
Oil and Gas Industry Electrification Heat Pump Applications

April 2026

Table of contents

1	Executive Summary	7
1.1	Objectives	7
1.2	Technology Review	7
1.3	Heat Pump Application Ranking and Evaluation	9
2	Background and Objectives	12
3	Methodology	14
3.1	Heat Pump Technology Review	14
3.2	Application Discovery	14
3.3	Application Evaluation	14
4	List of Abbreviations	16
5	Technology Review	19
5.1	Introduction to Heat Pump Technology	19
5.1.1	Overview	19
5.1.2	Coefficient of Performance (COP)	21
5.2	Heat Pump Types	22
5.2.1	Single-stage	24
5.2.2	Cascade	28
5.2.3	Mechanical Vapour Recompression (MVR)	29
5.2.4	Joule/Stirling	31
5.2.5	Transcritical	32
5.2.6	Sorption Heat Pump	33
5.2.7	Hybrid Heat Pump	36
5.3	Refrigerants	36
5.3.1	Water (R718)	37
5.3.2	Carbon Dioxide (R744)	37
5.3.3	Ammonia (R717)	38
5.3.4	Butane (R600) and Pentane (R601)	39
5.3.5	Hydrofluoroolefins (HFO)	39
5.3.6	Hydrochlorofluoroolefins (HCFO)	40
5.4	Compressors	41
5.4.1	Piston (Reciprocating) Compressors	41
5.4.2	Screw Compressors	41
5.4.3	Scroll Compressors	41
5.4.4	Turbo Compressors (including Centrifugal)	41
5.4.5	Rotational Heat Pumps	41

5.5 Technology Summary	42
6 Heat Pump Applications	46
6.1 Upstream.....	46
6.1.1 Review of Assets.....	46
6.1.2 Opportunities Identified	47
6.2 Midstream.....	49
6.2.1 Review of Assets.....	49
6.2.2 Opportunities Identified	51
6.3 Downstream	52
6.3.1 Review of Assets.....	52
6.3.2 Analysis of Application Within Heat Exchanger Networks.....	53
6.3.3 Opportunities Identified	54
6.4 Utilities Production.....	59
6.4.1 Review of Assets.....	59
6.4.2 Opportunities Identified	59
6.5 Ranking	60
6.5.1 Ranking Methodology and Parameters	60
6.5.2 Ranking Results.....	61
7 Application Evaluation and Comparison	65
7.1 General Basis.....	65
7.2 U1: Offshore Oil Heating	65
7.2.1 Process Description	65
7.2.2 Equipment and Electrical Infrastructure.....	66
7.2.3 Project Schedule	67
7.2.4 Project Risks and Implementation Difficulty.....	67
7.2.5 Project Costs and Economics	67
7.3 U2: GOSP Crude Stabiliser Reboiler	68
7.3.1 Process Description	68
7.3.2 Equipment and Electrical Infrastructure.....	69
7.3.3 Project Schedule	69
7.3.4 Project Risks and Implementation Difficulty.....	69
7.3.5 Project Costs and Economics	69

7.4 U4: Heavy Oil Hot Water Flood.....	70
7.4.1 Process Description	70
7.4.2 Equipment and Electrical Infrastructure.....	71
7.4.3 Project Schedule	71
7.4.4 Project Risks and Implementation Difficulty.....	71
7.4.5 Project Costs and Economics	71
7.5 MI: De-Ethimizer Reboiler	72
7.5.1 Process Description	72
7.5.2 Equipment and Electrical Infrastructure.....	73
7.5.3 Project Schedule	73
7.5.4 Project Risks and Implementation Difficulty.....	74
7.5.5 Project Costs and Economics	74
7.6 D3: FCC Propylene Splitter Reboiler	74
7.6.1 Process Description	74
7.6.2 Equipment and Electrical Infrastructure.....	75
7.6.3 Project Schedule	75
7.6.4 Project Risks and Implementation Difficulty.....	75
7.6.5 Project Costs and Economics	75
7.7 D4: SCU De-Octaniser Steam Reboiler	76
7.7.1 Process Description	76
7.7.2 Equipment and Electrical Infrastructure.....	76
7.7.3 Project Schedule	77
7.7.4 Project Risks and Implementation Difficulty.....	77
7.7.5 Project Costs and Economics	77
7.8 SI: LP Steam Generation.....	77
7.8.1 Process Description	77
7.8.2 Equipment and Electrical Infrastructure.....	78
7.8.3 Project Schedule	78
7.8.4 Project Risks and Implementation Difficulty.....	78
7.8.5 Project Costs and Economics	79
7.9 Summary.....	80
8 Conclusions.....	81
9 Appendix A: List of Heat Pump Applications	82
10 Appendix B: Priceseets Used	85

Client	Oil and Gas Climate Initiative (OGCI)
Project	Oil and Gas Industry Electrification – Heat Pump Applications
Project Number	522293
Document Title	Heat Pump Applications
Wood Document Number	522293-8110-001-001

Revision	Date	Reason for Issue	Prepared	Checked	Approved
O1	23 rd September 2024	Draft for Comment	RK/MDMG/ SG	MAC	MAC
1A	19 th December 2024	Final Issue	RK/MDMG/ SG	MAC	MAC
2A	4 th April 2025	Amendments to Final Report	RK/MDMG/ SG	MAC	MAC
3A	3 rd December 2025	Minor Amendments to Final Report	RK/MDMG/ SG	MAC	MAC

The information and data contained herein is provided by John Wood Group Plc or its subsidiary, solely for use by its client. No representation or warranty whatsoever, express or implied, is made to any third party, and no obligation or liability accepted, with respect to the veracity, adequacy, completeness, accuracy or use of any information contained herein.

The information and data contained herein is not, and should not be construed as, a recommendation by John Wood Group Plc or its subsidiary that any recipient of this document provide finance to the Project. Each recipient should make its own independent evaluation to determine whether to extend credit to the Project.

O

Executive Summary

1 Executive Summary

1.1 Objectives

Waste heat reduction and utilization is an increasingly important lever to reduce costs and greenhouse gas emissions in energy-intensive industries, such as oil and gas. An OGI study on Refining Industry Electrification suggested that heat pumps were one of the more promising and economically competitive technology options. The technology can achieve very high energy efficiency by upgrading lower temperature waste heat streams to more useful higher temperatures using an electrical motor. This study aims to expand on the potential for heat pump technologies by exploring potential applications in oil and gas upstream and downstream operations.

The objectives of this study are to:

- Review the current and emerging heat pump technologies relevant to the oil and gas industry.
- Discover potential applications of heat pumps across generalised upstream and downstream assets.
- Evaluate selected applications to gain insight into attractive technologies, benefits and economics.

1.2 Technology Review

This report reviewed a wide variety of heat pump technologies with results summarised in [Table 1](#).

The most proven technologies are those operating with lower grade heat sources and for low lift applications, namely with supply temperatures up to 135°C. The selection of heat pump working fluid will depend on the outlet temperature, with most vendor experience below 150°C.

Heat pumps with very high temperature lift beyond 100°C remain relatively small scale and economically unattractive against larger, lower lift applications. The exception to this is steam production whereby post-heat pump compression can be employed relatively cheaply, maintaining a reasonable efficiency as measured by coefficient of performance (CoP). Mechanical vapor recompression (MVR) systems using a heat source of sufficiently high temperature such as column overheads, can be used in applications requiring heat pump outlet temperatures up to 230°C. Stirling cycles, though currently restricted in scale, can achieve very high lift, providing outlet temperatures up to 250°C.

Table 1 Summary of Available Industrial Heat Pumps and Key Characteristics

Type	Compressor	Capacity (MWth)	Temperature Output (°C)	TRL	COP	Vendors	Refrigerants
Cascade	Centrifugal, Piston, Reciprocating, Screw, Turbo	0.03–10	115–200	4–9	1.74–13	8	R1233zd(E), R1336mzz(Z), R245fa, R290, R410a, R600, R717, R718, Others (HC, HFO)
Chemical Adsorption Heat Transformer	No compressor	>2	230	9	0.15–0.45	2	R717, R718, H3PO4 and derivatives
Joule Cycle	Centrifugal	0.7	150	6–7	4–7	1	Proprietary fluid
MVR–Open	Turbo	1–70	212 (40–230)	8–9	3.5–7.3	1	R718
MVR–Open or Semi-Open	Twin-screw, rotary vane, high-pressure centrifugal fan, positive displacement blower	0.5–30	150–188	6–9	3.1–5.3	3	R718
Not defined/Other	Centrifugal, Piston, Reciprocating, Screw, Turbo	0.03–70	120–280	4–9	2.5–10.3	5	R1233zd(E), R1234ze(E), R1234ze(Z), R290, R600, R600a, R601, R744
Single-Stage–Condenser Outlet Split (COS) Ejectors Cycle	Screw	0.3–3.3	120	9	2.2–5.3	1	R1233zd(E), R1234yf, R1234ze, R450A, R513A, R515B
Single-Stage–Economizer cycle	Twin-screw	0.624	175	9	2.5	1	R134a + R245fa mix, R718
Steam Compression–Closed	Piston	1–15	280	9	3.5–10.3	1	R718
Steam Compression–Open	Centrifugal, Reciprocating	0.03–10	120–160	4–9	2.5–5	2	R1224yd(Z), R1233zd(E), R1336mzz(Z), R245fa
Stirling Cycle	Piston	0.3–10	200–250	6–9	1.6–3.7	2	R704
Transcritical Cycle	Centrifugal, Piston, Turbo	0.1–50	100–150	7–9	2–5.5	4	R134a, R744
Twin or Multi-Cycle	Piston, Turbo, Twin-screw	0.3–30	120–200	6–9	2.9–3.6	3	R245fa, HFOs, Others (e.g. HC, siloxans)

1.3 Heat Pump Application Ranking and Evaluation

The study identified and ranked heat pump applications across the oil and gas value chain. Technology types were selected based on the process requirements. Example project analyses, supplemented by vendor feedback, provided insight into the limitations of some of the applications and technologies. Ranking was based on CoP, breadth of applicability, and single application duty, with a focus on applications with good power efficiency, economics and impact across industry.

The top economic performers were large, mostly downstream, distillation columns that could be integrated with low or low-moderate lifts between overheads and reboilers. However, due to existing high levels of heat integration in these facilities, most downstream applications were at higher required temperature.

Upstream heating was shown to also have feasible economics and an attractive scale. Steam production from a centralised, cooling water return source was shown to be attractive and competitive against electrode boilers over the project life despite a greater capital cost.

Utilisation of water and steam as the working fluid in a closed loop where appropriate was shown to produce an economic advantage via decreased CAPEX due to cheaper compression technology. Open-loop MVR was shown to be competitive in low-lift scenarios, with other closed loop refrigerant packages offering flexibility to low source temperatures.

Table 2 Summary of Cases

Case	Heat Source and Sink	Heat Pump Technology	Refrigerant	Thermal Duty (MW)	COP	CO ₂ Abated (t/h)	Estimated CAPEX (MMUSD)	CAPEX/ Thermal Duty Efficiency (\$/ kW)	CAPEX/CO ₂ Efficiency (MMUSD/ tCO ₂)	IRR (%)
U1	Offshore Crude Heating From Seawater	Multi-cycle	R600 (n-Butane)	7.0	3.0	2.0	22.2	3176	10.9	8%
U2	Crude Stabilisation From Compressor Coolers	Steam Compression – Closed Loop	R718 (Water)	8.9	4.2	2.6	14.5	1624	5.5	16%
U4	Hot Water Flood From Air/Other Ambient	Single Stage	R600 (n-Butane)	20.0	3.0	5.8	33.4	1672	5.7	14%
M1	De-Ethaniser Reboiler from De-Propaniser Overheads	Single Stage	R600 (n-Butane)	33.5	3.3	9.8	49.3	1471	5.0	16%
M1		Single Stage	R718 (Water)	33.5	4.1	9.9	27.2	811	2.8	27%
M1		MVR – Open Loop	-	20.4	2.5	5.9	35.4	1734	6.0	13%
D3	Propylene Splitter	MVR – Open Loop	-	66.6	7.2	19.8	59.0	885	3.0	28%
D4	Deoctaniser	Stirling	R704 (Helium)	7.6	1.4	2.15	45.0	5920	20.9	1%
S1	Steam Generation From Refinery Cooling Water Return	Two-stage with Economiser	R717 (Ammonia)	62.6	2.5	18.2	72.8	1163	4.0	18%

02

Background and Objectives

2 Background and Objectives

The Oil and Gas Climate Initiative (OGCI) Energy Efficiency in Industry Workstream (EEI WS) has formed a working group with the purpose of developing options for electrification based on technology, economics, and carbon reduction potential. Their work aims to inform OGCI members of the potential for electrification to contribute to carbon intensity reductions. In an OGCI EEI WS study on Refining Industry Electrification, heat pumps were identified as one of the more promising and economically competitive technology options. This study aims to expand on the potential for heat pump technologies by exploring potential applications in oil and gas upstream and downstream operations.

Energy efficiency is a key focus area for immediate-term decarbonization. Waste heat reduction and utilization is increasingly important to process design in energy-intensive industries and has largely been achieved through heat integration between streams, as well as exporting waste heat to other industries

or nearby municipalities. Existing and emerging heat pump technologies provide an opportunity to “upgrade” lower temperature waste heat streams to more useful higher temperatures via additional electrical motor input, enabling high efficiency of green power utilization in decarbonization initiatives.

The study’s primary aims are to:

- Review the current and emerging heat pump technologies relevant to the oil and gas industry.
- Discover potential applications of heat pumps across generalised upstream and downstream assets.
- Evaluate selected applications to gain insight into attractive technologies, benefits and economics.



OGC

Methodology

3 Methodology

3.1 Heat Pump Technology Review

Different available types of heat pumps are reviewed and explained, including key limitations to capacity and temperatures, maturity and efficiency. Working fluids and compressor technologies are also discussed.

Heat pumps for generation of upgraded heat are considered in the current work to provide constraints

and direction for application to representative assets; power generation, e.g. from Organic Rankine Cycles, is not included in the scope of review.

Existing literature is reviewed, complemented by technical dialogue with vendors for heat pump technologies.

3.2 Application Discovery

Wood subject matter experts and project experience are utilized to review typical upstream offshore and onshore, midstream, pipeline, refinery and petrochemical assets for major opportunity waste heat streams and local heat utilization via heat pumps.

For the refinery applications, the representative asset is chosen to align with the previous work on refinery electrification to enable direct comparisons.

Ranking and high-level screening of the heat pump applications is carried out to provide focus for further evaluation.

3.3 Application Evaluation

Simulation is employed to verify and supplement vendor and literature data for the selected applications, providing expected performance and sizing of key equipment.

Heat pump package vendor input is utilized to supplement previous costing and utility information, as well as utilizing further publicly available information. Conceptual-level total installed capital costs are provided, dependent on application and including any balance of plant. Operating costs are estimated from

calculated utility consumptions, CO₂ emissions savings and non-energy cost calculation. Economic modelling is aligned with the concurrent Refinery Electrification Economics study.

Plot space, project duration, electrical infrastructure and any specific feasibility concerns are also evaluated at a conceptual level, with comparisons drawn between technology options.

04

List of Abbreviations

4 List of Abbreviations

Abbreviation	Description
API	American Petroleum Institute
ARU	Amine Regeneration Unit
ATEX	European Union regulations for safety of products in explosive environments
B2L	Hazard class of refrigerants
CAPEX	Capital Expenditure
CO ₂	Carbon Dioxide
COP	Coefficient of Performance
COS	Condenser Outlet Split
ED	Extractive Distillation
EEl WS	Energy Efficiency in Industry Workstream
EN	European Standards
FCC	Fluid Catalytic Cracking
GOSP	Gas-oil Separation Plant
GWP	Global Warming Potential
H ₂ O	Water
H ₂ S	Hydrogen Sulphide
HCFO	Hydrochlorofluoroolefin
HDT	Hydrotreater
HFC	Hydrofluorocarbon
HFO	Hydrofluoroolefin
HP	High Pressure
HTHP	High-Temperature Heat Pump
ICA	Induced Condensing Agents
IHX	Internal Heat Exchanger
LLDPE	Linear Low-Density Polyethylene
LP	Low Pressure

Abbreviation	Description
LPG	Liquefied Petroleum Gas
LPS	Low Pressure Steam
MP	Medium Pressure
MPS	Medium Pressure Steam
MSC	Mechanical Steam Compression
MVR	Mechanical Vapour Recompression
MW _{th}	Megawatt Thermal (Thermal Power)
NGL	Natural Gas Liquids
NH ₃	Ammonia
ODP	Ozone Depletion Potential
OGCI	Oil and Gas Climate Initiative
PP	Polypropylene
SCU	Steam Cracking Unit
SWS	Sour Water Stripper
TDHP	Thermally Driven Heat Pump
TFA	Trifluoroacetic Acid
TRL	Technology Readiness Level
US	United States of America
VCC	Vapour Compression Cycle
VCHP	Vapour Compression Heat Pump

05

Technology Review

5 Technology Review

5.1 Introduction to Heat Pump Technology

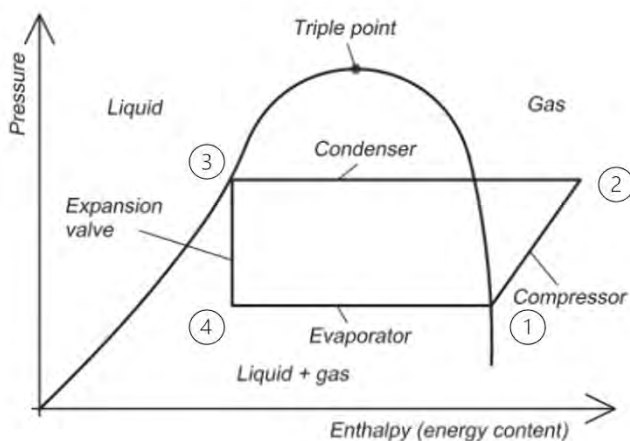
5.1.1 OVERVIEW

When optimising the design of heat-consuming processes within industrial plants, it is well established that direct heat exchange can be utilized when the heat source temperature exceeds that of the heat sink. However, in conventional operations, energy is often lost when the heat source temperature is lower than can be usefully employed elsewhere.

An electric heat pump is a device that consumes electricity to transfer heat from a lower temperature source to a higher temperature sink, utilizing a working fluid. The heat source is defined as a reservoir from which heat is recovered and upgraded, while the heat sink is the reservoir to which heat is supplied. This allows for the recovery of energy that would otherwise be lost as waste heat or utilization of energy from surroundings such as air and seawater.

Heat pumps operate by exploiting the thermodynamic properties of working fluids through temperature and pressure manipulation. For a closed loop, the process involves four main components: Evaporation, compression, condensation, and expansion.

Figure 1 Heat Pump Generic Pressure-Enthalpy Diagram



The above diagram represents a generic heat pump cycle.

- I. 1–2: The working fluid is compressed, using a compressor which has an electrical supply. The fluid is heated due to the compression, also raising the temperature at which it will condense. This compression is assumed to be isentropic.
- II. 2–3: The working fluid passes through a condenser where it begins to condense. Upon condensation energy is released and the fluid in the heat sink is subsequently heated.
- III. 3–4: The condensed fluid passes through an expansion valve where when the fluid is allowed to expand it is cooled down due to the phase change from liquid to gas. This expansion is assumed to be isentropic.
- IV. 4–1: By utilizing a heat source the liquid gas stream is evaporated. Energy is put into the system to convert any unconverted liquid into the gas phase.

Typical heat pump sink outlet temperatures are at or below 100°C, with devices capable of exceeding this threshold classified as High-Temperature Heat Pumps (HTHPs). A second category of heat pumps, known as Absorption/Adsorption Heat Pumps or Sorption Heat Pumps, utilizes thermal energy rather than electricity. These systems are powered by steam or combustion of fuel gas. This review refers to electric-driven heat pumps simply as “heat pumps” and to “sorption heat pumps” as a separate category.

