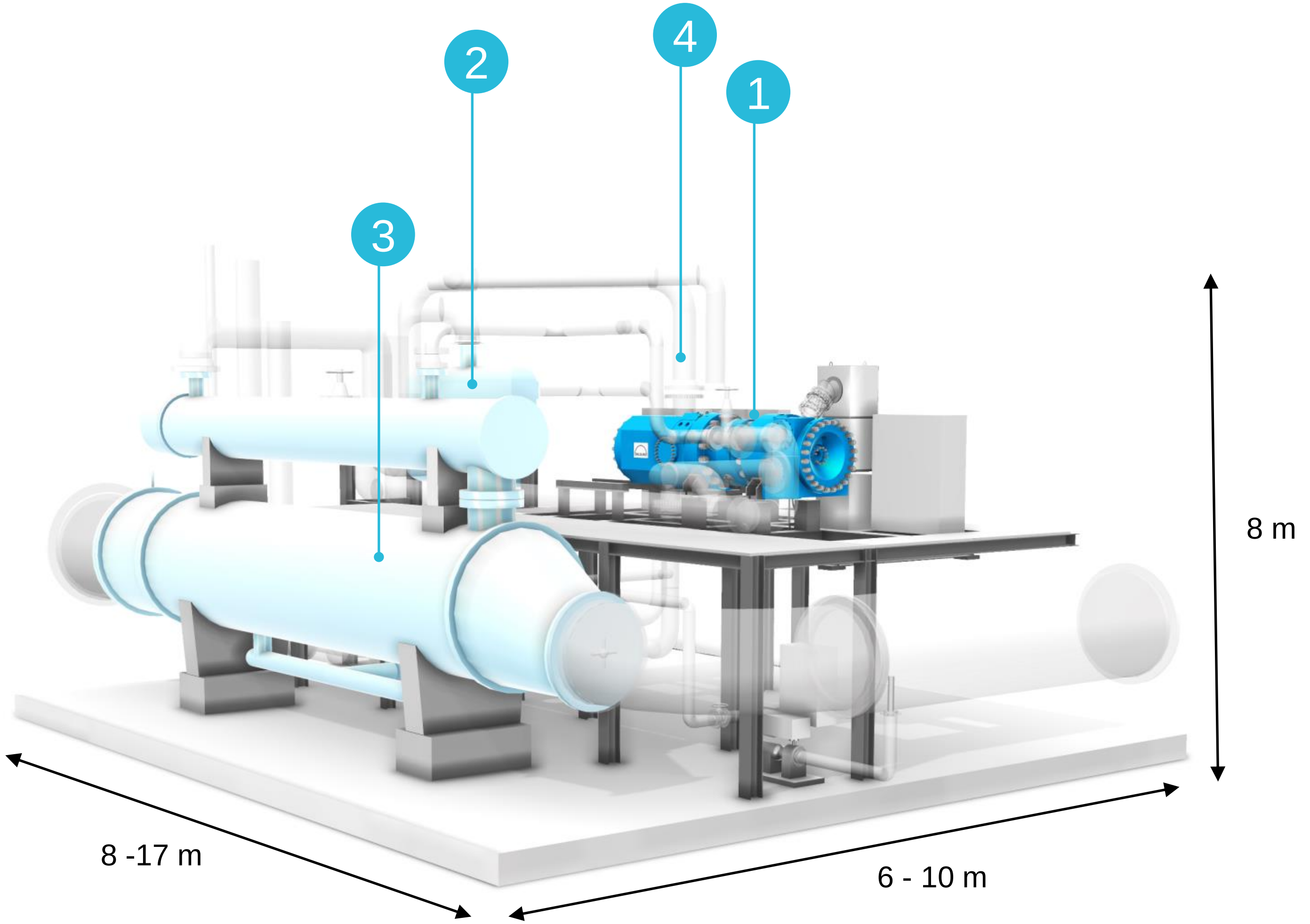
Transcritical CO_2 (TCC) heat-pump design

1 **Motor-Compressor HOFIM®** with integrated expander

2 **DH Heat Exchanger** (Condenser)

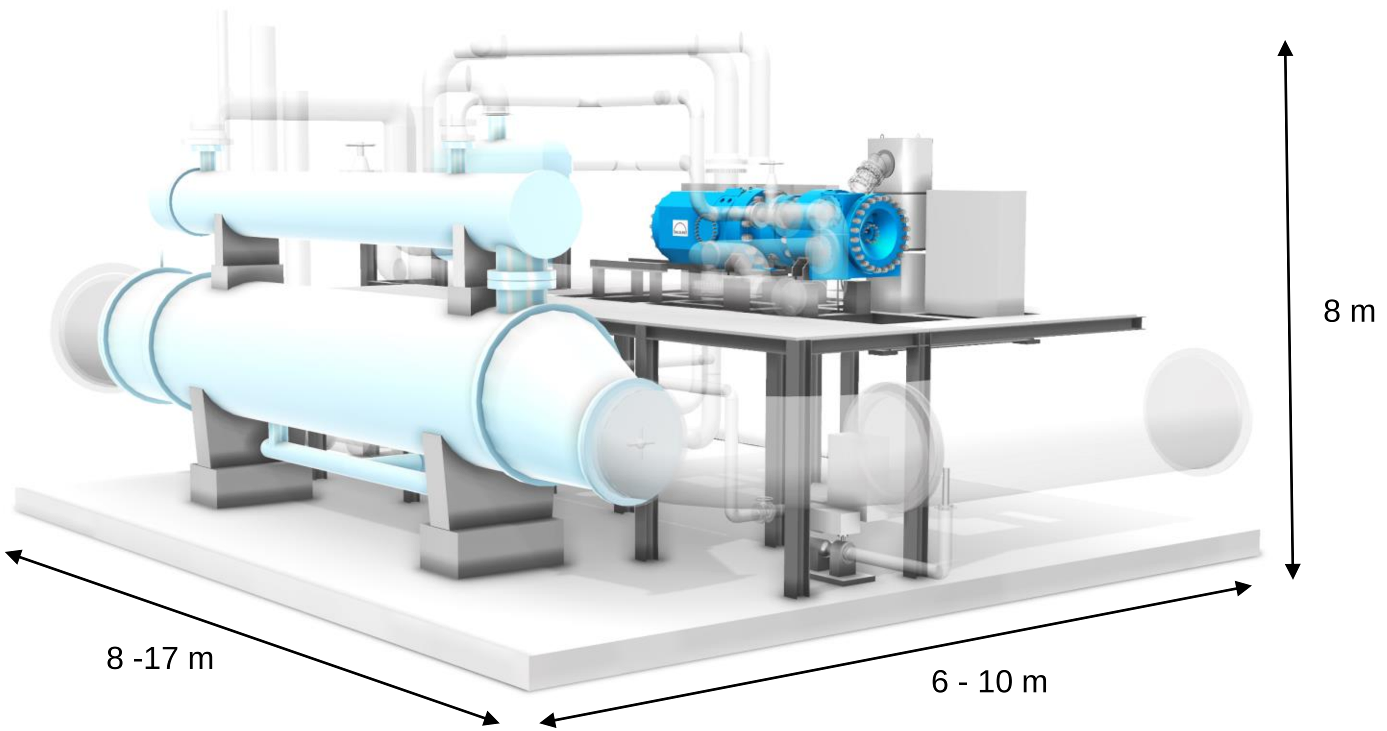
3 **Evaporator**

4 **Piping and steel structure**



Transcritical CO_2 (TCC) heat-pump design

- **Compressor (HOFIM)**
  - ➢ Electricity input 5 / 9 /16 MWel
  - ➢ Magnetic bearings (= no lube oil)
  - ➢ Hermetically sealed (= no leakage)
  - ➢ Integrated high-speed motor (10’000 – 18’000 rpm)
  - ➢ Reduced footprint (2/3)
  - ➢ Up to 220 bar
- **Thermal output: up to 50 MW_{th} heat + 30 MW_{th} cold** per unit per day
- **CO_2 (R744)** as refrigerant
- **Temperature levels 0° - 150+ °C**
- **Lifetime:** +35 years



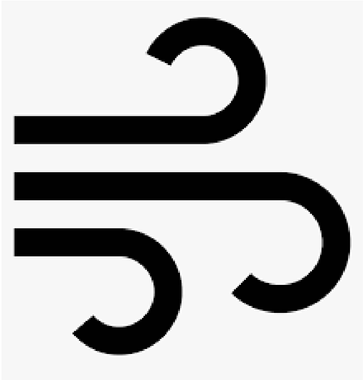
Heat sources for MAN heat-pumps

Source: lghvacstory.com

(Waste-)Water / liquid

Source: Rogers & Sons

Geothermal

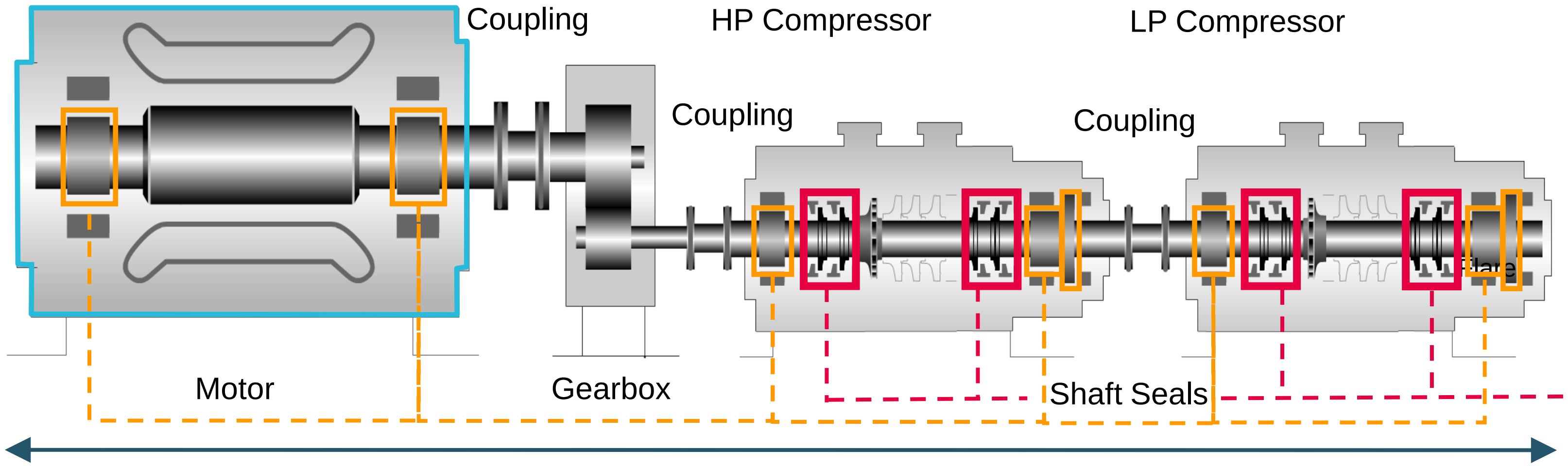


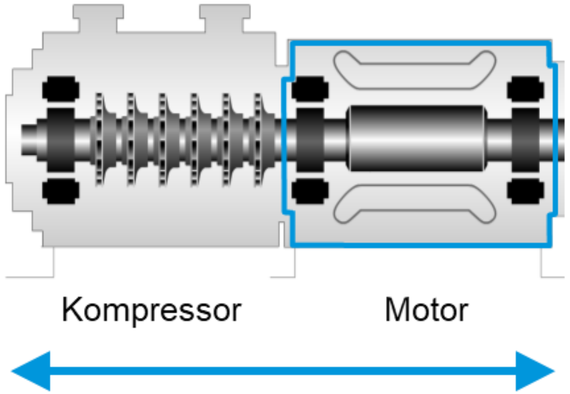
Ambient air

Industry waste heat

HOFIM Compressor for CO_2 (TCC) heat-pumps

High **S**peed **O**il **F**ree **I**ntegrated **M**otor compressor HOFIM™



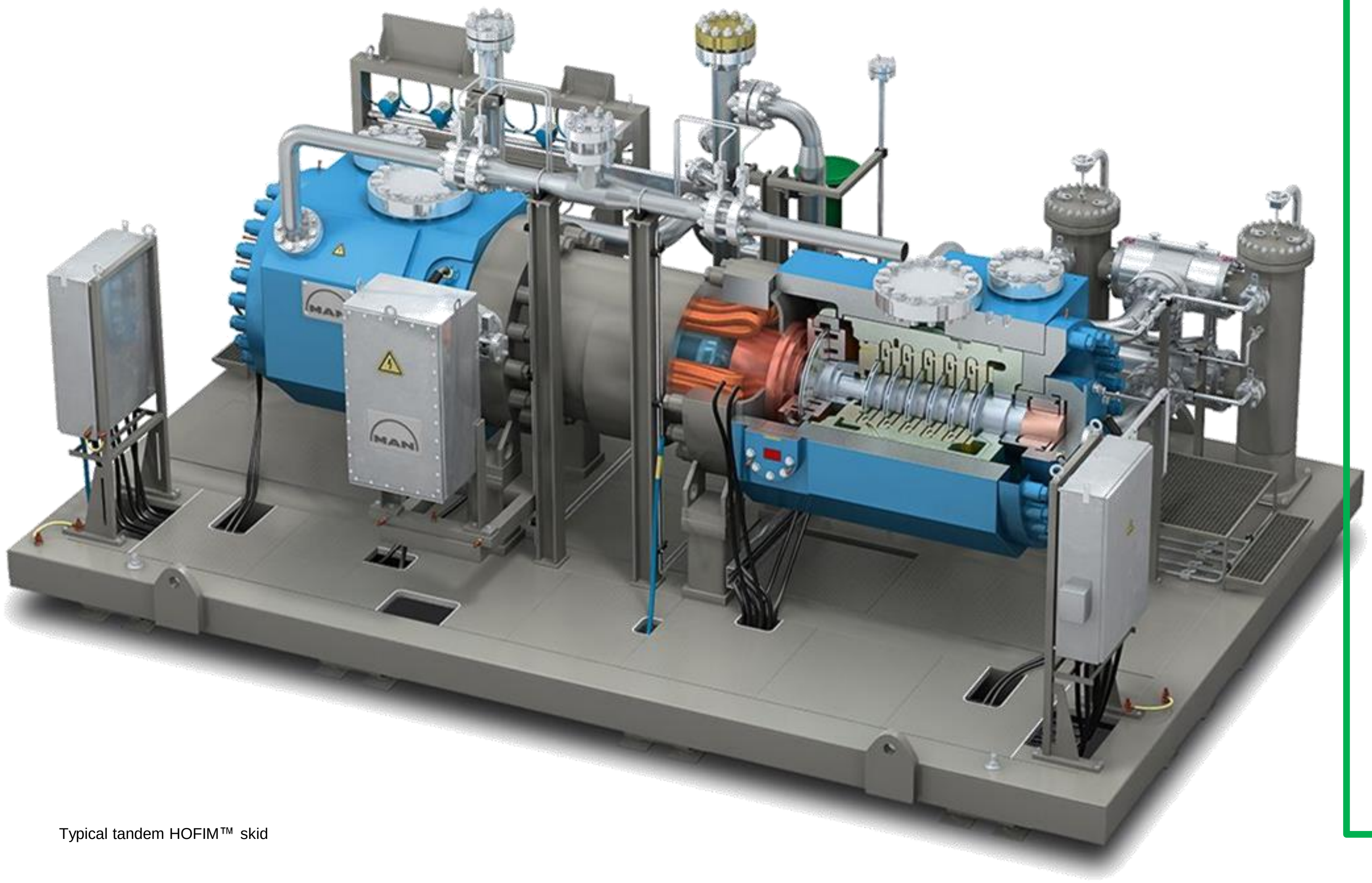


HOFIM™

- Reduced footprint (max. 4m x 8m)
- Integrated high-speed motor (10’000-18’000 rpm)
- No gearbox → noise reduction (ca. 90 dB)
- No lubrication oil due to magnetic bearings
- Hermetically sealed – No leakage / loss of refrigerant

Compression with HOFIM™

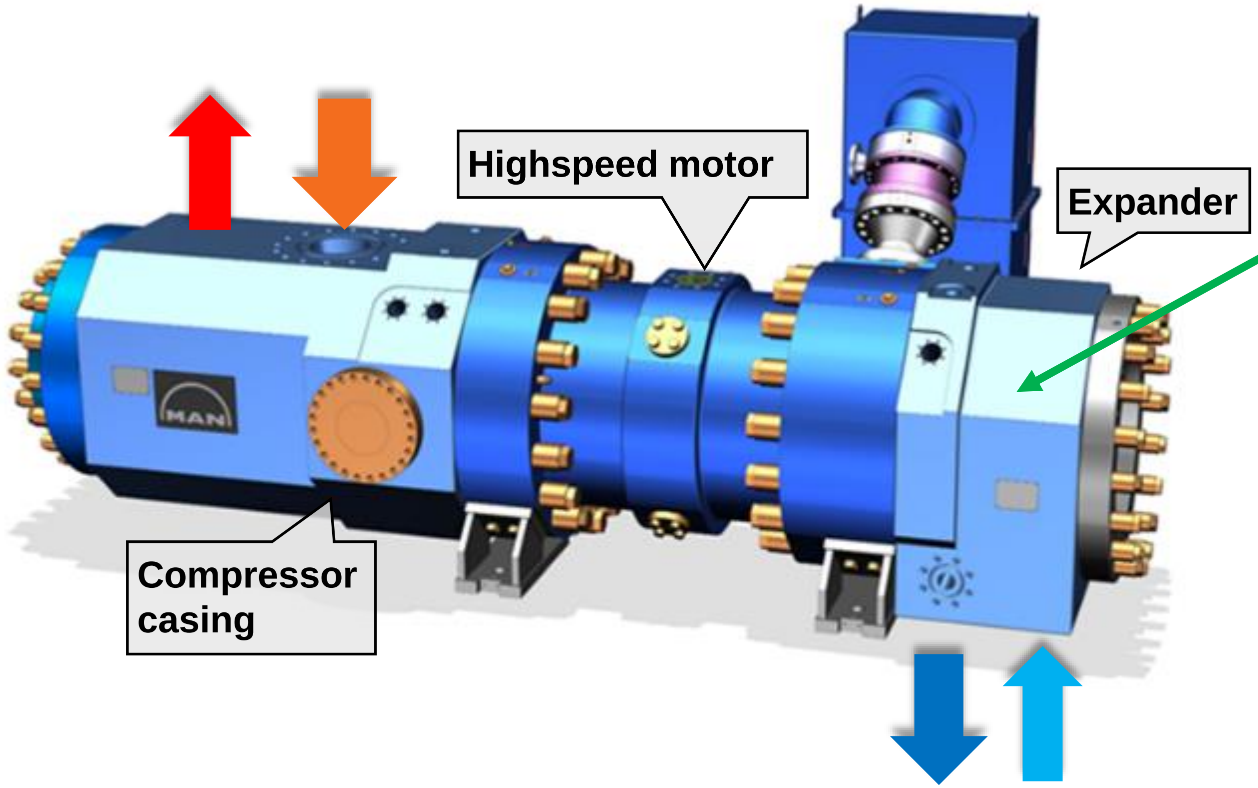
High speed Oil Free Integrated Motor compressor

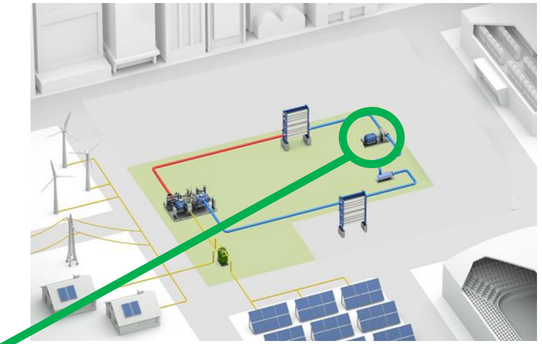


Typical tandem HOFIM™ skid

- Barrel compressor
- Highspeed motor
- Cooled by process gas – heat losses reintroduced into process
- Running on active magnetic bearings
- Reduced auxiliaries – **increased reliability**
- Fully electric – **remote control**
- Hermetically sealed – **no emissions**
- Overall **cost optimization** through reduced footprint & weight
- Sizes: 2 – 18 MW electrical input

The heart of the system: HOFIM® with integrated expander

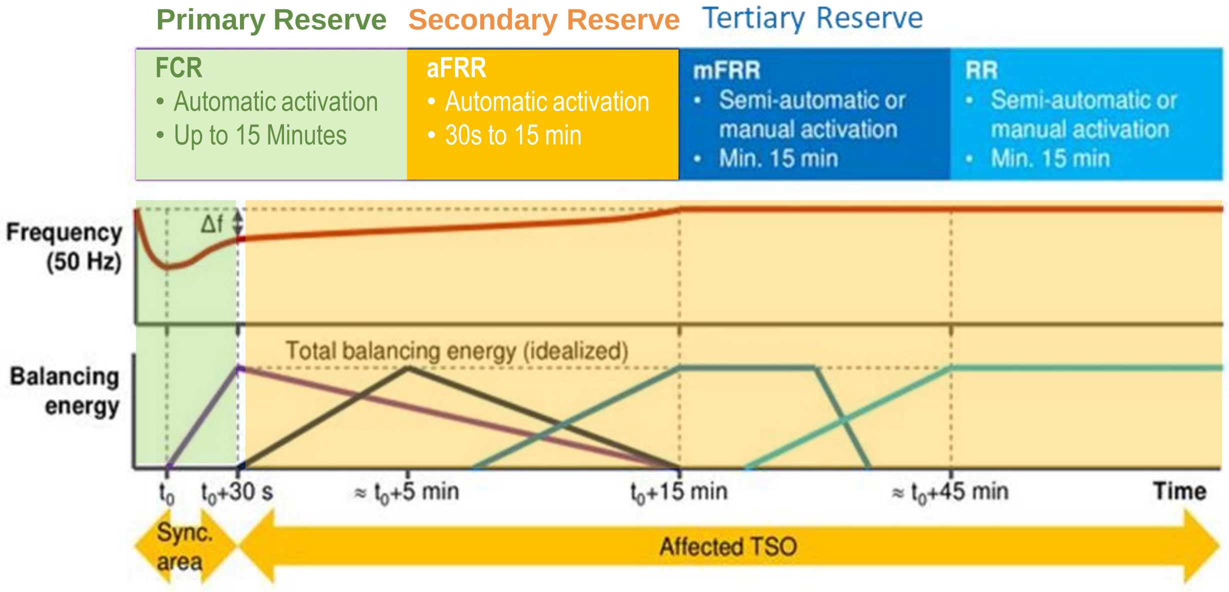




Power savings up to

10-15%

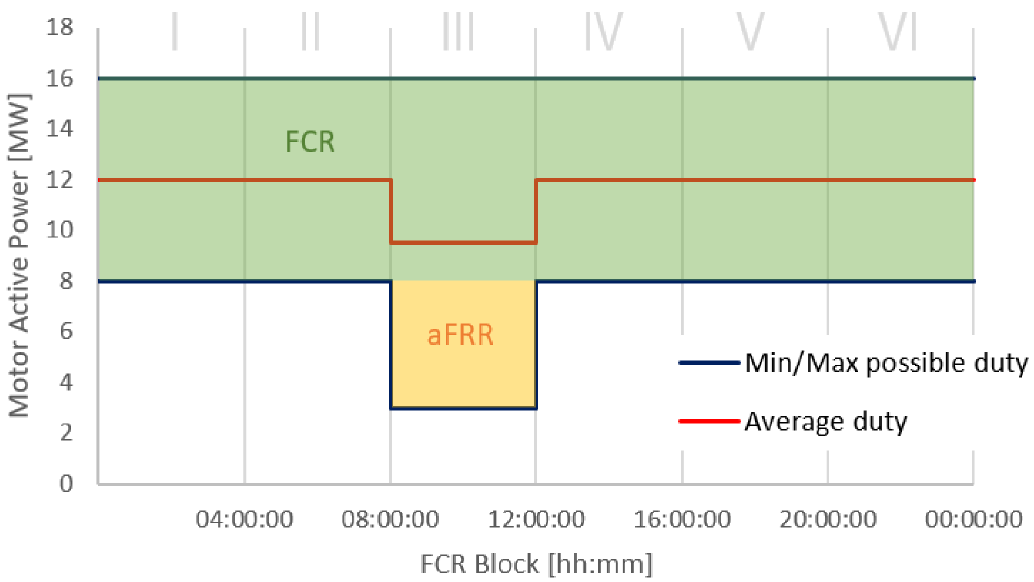
Heat-Pumps based on MAN HOFIM™ compressor technology enable fast grid balancing in <30 sec.