Figure 2 Heat Pump Generic Configuration

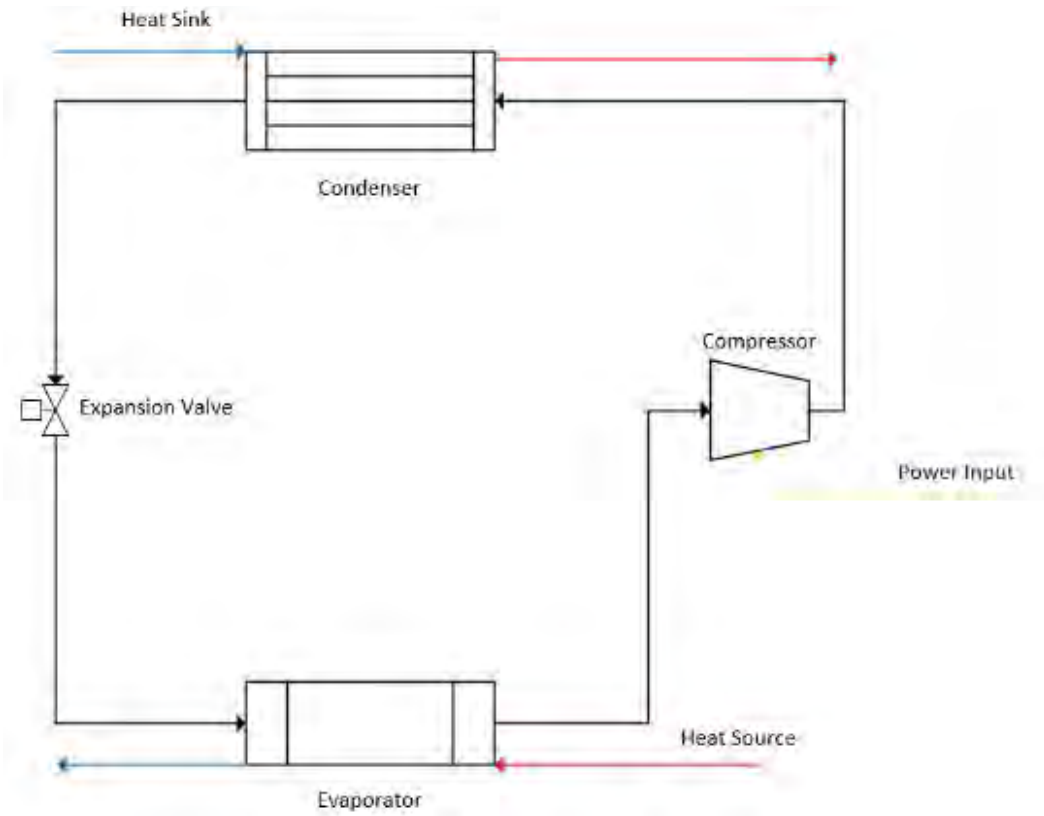
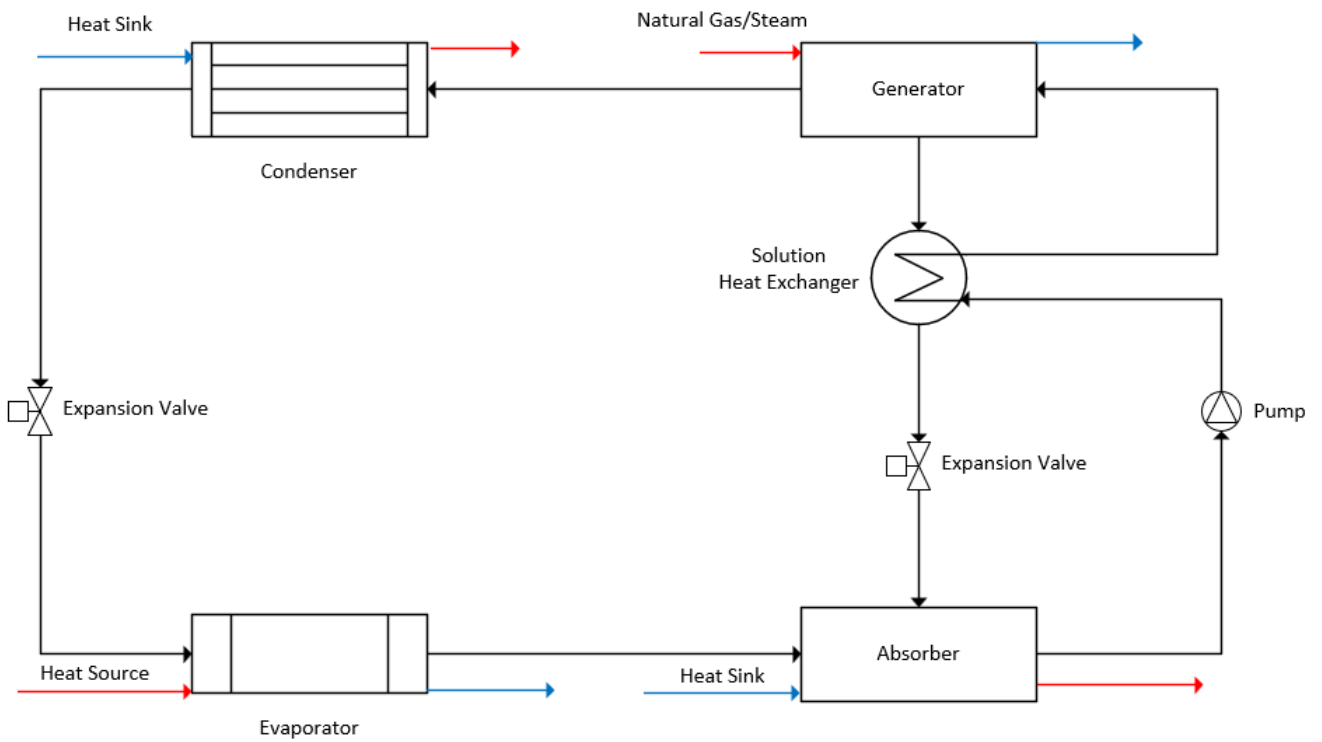


Figure 3 Example Sorption Heat Pump Generic Configuration



5.1.2 COEFFICIENT OF PERFORMANCE (COP)

The efficiency of a heat pump is quantified by its Coefficient of Performance (COP). This metric measures the amount of heating or cooling produced per unit of energy input, specifically the ratio of heat transferred to a hot reservoir compared to the work input required for that transfer. COP is applicable for both heat addition and removal processes, with a subscript 'h' denoting heating application. The theoretical maximum efficiency of a heat pump is known as the Carnot Efficiency:

Equation 1 Carnot COP

$$\text{COP}_{h,\text{Carnot}} = \frac{T_{\text{Cond}}}{T_{\text{Cond}} - T_{\text{Evap}}}$$

Where:

- $\text{COP}_{h,\text{Carnot}}$ is the Carnot Coefficient of Performance for heating.
- T_{Cond} is the condensation temperature (dew point) in K.
- T_{Evap} is the evaporation temperature (bubble point) in K.

In reality, there are losses that affect the efficiency:

Equation 2 Carnot Efficiency Factor

$$\text{COP}_h = \eta \cdot \text{COP}_{h,\text{Carnot}}$$

Where:

- COP_h is the Coefficient of Performance for heating.
- η is the efficiency factor (typically 50–70%).

The Carnot Efficiency is limited to applications where dew and bubble points are at specific temperatures. For transcritical heat pumps, where there is no condensation temperature but a temperature range, the theoretical maximum efficiency is given by the Lorenz equation:

Equation 3 Lorenz COP

$$\text{COP}_{h,\text{Lorenz}} = \frac{T_{\text{Heat Sink,LM}}}{T_{\text{Heat Sink,LM}} - T_{\text{Heat Source,LM}}}$$

Where:

- $\text{COP}_{h,\text{Lorenz}}$ is the Lorenz Coefficient of Performance for heating.
- $T_{\text{Heat Sink,LM}}$ is the Log mean temperature of the Heat Sink, in K.
- $T_{\text{Heat Source,LM}}$ is the Log mean temperature of the Heat Source, in K.

The log mean temperature is calculated as:

Equation 4 Log Mean Temperature

$$T_{\text{LM}} = \frac{T_{\text{in}} - T_{\text{out}}}{\ln\left(\frac{T_{\text{in}}}{T_{\text{out}}}\right)}$$

This is used for streams experiencing temperature “glide” where the temperature changes substantially over the condenser and/or evaporator. Similar to the Carnot COP, in reality there are factors that affect efficiency as the electrical energy powering the compressor is partly absorbed by the working fluid:

Equation 5 Lorenz Efficiency Factor

$$\text{COP}_h = \eta \cdot \text{COP}_{\text{Lorenz}}$$

For large-scale, well-designed heat pumps $\eta \approx 50\%$.

The COP formula is defined as:

Equation 6 COP_h

$$\text{COP}_h = \frac{\dot{Q}_{\text{Condenser}}}{\dot{E}_{\text{Compressor}}} \approx \frac{\dot{Q}_{\text{Evaporator}}}{\dot{E}_{\text{Compressor}}} + 1$$

Where:

- $\dot{Q}_{\text{Condenser}}$ is the heat rate at the condenser.
- $\dot{Q}_{\text{Evaporator}}$ is the heat rate at the evaporator.
- $\dot{E}_{\text{Compressor}}$ is the power input to the compressor.

It is important to note that most of the electrical energy driving the compressor is converted to heat

5.2 Heat Pump Types

Many different technologies of heat pumps have been developed to enhance the applicability to different processes. These are summarised in [Table 4](#) and described further in the sections below.

and released into the refrigerant. Consequently, more heat is available at the condenser than is extracted at the evaporator. A higher COP value indicates greater efficiency, as it represents more heat recovery per unit of electrical energy input. For example:

- A heat pump with a COP of 4 requires 1 kW of electric energy input to release 4 kW of heat at the condenser.
- At the evaporator, approximately 3.0–3.5 kW of heat is extracted.
- The difference between the energy at the condenser and evaporator is attributed to the additional heat generated by the compressor.

This relationship demonstrates the energy-multiplying effect of heat pumps, making them an efficient solution for various heating applications.

Table 4 Characteristics Summary of Available Industrial Heat Pumps

Type	Description	Key Features
Single-stage Direct expansion	Refrigerant directly absorbs heat from source	Efficient, but limited capacity
Single-stage Pump expansion	Uses pump instead of expansion valve	Higher efficiency, more complex
Single-stage with internal heat exchanger	Includes additional heat exchange	Improved efficiency over basic single stage
Single-stage with economizer	Uses vapor injection to improve capacity	Higher capacity and efficiency
Twin/multi cycle	Multiple refrigeration cycles in one system	Flexible operation, improved efficiency
Single-stage with COS ejectors	Uses ejector for expansion process	Improved efficiency, especially in cooling
Cascade	Two-stage system with separate refrigerants	Wide temperature lift, high efficiency
Mechanical vapor compression	Standard electrically-driven cycle	Widely used, moderate to high efficiency
Steam compression	Uses water as refrigerant	High temperatures, industrial applications
Joule	Gas cycle, uses air as working fluid	Simple, lower efficiency than vapor compression
Stirling	Closed-cycle regenerative heat engine	High efficiency potential, complex mechanism
Transcritical	Operates above critical point of refrigerant	Good for large temperature glide, often uses CO ₂
Absorption heat pump	Uses thermal energy instead of mechanical	Can use low-grade heat, lower electrical demand
Absorption heat transformer	Upgrades waste heat temperature	Industrial applications, temperature boosting
Adsorption heat pump	Uses solid sorbent instead of liquid	Can use very low-grade heat, intermittent operation
Hybrid heat pump	Combines two or more cycle types	Flexible, can optimize for varying conditions

5.2.1 SINGLE-STAGE

The single-stage heat pump represents the most fundamental configuration in heat pump technology. This system employs a basic refrigeration cycle, utilizing the latent heat of condensation and evaporation of a working fluid to facilitate heat transfer from a lower temperature source to a higher temperature sink.

Several variations of the single-stage configuration have been developed to enhance performance and efficiency:

1. **Pump Expansion:** Utilizes a gas-liquid separation vessel and a pump to decrease volumetric flow to the evaporator.
2. **Internal Heat Exchanger (IHX):** This modification improves cycle performance by facilitating additional heat exchange within the system.
3. **Economizer:** Incorporated to reduce power consumption, thereby increasing overall system efficiency.
4. **Twin or Multi-cycle Systems:** These configurations employ two or more cycles operating in parallel or series, offering advantages in scenarios with larger temperature differentials.
5. **Condenser Outlet Split (COS) Ejector Cycle:** This variant aims to increase efficiency and reduce losses through the strategic use of an ejector.

The following sections provide a more detailed examination of the single-stage heat pump and its variants, exploring their operational principles, advantages, and specific applications.

5.2.1.1 Direct Expansion

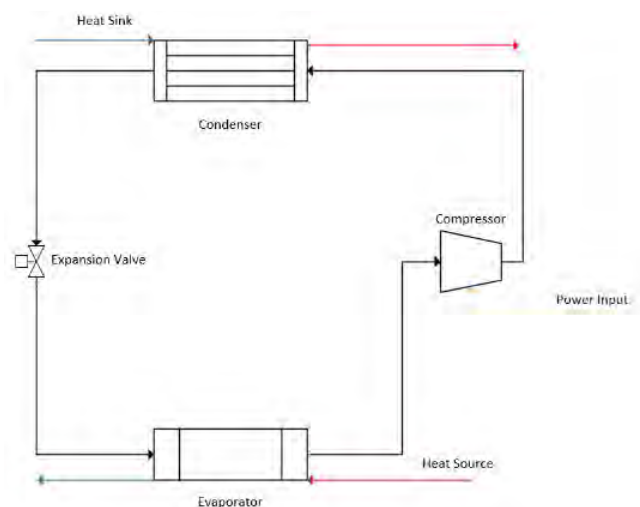
The figure illustrates a system employing direct expansion, a process in which the entire refrigerant volume exiting the expansion device is fed into the evaporator. During expansion, the refrigerant undergoes a substantial pressure reduction, resulting in partial evaporation and the formation of what is known as flash gas.

The refrigerant, now a mixture of gas and liquid, enters the evaporator. It is important to note that only the liquid component of this mixture possesses the capacity to evaporate within the evaporator. Once the refrigerant has completely evaporated and achieved a slight degree of superheat, it proceeds to the compressor. This superheating is crucial to prevent potential damage to the compressor from liquid slugging. Liquid slugging is a phenomenon that occurs when compressing liquid instead of gas.

The flow of refrigerant through the expansion device is regulated based on the degree of superheat measured at the evaporator outlet. Concurrently, the compressor capacity is modulated in response to the condensation temperature at the compressor discharge.

This direct expansion configuration represents a fundamental approach to refrigerant management within heat pump systems, balancing efficiency with equipment protection and operational control.

Figure 4 Direct Expansion Heat Pump



5.2.1.2 Pump Expansion

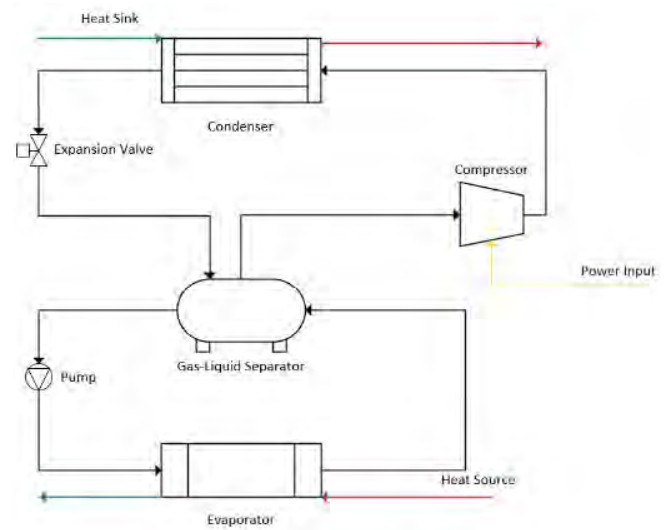
Another variant of mechanical heat pumps is the pump system heat pump. The operational principle of this configuration is illustrated in the accompanying figure. A key component of the pump system is a separator vessel. From this vessel, liquid refrigerant is pumped to the evaporator. Within the evaporator, the refrigerant undergoes partial evaporation, resulting in a mixture of liquid and gaseous refrigerant, which is returned to the separator vessel. The separator then efficiently divides this mixture into its liquid and vapor components. The liquid is recirculated to the evaporator, while the vapor is directed to the compressor.

This configuration offers several advantages:

1. Compact evaporator design: Smaller evaporators can be employed compared to direct expansion systems of equivalent capacity, as the volumetric flow consists of only liquid refrigerant.
2. Improved efficiency: The continuous circulation of liquid refrigerant enhances heat transfer in the evaporator. As opposed to direct expansion where only the liquid portion has the ability to undergo evaporation.

However, the system does require additional components, namely a refrigerant pump and a separation vessel, which may increase complexity and initial costs. Pump system heat pumps are particularly well-suited for large-scale industrial applications. They are especially prevalent in ammonia-based systems, as ammonia direct expansion systems are highly susceptible to contamination of the expansion device. Furthermore, the overheating of refrigerant in direct expansion systems can lead to elevated discharge temperatures, potentially degrading the compressor lubricant.

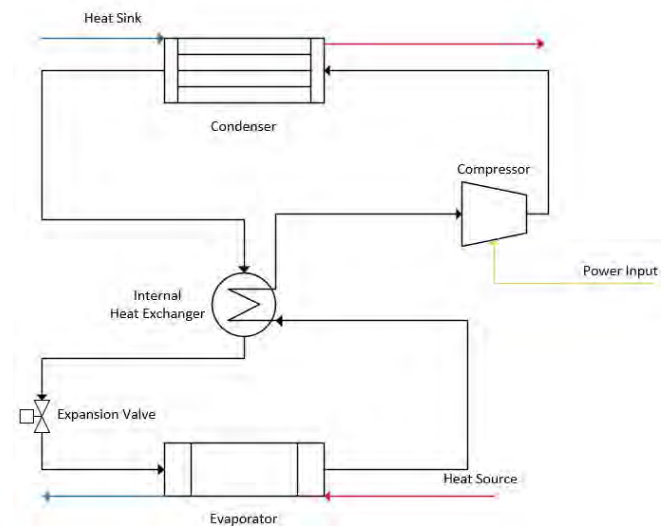
Figure 5 Pump Expansion Heat Pump



5.2.1.3 Single-stage with Internal Heat Exchanger

Incorporation of an internal heat exchanger (IHx) can enhance cycle performance, with its efficiency largely dependent on the thermodynamic properties of the selected refrigerant. This modification is particularly advantageous for refrigerants characterized by a saturated vapor curve with a positive slope ($dT/ds > 0$), which requires significant superheating to prevent wet compression.

Figure 6 Single-stage Cycle With IHX



5.2.1.4 Single-stage with Economizer

The economizer cycle represents an advanced configuration in heat pump systems, designed to enhance overall efficiency. In this arrangement, a portion of the refrigerant stream is diverted after the condenser and passed through an expansion valve, reducing its pressure to an intermediate level. This expansion process results in a temperature decrease and partial evaporation of the diverted stream, creating a gas-liquid mixture.

Subsequently, heat exchange occurs between the high-pressure liquid refrigerant from the condenser outlet and the partially evaporated, intermediate-pressure refrigerant. This heat transfer process leads to the complete evaporation of the diverted stream within the economizer heat exchanger. The fully vaporized refrigerant at intermediate pressure is then introduced into the compressor at an appropriate stage.