- ➢ Increase & decrease el. power consumption in < 30sec by +/- 30% during heat supply
- ➢ Run DH stable operation down to 20% of the nominal duty with thermal storage as buffer

Additional revenue per year (200 days)

	FCR	aFRR cap	aFRR ava	aFRR act	Total
Belgium	€ 536’800	€ 17’600	€ 16’800	€ 84’000	**€ 655’200**
Austria	€ 421’600	€ 17’600	€ 16’800	€ 84’000	**€ 540’000**
Switzerland	€ 421’600	€ 17’600	€ 16’800	€ 84’000	**€ 540’000**
Germany	€ 421’600	€ 17’600	€ 16’800	€ 84’000	**€ 540’000**
Netherlands	€ 421’600	€ 17’600	€ 16’800	€ 84’000	**€ 540’000**
Slovenia	€ 421’600	€ 17’600	€ 16’800	€ 84’000	**€ 540’000**
Denmark	€ 421’600	€ 17’600	€ 16’800	€ 84’000	**€ 540’000**
Czech Republic	€ 421’600	€ 17’600	€ 16’800	€ 84’000	**€ 540’000**
France	€ 381’600	€ 17’600	€ 16’800	€ 84’000	**€ 500’000**



World’s first of its kind

MAN’s Subsea HOFIM™ in operation since **September 2015**

140’000+ operating hours / 100% reliabilty

Åsgard Subsea Compression

- Water depth 300 m
- Gas pressure 220 bar
- Power rating 2 x 11.5 MW

equinor

AkerSolutions

Link to animation

Esbjerg (DK) Project – Largest CO_2 Heat-Pump ever built !

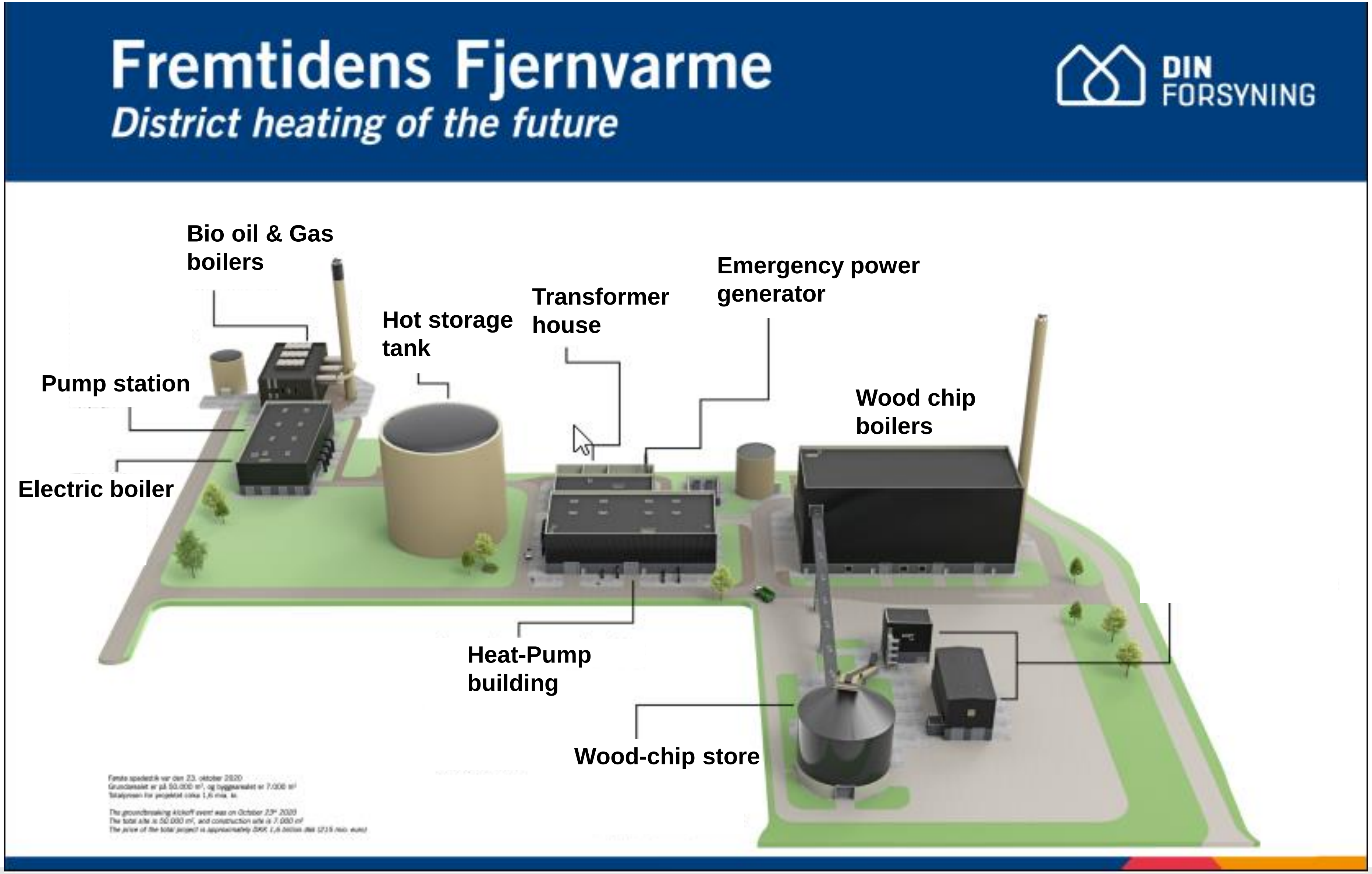
Project drivers:

- Green energy transition: From coal to RES & HPs
- District heating for 25‘000 households (100‘000 citizens)
- CO_2 savings:100‘000 t / year = ~55‘000 cars

MAN-ES USPs:

- CO_2 as refrigerant – natural gas / environmentally friendly
- High lift – from 1°C seawater to 90°C forward temp.
- 2 Heat-Pumps with 25MWth each (2x 11.5MWel input)
- HOFIM Compressor – magnetic bearings / hermetically sealed

Esbjerg (DK) project



Esbjerg (DK) project

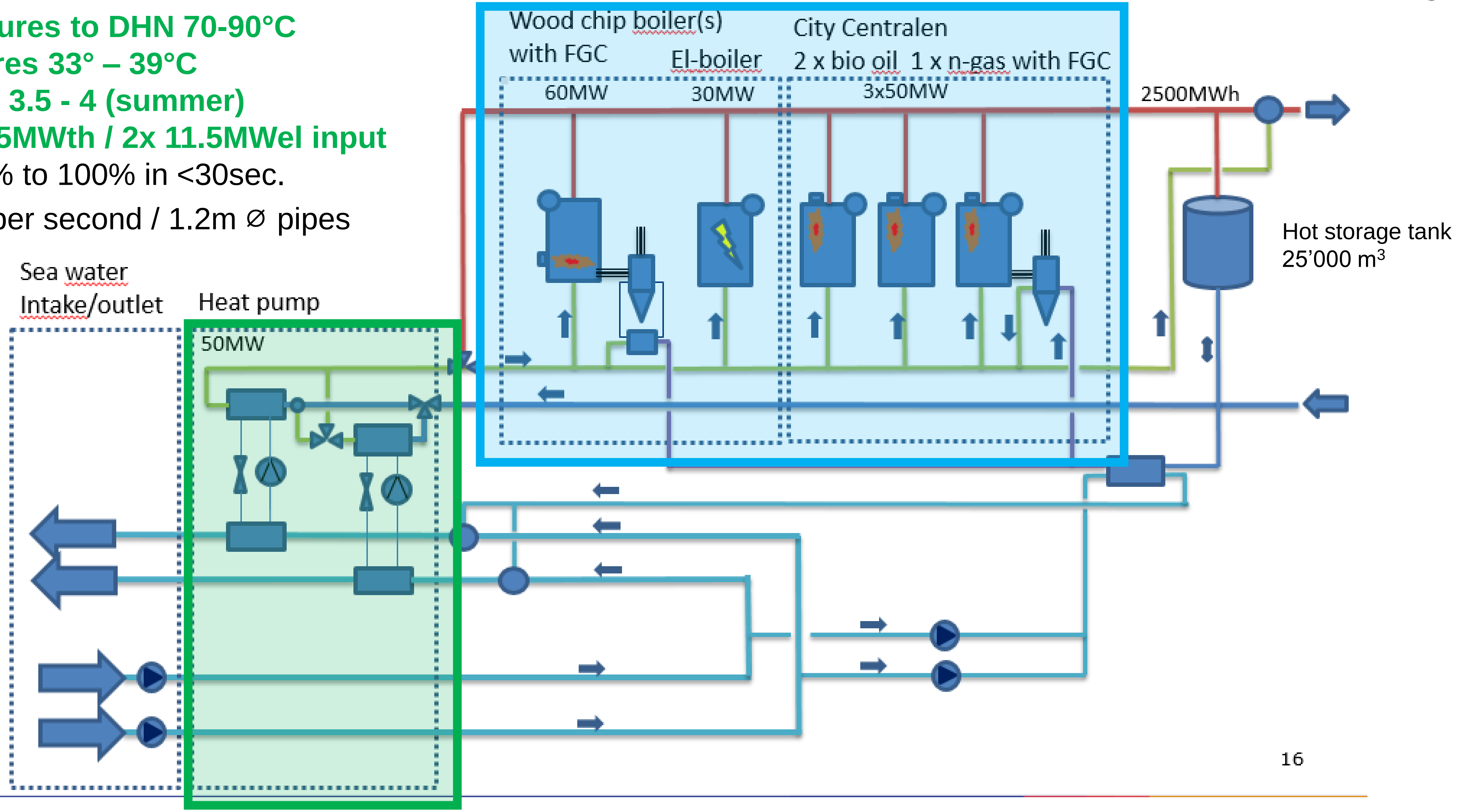
- **Forward temperatures to DHN 70-90°C**
- **Return temperatures 33° – 39°C**
- **COP 3.3 (winter) – 3.5 - 4 (summer)**
- **Heat-Pumps: 2x 25MWth / 2x 11.5MWel input**
- From turndown 50% to 100% in <30sec.
- 4000 litre of water per second / 1.2m ⌀ pipes

Seawater outlet temperatures

-1 – 18°C

Seawater inlet temperatures

1 – 20°C



MAN Energy Solutions
Future in the making

Esbjerg (DK) project

Esbjerg (DK) project

MAN Energy Solutions
Future in the making

MAN Compressor in factory

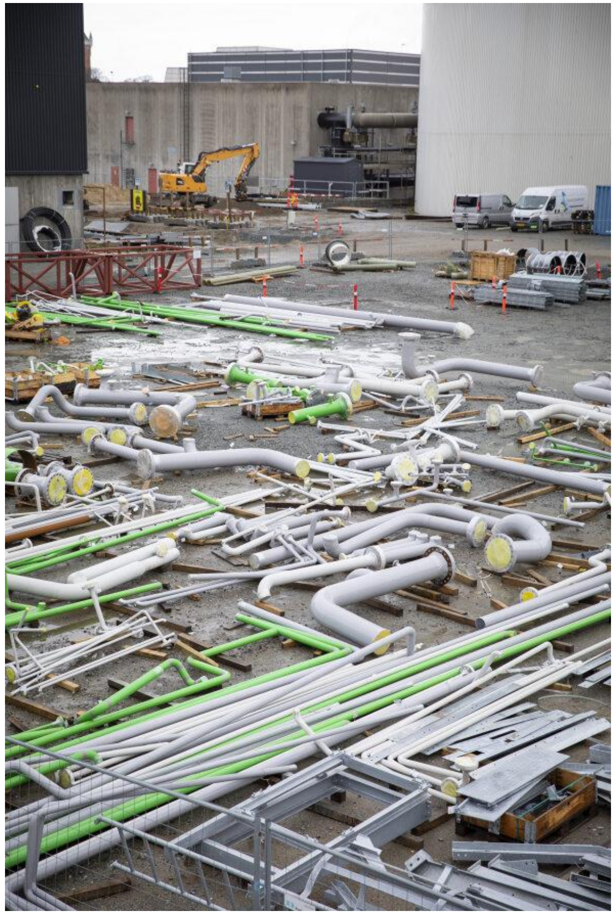
MAN Compressor @ site in Esbjerg

CO_2 storage tank

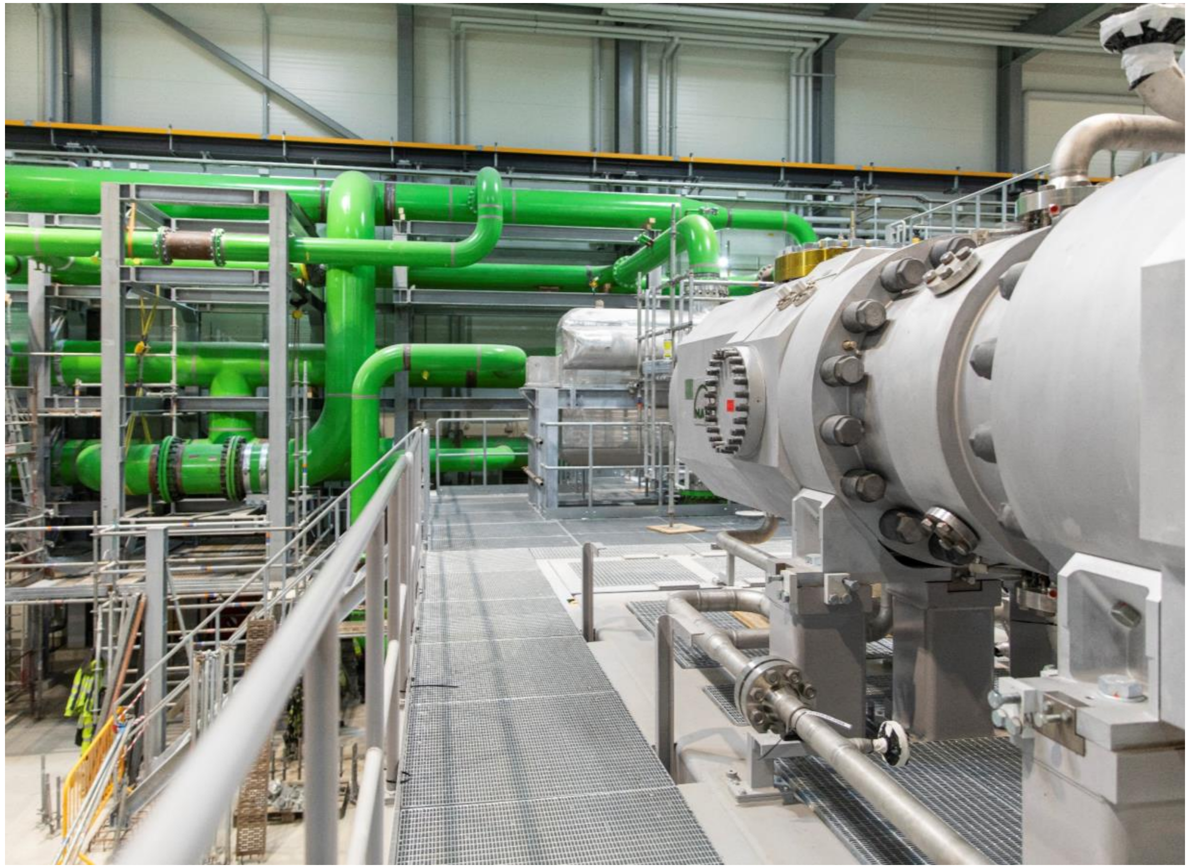
Esbjerg project




Esbjerg (DK) project



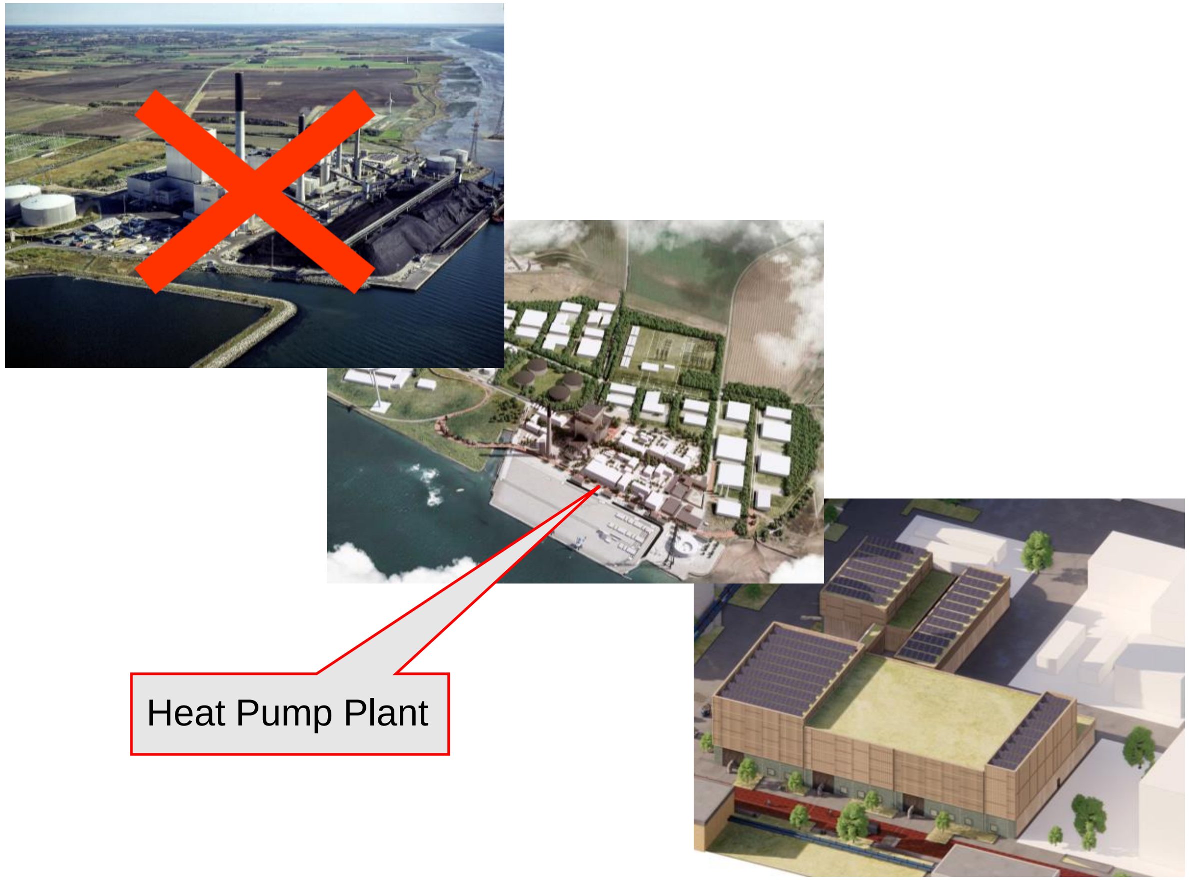
Esbjerg (DK) project

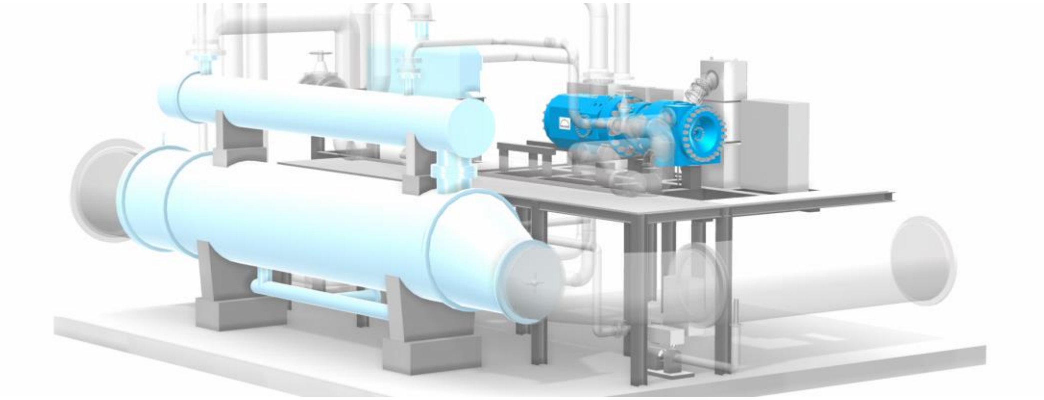


Esbjerg (DK) project

MAN wins second in a row seawater heat-pump project !

Aalborg Forsyning





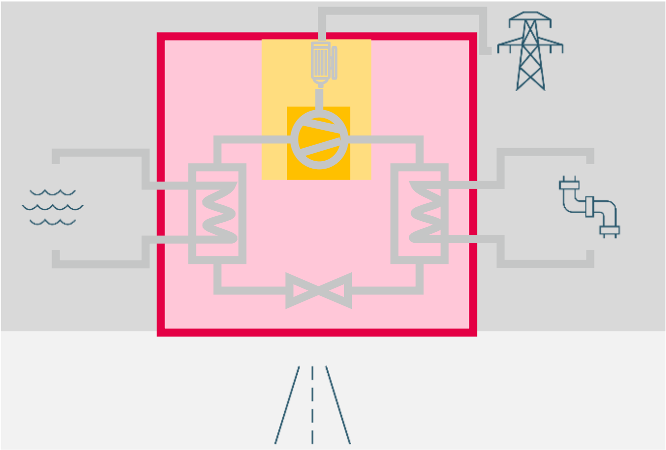
- 3 seawater CO_2 heat-pumps (option for 4th)
- 134 MW thermal output (~ 44 MW thermal each)
- ~ 14+ MW electrical input per compressor
- 40’000 m^3 thermal storage
- Going operational April 2027

MAN scope of works

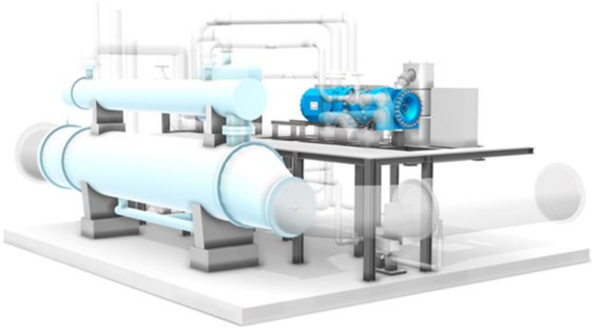
Project scope

<u>MAN Energy Solutions delivery</u>

- ➢ Compressor unit
- ➢ Heat Exchanger (Condenser) on hot side
- ➢ Evaporator on cold side
- ➢ Complete piping and steel structure
- ➢ Refrgerant tank
  - Valves, instrumentation, connecting cables, DHN water pumps, seawater pumps
  - Complete electrical scope
  - Complete control system
  - FAT of main equipment
  - Installation and commissioning
  - On site testing



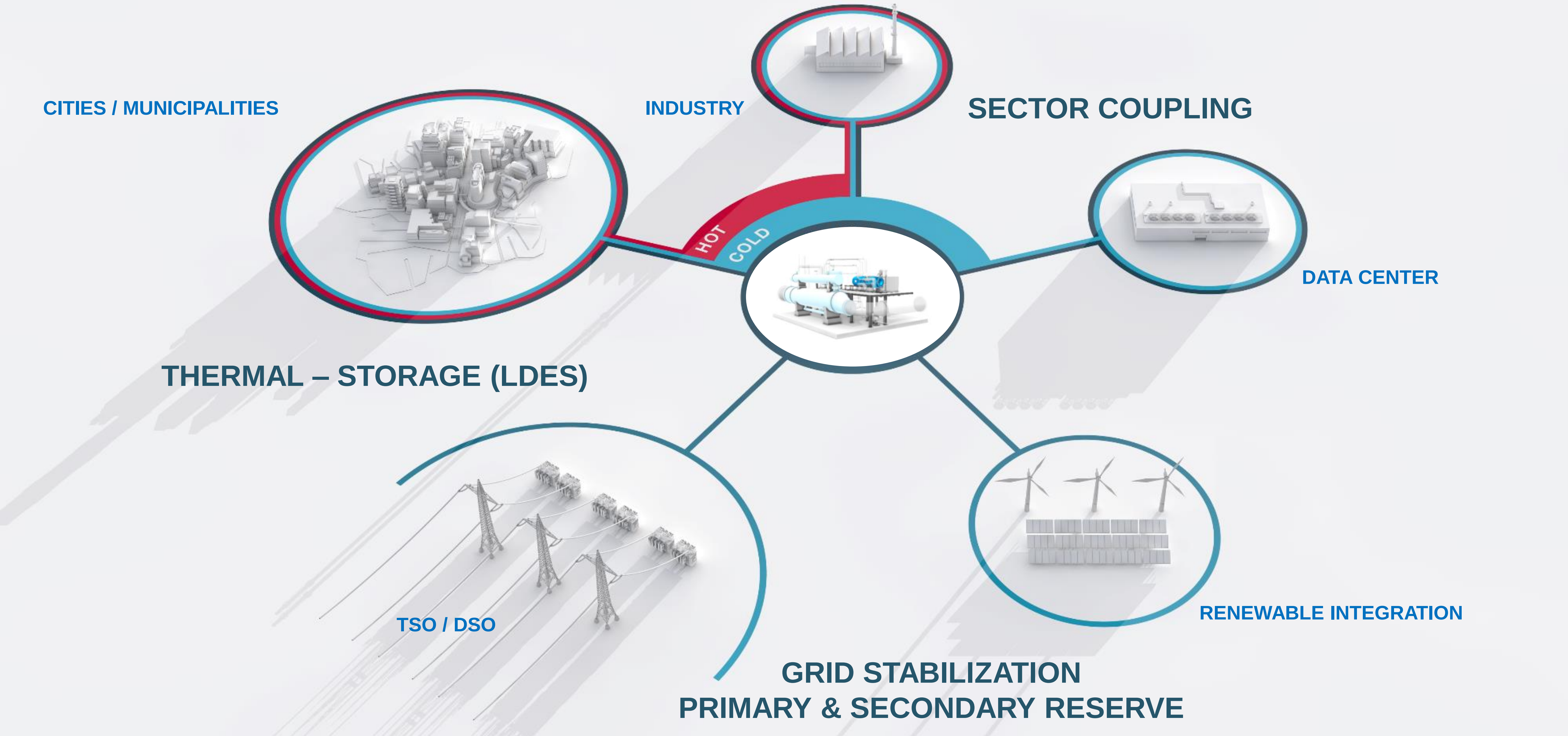
Typical scope of delivery



Grid, heat-sink and heat-source connection

Civil work (e.g. roads, buildings)

Large heat-pumps are highly relevant to the energy system



MAN Energy Solutions
Future in the making

Thanks for your attention.