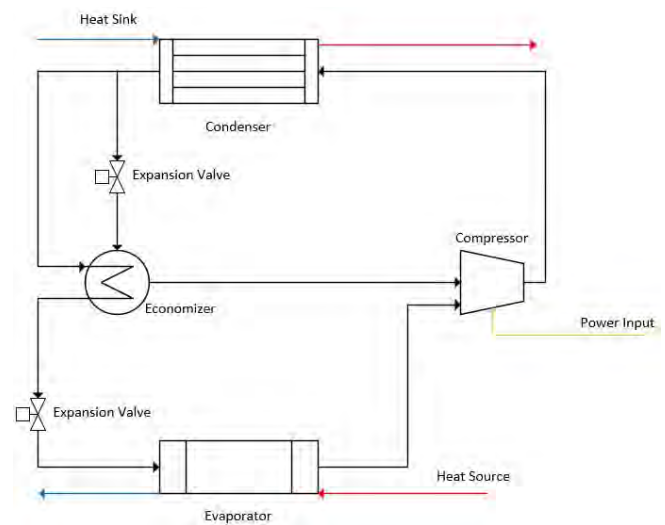
Meanwhile, the remaining liquid refrigerant undergoes further expansion before entering the evaporator. This configuration results in a higher refrigerant mass flow through the condenser compared to the evaporator.

The key advantage of this cycle lies in its compression strategy:

1. A portion of the refrigerant mass flow is compressed from the low pressure (evaporator) to high pressure (condenser).
2. The remaining portion is compressed only from the intermediate pressure to high pressure.

This split compression approach reduces overall power consumption while maintaining the same heating capacity, thereby improving system efficiency. The economizer cycle is particularly beneficial in applications requiring significant temperature lifts or in systems where enhanced performance is crucial.

Figure 7 Economizer Cycle



5.2.1.5 Twin/Multi Cycle

The twin/multi-cycle heat pump configuration comprises two or more single-stage heat pump units with their respective heating reservoirs, sources, and sinks connected either in series or parallel. This arrangement offers enhanced flexibility and efficiency in managing substantial temperature differentials.

In a serial connection, the configuration is designed to address high temperature differences between inlet and outlet. Due to the varying operating temperatures across the system, each cycle within the configuration experiences a distinct Coefficient of Performance (COP). As evidenced by [Equation 5](#) the cycle operating with a lower temperature lift achieves a higher COP.

The multi or twin cycle configuration presents significant advantages in operating conditions characterized by larger temperature differentials, whether between the source inlet and outlet or between the sink inlet and outlet. The primary benefit lies in distributing the heating capacity and temperature lift across multiple refrigerant cycles or compressors, rather than relying on a single unit to manage the entire load.

This approach allows for:

1. Optimized performance across varying temperature ranges.
2. Improved overall system efficiency.
3. Enhanced flexibility in meeting diverse heating or cooling demands.
4. Potential for better load matching and capacity control.

By leveraging the strengths of multiple cycles, each operating in its optimal range, the twin/multi-cycle configuration can achieve superior performance in applications where traditional single-stage systems may struggle to maintain efficiency.

Figure 8 Twin/Multi Cycle for High Temperature Lift at Heat Source and Sink

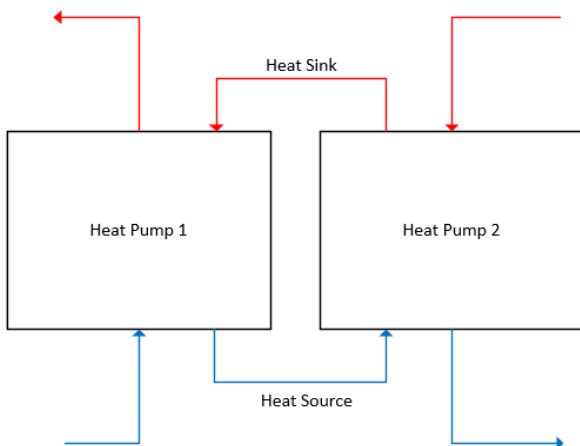


Figure 9 Twin/Multi Cycle for High Temperature Lift at Heat Sink

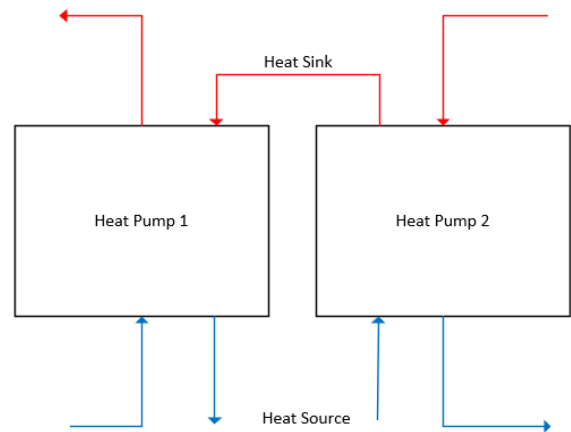
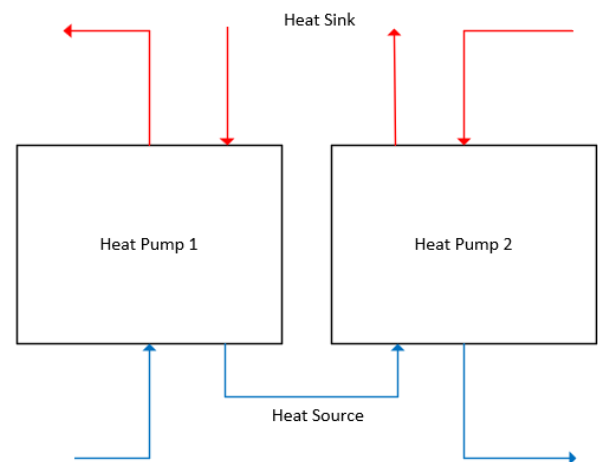


Figure 10 Twin/Multi Cycle for High Temperature Lift at Heat Source



5.2.1.6 Single-stage with Condenser Outlet Split (COS) Ejectors cycle

The incorporation of an ejector represents an innovative approach to enhancing efficiency and minimizing losses in heat pump systems. This configuration modifies the single-stage design by integrating high-pressure ejector and a secondary evaporator. The fundamental principle involves utilizing the expansion of high-pressure refrigerant to compress entrained low-pressure refrigerant.

In operation, the high-pressure refrigerant accelerates through the nozzle. Subsequently, low-pressure refrigerant from the evaporator is injected into the mixing zone, where it entrains into the high-pressure stream. As the combined flow passes through the

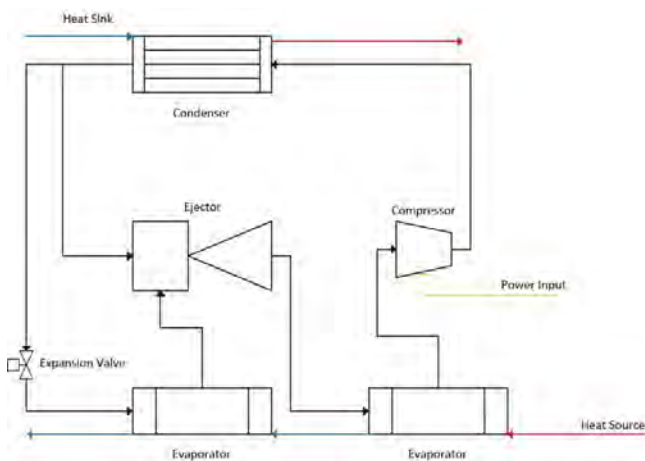
diffuser, a simultaneous reduction in velocity results in the establishment of an intermediate pressure level.

This intermediate pressure reduces the differential that the compressor must overcome between the condenser and evaporator, compared to a conventional single-stage cycle. The benefits of this approach include:

1. Enhanced overall system efficiency.
2. Reduction of thermodynamic losses.

Notably, ejector systems demonstrate versatility in their application. They can be effectively combined with other efficiency-enhancing configurations, such as internal heat exchangers and economizers, to further optimize system performance.

Figure 11 Cycle with Condenser Outlet Split (COS) Ejectors



5.2.2 CASCADE

The cascade heat pump configuration represents a sophisticated approach to managing large temperature differentials and improving system efficiency. This design incorporates two distinct refrigeration cycles (a low-temperature and a high-temperature cycle) interconnected by a specialized heat exchanger known as an evaporator-condenser.

Key features of the cascade system include:

1. Dual Cycle Integration:

- The low-temperature cycle and high-temperature cycle operate independently but are thermally coupled.
- The evaporator-condenser serves as the interface between the two cycles.

2. Heat Exchange Process:

- Within the evaporator-condenser, the refrigerant of the low-temperature cycle undergoes condensation.
- Simultaneously, the refrigerant of the high-temperature cycle evaporates, absorbing heat from the low-temperature cycle.

3. Pressure Management:

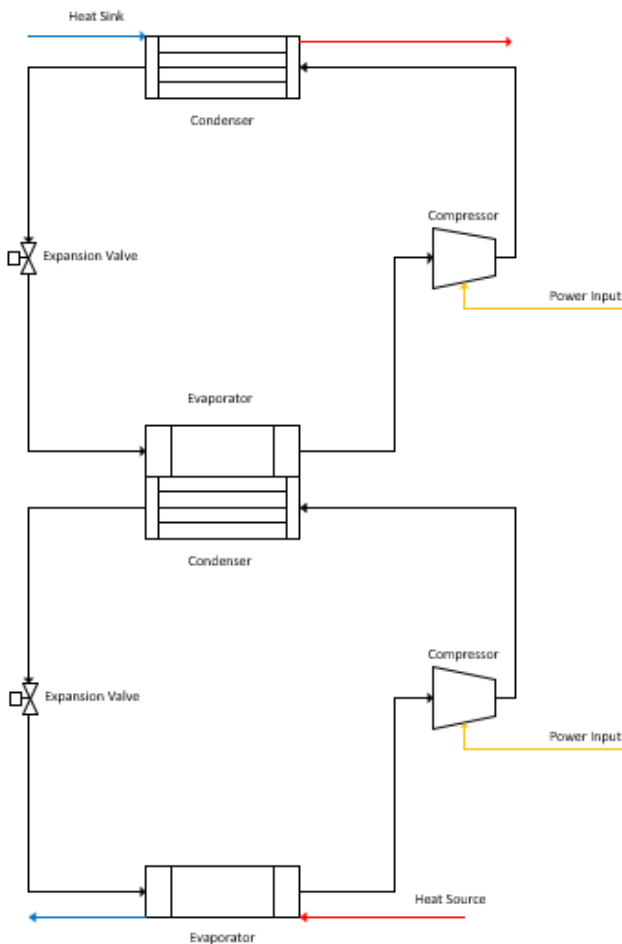
- Each individual refrigeration cycle operates across a lower pressure ratio compared to a single-stage configuration.
- This reduced pressure differential contributes to increased overall system efficiency, particularly in applications requiring high temperature lifts.

4. Efficiency and Output Characteristics:

- The cascade configuration demonstrates enhanced efficiency, especially when managing substantial temperature differences.
- However, as one cycle serves as the heat source for the other, the overall heat output is comparatively lower than that of a twin cycle configuration.

The cascade system offers a balanced approach, optimizing efficiency at the expense of maximum heat output. This trade-off makes it particularly suitable for applications where efficiency is paramount, and the required temperature lift is beyond the practical limits of single-stage systems.

Figure 12 Cascade Cycle



5.2.3 MECHANICAL VAPOUR RECOMPRESSION (MVR)

Mechanical Vapor Recompression (MVR) systems are categorized into two primary configurations, open and semi-open. These systems offer efficient heat recovery and energy optimization in industrial processes.

Open MVR Configuration:

- Vapor from an industrial process is directly compressed to a higher pressure and temperature.
- The compressed vapor is then condensed within the same process, providing heat.
- A typical application is a condenser-reboiler in a distillation column.

Semi-Open MVR Configuration:

- Compressed vapor transfers heat to the process indirectly via a heat exchanger.
- This configuration is commonly used for applications such as steam production.

Key Characteristics of MVR Systems are:

1. Refrigerant:
 - Most frequently designed for R-718 (water) as the working fluid.
 - Other process vapours are also utilized, particularly in the petrochemical industry.
2. Performance:
 - High efficiency due to the elimination of one or two heat exchangers (evaporator and/or condenser).
 - Generally, operates with small temperature lifts.
 - Coefficient of Performance (COP) can exceed ten for certain applications.
3. Compressor Selection:
 - In principle, all common compressor types are suitable for MVR applications.
 - The specific high-temperature application and its operating conditions determine the most appropriate compressor type.

MVR systems represent a versatile and efficient approach to heat recovery and energy optimization in industrial processes. Their ability to operate with high COPs and adapt to various process requirements makes them valuable in enhancing overall energy efficiency in industrial settings.

Figure 13 Open MVR Configuration

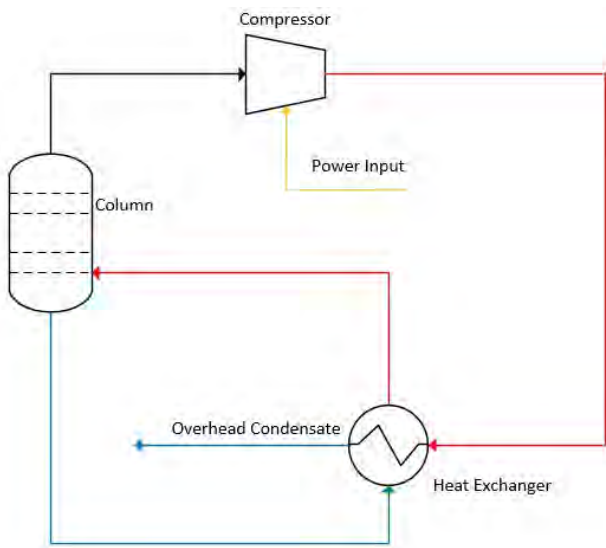
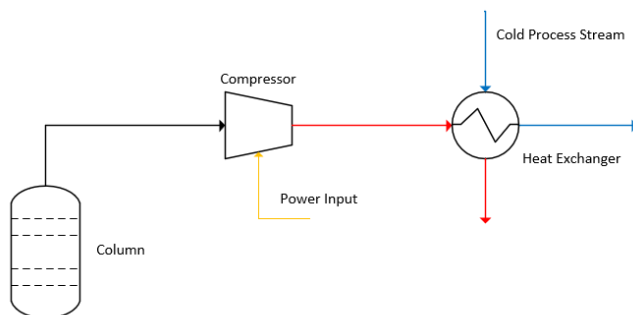


Figure 14 Semi-Open MVR Configuration



5.2.3.1 Steam Compression Systems

Steam compression systems can be implemented in both closed and open configurations, each offering distinct advantages for different applications:

1. Closed Systems:

- These systems operate on a conventional heat pump cycle, utilizing water (R-718) as the working fluid.
- The refrigerant circulates within a sealed loop, transferring heat from a low-temperature source to a high-temperature sink.

2. Open Systems:

- In these configurations, steam is directly utilized and distributed through steam networks.
- They provide heat to various processes, such as steam injection or as a heating utility in industrial applications.
- Open systems often integrate with existing steam infrastructure in industrial settings.

Compressor technologies for steam compression encompass a range of equipment types:

1. Mechanical Vapor Recompression (MVR) technologies.
2. Adapted gas compression equipment.
3. Novel developments based on compression equipment from other heat pump applications.

Each compressor type offers specific advantages in terms of efficiency, capacity, and suitability for different operating conditions. The selection of the appropriate compressor technology depends on factors such as the required pressure ratio, steam flow rate, and temperature levels involved in the process. These are discussed in more detail in Section 5.4.

5.2.4 JOULE/STIRLING

Joule and Stirling cycle heat pumps represent a distinct class of thermodynamic systems, characterized by their unique operational principles. The primary distinguishing feature of these cycles, compared to other configurations, is that the working fluid remains in the gas phase throughout the entire cycle, and heat transfer occurs exclusively through sensible heat exchange. This characteristic sets them apart from vapor compression systems.

These heat pumps can be designed as either single-stage or multi-stage units, offering flexibility to meet various application requirements and efficiency goals. The differentiation between Joule and Stirling cycles lies in their compression and expansion processes. In a Joule cycle, the heat pump utilizes isentropic processes for compression and expansion, often associated with gas turbine-based systems. Conversely, a Stirling cycle employs isothermal processes for compression and expansion, noted for its theoretical high efficiency in certain temperature ranges.

Carbon dioxide (CO₂) is frequently employed as the working fluid in both Joule and Stirling cycle heat pumps. CO₂ is preferred due to its relatively low critical point, enabling efficient operation in transcritical cycles. This choice of refrigerant contributes to the unique capabilities of these systems in specific applications, particularly where high temperatures or the absence of phase change is desirable.

The selection between Joule and Stirling cycles depends on factors such as the required temperature range, efficiency targets, and system complexity considerations.

5.2.4.1 Joule

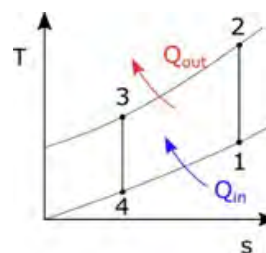
The Joule cycle, also known as the reversed Brayton cycle, is a unique thermodynamic process characterized by the absence of phase change, as the working fluid remains in a gaseous state throughout the entire cycle. This results in heat transfer occurring solely through sensible heat exchange, without the involvement of latent heat. The Joule cycle is particularly well-suited for applications with significant temperature differences

between heat sources and sinks, offering advantages in scenarios where traditional vapor compression cycles may be less effective or impractical. Its flexibility makes it especially valuable in industrial processes or high-temperature heat recovery systems.

In the following, the stages of the ideal Joule cycle are described as depicted in T-S Diagram of The Joule Cycle (Source: AIT).

1. Isentropic compression from state 1 to state 2 (higher temperature and pressure).
2. Isobaric heat transfer to the heat sink from 2 to 3.
3. Isentropic expansion from state 3 to 4.
4. Isobaric heat uptake from the heat source from state 4 to 1.

Figure 15 T-S Diagram of The Joule Cycle (Source: AIT)



5.2.4.2 Stirling

The Stirling cycle, also known as the Philips process, is an advanced gas compression system primarily used in low-temperature refrigeration. It consists of four thermodynamic processes: two isochoric and two isothermal state changes, implemented in a two-chamber machine connected by a highly efficient regenerator. The cycle's key features include adaptability to various external temperatures, load regulation through charge pressure adjustments, and suitability for high temperature lifts. Pioneered by Philips to reach extremely low temperatures (20 K), the Stirling cycle's efficiency is primarily limited by mechanical implementation rather than thermodynamic constraints. This makes it particularly valuable for applications requiring significant temperature differentials and in diverse cooling scenarios.

In the following, the stages of the ideal Stirling process are described as depicted in T-s Diagram of The Stirling Process (Source: AIT).

1. Isothermal compression from 2 to 3 in the first chamber, volume change work is done to the gas at a constant temperature, heat is released to the heat sink.
2. Gas is transferred to the second chamber at a constant volume from 3 to 4, the regenerator is heated, the gas is cooled. For constant volume, the movement of the two pistons is synchronized mechanically.
3. Isothermal expansion from 4–1, volume change work is released, the piston is moved, the gas heated by the heat source to keep the temperature constant.
4. Gas is transferred back to first chamber at constant volume from 1–2, the gas is heated by the regenerator.