Raymond.Decorvet@man-es.com
Global Business Development ETES

NETPOWER

Transforming Natural Gas into Clean Power

2024 ETN Global sCO_2 Balance of Plant webinar

NET Power decarbonizes natural gas power generation

NET Power's power plant transforms natural gas into clean, emission-free power

NET Power Overview

- **Who we are:** NET Power is a US-based clean energy technology company that has developed a **gas-based power plant that generates clean power with near-zero emissions**
- **Innovative design:** NET Power's patented technology employs **oxy-combustion and utilizes supercritical CO_2** as the turbine's working fluid to efficiently produce clean, low-cost power and deliver a pure stream of CO_2 for sequestration or utilization
- **Proven technology:** Demonstration plant in La Porte, TX (50 MWth) was commissioned in 2018 and has achieved over **1,500 operational hours and synchronized to the Texas grid** in 2021
- **Preparing for global deployment:** Agreement with **Baker Hughes** to design and manufacture key plant equipment; expect first deliveries in 2026-2027; **standardized design enables economies of scale and rapid deployment**
- Several projects in various stages of development, **first utility-scale plant expected online in 2027-2028**
- **Positioning for long-term success: NET Power went public in June 2023** and successful energy entrepreneur Danny Rice became NET Power's CEO

Strategic Shareholders

OXY Occidental
Baker Hughes
Constellation.
SK

Combined Market Value > $200 billion

NET Power's Demonstration Facility in La Porte, Texas

NETPOWER

NET Power's innovation harnesses CO_2 for clean power

Patented power cycle that avoids the creation of criteria pollutants and captures nearly all carbon emissions

NET Power Cycle Overview

- NET Power's platform uses a semi-closed loop cycle that inherently captures CO_2 and produces power
- It does so by combining two processes: **oxy-combustion**, which produces CO_2 and H_2O, with a **CO_2 power cycle**
- The CO_2 from oxy-combustion is recirculated back to the combustor and a portion (~850k tonnes CO_2 per year) is exported for utilization or sequestration

NET Power Cycle Steps

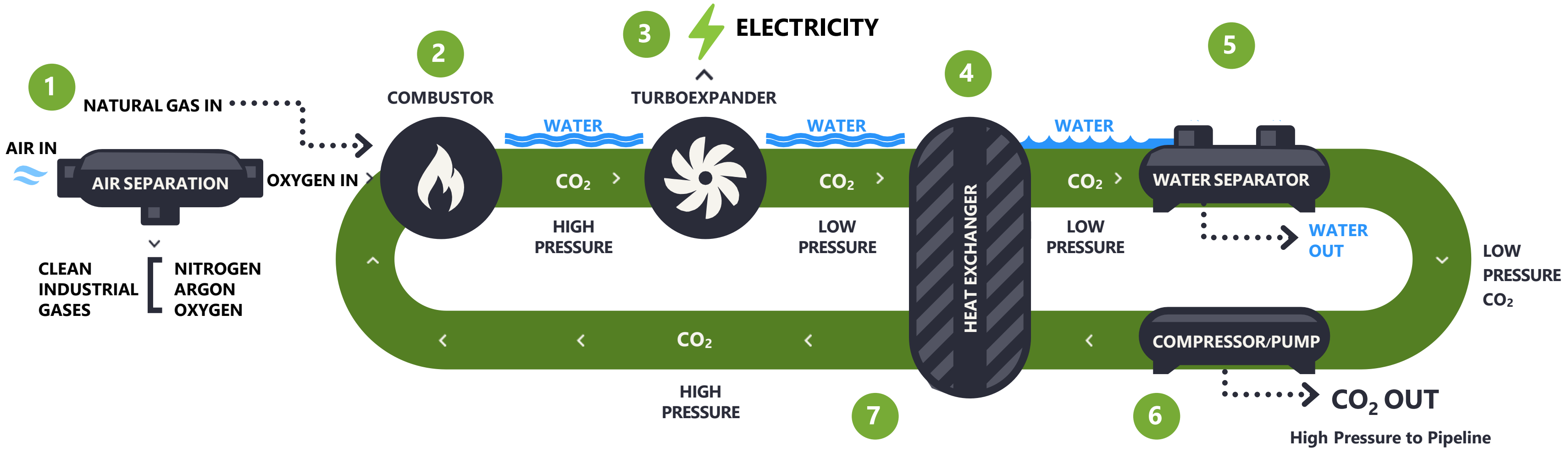
1. Air Separation Unit separates oxygen from air
2. Natural gas and oxygen combine resulting in CO_2 and water vapor
3. The CO_2 mixture expands and turns the turboexpander to generate electricity
4. The CO_2 mixture goes into the heat exchanger to cool
5. Water is removed from the CO_2
6. CO_2 is repressurized, captured CO_2 is exported for sequestration or commercial use
7. Recirculated CO_2 is reheated to be used again in the process

KEY TARGETED STATISTICS:

Generation capacity:
~250 MWe

Feedstock:
~50 MMscfd natural gas

CO_2 exported[(1)]:
~850k tonnes / year



1. *Assumes 92.5% capacity factor.*

NET Power's test facility validates and de-risks the technology

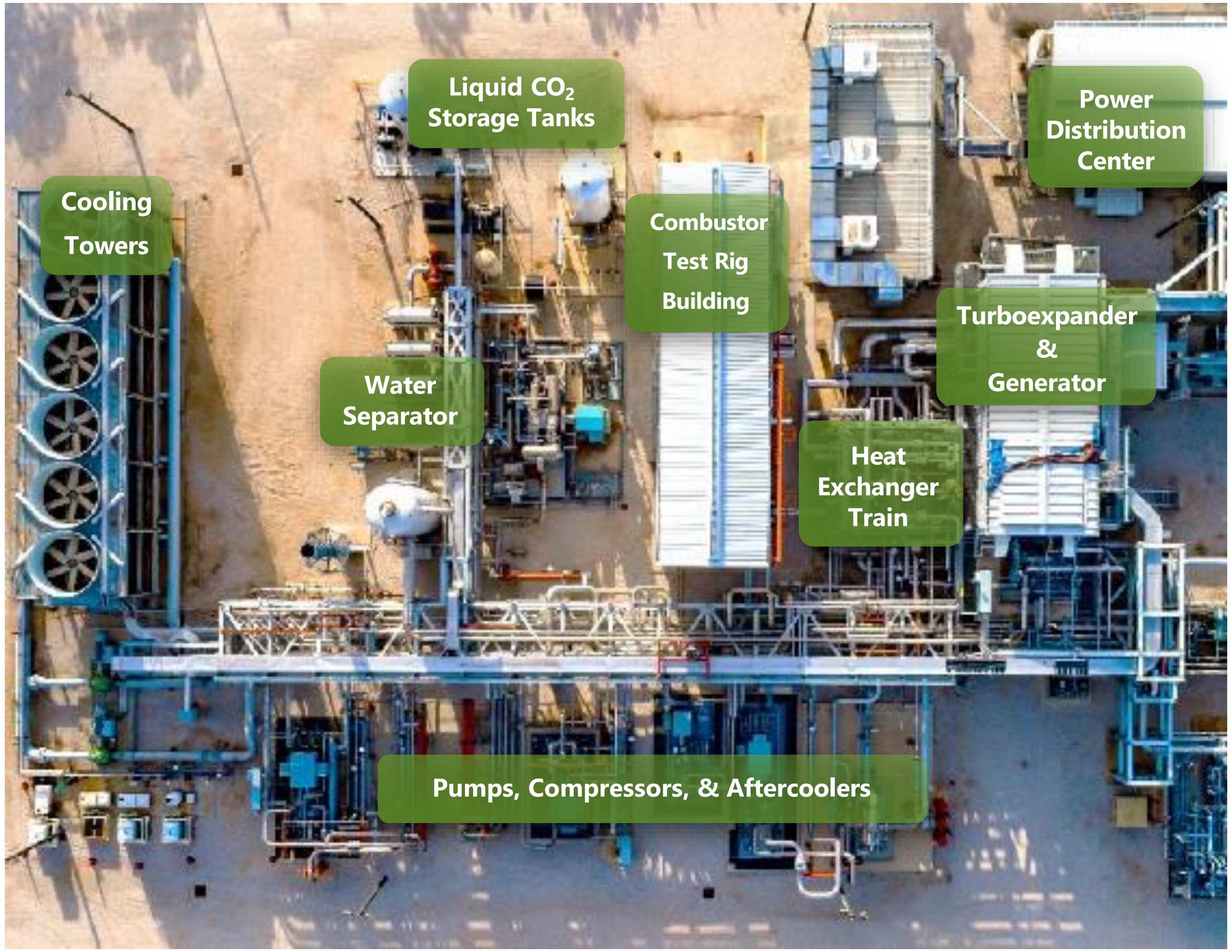
Three separate testing campaigns completed between 2018-2021 provide technology validation

Facility Overview

- 50 MWth industrial scale (5-acre footprint)
- Commissioned March 2018 with >1,500-hrs runtime
- Initially designed to validate, de-risk NET Power Cycle
- Currently upgrading to support Baker Hughes technology demonstration in parallel with utility-scale program

Key Accomplishments

- sCO_2 turbine generated power while synchronized to grid
- NET Power's controls architecture optimized. Multiple 24-hour test campaigns (completed 2018-2021) including start/stop sequences, steady state and ramping operations.
- Facility exceeded 925°C design temperature and 300 bar pressure. Heat exchanger performance tested at temperatures meeting and exceeding required benchmarks.



NETPOWER

Baker-Hughes provides critical expertise and equipment

Turboexpander architecture leverages decades of Baker Hughes experience across its technology portfolio and installed fleet

Technology & Commercial Development

NET Power and Baker Hughes partnered to advance the system integration process design of the NET Power Technology and bring the technology to market

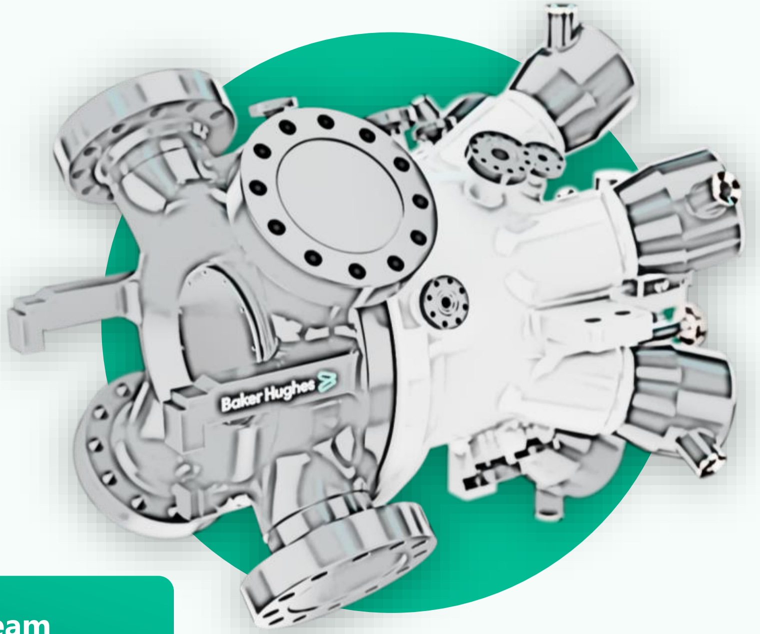
Key Process Equipment & Services

Baker Hughes will supply key equipment and services for NET Power Plants including:

- Turboexpander & Combustor
- Key pumps and compressors
- Additional BOP equipment
- Equipment Service Agreements

sCO2 Turboexpander

World's first supercritical CO_2 turboexpander designed for high temperature **(~1,000^{0}C)**, high pressure **(330 bar)**, and CO_2 as working fluid.