Figure 16 T-s Diagram of The Stirling Process
(Source: AIT)

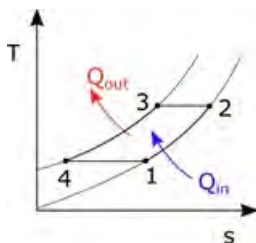
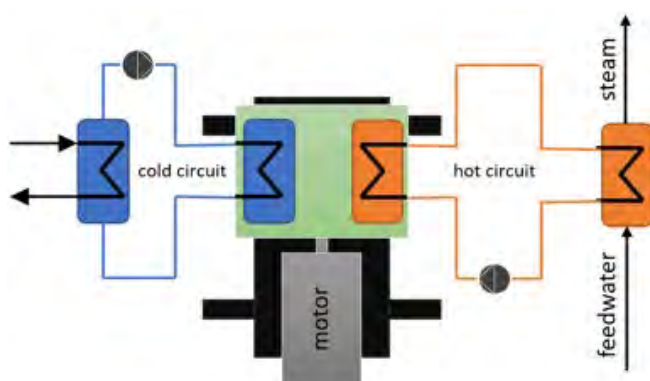


Figure 17 Example Process Schematic of The Stirling Process
(Source: Olvondo)



5.2.5 TRANSCRITICAL

Transcritical heat pump cycles represent a unique approach in thermodynamic systems, operating in a regime that bridges conventional subcritical cycles and purely gaseous Joule/Stirling cycles. The defining characteristic of a transcritical cycle is its operation above the refrigerant's critical point during heat release, while heat absorption occurs in the subcritical range.

Transcritical heat pump cycles are characterized by three key features that distinguish them from conventional systems. First, heat release occurs at a gliding temperature above the refrigerant's critical point, contrasting with the condensation process in subcritical cycles. Second, heat absorption takes place during evaporation in the subcritical range, similar to conventional heat pumps. Third, the refrigerant transitions between supercritical and subcritical states, unlike Joule/Stirling cycles where it remains gaseous throughout. Carbon dioxide (CO_2) is the most commonly used refrigerant in transcritical processes, particularly suited for applications such as hot water generation. CO_2 has a critical pressure of 73.8 bar and a critical temperature of 31°C. In a typical CO_2 transcritical cycle, heat absorption in the evaporator occurs below 71 bar, while heat release in the gas cooler takes place above 71 bar, over a temperature range. The unique behaviour of transcritical CO_2 systems allows them to efficiently manage high temperature lifts, making them particularly effective in certain heating applications, especially when coupled with low-temperature heat sources. This characteristic renders the transcritical cycle advantageous in scenarios requiring significant temperature differentials. However, the implementation of these systems comes with challenges, notably high operating pressures, and specific temperature requirements.

Efficiency Considerations:

- Coefficient of Performance (COP) calculation requires using the log mean temperature in the gas cooler temperature range, as there is no fixed condensation temperature.

Advantages:

- High temperature lift capability in the gas cooler (30–40°C).
- Efficient with low-temperature water heating applications.
- Potential for higher efficiency compared to conventional cycles in specific conditions.

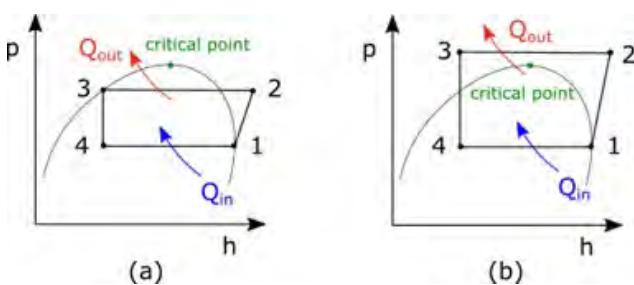
Disadvantages:

- Efficiency is highly dependent on the heat sink inlet temperature.
- Requires high operating pressures, often exceeding 100 bar.

In the following, the stages of the ideal transcritical cycle are described as depicted in P-H Diagram of (a) Subcritical and (b) Transcritical Heat Pump Cycle (Source: AIT)

1. The isentropic compression from state 1 to state 2 (higher temperature and pressure).
2. Isobaric heat transfer to the heat sink from 2 to 3.
3. Isenthalpic expansion from state 3 to 4.
4. Isobaric heat uptake from the heat source from state 4 to 1.

Figure 18 P-H Diagram of (a) Subcritical and (b) Transcritical Heat Pump Cycle (Source: AIT)

**5.2.6 SORPTION HEAT PUMP**

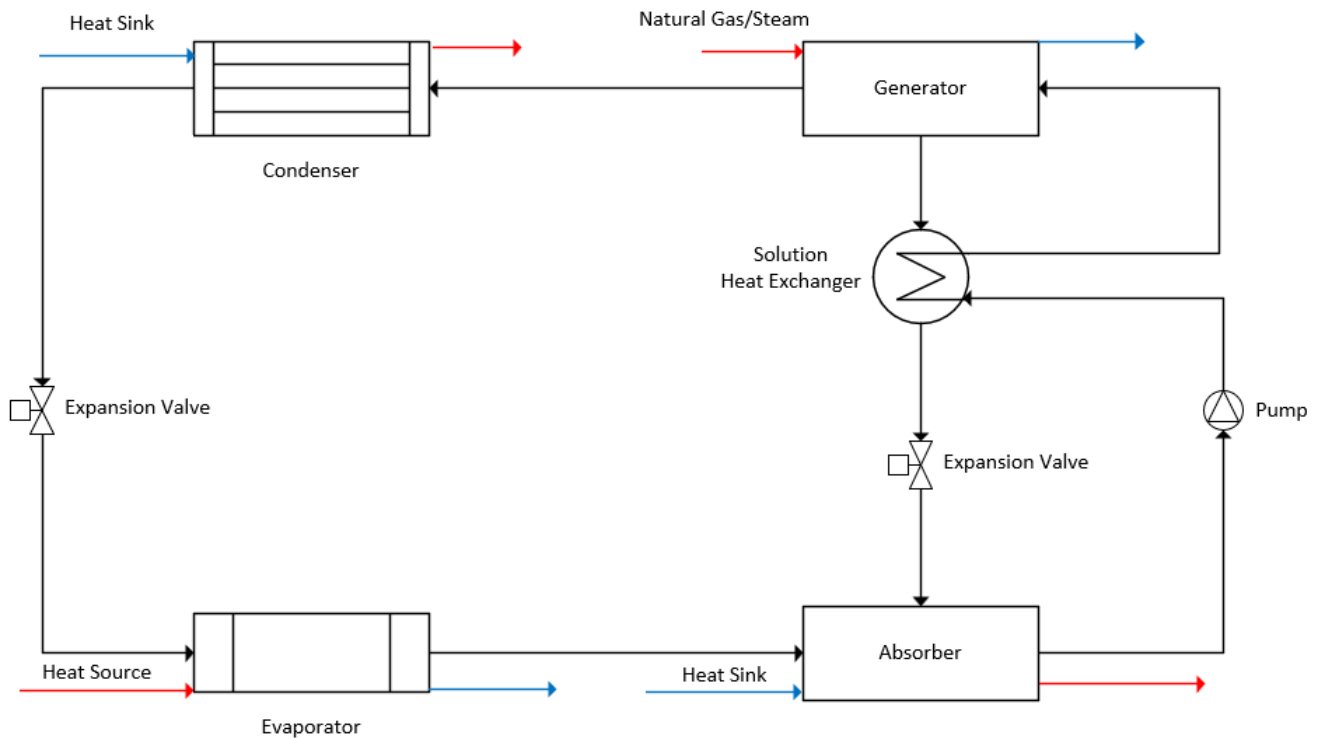
Thermally driven heat pumps (TDHPs), including absorption and adsorption systems, represent an alternative approach to heat transfer that distinguishes itself from conventional vapor compression heat pumps (VCHPs). While VCHPs primarily rely on mechanical power, typically from an electric drive, to operate their compressors, TDHPs are mainly powered by thermal energy, such as steam or natural gas combustion. This fundamental difference in energy source gives TDHPs unique advantages, particularly in scenarios where both heating and cooling capabilities are required.

5.2.6.1 Absorption Heat Pump

Absorption heat pumps, a type of TDHP, operate on the principle of absorption and evaporation of a refrigerant. This process involves two key components: the refrigerant, which undergoes phase changes to facilitate heat transfer, and the absorption medium, which absorbs and releases the refrigerant. The interplay between these components forms the core of the absorption heat pump's functionality, enabling efficient heat transfer across a variety of applications. Absorption machines can be further classified into two categories based on their primary function: absorption heat pumps for heat amplification and absorption heat transformers for temperature upgrading.

In absorption heat pumps, two common working pairs are used: Lithium Bromide (LiBr) and water, and ammonia and water. In the first pair, water serves as the refrigerant, while Lithium Bromide acts as the absorption medium. In the second pair, ammonia is the refrigerant, with water functioning as the absorption medium. These combinations leverage the unique properties of each substance to facilitate efficient heat transfer in the system.

These working pairs are selected based on their thermodynamic properties and compatibility, enabling efficient heat absorption and rejection cycles in the system. The choice between these pairs often depends on the specific temperature requirements and operational conditions of the application.

Figure 19 Thermodynamic Cycle of a Single-Effect Absorption Heat Pump

The figure above shows the principle of operation of an absorption heat pump. It is based on a heat pump that uses the pair Ammonia and water ($\text{NH}_3/\text{H}_2\text{O}$). The absorption heat pump consists of two loops. The loop on the right represents the absorption medium and the circulation loop at the left represents the refrigerant.

Furthermore, the standard configuration of an absorption heat pump is the single-effect cycle illustrated in [Thermodynamic Cycle of a Single-Effect Absorption Heat Pump](#). This cycle operates on two pressure levels: the generator and condenser function at high pressure, while the evaporator and absorber operate at a lower pressure.

Absorption Medium Cycle

In the generator of the heat pump, thermal energy is introduced, causing the refrigerant to evaporate from the absorption medium at high pressure. The absorption medium then undergoes a pressure reduction via an expansion device before flowing to the absorber. Inside the absorber, the gaseous ammonia (NH_3) is absorbed by the water, which serves as the absorption medium. This absorption process

releases useful heat at an intermediate temperature. The pressure of the resulting mixture is subsequently increased using a pump, allowing it to flow back to the generator. To enhance efficiency, a solution heat exchanger is employed to preheat the cold mixture with the hot mixture.

Refrigerant Cycle

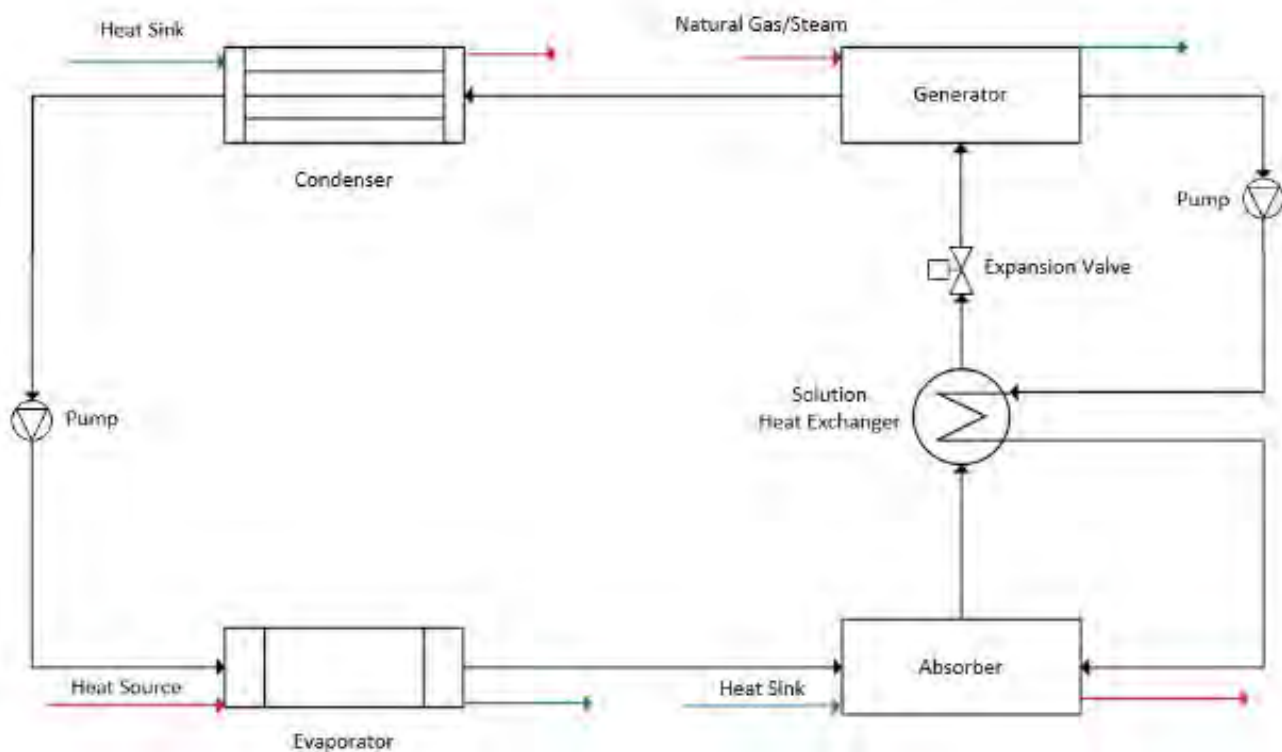
In the generator of the heat pump, thermal energy is introduced, causing the refrigerant to evaporate from the absorption medium at high pressure. The resulting gas then flows to the condenser, where ammonia (NH_3) is condensed subsequently releasing heat to its surroundings. This liquid ammonia then undergoes a pressure reduction through an expansion device before moving to the evaporator. At low temperatures, heat is added to the ammonia, causing it to evaporate. While waste heat can serve as the heat source, the evaporator can also be utilized for cooling purposes. The gaseous ammonia then travels to the absorber, where it is absorbed by water, releasing useful heat in the process.

5.2.6.2 Absorption Heat Transformer

This cycle operates on two pressure levels. However, in contrast to the absorption heat pump in the absorption heat transformer the generator and condenser function at low pressure, while the evaporator and absorber operate at a higher pressure.

Absorption Heat Transformers have the ability to upgrade low to medium temperature waste heat to higher temperature levels, utilizing heat that would otherwise be lost. Furthermore, they operate with minimal electrical power consumption relying primarily on thermal energy, thereby reducing operational costs, and contributing to lower overall energy usage.

Figure 20 Thermodynamic Cycle of a Single-Effect Absorption Heat Transformer



5.2.6.3 Adsorption Heat Pump

Adsorption heat pumps are similar to absorption heat pumps, with the primary difference being the method of sorption used. While absorption heat pumps utilize liquid-sorption, adsorption heat pumps employ solid-sorption. In an adsorption heat pump, the refrigerant vapor is adsorbed onto a solid adsorbent material, such as silica gel or activated carbon, during the low-pressure phase. When heat is applied, the refrigerant is desorbed from the solid adsorbent, allowing it to evaporate and subsequently condense to release heat. This solid-sorption process can provide advantages in terms of system simplicity and reduced environmental impact, as it often requires fewer complex components and can utilize a wider range of refrigerants.

Both absorption and adsorption heat pumps may still require some electrical power, for instance to operate pumps, but the amount is considerably less than that needed by VCHPs. This characteristic, combined with their ability to utilize thermal energy sources, makes thermally driven heat pumps, particularly absorption and adsorption systems, attractive options for applications where excess utilities are available or where simultaneous heating and cooling is needed.

5.2.7 HYBRID HEAT PUMP

Hybrid heat pumps, also known as compression-resorption heat pumps, represent an innovative approach that combines the technologies of absorption and compression heat pumps. These systems utilize a mixture of media, typically ammonia (NH_3) and water, to achieve enhanced performance characteristics.

The key feature of hybrid heat pumps is the non-constant temperature at which heat is extracted and emitted, resulting from changes in the working fluid composition during absorption and desorption processes. This temperature glide can lead to increased system efficiency.

One significant advantage of hybrid heat pumps is their ability to achieve large temperature lifts while maintaining a high Coefficient of Performance (COP). This is due to the favourable temperature glide during absorption and desorption, which allows for a decreased compression ratio compared to conventional mechanical heat pumps. Consequently, an equivalent temperature lift can be realized with a lower compression ratio, potentially resulting in a higher COP.

Another benefit is the higher achievable condensation temperature compared to conventional systems. This is attributed to the lower saturation pressure of the mixture, which is significantly reduced compared to pure gaseous refrigerants.

5.3 Refrigerants

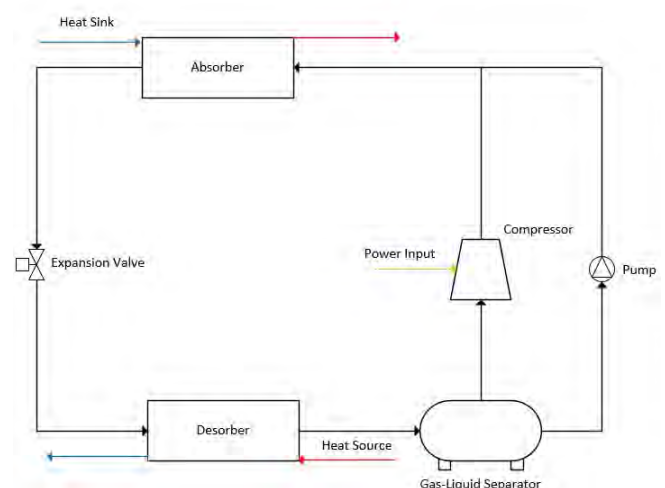
The selection of a working fluid for heat pumps is primarily determined by the system's operational temperature requirements. Optimal efficiency is achieved when the fluid's thermodynamic properties align closely with the process demands. For subcritical cycles, the critical temperature of the fluid sets the upper application limit, with efficient operation typically ensured by maintaining a condensation temperature about 15 K below this critical point. Temperature Application Ranges for Different

To optimize the temperature glide range, the size of the absorber and desorber can be increased, although this may result in higher capital expenditure (CAPEX).

Despite these advantages, hybrid heat pumps face challenges:

- 1. Technical complexity:** The integration of absorption and compression technologies results in a more intricate system.
- 2. Cost:** The complexity and specialized components contribute to higher overall costs.
- 3. Limited manufacturers:** Due to the specialized nature of these systems, there are fewer manufacturers in the market.

Figure 21 Hybrid Heat Pump Configuration



Working Fluids in HTHP Applications (Source: OST-IES) visually represents the temperature application ranges for various working fluids, serving as a guide for appropriate fluid selection based on the specific temperature needs of the heat pump application. This approach emphasizes the importance of matching fluid characteristics to the desired temperature range and lift for maximizing system performance.

Refrigerants are classified using a standardized system of tags and numerical codes:

- **R–Designates a refrigerant.**
- **R000-R399:** Chemical refrigerants with composition determined by their code number.
- **R400-series:** Zeotropic mixtures with an evaporation and condensation range.
- **R500-series:** Azeotropic mixtures with a fixed evaporation and condensation point.
- **R600-series:** Other organic refrigerants.
- **R700-series:** Inorganic refrigerants.

A variety of refrigerants exists and are available, some common refrigerants for Heat Pump applications are discussed in more detail below.

5.3.1 WATER (R718)

Water (R718) as a refrigerant in heat pump systems offers unique characteristics and challenges:

1. **Environmental benefits:** Water is entirely benign to the environment, making it an attractive option from a sustainability perspective.
2. **High-temperature applications:** Water is particularly suitable for applications requiring temperatures above 100°C, leveraging its high normal boiling point and large latent heat.
3. **Subcritical cycle considerations:** When used in subcritical cycles, a significant portion of the heat pump cycle may operate below atmospheric pressure due to water's 100°C boiling point at standard conditions.
4. **Compressor requirements:** The low density of water vapor necessitates large compressors or high-speed oil-free turbo compressors with high flow rates and low-pressure ratios. This is to compensate for the low vapor density and achieve the required heat transfer.

5. **Multi-stage compression:** Due to the high required swept volume and pressure ratio, several compression stages are often necessary. These stages typically include intermediate cooling (e.g., water injection) to maintain tolerable discharge temperatures.
6. **Mechanical Vapor Recompression (MVR) systems:** These are commonly employed for water-based heat pumps, utilizing large compressors to handle the high volumetric flow rates required.

While water as a refrigerant presents challenges in terms of system design and compressor specifications, its environmental friendliness and suitability for high-temperature applications make it a compelling option for certain heat pump scenarios, particularly where sustainability and high-temperature operation are prioritized.

5.3.2 CARBON DIOXIDE (R744)

Carbon dioxide (CO₂), designated as R744, is a natural refrigerant with unique properties that make it particularly suitable for certain heat pump applications:

1. **Critical point:** CO₂ has a relatively low critical temperature of 31°C and a high critical pressure of 73.6 bar. This characteristic allows for efficient operation in transcritical cycles.
2. **Temperature range:** CO₂ heat pumps can achieve heat sink temperatures of approximately 90 to 120°C in transcritical cycles, making them suitable for various high-temperature applications.
3. **Transcritical operation:** Above its critical temperature of 31°C, CO₂ exhibits a temperature glide instead of constant-temperature condensation. This feature allows for efficient heat transfer over a range of temperatures in the gas cooler.
4. **Suitability for specific applications:** The high temperature difference achievable in the gas cooler makes CO₂ particularly well-suited for hot water or air heating processes.

5. **Efficiency considerations:** R744 is most feasible as a high-temperature heat pump (HTHP) working fluid when the return temperature of the heat sink is low and not significantly above the critical temperature.
6. **Environmental benefits:** As a natural refrigerant, CO₂ has minimal environmental impact compared to synthetic refrigerants.
7. **Versatility:** CO₂ is often used in combination with other natural refrigerants like ammonia in cascade systems, leveraging the strengths of both fluids.

These characteristics make CO₂ an attractive option for heat pump systems, especially in applications where its unique thermodynamic properties can be effectively utilized to achieve high efficiency and performance in high-temperature heating scenarios.

5.3.3 AMMONIA (R717)

Ammonia (R717) is a widely used refrigerant in industrial refrigeration and heat pump applications, offering several advantages:

1. **Temperature range:** Commonly used in systems up to about 90°C heat sink temperature, with special compressor designs allowing operation up to 110°C and 76 bar pressure.
2. **Volumetric heating capacity:** Ammonia has a high volumetric heating capacity compared to other working fluids, due to its low molecular weight and high vaporization latent heat.
3. **Efficiency:** Its thermodynamic properties make it highly efficient in heat pump applications.
4. **Environmental impact:** As a natural refrigerant, ammonia has zero global warming potential (GWP) and zero ozone depletion potential (ODP).

5. **Applications:**
 - Primarily used in industrial refrigeration systems.
 - Applicable in heat pumps for temperatures above 80°C.
 - Suitable for large-scale systems.
6. **Regulations:** Ammonia systems are regulated under specific guidelines, such as the Dutch regulation NPR-7600, due to its toxicity and safety considerations.
7. **Safety considerations:** Classified as a B2L refrigerant (lower flammability, higher toxicity), requiring certain safety precautions in system design and operation.
8. **Compressor technology:** For higher temperature applications, special cast steel construction is needed to withstand the high discharge pressures.

While ammonia presents some challenges in terms of toxicity and safety requirements, its excellent thermodynamic properties and environmental benefits make it a preferred choice for many large-scale industrial refrigeration and heat pump applications, especially where high efficiency and environmental sustainability are prioritized. Facilities normally containing inventories of higher hazard materials, such as downstream assets, are expected to be capable of incorporating ammonia into their safety management processes, whereas facilities such as offshore production are expected to be limited to hydrocarbon or lower hazard refrigerant systems.

5.3.4 BUTANE (R600) AND PENTANE (R601)

Hydrocarbons n-butane (R600) and n-pentane (R601) are natural refrigerants with favourable environmental characteristics and thermodynamic properties suitable for high-temperature heat pump (HTHP) applications:

1. Environmental impact:

- Zero Ozone Depletion Potential (ODP).
- Very low Global Warming Potential (GWP).

2. Thermodynamic properties:

- R600 (n-butane) critical temperature: 152°C at 38.0 bar.
- R601 (pentane) critical temperature: 196.6°C at 33.7 bar.

3. Temperature range:

- R600 is suitable for HTHPs with condensation temperatures up to about 120°C.
- Applicable in heat pumps for temperatures above 80°C.

4. Compressor compatibility:

- Standard compressors can achieve the required temperatures for R600.

5. Safety considerations:

- Classified as A3 (highly flammable)
- Requires special safety measures due to high flammability.
- Regulated under standards such as NPR-7600 and EN 378-1:2016.

6. Applications:

- Primarily used in refrigeration.
- Suitable for commercial and industrial heat pump applications.

The use of hydrocarbons like R600 in heat pump systems offers a balance of environmental benefits and high-temperature performance. However, their implementation requires careful consideration of safety measures and adherence to relevant regulations due to their flammability.

5.3.5 HYDROFLUOROOLEFINS (HFO)

Hydrofluoroolefins (HFO's) are emerging as more environmentally friendly alternatives to hydrofluorocarbons (HFCs) in heat pump applications, offering low global warming potential (GWP) and zero ozone depletion potential (ODP). Key HFOs include:

1. **R-1234yf and R-1234ze(E):** Potential replacements for R-134a, classified as mildly flammable (A2L) with low toxicity.
2. **R-1336mzz(Z):** Suitable for high-temperature heat pumps (HTHPs), with a high critical temperature (171.3°C), low GWP of 2, and safety class A1. It is effective for temperatures up to 160°C in waste heat recovery and steam generation.
3. **R-1336mzz(E):** Has a low GWP of 18 and critical temperature of 130.4°C, suitable for various heat recovery applications.
4. **R-1234ze(Z):** Promising for HTHP applications, with a critical temperature of 150.1°C and GWP less than 1.

While these refrigerants offer significant environmental benefits, concerns exist about the production of trifluoroacetic acid (TFA) from their atmospheric decomposition, particularly for R-1234yf. Current research suggests TFA levels from HFO degradation do not pose significant environmental risks, but further study is needed.

These HFOs provide a balance of environmental friendliness and high-temperature performance, making them attractive options for advanced heat pump systems, especially in industrial and waste heat recovery applications.

5.3.6 HYDROCHLOROFUOROOLEFINS (HCFO)

Hydrochlorofluoroolefins (HCFO's) R-1233zd(E) and R-1224yd(Z) are promising refrigerants for high-temperature applications, particularly in centrifugal chillers and heat pumps for waste heat recovery. Key features include:

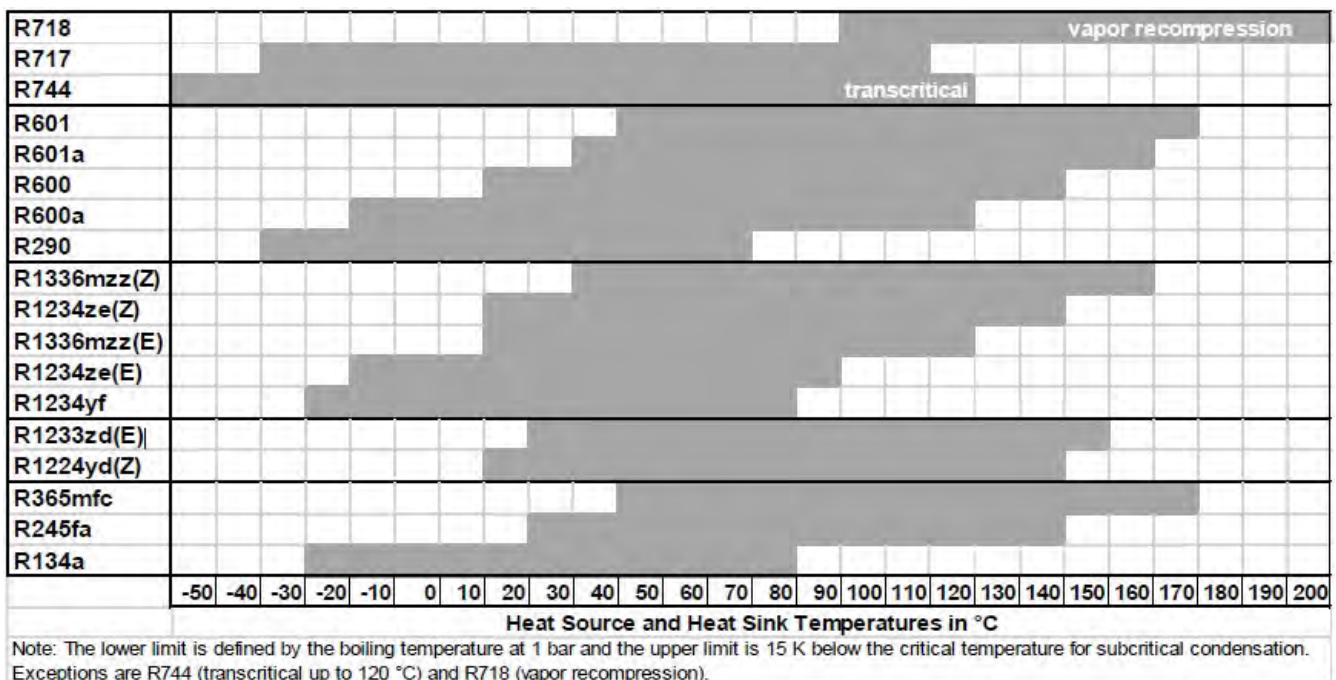
1. High critical temperatures (165.5°C for R-1233zd(E)).
2. Low Global Warming Potential (GWP less than 1 for R-1224yd(Z)).
3. Extremely low Ozone Depletion Potential (ODP) despite containing chlorine.
4. Short atmospheric lifetimes (21–40 days).
5. Safety classifications of A1 (low toxicity, non-flammable).

6. Compatibility with common materials and synthetic oils.

R-1233zd(E) has the added advantage of low trifluoroacetic acid (TFA) formation. These refrigerants offer a good balance of performance, safety, and environmental considerations for high-temperature heat pump applications.

In summary, a diverse range of refrigerants offers various options for heat pump applications, each with specific advantages and considerations regarding efficiency, environmental impact, and operational characteristics. Application of specific working fluids is optimised by technology vendors and for specific process designs. General temperature ranges of application have been summarised by the OST's Institute for Energy Systems in [Temperature Application Ranges for Different Working Fluids in HTHP Applications](#) (Source: OST-IES).

Figure 22 Temperature Application Ranges for Different Working Fluids in HTHP Applications
(Source: OST-IES)



5.4 Compressors

Compressors are the core component of compression heat pumps, responsible for elevating the gaseous refrigerant from a lower to a higher-pressure level, significantly impacting the system's efficiency. Various compressor types are employed in high-temperature heat pumps (HTHPs), each with distinct characteristics:

5.4.1 PISTON (RECIPROCATING) COMPRESSORS

Piston compressors operate through the suction and compression of gas via piston movement. They offer a simple design and a wide application range; however, they may produce pulsating volume flows and carry the risk of liquid hammer.

5.4.2 SCREW COMPRESSORS

Screw compressors utilize counter-rotating screw-shaped rotors for compression. They provide a compact design and high operational speeds, but they require oil injection for sealing and may experience oil degradation at high temperatures.

5.4.3 SCROLL COMPRESSORS

Scroll compressors compress gas through interacting spiral elements. They are known for their low vibration and quiet operation, as well as their resistance to liquid hammer; however, they have a limited capacity range.

5.4.4 TURBO COMPRESSORS (INCLUDING CENTRIFUGAL)

Turbo compressors, including centrifugal types, operate by transferring energy via rotating impellers and increasing pressure through diffusers. They are compact, capable of high flow rates, and offer good speed control with low wear. However, they have low pressure ratios per stage and are notably used in water vapor recompression systems, often as oil-free high-speed variants.

5.4.5 ROTATIONAL HEAT PUMPS

Rotational heat pumps utilize centrifugal potential based on the Joule process. Their design features heat exchangers mounted on a rotor with integrated piping and a fan for gas circulation, offering a unique approach that differs from conventional compression methods.

Most of these compressor types are typically driven by electric motors. The choice of compressor depends on the specific application requirements, including capacity, efficiency, and operational conditions of the HTHP system.

5.5 Technology Summary

Table 6 provides a summary of the technologies explored with current single train capacity, sink temperature (output), efficiency (defined as COP) and maturity (defined as Technology Readiness Level).

Technology Readiness Level (TRL) is defined in [Definition of TRL](#) per the European Union definition, global definitions are similar.

Table 5 Definition of TRL

Technology Readiness Level (TRL)	European Union Definition
1	Basic principles observed
2	Technology concept formulated
3	Experimental proof of concept
4	Technology validated in lab
5	Technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
6	Technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
7	System prototype demonstration in operational environment
8	System complete and qualified
9	Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

Table 6 Summary of Available Industrial Heat Pumps and Key Characteristics

Type	Compressor	Capacity (MWth)	Temperature Output (°C)	TRL	COP	Vendors	Refrigerants
Cascade	Centrifugal, Piston, Reciprocating, Screw, Turbo	0.03–10	115–200	4–9	1.74–13	8	R1233zd(E), R1336mzz(Z), R245fa, R290, R410a, R600, R717, R718, Others (HC, HFO)
Chemical Adsorption Heat Transformer	No compressor	>2	230	9	0.15–0.45	2	R717, R718, H3PO4 and derivatives
Joule Cycle	Centrifugal	0.7	150	6–7	4–7	1	Proprietary fluid
MVR–Open	Turbo	1–70	212 (40–230)	8–9	3.5–7.3	1	R718
MVR–Open or Semi-Open	Twin-screw, rotary vane, high-pressure centrifugal fan, positive displacement blower	0.5–30	150–188	6–9	3.1–5.3	3	R718
Single-Stage–Condenser Outlet Split (COS) Ejectors Cycle	Screw	0.3–3.3	120	9	2.2–5.3	1	R1233zd(E), R1234yf, R1234ze, R450A, R513A, R515B
Single-Stage–Economizer cycle	Twin-screw	0.624	175	9	2.5	1	R134a + R245fa mix, R718
Steam Compression–Closed	Piston	1–15	280	9	3.5–10.3	1	R718
Steam Compression–Open	Centrifugal, Reciprocating	0.03–10	120–160	4–9	2.5–5	2	R1224yd(Z), R1233zd(E), R1336mzz(Z), R245fa
Stirling Cycle	Piston	0.3–10	200–250	6–9	1.6–3.7	2	R704
Transcritical Cycle	Centrifugal, Piston, Turbo	0.1–50	100–150	7–9	2–5.5	4	R134a, R744
Twin or Multi-Cycle	Piston, Turbo, Twin-screw	0.3–30	120–200	6–9	2.9–3.6	3	R245fa, HFOs, Others (e.g. HC, siloxans)
Others	Centrifugal, Piston, Reciprocating, Screw, Turbo	0.03–70	120–280	4–9	2.5–10.3	5	R1233zd(E), R1234ze(E), R1234ze(Z), R290, R600, R600a, R601, R744

Industrial refrigeration-type package units appear to dominate at lower duties (well below 10 MW). Bespoke process designs utilizing process industry compressors are required at higher duties (above 7 MW). Though industrial examples and TRL are more established for lower duties, the rotating equipment technology is well proven for the higher duty range, hence the single train/duty boundaries are less critical.

From the available heat pump applications, it can be observed that the supply (sink) temperature of the heat pump system appears to be critical in guiding the type of technology chosen. Sink temperatures of up to ca. 135°C are expected to be achievable from ambient or other low-grade sources, generally requiring a closed loop refrigerant cycle to enable extraction of heat at low temperature.

Applications for up to 230°C can be obtained with an MVR system provided with a heat source of sufficiently high temperature such as column overheads. The TRL for MVR is high for low-lift applications where very high COPs can be achieved. However, this type of heat pump is generally not applied where the source temperature is low or lift is high.

Up to 250°C sink temperatures can be achieved with a Stirling Cycle. Stirling cycle applications have also been found to be restricted to small heating duties per train, requiring many trains for viable industrial applications.

For raising utilities from heat pump systems, applications to ca. 135°C hot water or saturated steam are currently feasible in closed-loop heat pumps. Applications up to 280°C require post-compression.

It is also worth noting that the refrigerant choice is also highly dependent on heat pump outlet temperature, with little vendor experience above 150°C.



106 Heat Pump Applications

6 Heat Pump Applications

Typical applications of heat pumps in the oil and gas value chain have been categorised into three industry areas:

- Upstream including onshore and offshore production, often remote and modular. The boundary of upstream processing is assumed to include basic gas and oil separation and compression.
- Midstream assets such as gas processing, natural gas liquids processing and terminals. These assets include gas and liquid fractionation and gas treatment such as removal of sulphur compounds.

- Downstream, comprising oil refining, olefins production and basic petrochemicals units.

For all representative assets, it is assumed that the base case for application of heat pumps has already explored best practice heat integration as this is expected to provide better incremental economics than heat pump implementation.

The advantage of heat pump application is provided by utilisation of waste heat. Therefore, sources and sinks are attempted to be matched to enable lift to be minimised and, where possible, condensing duty in the source stream to be utilised.

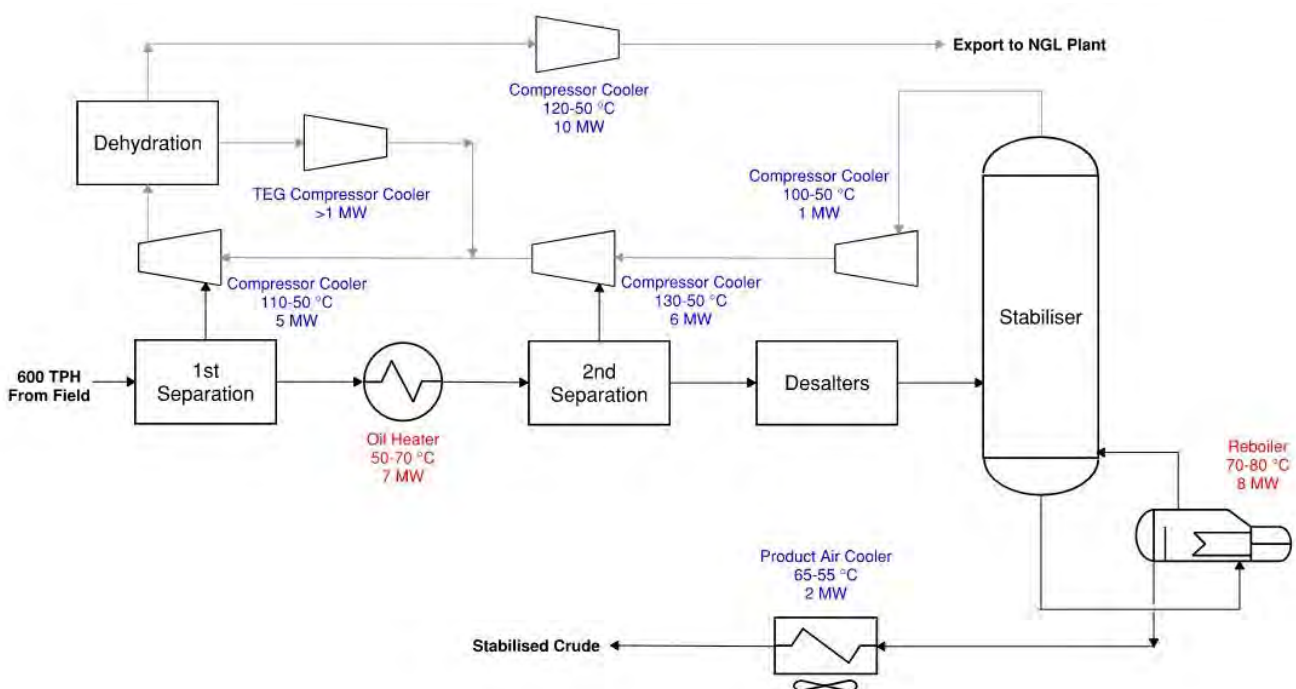
6.1 Upstream

6.1.1 REVIEW OF ASSETS

Upstream applications can cover a wide range of types of assets such as remote unconventional oil wells feeding into a collection and processing system, simple offshore production with minimal processing, or onshore centralised gas/oil separation plants from a local field.