5,000+ Gas Turbines

800+ Steam Turbines

8,000+ Centrifugal Compressors

300+ CO_2 Equipment

NET Power and Baker Hughes begin joint test campaign

Technology Test Campaign

- Preliminary process safety analysis for future validation completed for plant modifications
- Combustor component testing commencing in 2024
- Demonstration and utility-scale combustor can testing in 2025
- Demonstration turboexpander testing expected in 2026

Test Campaign Preparation Activities

Relocation of recycle CO_2 compressor

Relocated and converting to electric drive from prior shaft-driven configuration

Piping & instrumentation enhancements

Optimizing plant controls and data acquisition instrumentation

Updates to distributed control system

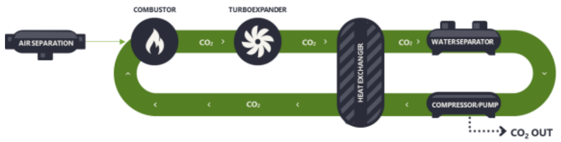
Implementation of advanced control narratives for demonstration

NETPOWER

Concurrent product development and demonstration accelerate commercialization

Process & Equipment Development

- Cycle optimization
- Utility-scale plant design
- Baker Hughes (BH) equipment
- Validation & demonstration strategy

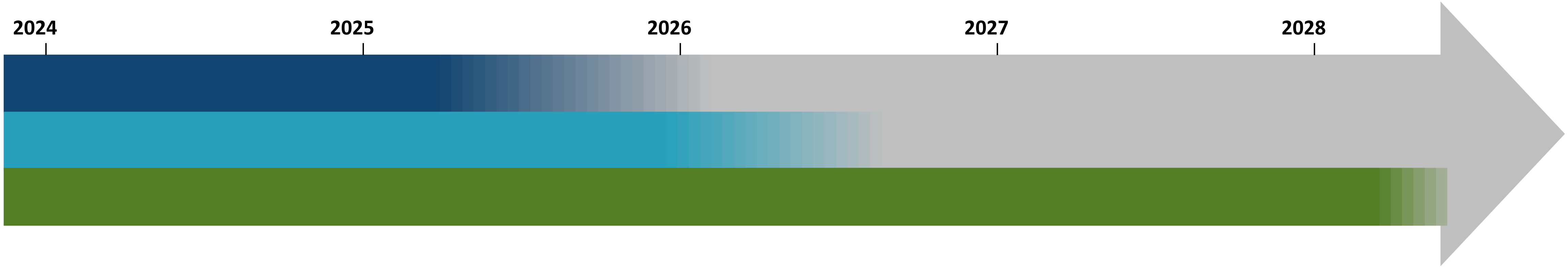


Demonstration

- La Porte test facility modifications
- BH combustor demonstration
- BH turboexpander demonstration
- Controls refinement

Utility-Scale Deployment

- Integrated FEED
- Detailed design
- Construction & commissioning
- Performance validation



NETPOWER

NET Power's supply chain strategy supports ramp-up in deployments

Turboexpander
Baker Hughes

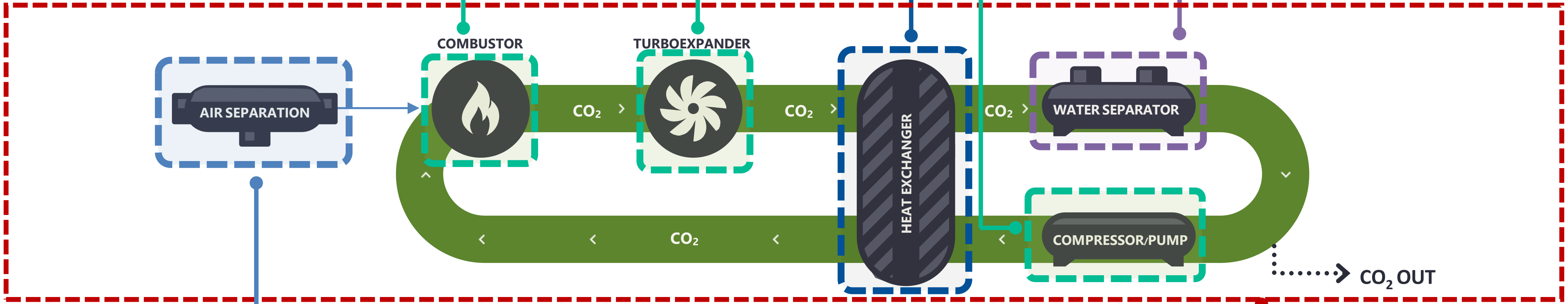
- Exclusive licensed supplier for turboexpander and other turbomachinery and technology
- Joint commercialization ensures manufacturing slot visibility & timing
- Ownership in NPWR aligns incentives

Heat Exchanger
LUMMUS TECHNOLOGY

- Strategic supply agreement with Lummus Technology
- Global supply chain network enables NET Power deployments at scale
- 25,000+ HXRs designed and supplied globally, including high pressure applications

Balance of Plant

- Licensed supplier list to include control systems and other suppliers based on value of standardization and reduced risk
- Service providers to be included (O&M, Engineering services, etc.)



Air Separation Unit

- Licensed supplier approach with world class suppliers
- Provision of both Sale of Equipment and Sale of Gas options to drive price transparency and improve project economics

Modularization

- Licensed modularization suppliers for supply of integrated equipment, structural steel, piping, electrical, etc.
- Enables a "manufacturing mode" supply chain approach with diversity of supply

EPC
ZACHRY

- Future licensed and pre-qualified world class EPC providers identified through FEED
- Protects NPWR IP and enables common standard design across multiple EPC's
- Engineering, craft labor, and schedule reduced to enable robust delivery growth

NETPOWER

Project Permian: The first utility-scale NET Power Plant

Project goal is to demonstrate clean, reliable and safe operations

Project Permian Background

- 250 MW plant to be located near Midland-Odessa, Texas with existing gas, power and CO_2 infrastructure
- FEED work with Zachry commenced in Q1 2023 and is expected to conclude in 2H 2024
- Submitted interconnection application in ERCOT
- Captured CO_2 will be tied into Oxy's extensive CO_2 network in West Texas

Supportive Investors and Strategic Partners

Occidental, Constellation, SK, Baker Hughes, Lummus Technology, Zachry

De-risked SN1 Location

Project Permian location de-risks first-of-a-kind utility-scale deployment:

- Access to abundant, low-cost natural gas
- High visibility into CO_2 and power offtake and necessary permitting
- **Goal: Safe, reliable operations at utility-scale**

1H 2024: Release initial long-lead equipment orders

2H 2027 / 1H 2028: Initial power generation

Anticipated Project Timeline

NETPOWER

NET Power Delivers the Energy Trifecta

CLEAN

24 hours/day, 7 days/week

Baseload, dispatchable, and peaking capabilities complement variable renewable generation for a more robust and resilient electric grid

AFFORDABLE

Competitive power production

State-of-the-art modularized standard design reduces costs and maximizes returns. Small footprint, high efficiency.

RELIABLE

High carbon capture capability

97%+ inherent carbon capture generating pipeline-ready CO_2 through patented oxy-combustion process

NETPOWER

STEP Pilot Plant Inventory Management System

ETN BOP Webinar
Feb. 14, 2024

Joshua Warren
Senior Research Engineer

SwRI is an Applied Research & Development Company

- Founded in 1947, based in San Antonio, Texas
- 501 (c)(3) nonprofit corporation
  - Internal research
  - New laboratories
- ~$726M annual revenue
  - Industry and government contracts
- Over 2,700 employees
- 1,500+ acre campus
- Customer-Centric IP policy
- Deep Sea to Deep Space®…and everything in between

Alvin Pressure Hull

Pluto from New Horizons Spacecraft

SwRI's Roles in the STEP Pilot Plant Project

- The STEP Demo is a project funded by DOE NETL and led by GTI Energy in partnership with SwRI and GE Global Research
  - 10 MWe sCO2 Pilot Plant,
  - TRL3 to TRL7
  - $156M Budget over 7 Years
- SwRI Roles:
  - Host site
  - System integration and operation
  - Data acquisition & controls
  - Piping
  - Inventory Management System
  - Turbine design & fabrication (with GE)
  - Heater protection valve
- Mechanical completion Oct 2023
- Simple Cycle commissioning and testing through ~Mar 2024

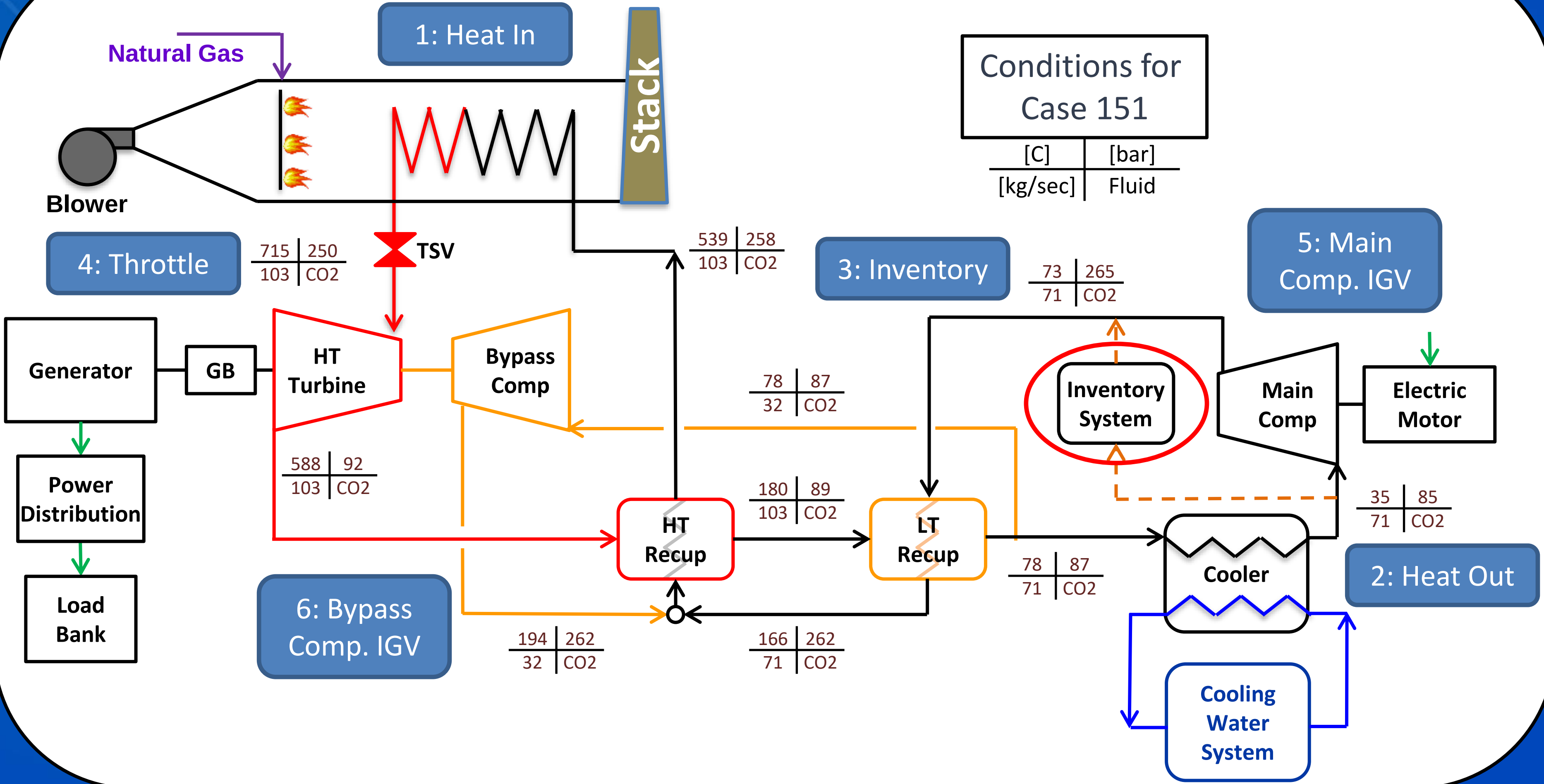
NATIONAL ENERGY TECHNOLOGY LABORATORY

gti SwRI GE

Recompression Closed Brayton Cycle

Objectives

- **High performance** cycle configuration
- Turbine inlet up to **715°C**
- **Parallel compressors** with **different head curves**
- Multiple Heat Exchangers
- **Measure** system and component **performance**
- Evaluate operability
- Demonstrate **pathway to 50% thermal efficiency**



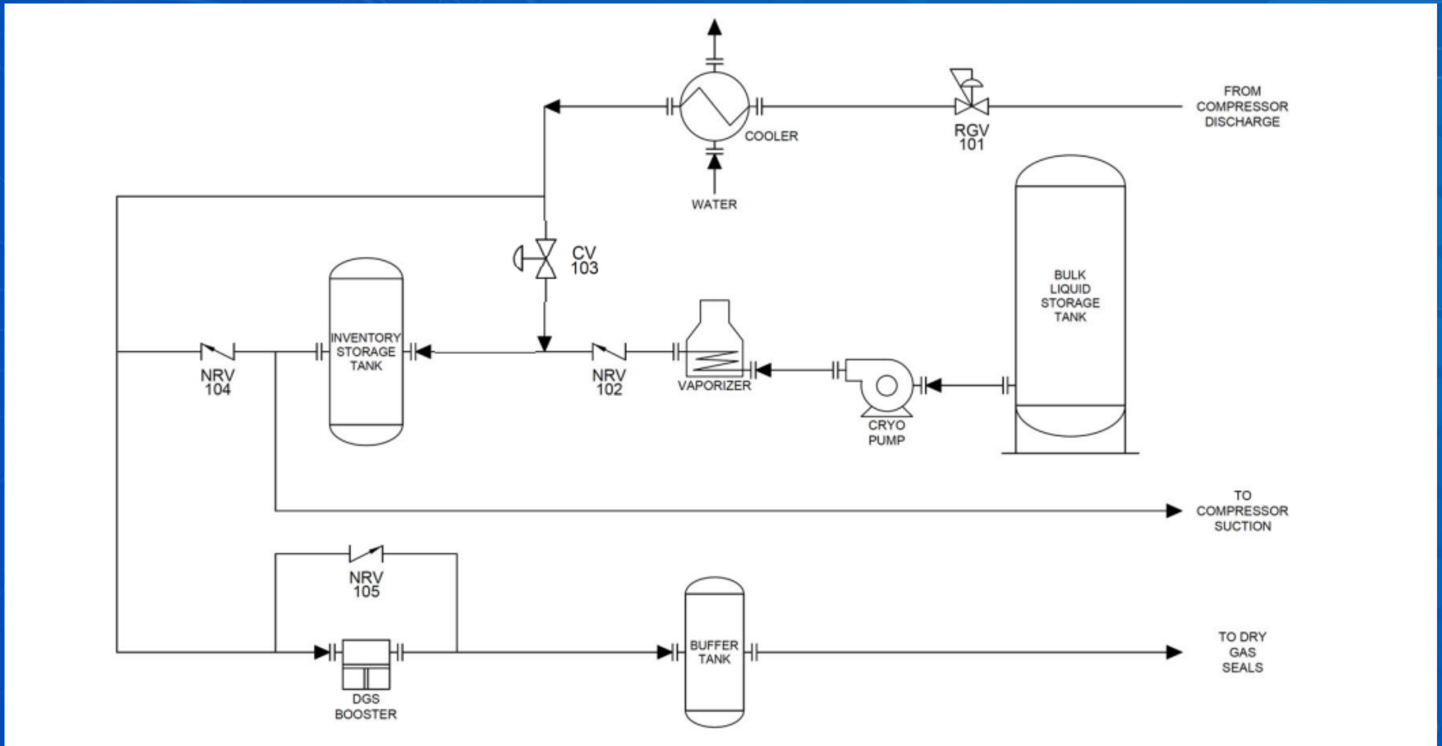
STEP DEMO | NATIONAL ENERGY TECHNOLOGY LABORATORY | gti | SwRI | GE

Why have an IMS?

- Controls the amount of CO2 in the system (which affects system load)
- Responsible for initial fill of system
- Supports Auxiliary systems like Dry Gas Seals (DGS)
- Can enable fast transitions between load points

Model Names	Cycle Configuration	Description	Load %	Net Power Level (MWe)	Cooler Exit Temperature	Turbine Inlet Temperature	Cycle Efficiency
133	Simple	Simple cycle minimum load case	Min	2.5	35°C	500°C	22.6%
136	Simple	Simple cycle maximum load case	Max	6.4	35°C	500°C	28.3%
151	Recompression	Baseline case	100%	10.0	35°C	715°C	43.4%
152	Recompression	"Hot" Day Case	70%	6.6	50°C	675°C	37.4%
153	Recompression	"Cold" Day Case	100%	9.9	20°C	525°C	36.8%
154	Recompression	Partial load case using inventory control	40%	4.0	35°C	715°C	37.0%
155	Recompression	RCBC at 500°C turbine inlet temperature	70%	6.9	35°C	500°C	32.5%
157	Recompression	Partial load case using TSV throttling (transient condition)	40%	4.2	35°C	715°C	30.8%
157a	Recompression	Partial load case using TSV throttling	40%	3.9	35°C	675°C	29.6%

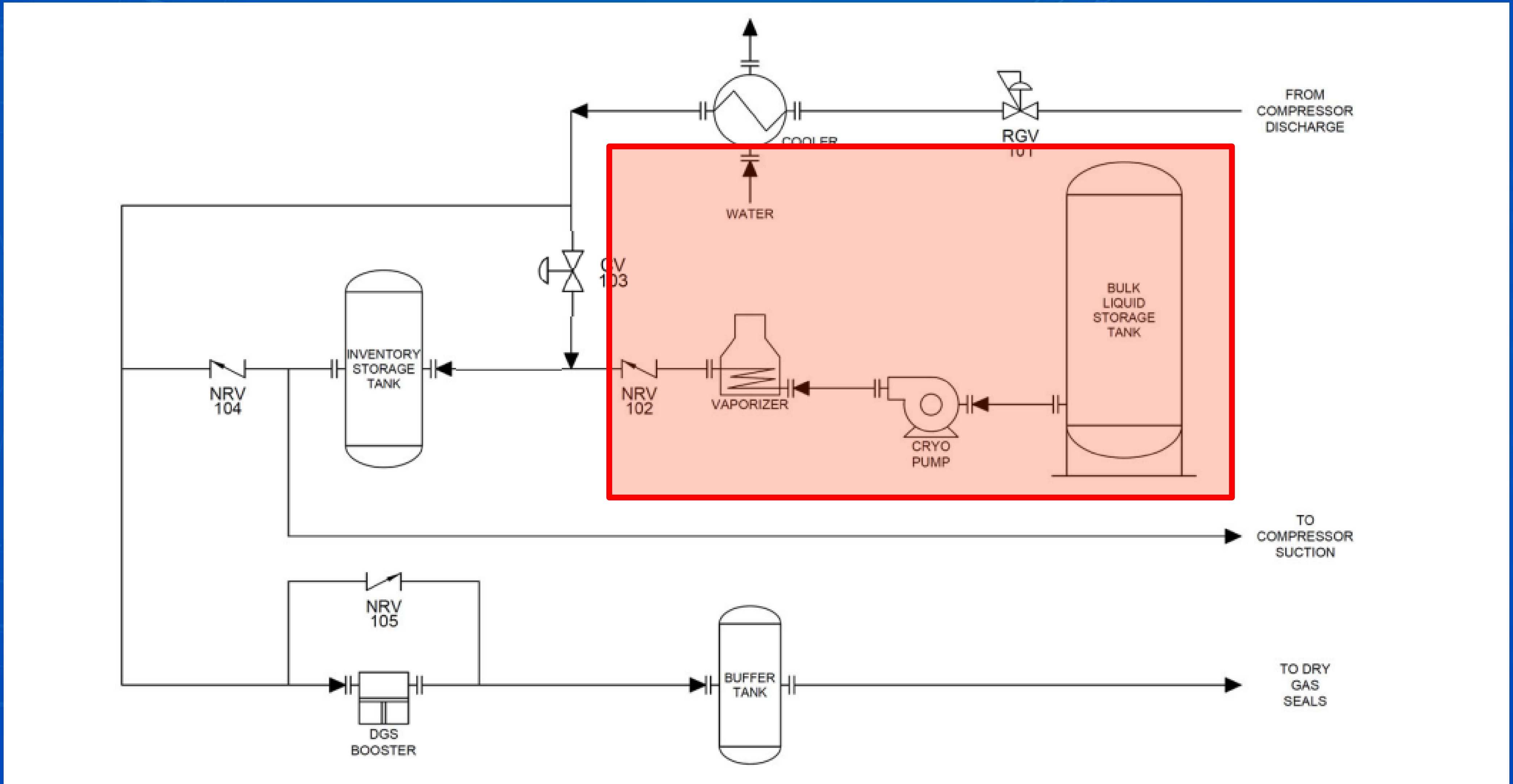
Inventory Management System



Primary Functions of IMS

- Liquid supply and fill system
- Inventory control
- DGS Supply
- Other auxiliary supplies

Liquid Storage and Fill System



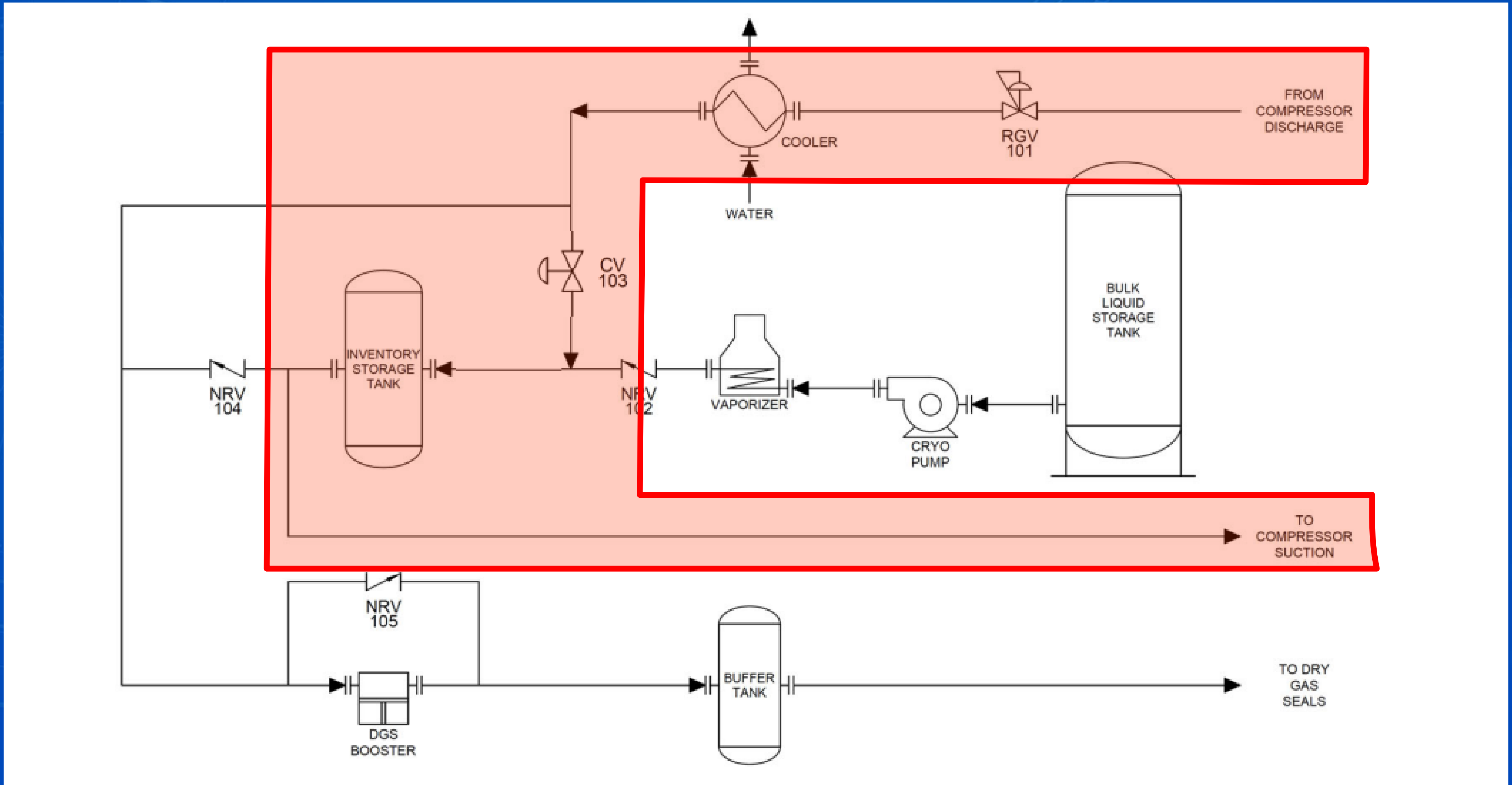
Fill System

- 30 Ton liquid storage tank
- Dual redundant liquid pump system
  - Sizing has to match vaporizer duty or use VFD to meet required outlet temp to process
- Process vaporizer to provide vapor > 40°C