The representative asset shown in Figure 23 covers typical heat requirements and waste heat either for one integrated processing plant, or potentially split between offshore or distributed assets before being routed to centralised processing and export.

Figure 23 Upstream Processing Schematic



The first major heat requirement is an oil heater to carry out simple separation in separation drums and to provide sufficient temperature for efficient desalting. The duty requirements are dependent on feed temperature and any pipeline logistics required from the field.

The second major heat requirement is the reboiler on the stabiliser column which is relatively low temperature compared with downstream processing.

Depending on utilities configuration, the reboiler and oil heater could be connected to a thermal fluid/hot oil circuit, or heated by steam. Both designs would typically use a fired heater to provide heat to the hot oil or raise steam.

Waste heat sources were found to be mostly related to compression of gases, with significant duties lost to air and/or water prior to export. It is noted that a heavier crude would shift the balance of heat available from compressor cooling towards required oil heating.

Onshore oil heating via a heat pump could draw heat from ambient air, cooling water or from the compressor coolers. Offshore assets would be expected to only comprise of basic oil heating, if any is required for flow assurance. Heat sources for a heat pump in this case would be limited to seawater or compressor coolers.

Heater/treaters such as those common in the US may have no compression so heat sources would need to be environmental.

Many upstream assets both onshore and offshore currently utilise gas turbines to provide power generation and heat. For the purposes of this study, brownfield applications of heat pumps assume that the gas turbines are decommissioned as part of decarbonisation via electrification of shaftwork, hence this high-temperature waste heat is not available.

6.1.2 OPPORTUNITIES IDENTIFIED

6.1.2.1 Opportunity U1: Offshore Oil Heating

Industry Area: Upstream Offshore

Description: Heating is often required to increase the produced oil temperature from ambient to crude separation temperature or as required for flow assurance. The existing heat source (e.g. gas turbine exhaust) is assumed to be decommissioned.

Sink(s): Heating of product oil by 7 MW (typical)

Sink Temperature Range: <100°C

Source(s): Potential to extract heat from seawater. Cooling water outfall or compression coolers could be utilised on more complex assets.

Source Temperature Range: 0–20°C for typical seawater

Technical Feasibility: Heat pump application from seawater to municipal heating has been applied. However, the temperature lift may be slightly greater in this application and space and weight are concerns in an offshore environment. Where seawater cooling is present for compressors or other equipment, the return stream could be utilised to boost efficiency. For platform modification a weight review would be required, though electrification and removal of a gas turbine generator could remove 250 te of additional equipment.

Breadth of Applicability: This could be applied in the majority of offshore production assets where oil product heating is required, and the existing heat source is able to be replaced via electrification.

Operational Difficulty: Offshore remote location and associated high maintenance cost. The heat pump working fluid could be limited to hydrocarbon or CO₂ to avoid adding hazardous inventory to an offshore operation.

6.1.2.2 Opportunity U2: GOSP Crude Stabilizer Reboiler

Industry Area: Upstream Onshore

Description: Requirement to replace steam or hot oil in a relatively low temperature reboiler heater. The column does not have an overhead condenser, hence waste heat sources would need to be from elsewhere in the asset.

Sink(s): Reboiler requiring 10 MW (typical)

Sink Temperature Range: 70–80°C

Source(s): Potential to extract heat from compression coolers and product coolers

Source Temperature Range: 50–130°C

Technical Feasibility: Heat pump technology is feasible at this temperature and scale, either using a closed circuit or intermediate steam generation. Extraction of heat indirectly from cooling water outflows may be simpler than replacing compressor discharge exchangers, but will provide a lower COP.

Breadth of Applicability: Broad applicability to more complex gas/oil and crude separation facilities

Operational Difficulty: Control complexity is increased. A spare/startup reboiler or steam supply may be required

6.1.2.3 Opportunity U3: Remote Unconventional Field

Industry Area: Upstream Onshore

Description: Duty required for separation heaters and stabilisers. Applications are anticipated to be for high API (light) oil. Current designs use gas combustion heaters or glycol/steam circuits. Ambient temperature and therefore duty can be seasonal.

Sink(s): Heating from ambient to <100°C depending on flow/separation requirements. 5–40 MW

Sink Temperature Range: <100°C

Source(s): Environmental heat

Source Temperature Range: Ambient temperature

Technical Feasibility: Power supply is an issue for many remote producers. If power supply can be obtained, heat pump capabilities over this range of temperatures are feasible.

Breadth of Applicability: Many distributed fields in the US and elsewhere could be retrofitted.

Operational Difficulty: Operation would require training or specialist maintenance support. Remote monitoring would assist in skills requirements. Mobile skids could be designed which could be re-used.

6.1.2.4 Opportunity U4: Heavy Oil Hot Water Flood

Industry Area: Upstream Onshore

Description: Hot water flooding is used for heavy oil recovery. Current technology would be hydrocarbon combustion to steam or hot water generation.

Sink(s): Water for injection 5–40 MW

Sink Temperature Range: From ambient to < 100°C

Source(s): Environmental (air or ground) heat

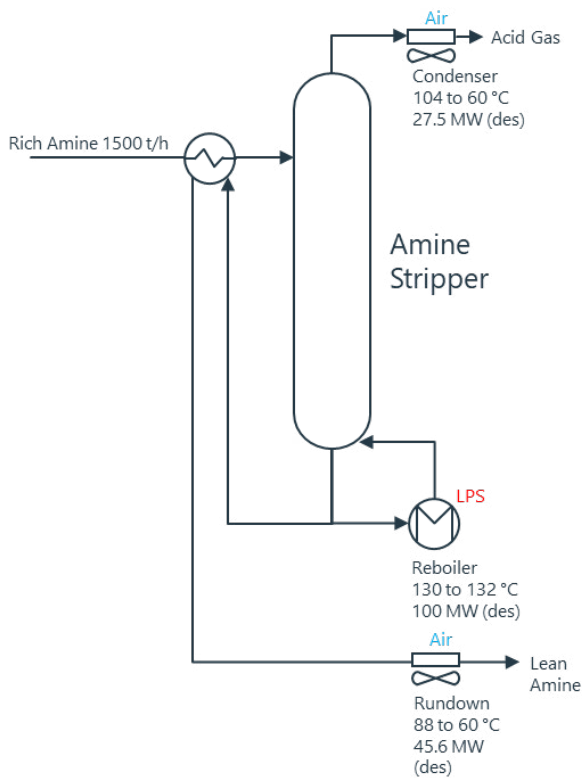
Source Temperature Range: Ambient Temperature

Technical Feasibility: Heat pump capability is expected to be sufficient for this application. Some applications may be remote with power supply issues.

Breadth of Applicability: Broad application to heavy oil producers. May be more applicable to hot water rather than steam flood as this can be over a longer period and centralised.

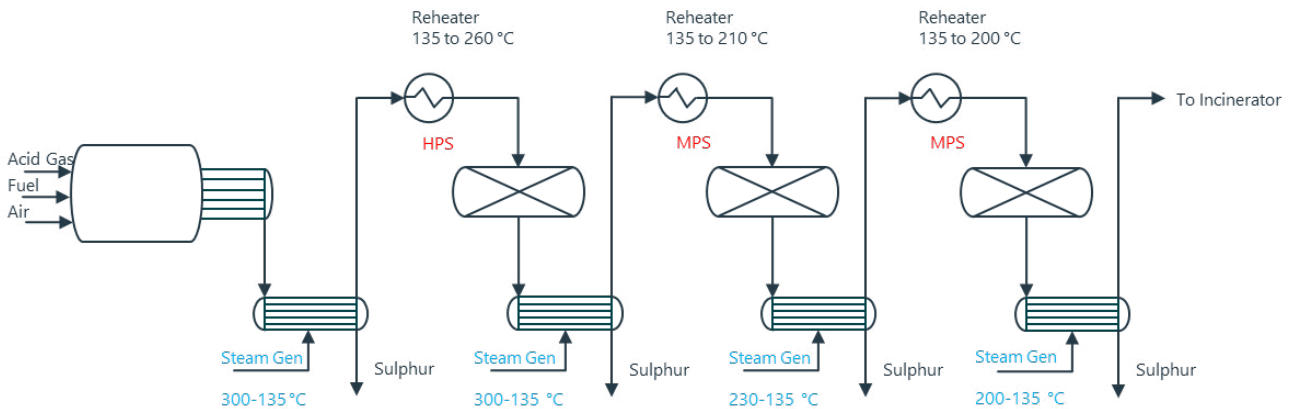
Operational Difficulty: The range of temperatures should be considered. Operation would require training or specialist maintenance support. Remote monitoring would assist in skills requirements.

Figure 25 Amine Regeneration Schematic



Sulphur recovery unit configurations vary widely. A typical configuration is provided in Figure 26, without showing further amine scrubbing (tail gas treatment) to remove additional sulphur.

Figure 26 Sulphur Recovery Unit (Claus) Schematic



The Claus Process burns hydrogen sulphide which produces heat, such that overall the system is able to export steam. The reheaters utilise a higher grade of steam than is produced by the sulphur condensers to allow optimal reaction temperatures. However, heat integration options would be considered prior to heat pumps in this case, and no waste heat is available for the heat pump to utilise.

If the site had an excess of low pressure steam, an alternative would be to upgrade the low grade steam to higher grade steam via simple compression.

6.2.2 OPPORTUNITIES IDENTIFIED

6.2.2.1 Opportunity M1: De-Ethanoliser Steam Reboiler

Industry Area: NGL Recovery Plant

Description: A moderate-high duty at moderate temperature is required in this typical De-Ethanoliser column, with possible heat sources derived from the overheads of other columns.

Sink(s): Reboiler requiring 34 MW duty

Sink Temperature Range: 94–100°C

Source(s): Potential to extract heat from De-Propaniser overhead cooler providing 48 MW

Source Temperature Range: 63°C
(Condensing Propane)

Technical Feasibility: Temperature lift is only moderate with required duty expected to be feasible. However, matching a different column overhead or other heat source with the reboiler may restrict the heat pump type, complicate the hydraulics and create plot layout issues.

Breadth of Applicability: Most NGL recovery assets.

Operational Difficulty: Increased complex rotating equipment, but within expected site existing experience.

6.2.2.2 Opportunity M2: De-Propaniser Steam Reboiler

Industry Area: NGL Recovery Plant

Description: A large duty at moderate-high temperature is required in De-Propaniser column, with possible heat source from the same column overhead condenser. These overheads typically exchange heat against air. Mechanical vapour recompression could utilise the overhead duty as part of the reboiler requirement.

Sink(s): Reboiler requiring 55 MW duty

Sink Temperature Range: 135–145°C

Source(s): Potential to extract heat from overhead cooler 48 MW

Source Temperature Range: 63°C
(condensing propane)

Technical Feasibility: Large amount of heat at high temperature (high temperature lift). Could require novel technology or combination of technologies, leading to decreased capital and thermal efficiency. High duty may limit feasibility for lower-TRL technologies.

Breadth of Applicability: Most NGL recovery assets.

Operational Difficulty: Less common technology or combination of technologies is likely to increase complexity of operation.

6.2.2.3 Opportunity M3: De-Butanoliser Steam Reboiler

Industry Area: NGL Recovery Plant

Description: A moderate duty at moderate-high temperature is required in the De-Butanoliser column, with possible heat source from the same column overhead condenser. These overheads typically exchange heat against air. Mechanical vapour recompression could utilise the overhead duty as part of the reboiler requirement.

Sink(s): Reboiler requiring 26 MW duty

Sink Temperature Range: 125–135°C

Source(s): Potential to extract heat from overhead cooler 37 MW

Source Temperature Range: 66°C

Technical Feasibility: Moderate duty at high temperature (high temperature lift). Could require novel technology or combination of technologies, leading to decreased capital and thermal efficiency, but duty required is expected to be more feasible than other larger applications.

Breadth of Applicability: Most NGL recovery assets.

Operational Difficulty: Less common technology or combination of technologies is likely to increase complexity of operation.

Reactor heaters and fractional distillation generally have high temperature requirements (>300°C) hence are not a good fit for heat pumps. Adding low grade heat at the start of a preheat train is also expected to exhibit low efficiency as demonstrated in Section 6.3.2 below.

Therefore, applications for heat pumps in downstream assets are focused on:

- Distillation column reboilers utilising local heat sources, often using waste overhead heat. Close boiling range separation indicates increased efficiency of the heat pump application as the temperature in the overhead is closer to the reboiler.
- Lower-temperature heaters using low or medium pressure steam for certain reactors and separation
- Steam generation to replace on-purpose generation by the site utilities where the site does not have excess steam at those steam levels.

Though waste heat is expected to be plentiful in downstream assets at elevated temperature, it should be noted that a large heat duty is also available in the cooling water return. The typical refinery studied here would circulate 20,000 m³/hr of cooling water at a temperature up to 40–50°C and a heating duty of 230 MW.

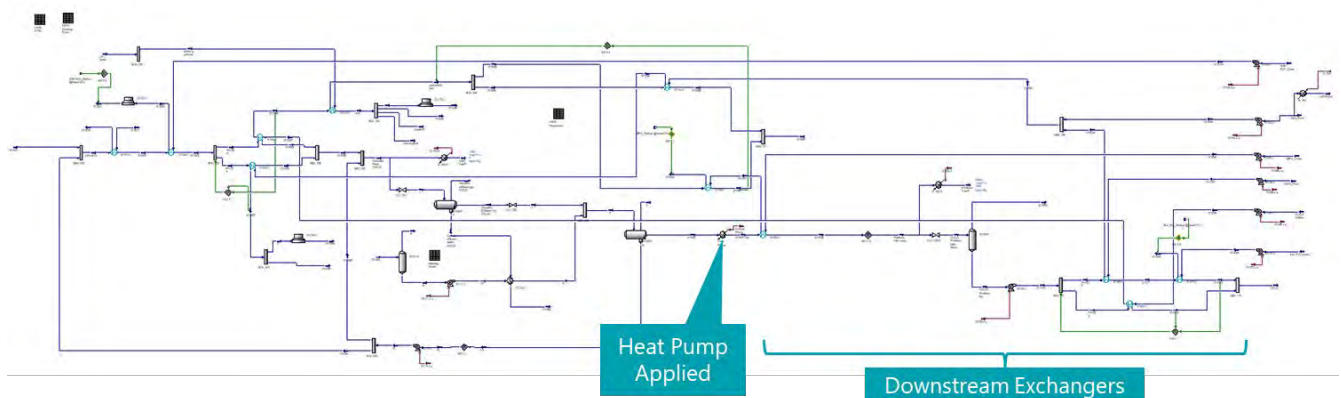
6.3.2 ANALYSIS OF APPLICATION WITHIN HEAT EXCHANGER NETWORKS

Where processes require high temperature for reaction or separation, the design of the process typically includes preheat by heat integration, often followed by a fired heater or other high temperature heat input.

Processes requiring temperatures of 300°C or more often include complex heat exchanger networks and technologies to minimise exchanger approach temperature. As waste heat is typically available in the 50–100°C range around a highly heat integrated process, the opportunities to upgrade waste heat for use in high temperature processes would need to be applied within the preheat train.

An example of this application is given below. Crude Distillation Unit Preheat Train demonstrates the complexity of a typical crude distillation unit preheat train upstream of the fired heater. Pumparounds and rundown streams provide preheat to the feed, with the remaining duty provided by a fired heater. The fired duty can range from 30–100 MW depending on unit design and scale, hence reducing fired emissions represents a very large opportunity.

Figure 28 Crude Distillation Unit Preheat Train



To ensure a reasonable efficiency of the heat pump, it was assumed that the heat pump would provide 150°C heat sourced from waste heat streams and upgraded via a heat pump. This temperature would therefore be applied part way along the preheat train, but still upstream of the hottest exchangers.

Aligned with Pinch technology principles, application of heat at this stage of the preheat train does unload the fired heater to an extent, but will make the hottest exchangers less efficient due to reduction in temperature difference. In the case studied and depending on the network operation, 0.5–0.65 kW is saved in heater duty for every 1 kW added by the heat pump. This would be a significant hindrance to the economics and effectiveness of a heat pump project when compared with other applications.

6.3.3 OPPORTUNITIES IDENTIFIED

Due to the number of potential applications within the downstream facilities, the opportunities are tabulated in [Table 7](#) and [Table 8](#) for the refinery and petrochemicals representative assets respectively. The opportunities are listed by heating requirement, with any related waste heat from an overhead condenser listed alongside it. As anticipated above, when very high temperature heat requirements are removed, the majority of applications are reboilers with some lower temperature heaters.

Table 7 Fuels Refinery – High Complexity

Unit	Equipment	Required T in–T out (°C, approx.)	Required Duty (MW)	Overhead T in–T out (°C, approx.)	Overhead Duty (MW)
C3/C4 Splitter	Fractionation Column Reboiler	100–100	3.4	50–40	2.7
Sat Gas Plant/ Treater/LPG Separation	Fractionation Column Reboiler	70–70	1.9	50–40	1.2
FCC Gasoline HDT	Splitter Reboiler	190–190	5.9	100–60	4.8
FCC Gasoline HDT	Stabilizer Reboiler	190–190	2.6	130–50	4.6
Isom	Regenerant Vaporiser	50–160	1.1	300–50	2.1
Isom	Stabilizer Reboiler	180–180	9.2	90–40	3.0
Isom	Raffinate Column Reboiler	120–130	10.2	70–50	10.3
Isom	Extract Column Reboiler	130–130	4.9	70–50	3.9
Alky	Depropaniser Reboiler	110–110	0.3	60–50	0.3
Alky	Deisobutaniser Reboiler	110–130	13.9	70–40	16.0
Alky	Debutaniser Reboiler	170–190	4.4	70–50	3.9
FCC	Stripper Steam Reboiler	90–110	23.4	70–40	29.9
FCC	Debutanizer Reboiler	170–180	81.6	60–50	84.7
FCC	C3 Splitter Reboiler	70–70	89.2	50–50	88.6
Amine (SWS)	ARU Regen Reboiler	130–130	40.9	100–60	29.9
Amine (SWS)	SWS Regen Reboiler	130–130	13.6	40–30	3.5
Unsaturated Gas Plant	Debutaniser Reboiler	110–110	[Hot Oil]	50–50	-

Table 8 Petrochemicals – Olefins and Polyolefins

Unit	Equipment	Required T in–T out (°C, approx.)	Required Duty (MW)	Overhead T in–T out (°C, approx.)	Overhead Duty (MW)
SCU	Dilution Steam Superheater	170–190	2.3	-	-
SCU	H ₂ S Stripper Reboiler	140–140	4.7	110–40	3.4
SCU	Depentaniser Reboiler	130–130	8.1	70–50	6.8
SCU	Depentanizer Reboiler	150–150	4.8	110–50	0.4
SCU	Deoctaniser Reboiler	180–180	7.6	90–40	11.3
SCU	Process Water Stripper Reboiler	120–120	10.2	-	-
SCU	Medium Gasoline Heater	110–130	2.1	-	-
SCU	Cold Flare Methanol Vaporiser	120–120	18.3	-	-
SCU	Amine Stripper Reboiler	130–130	61.8	110–50	13.4
SCU	HP Depropaniser Reboiler	80–80	11.7	70–70	5.8
SCU	LP Depropaniser Reboiler	80–80	12.1	0–(-20)	11.7
SCU	Debutaniser Reboiler	130–130	11.9	50–50	11.4
LLDPE	Butene Reboiler	40–40	0.2	40–40	0.2
LLDPE	Hexene Reboiler	100–100	0.4	100–100	0.2
LLDPE	Nitrogen Pre-heater	30–100	0.4	-	-
LLDPE	ICA Reboiler	60–60	0.1	60–60	0.1
PP	Gas Polymerization Heater	40–90	0.5	-	-
PP	After Treatment Jacket Heater	Ambient–90	0.1	-	-
PP	Extruder	-	160 kg/h MPS	-	-
Aromatics	Reformate Splitter Reboiler	190–190	7.0	120–90	19.0
Aromatics	ED Column Reboiler	160–170	5.6	100–80	3.1
Aromatics	Stripper Column Reboiler	180–190	3.4	70–60	10.1

The distribution of the above downstream applications is provided by sink temperature ranges and by temperature lift in [Table 9](#) and [Table 10](#). COP is clearly correlated with lower sink temperatures and low lift and a significant total duty and number of applications exist within the most favourable categories of these parameters.