Sizing of fill system is a critical input for plant depressurized startup times

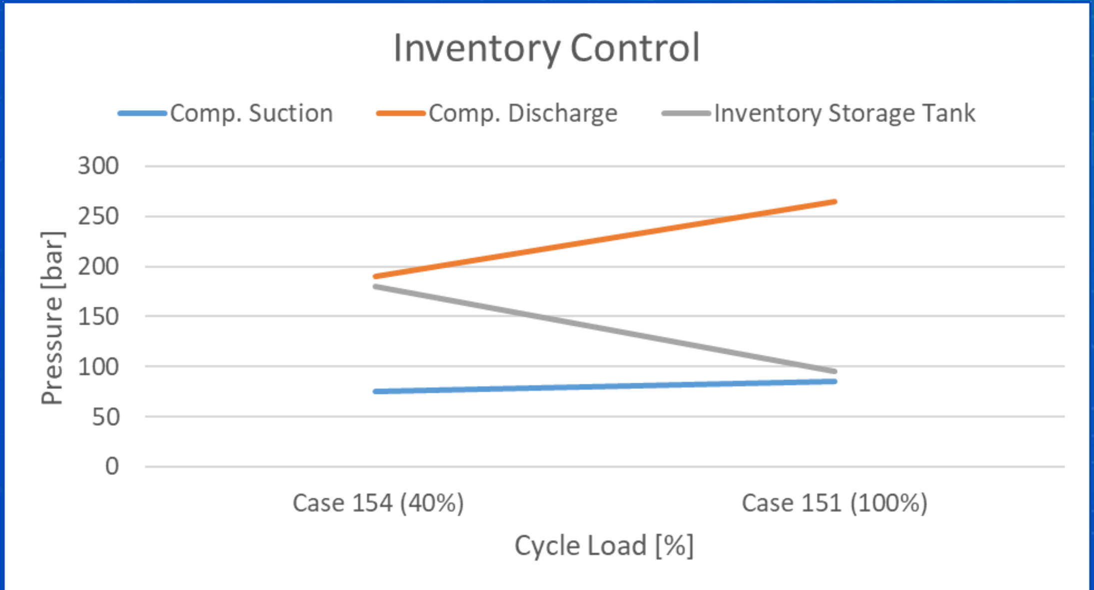
SwRI

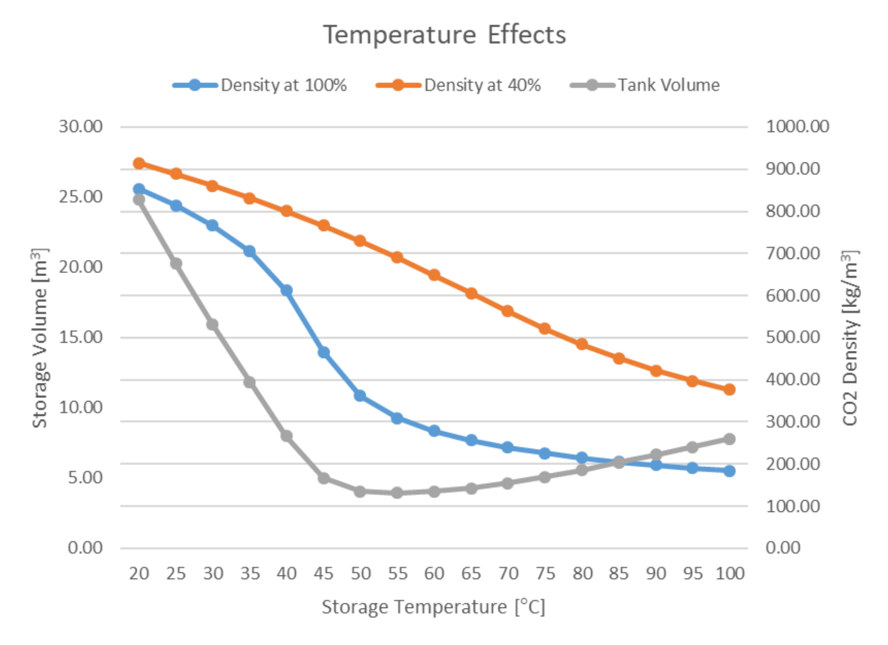
Inventory Storage and Control



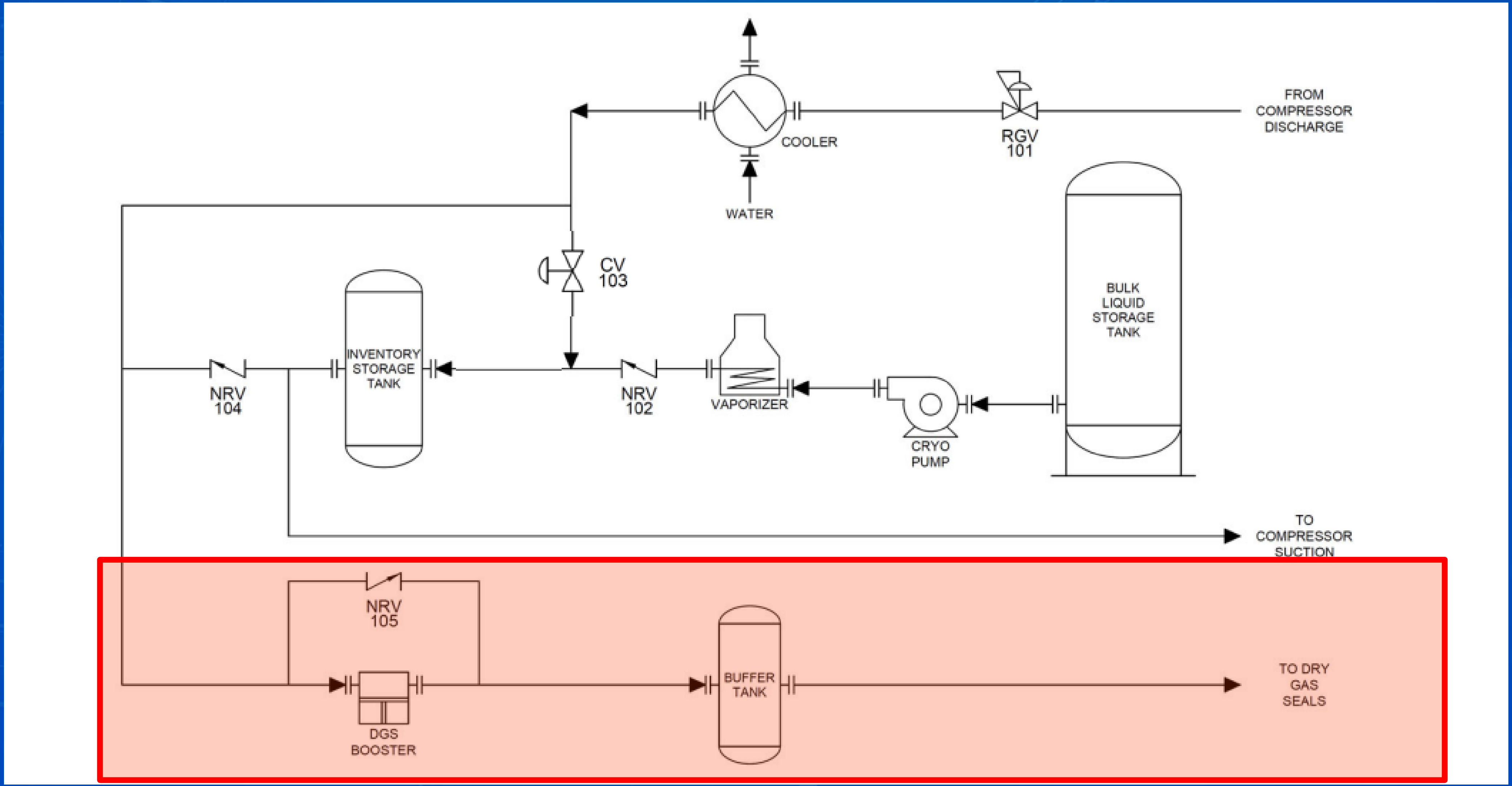
Inventory Control

- Allows movement of CO_2 from the process to the storage tanks and back
- Flow Drivers:
  - Natural Pressure Differential
  - Pumping system or small compressor
- Temperature of storage tanks has significant effect on capacity



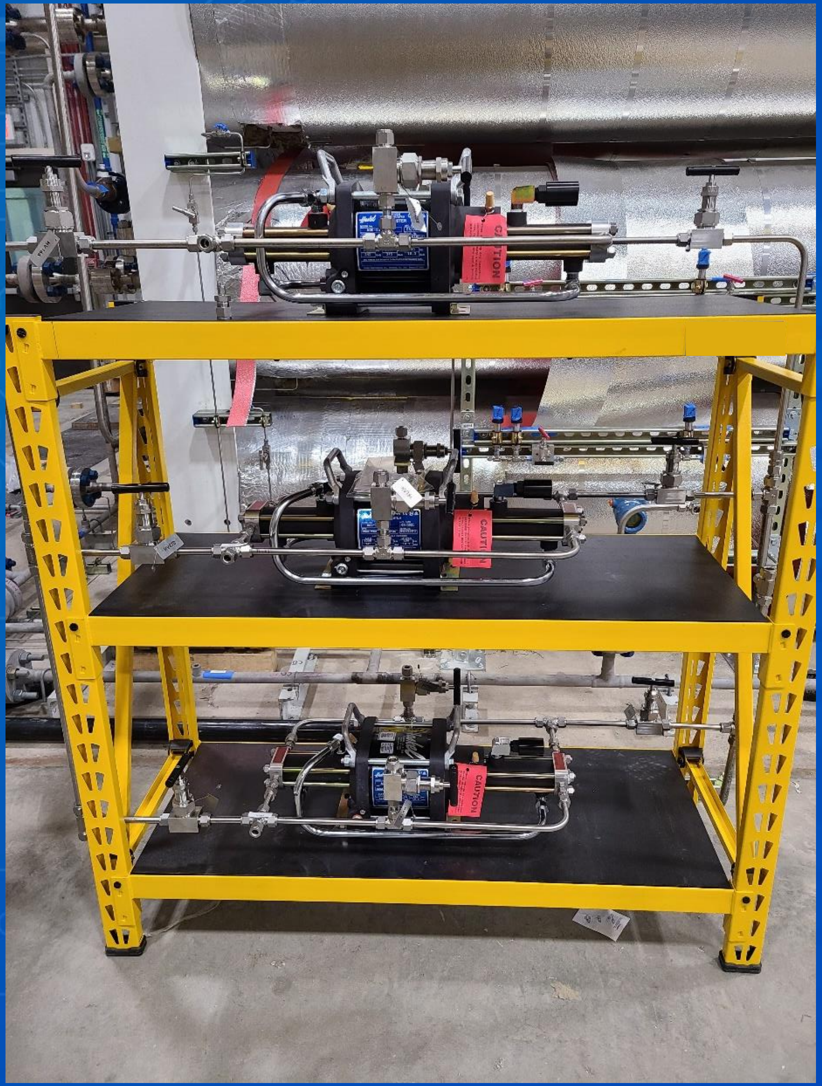


DGS Supply


COOLER
WATER
RGV 101
FROM COMPRESSOR DISCHARGE
CV 103
INVENTORY STORAGE TANK
NRV 104
NRV 102
VAPORIZER
CRYO PUMP
BULK LIQUID STORAGE TANK
TO COMPRESSOR SUCTION
NRV 105
DGS BOOSTER
BUFFER TANK
TO DRY GAS SEALS

DGS Supply

- During operation this segment is passive as compressor discharge provides DGS supply flow
- Buffer tank acts as an accumulator or run-down tank during transients and shutdown process
- Boost pumps provide pressure increase to drive flow during pressurized holds



Questions?

Thank you!

Joshua Warren
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Mechanical Engineering Division

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San Antonio, Texas 78238-5166

Thank you and see you next time!

Question / comments?

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