Table 9 Distribution of Downstream Applications by Sink Temperature

Sink Temperature Range (°C)	Number of Applications	Duty (MW)	COP
Ambient-50	2	0.2	N/A
50–100	8	139.3	7.7
100–150	19	241	4.3
150–200	10	129.6	1.9
Total	39	510.1	4.5

Table 10 Distribution of Downstream Applications by Temperature Lift

Mean Temperature Lift (°C)	Number of Applications	Duty (MW)	COP
0–50	10	168.9	8.7
50–75	13	118.6	3.5
75–100	4	44.6	2.3
>100	12	178	1.8
Total	39	510.1	4.5

A selection of opportunities is detailed in the sections below capturing a range of applications.

6.3.3.1 Opportunity D1: Alkylation Unit – De-Isobutaniser Reboiler

Industry Area: Fuels Refining

Description: A large duty is required for splitting the close boiling range chemicals. The overhead is typically exchanged against water or air. Mechanical vapour recompression could utilise the overhead duty as part of the reboiler requirement. Moderate temperature lift is expected.

Sink(s): Displacement of steam. 14 MW is required in this representative case.

Sink Temperature Range: 110–130°C

Source(s): Overhead condensing at 16 MW matches well with the reboiler duty

Source Temperature Range: 40–70°C, though the majority of duty is expected closer to 70°C.

Technical Feasibility: MVR for high reflux columns has been installed successfully.

Breadth of Applicability: Close boiling range columns (refinery and petrochemical).

Operational Difficulty: Increased complex rotating equipment, but within existing site experience.

6.3.3.2 Opportunity D2: FCC – De-Butaniser Reboiler

Industry Area: Fuels Refining

Description: One of the largest reboiler duty identified in downstream refining corresponds to the FCC debutaniser column. A large amount of heat at high temperature is required to stabilise the feed. The overhead is typically exchanged against air and cooling water. A mechanical vapour recompression configuration could utilise the overhead duty as part of the reboiler requirement.

Sink(s): Reboiler requiring 82 MW

Sink Temperature Range: 170–180°C

Source(s): Potential to extract heat from overhead cooler (85 MW)

Source Temperature Range: 50–60°C

Technical Feasibility: Large amount of heat at high temperature and high temperature lift. The high lift could require novel technology or combination of technologies, leading to decreased capital and thermal efficiency. Very high duty may limit feasibility for lower-TRL technologies.

Breadth of Applicability: Debutanisers and stabilisers in refining are common, requiring high temperature reboilers.

Operational Difficulty: Less common technology or combination of technologies is likely to increase complexity of operation.

6.3.3.3 Opportunity D3: FCC – Propylene Splitter Reboiler

Industry Area: Fuels Refining

Description: Another of the largest reboiler duties identified in refining is the propane/propylene splitter downstream of the fluidised catalytic cracker or integrated with a steam cracking unit. A large amount of heat at medium temperature is required. The overhead temperature is close to the reboiler temperature and typically exchanges heat against air and cooling water. Mechanical vapour recompression could utilise the overhead duty as part of the reboiler requirement.

Sink(s): Reboiler requiring 89 MW duty. Supplemental heat input via heat integration from nearby operations is assumed.

Sink Temperature Range: 70°C

Source(s): Potential to extract heat from the same column's overhead cooler (89 MW).

Source Temperature Range: 50°C

Technical Feasibility: Industrial examples exist. Relatively small temperature lift. Expected to be a large custom process design for the highest COP.

Breadth of Applicability: Close boiling range columns (refinery and petrochemical).

Operational Difficulty: Increased complex rotating equipment, but within site existing experience.

6.3.3.4 Opportunity D4: SCU – De-Octaniser Reboiler

Industry Area: Petrochemicals

Description: Moderate heat at high temperature is required in De-Octaniser columns within the olefins production area, with a possible heat source in the same column's overheads. These overheads typically exchange heat against air and cooling water. Mechanical vapour recompression could utilise the overhead duty as part of the reboiler requirement.

Sink(s): Reboiler requiring 8 MW duty

Sink Temperature Range: 180°C

Source(s): Potential to extract heat from overhead cooler at 11 MW

Source Temperature Range: 40–90°C

Technical Feasibility: Moderate amount of heat at high temperature and high temperature lift. This could require novel technology or combination of technologies, leading to decreased capital and thermal efficiency, but is likely to be feasible at the lower duty required.

Breadth of Applicability: High lift at moderate duty is widely applicable in various distillation columns.

Operational Difficulty: Less common technologies or combination of technologies are likely to increase complexity of operation.

6.3.3.5 Opportunity D5: LLDPE – Butene Reboiler**Industry Area:** Petrochemicals

Description: Small heat pumps can be installed in a variety of applications in downstream refining and petrochemicals, for example in component splitters such as Butene or Hexene columns. This example is applied to the reboiler of a butene column within a common LLDPE polymerisation unit. The temperature of both sink and source are typically low and a various mechanical vapour recompression configurations could utilise the overhead duty as part of the reboiler requirement.

Sink(s): Reboiler requiring 0.2 MW duty**Sink Temperature Range:** ca. 45°C**6.4 Utilities Production****6.4.1 REVIEW OF ASSETS**

Steam production heat pump applications can be generally applied to many assets, either feeding into specific users at customised conditions, or utilised flexibly in the site steam headers.

Typical steam conditions for low pressure steam provide a good fit for current heat pump technologies at ca. 150°C. Medium pressure steam can also be produced using a combination of heat pump and post-compression technologies.

The potential opportunity for application to an asset is limited to the steam balance, i.e. how much on-purpose lower-level steam is produced by the site via letdowns or turbines. For the high complexity refinery example studied, a large quantity of low pressure steam is produced by letdowns and turbines and available waste heat is far in excess of this duty.

6.4.2 OPPORTUNITIES IDENTIFIED**6.4.2.1 Opportunity S1: LP Steam Generation****Industry Area:** Utilities

Description: LP steam can be generated from a wide range of waste heat sources utilising closed loop

Source(s): Potential to extract heat from overhead cooler (0.2 MW).

Source Temperature Range: ca. 40°C

Technical Feasibility: Low temperature heat and low temperature lift requirements. Heat pumps in propane/propylene columns with closer reboiler/condenser temperature have been successfully installed.

Breadth of Applicability: Has multiple applicable areas for small duties. However, small economy of scale limits application. Maintenance and operational requirements disadvantage multiple small heat pump systems.

Operational Difficulty: Increased complex rotating equipment, but within existing site experience.

heat pumps at reasonable efficiency. Alternatively, a centralised source such as the cooling water return header could be utilised.

Sink(s): LP steam header**Sink Temperature Range:** 150°C**Source(s):** Various, including cooling water return.**Source Temperature Range:** 30–90°C depending on source

Technical Feasibility: Production of steam using heat pumps is within the experience of vendors and the potential for centralised systems away from process unit zoning may provide cost and feasibility advantages.

Breadth of Applicability: Where assets have LP steam requirements produced by boilers via let downs or turbines.

Operational Difficulty: Operation and maintenance would require training but is expected to be within the equipment experience of a utilities area.

6.4.2.2 Opportunity S2: MP Steam Generation

Industry Area: Utilities

Description: MP steam can be generated from a wide range of waste heat sources utilising closed loop heat pumps and supplemented by post compression at reasonable efficiency. Alternatively, a centralised source such as the cooling water return header could be utilised.

Sink(s): MP steam header

Sink Temperature Range: >200°C

Source(s): Various, including cooling water return.

Source Temperature Range: 30–90°C depending on source

Technical Feasibility: Production of steam using heat pumps is within the experience of vendors and the potential for centralised systems away from process unit zoning may provide cost and feasibility advantages.

Breadth of Applicability: Where assets have MP steam requirements produced by boilers via let downs or turbines.

Operational Difficulty: Operation and maintenance would require training but is expected to be within the equipment experience of a utilities area.

6.5 Ranking

6.5.1 RANKING METHODOLOGY AND PARAMETERS

The application opportunities selected for discussion above provide representative coverage of the opportunities found in across the various asset types. Therefore, the rankings can be extrapolated to similar applications.

Ranking parameters were selected as shown in [Table 11](#) to provide a view of the efficiency drivers, industrial importance in terms of size and frequency of application, as well as the likely difficulties encountered.

Table 11 Ranking Parameters

Category	Ranking Description	Weighting
Sink Temperature Range (1–4)	1 = >150C 2 = 100–150C 3 = 50–100C 4 = Ambient–50C	0%
Mean Temperature Lift (1–4)	1 = >100C 2 = 75–100C 3 = 50–75C 4 = 0–50C	0%
Technical Feasibility (1–5)	Higher is better (higher is more feasible). Factors affecting this parameter: Technology Readiness Level (TRL) anticipated to be required, required space, weight, scale and access to electricity	20%
Breadth of Applicability (1–5)	Higher is better (higher is more common). Factors affecting this parameter: Number of estimated industrial applications.	20%

Category	Ranking Description	Weighting
Operational Difficulty (1–5)	Higher is better (higher is easier to operate). Factors affecting this parameter: Location remoteness, maintenance cost, fluid hazard level and control difficulty.	10%
Coefficient of Performance (COP) (1–5)	1 = COP < 2 2 = COP between 2 and 3 3 = COP between 3 and 4 4 = COP between 4 and 6 5 = COP > 6.	40%
Single Application Duty (1–5)	1 = Duty < 5 MW 2 = Duty between 5 and 10 MW 3 = Duty between 10 and 15 MW 4 = Duty between 15 and 30 MW 5 = Duty > 30 MW.	10%

Weighting was agreed with the OGCI working group and some parameters were included for information only with weighting set to zero.

COP was viewed as the most important parameter as this provides the driver for a heat pump project. Poor COP would utilise less waste heat, require larger equipment as well as demanding higher power requirements. Mean temperature lift was set to zero weighting and provided for information only as this would correlate with the COP.

Breadth of applicability and single application duty together were given comparatively high weighting to reflect whether this application is of broad interest to the industry.

Operational difficulty was given a relatively low weighting as the applications generally will have a feasible, if difficult, way forward that can be captured in the other parameters.

Technical feasibility was given a moderate weighting. This is an important contribution to how costly the project would be, including indirect impacts of equipment footprint. Sink temperature range was set to zero weighting and provided for information only as this would correlate to an extent with the technology selected and its TRL.

6.5.2 RANKING RESULTS

The ranking results are summarised in [Table 12](#).

Table 12 Ranking Summary

Application	Application Benefit					Feasibility and Operation		Comments	Weighted Score
	Sink Temperature Range (1-4)	Mean Temperature Lift (1-4)	Breadth of Applicability (1-5)	COP (1-5)	Single Application Duty (1-5)	Technical Feasibility (1-5)	Operational Difficulty (1-5)		
U1: Offshore Oil Heating	3	4	5	4	2	2	3	Operational and technical difficulty increased due to offshore location. However, duty is manageable and efficiency is good.	3.5
U2: GOSP Crude Stabiliser Reboiler	3	4	5	5	2	5	4	Strong efficiency benefit and proven temperature range.	4.6
U3: Remote Unconventional Field	3	3	4	3	4	4	4	Ambient source limits efficiency, but would be relatively simple if power supply is possible (remote location).	3.6
U4: Heavy Oil Hot Water Flood	3	3	4	3	4	4	4	Similar to above remote unconventional field. Significant emissions advantage over current gas fired heaters.	3.6
M1: De-C2 Steam Reboiler	3	4	5	5	5	3	5	Technical feasibility or efficiency could be limited by linking different column overheads and reboilers	4.6
M2: De-C3 Steam Reboiler	2	2	5	2	5	1	4	High lift and duty leading to reduced efficiency and technical feasibility.	2.9
M3: De-C4 Steam Reboiler	2	3	5	3	4	2	4	High lift with significant duty limits efficiency and technical feasibility.	3.4
M4: Amine Regenerator	2	4	4	4	5	3	5	Very high duty with moderate lift should be feasible but would require a large installation.	4.0
D1: Alkylolation Unit: De-iC4 Reboiler	2	3	2	3	3	5	5	Moderate lift and duty should be feasible for a closed loop or open loop heat pump design.	3.4
D2: FCC: De-Butaniser Reboiler	1	1	5	1	5	1	4	Debutanisers generally have high lift requirements and low efficiencies. Large duty required combines to low technical feasibility.	2.5
D3: FCC: C3 Splitter Reboiler	3	4	2	5	5	5	5	Industrially applied in this service. High efficiency possible.	4.4
D4: SCU: De-Octaniser Reboiler	1	1	4	1	2	1	4	Very high lift required with low efficiency.	2.0
D5: LLDPE: Butene Reboiler	4	4	3	5	1	5	5	Low duty reduces priority of application	4.2
S1: LP Steam Generation	2	3	5	3	5	5	5	If LP steam short, this is a well proven use of waste heat	4.2
S2: MP Steam Generation	1	2	5	3	5	5	5	Reduced efficiency versus LP steam but with broader usage	4.2

The highest ranked applications mostly follow the COP expected to be achieved, which highlights distillation where a relatively high temperature overhead heat source can be matched with relatively close temperatures in the reboiler. M1, D3 and D5 are examples of this.

The upstream examples where the sink temperature is relatively low (U1-4) also perform well in the ranking due to good feasibility and efficiency across a number of factors. Offshore application is penalised by the additional complexity of on-platform projects and operation.

Amine regeneration is also shown to be attractive despite a medium lift requirement. The scale and number of applications for this type of process operation demonstrate its importance for consideration.

Steam generation from various waste heat streams is expected to result in a moderate COP, but can be centralised and is flexible in utilisation, hence this is shown to be an important application.

07

Application Evaluation and Comparison

7 Application Evaluation and Comparison

7.1 General Basis

Example projects were evaluated at a conceptual level using a combination of vendor feedback, process simulation and in-house sizing and cost estimation. Where possible, COP and equipment limitations claimed by vendors and literature sources was validated by simulation and the simulation results used for specific cases studied.

Capital cost is provided on a concept-level, North-West European Total Installed Cost (TIC) basis, excluding:

- Owners Costs
- FEED costs and earlier phases
- Contingency
- Forward Escalation
- Operating Costs

Economic evaluation is aligned with the OGCI Refining Industry Electrification Economics study with the following selected as economic inputs:

- 10% discount rate
- 2.1% non-energy OPEX on CAPEX
- 8,000 operating hours per year
- High power and fuel pricesets and medium carbon emissions pricing. Pricesets provided in Appendix B.
- 2024 to 2060 project horizon for NPV and IRR calculation

Carbon emissions avoided are calculated on a consistent basis assuming the heat duty provided by the heat pump would have been provided by combustion of natural gas at 80% thermal efficiency. Where this is conservative, it is noted in the discussion. Natural gas supply emissions are included on a CO₂ equivalent basis, resulting in a total carbon intensity of 100% efficiency natural gas combustion of 240 g(CO₂_{eq})/kWh.

Evaluation economics are additionally presented as a flat emissions price required for zero NPV over the project lifespan. This illustrates the level of emissions pricing support required for the project to break even. Power and fuel are priced as above.

7.2 UI: Offshore Oil Heating

7.2.1 PROCESS DESCRIPTION

As described in Section 6, oil production can involve heating of the oil from ambient to temperatures typically below 100°C before flashing for vapour pressure control. This can occur onshore where many smaller or fewer larger production flows are gathered prior to export, or this could occur in an offshore location, often to condition the produced oil for pipeline flow assurance.

In an offshore location, the existing heat source is typically from a gas turbine exhaust, hence replacing the heater with a heat pump would simultaneously involve decommissioning of the gas turbine and commissioning electrical import to the asset.

The representative example requires 7 MW of duty, heating from ambient to 70°C. Heat sources for a heat pump would be limited to the surrounding environment

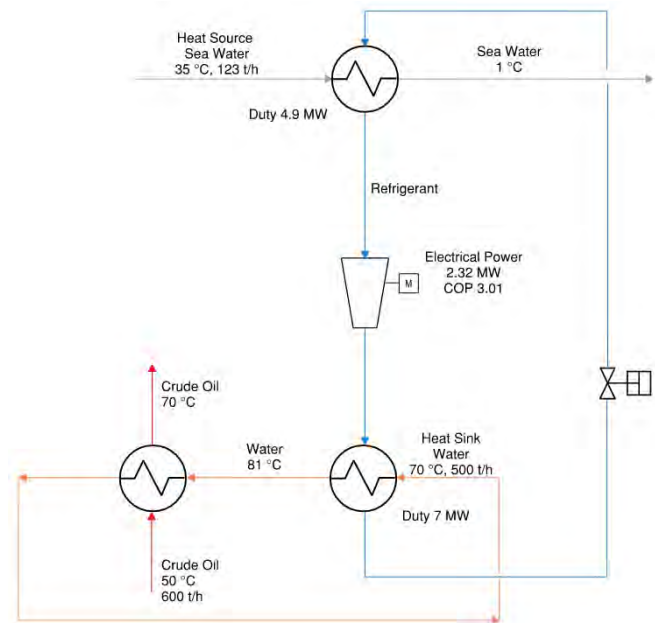
as no significant waste heat is expected to be present, hence seawater has been assumed to be utilised. Re-injection compressors and their coolers may be present, but have not been assumed to be utilised in this case.

The low temperature source and sink generally favours a closed loop heat pump using non-water refrigerant. Vendor feedback supports a design similar to that illustrated in [Figure 29](#), with normal butane utilised as a refrigerant, which is relatively low hazard compared to ammonia inventory. De-inventorising of the n-butane within the heat pump is expected to be necessary in an emergency scenario, which would be via existing flare systems.

Sea water is exchanged against the refrigerant using a low-approach temperature exchanger and the hot compressor outlet is exchanged against a hot water or heat transfer fluid loop which is in turn exchanged with the produced crude. Direct exchange between the crude and the refrigerant within the heat pump package was not supported by vendor feedback. The closed heat transfer loop has been found to be present in reviewed complex offshore installations, hence the heat source for part or all of this circulation system would be replaced with the heat pump.

Review of existing, complex processing platforms suggests that a cooling water lift system and circulation back to sea is expected to be present at a much higher capacity than required for the heat pump, hence the heat source is assumed to be from the cooling water return at a temperature above ambient.

Figure 29 Offshore Oil Heating Example Application Schematic



7.2.2 EQUIPMENT AND ELECTRICAL INFRASTRUCTURE

The heat pump circuit is anticipated to be supplied as a vendor package including all instruments, control and vendor support required for the heat pump itself. The connecting pipe runs, hot fluid loop and exchange with the fouling resistant crude oil exchanger are expected to be additional project items to be included in the overall design.

Electrical infrastructure is anticipated to be required due to the significant additional load added to the asset.

Power supply to the platform will be required when electrifying the asset independent of the heat pump project. This scope would depend on the type of power source selected (e.g. shore-based supply or offshore wind) and has not been included within the project scope.

7.2.3 PROJECT SCHEDULE

Project schedule in this application will be dictated by offshore project and maintenance considerations for construction and tie ins. The project is anticipated to take ca. 3 years from FEED to Ready-For-Start-Up if maintenance windows and offshore construction is available.

7.2.4 PROJECT RISKS AND IMPLEMENTATION DIFFICULTY

Centre of gravity and weight are major concerns in the offshore environment. For platform modification a detailed weight review would be required, though electrification and removal of a gas turbine generator could remove ca. 250 tonnes of additional equipment which should make retrofit into an existing asset feasible without building a new platform.

Any modification in an offshore environment carries greater project risk and increased maintenance cost. The heat pump technology is not familiar to offshore crews, hence will require training for both operations and maintenance crews.

Where the refrigerant is hydrocarbon, platform safety procedure review will be required, including inventory management in emergency scenarios.

7.2.5 PROJECT COSTS AND ECONOMICS

Table 13 shows the key project economic drivers and economic results. NPV is very slightly negative for the 10% discount rate applied. Uncertainty regarding CAPEX in the offshore location is relatively high, which could change the attractiveness of the rate of return easily from its current value.

However, the calculated carbon emissions abated are likely to be conservative versus the replaced heat source combustion efficiency, hence any economics supported by future carbon pricing could have significant upside.

Table 13 Summary of Project Cost and Economics

Parameter	Value
Thermal Output Power (MW)	7.0
Electrical Input Power (MW)	2.3
COP	3.0
CO _{2eq} Emissions Abated (t/h)	2.0
Fuel Use Avoided (MW)	8.8
Estimated Capital Cost (MMUSD)	22.2
NPV (MMUSD)	-4.6
IRR (%)	8
Breakeven CO ₂ Price (USD/tCO _{2eq})	138

7.3 U2: GOSP Crude Stabiliser Reboiler

7.3.1 PROCESS DESCRIPTION

The Gas/Oil separation plant stabiliser reboiler represents a potential unit operation in a centralised primary oil separation facility whereby the export-quality oil and sales gas are separated by a stabiliser column. The existing heat source is anticipated to be LP steam, but could also be a heat transfer fluid.

The representative example requires 9 MW of duty in the reboiler at a temperature of 70–100°C. This type of column does not include an overhead condenser, hence heat sources for a heat pump could be ambient air, cooling water return or could take advantage of gas compression waste heat commonly associated with this type of facility. In this example, the sales gas compression provides excess heat for this reboiler at a temperature glide between 130–50°C.

This temperature range could be provided by multiple technologies. An open-loop compression of the sales gas was discounted as re-routing of the large sales gas stream and utilisation of solely sensible heat in the

stream is likely to be uneconomic and potentially infeasible if the operations are not adjacent.

Vendor feedback and initial costing supports the utilisation of a low-pressure closed loop heat pump with water refrigerant as the working fluid. This is anticipated to be competitive due to the ability to specify lower-cost compression trains.

Figure 30 illustrates application of a closed-loop water-based heat pump with 10°C approach temperature on the sales gas and reboiler streams. Very low pressure evaporation of water is used to extract heat from the sales gas compressor discharge, with 7 individual fan units provided to compress the steam to the required condensing temperature for reboiling. Figure 31 illustrates two potential configurations for the compressor trains, differentiated by the reduction in temperature between stages by intercooling or desuperheating. Desuperheating was shown to provide an overall COP increase of ca. 0.5 so has been utilised in the below analysis.

Figure 30 GOSP Crude Stabiliser Example Application Schematic

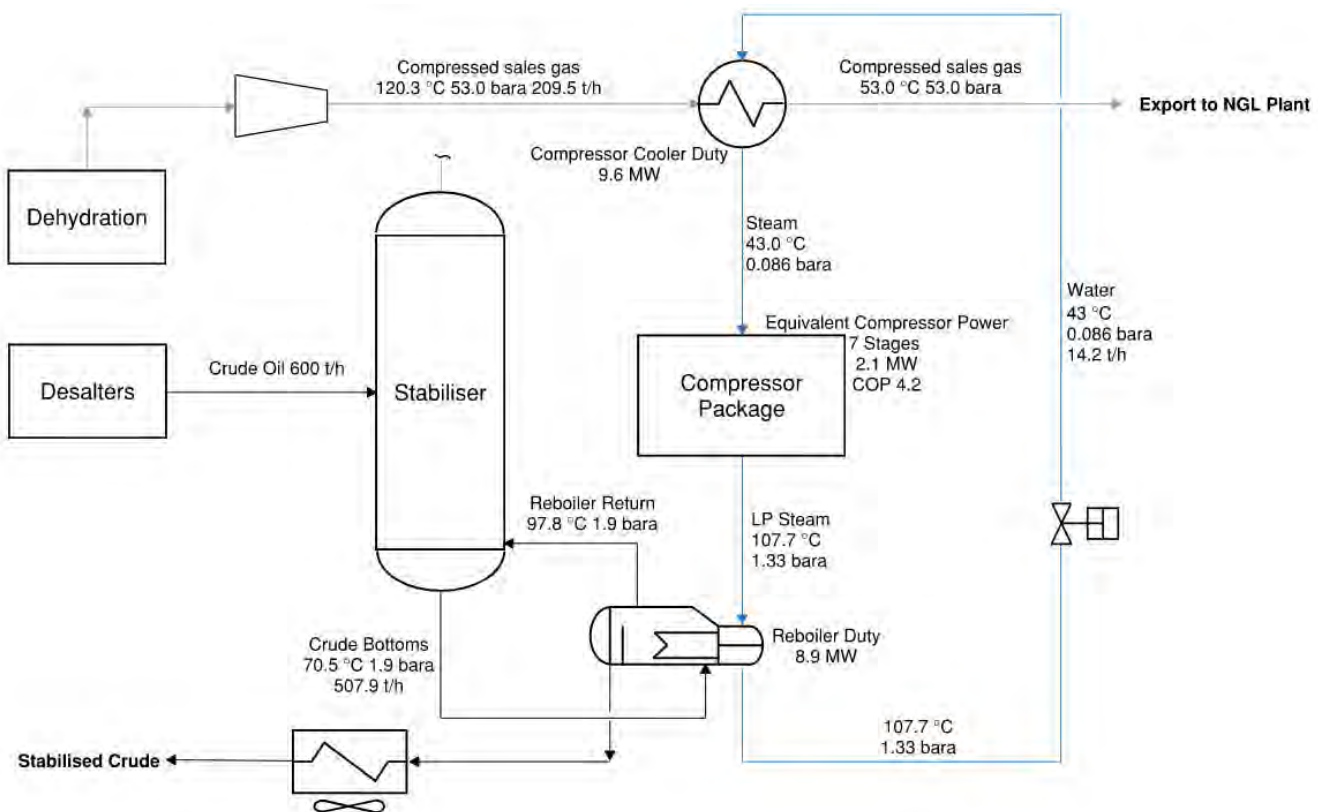
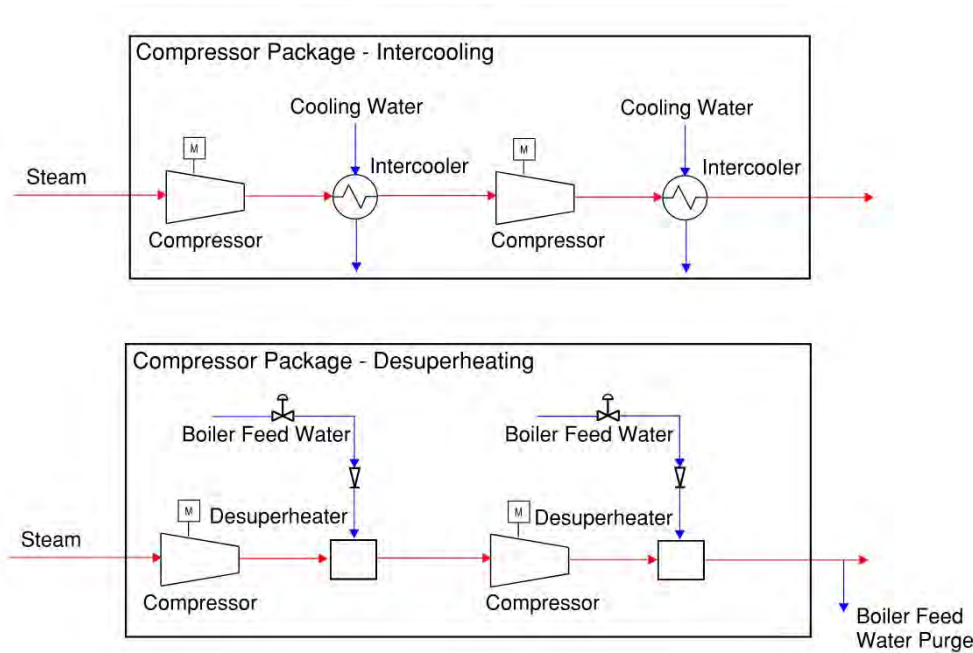


Figure 31 Interstage Cooling and Desuperheating Details



7.3.2 EQUIPMENT AND ELECTRICAL INFRASTRUCTURE

The compression train is anticipated to be supplied by a single vendor, including motors and variable speed drives. The connecting pipe runs and exchangers are expected to be additional project items to be included in the overall design.

The first stage compressor suction pipework and rotating equipment sizing are large, hence vendor sizing of the train was received. A suction pipework diameter of 0.9 m could be required using typical velocity criteria.

A relatively minor scope of electrical infrastructure has been allowed for to expand the current substation and transformer provision.

7.3.3 PROJECT SCHEDULE

The project schedule is expected to be able to proceed alongside operating plant, with major tie ins during planned shutdowns. The project is anticipated to take ca. 3 years from FEED to Ready-For-Start-Up with sufficient turnaround planning.

7.3.4 PROJECT RISKS AND IMPLEMENTATION DIFFICULTY

Complexity of control is increased due to the heat pump operation and additional training requirements are anticipated. Utilisation of steam as the working fluid enables supplemental or start-up steam from an external supply to be used in the reboiler.

Space requirements close to the heat source and reboiler are significant due to the economic solution of individual compressor stages.

7.3.5 PROJECT COSTS AND ECONOMICS

Table 14 shows the key project economic drivers and economic results. NPV and IRR are shown to be strong for the project, supported by high COP and moderate scale.

Some lower-complexity sites are likely to have lower combustion efficiencies than referenced, which may give an upside, though for a centralised site with a stabiliser tower, best practice operation would limit this additional opportunity.

Table 14 Summary of Project Cost and Economics

Parameter	Value
Thermal Output Power (MW)	8.9
Electrical Input Power (MW)	2.1
COP	4.2
CO ₂ eq Emissions Abated (t/h)	2.6
Fuel Use Avoided (MW)	11.1
Estimated Capital Cost (MMUSD)	14.5
NPV (MMUSD)	10.2
IRR (%)	16
Breakeven CO ₂ Price (USD/tCO ₂ eq)	27

7.4 U4: Heavy Oil Hot Water Flood

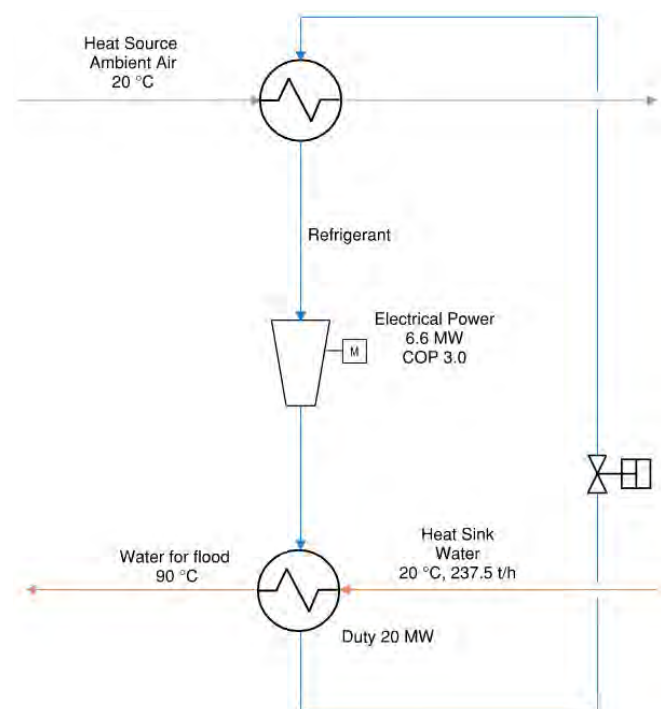
7.4.1 PROCESS DESCRIPTION

This application targets energy used for heavy oil recovery in onshore production. This is typically achieved by steam or hot water injection, though hot water is anticipated to give a more sustained, centralised requirement for heat. Steam injection is generally being replaced by hot water flood to lower carbon intensity. The current heat source is typically hydrocarbon combustion to heat water at 5–40 MW.

The representative example requires 20 MW of heat at 90°C. Facilities are usually remote from other industry, hence sources of waste heat are not expected to be available. Therefore, environmental heat is expected to be used (air, water or ground source).

The low temperature source and sink generally favours a closed loop heat pump using non-water refrigerant. Vendor feedback supports a design conceptually similar to that illustrated in [Figure 32](#), with normal butane (n-butane) utilised as a refrigerant and water for injection exchanged directly against the heat pump circuit.

Figure 32 Heavy Oil Hot Water Flood Example Application Schematic



Application U3 (Remote Unconventional Field Crude Heating) is expected to produce similar economics and project scope to U4 at a similar duty and temperature requirement, hence has not been evaluated separately. Heat transfer to the crude oil in U3 would be indirect, but an existing circulating heat transfer fluid system is assumed to be utilised.

7.4.2 EQUIPMENT AND ELECTRICAL INFRASTRUCTURE

The heat pump circuit is anticipated to be supplied as a vendor package including all instruments, control and vendor support required for the heat pump itself. Process connections are expected to be minimal in this case to tie into the existing hot water supply.

Electrical infrastructure is anticipated to be required due to the significant additional load added to the asset, hence substation and transformer expansion is included.

7.4.3 PROJECT SCHEDULE

Project is likely to be achievable in under 3 years from FEED to Ready-For-Start-Up considering the package nature and ease of tie-ins.

7.4.4 PROJECT RISKS AND IMPLEMENTATION DIFFICULTY

Due to the package-type supply of the heat pump and relatively simple tie ins, project risk is reduced for this type of asset. Electrical connection could be an issue for remote locations.

Range of temperature from day to night and season to season would need to be considered in design. Operation would also require training or specialist maintenance support. Remote monitoring would assist in skills shortages.

Space restrictions for this type of asset are not anticipated to be an issue.

7.4.5 PROJECT COSTS AND ECONOMICS

Table 15 shows the key project economic drivers and economic results. NPV is positive and an attractive IRR is expected from the project parameters used. The calculated carbon emissions abated are likely to be conservative versus the replaced heat source combustion efficiency, hence any economics supported by future carbon pricing could have significant upside.

A comparison has been made with an alternative electrification method whereby direct electrical heating via an element heater is applied, using equivalent economic calculation parameters. Capital cost for this alternative is slightly higher, including increased electrical infrastructure costs due to a much greater power demand. Overall economics over the project lifespan are shown to be significantly worse due to the power utility cost.

Table 15 Summary of Project Cost and Economics

Parameter	n-Butane Heat Pump	Direct Electrical Heating
Thermal Output Power (MW)	20.0	20.0
Electrical Input Power (MW)	6.6	20.0
COP	3.0	1.0
CO _{2eq} Emissions Abated (t/h)	5.8	4.9
Fuel Use Avoided (MW)	25.0	25.0
Estimated Capital Cost (MMUSD)	33.4	29.1
NPV (MMUSD)	16.6	-14.4
IRR (%)	14	6
Breakeven CO ₂ Price (USD/tCO _{2eq})	104	156

7.5 MI: De-Ethanizer Reboiler

7.5.1 PROCESS DESCRIPTION

The application to a Natural Gas Liquids (NGL) separation plant de-ethanizer reboiler allows analysis of multiple heat pump configurations. The reboiler in the representative asset requires 34 MW at a temperature of ca. 90–100°C and the opportunity exists to match this with the condensing duty of the adjacent de-propaniser overhead.

Closed loop heat pumps, either using water with cost-efficient compressor train designs, or using n-butane with proprietary, integrated compressor stages in a vendor-supplied skid could be employed. Alternatively,

an open-loop compression of the overhead into the reboiler could be utilised, though lift is not as low as would be targeted for this technology.

Figure 29 above represents the concept of the n-butane closed loop heat pump, which would include indirect heat transfer with water as a heat transfer medium.

Figure 33 represents this application as a water-based closed loop design, and Figure 34 represents the open-loop design.

The compressor package referenced is as per Figure 31.

Figure 33 De-Ethanizer Reboiler Closed Loop Example Application Schematic

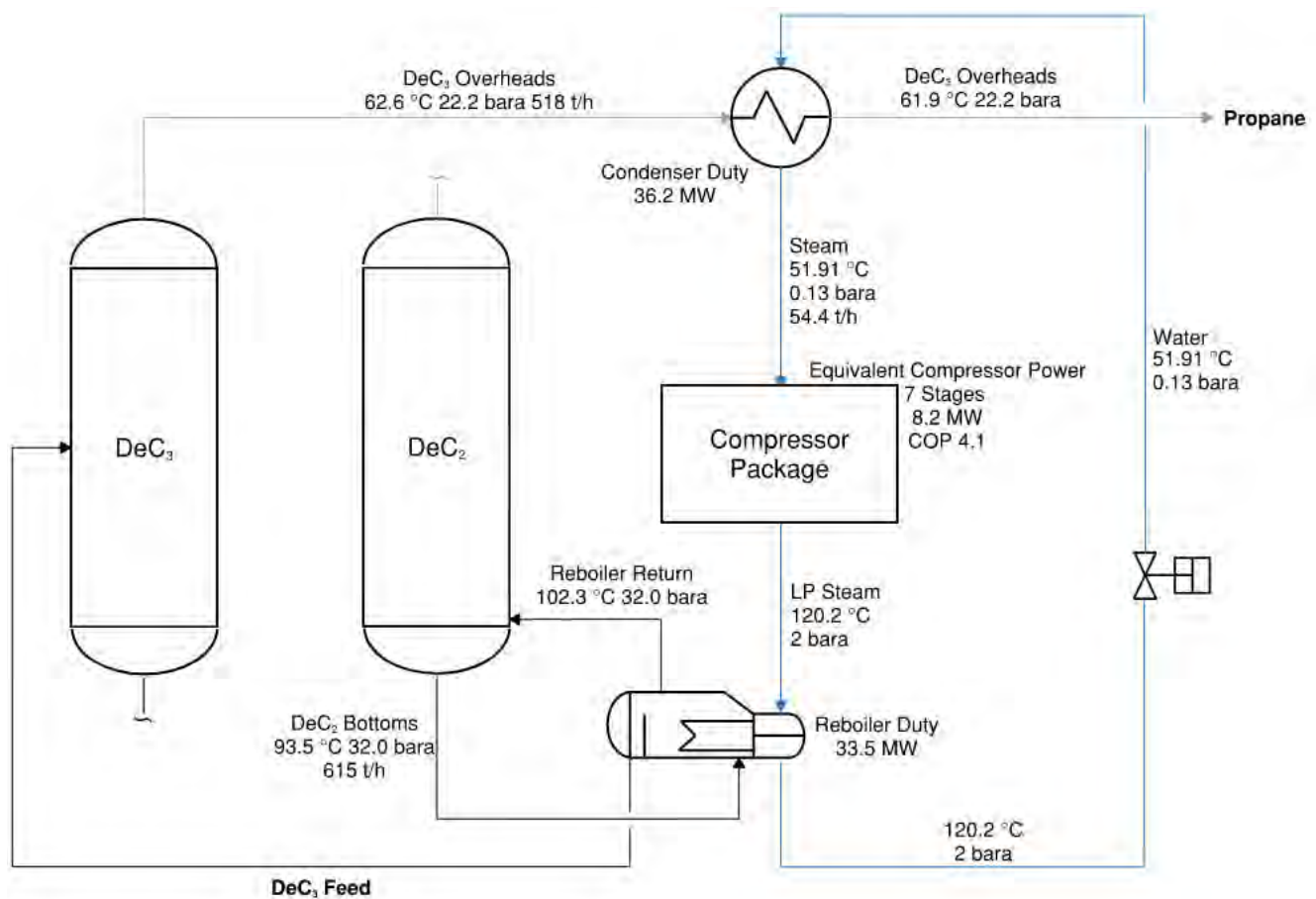
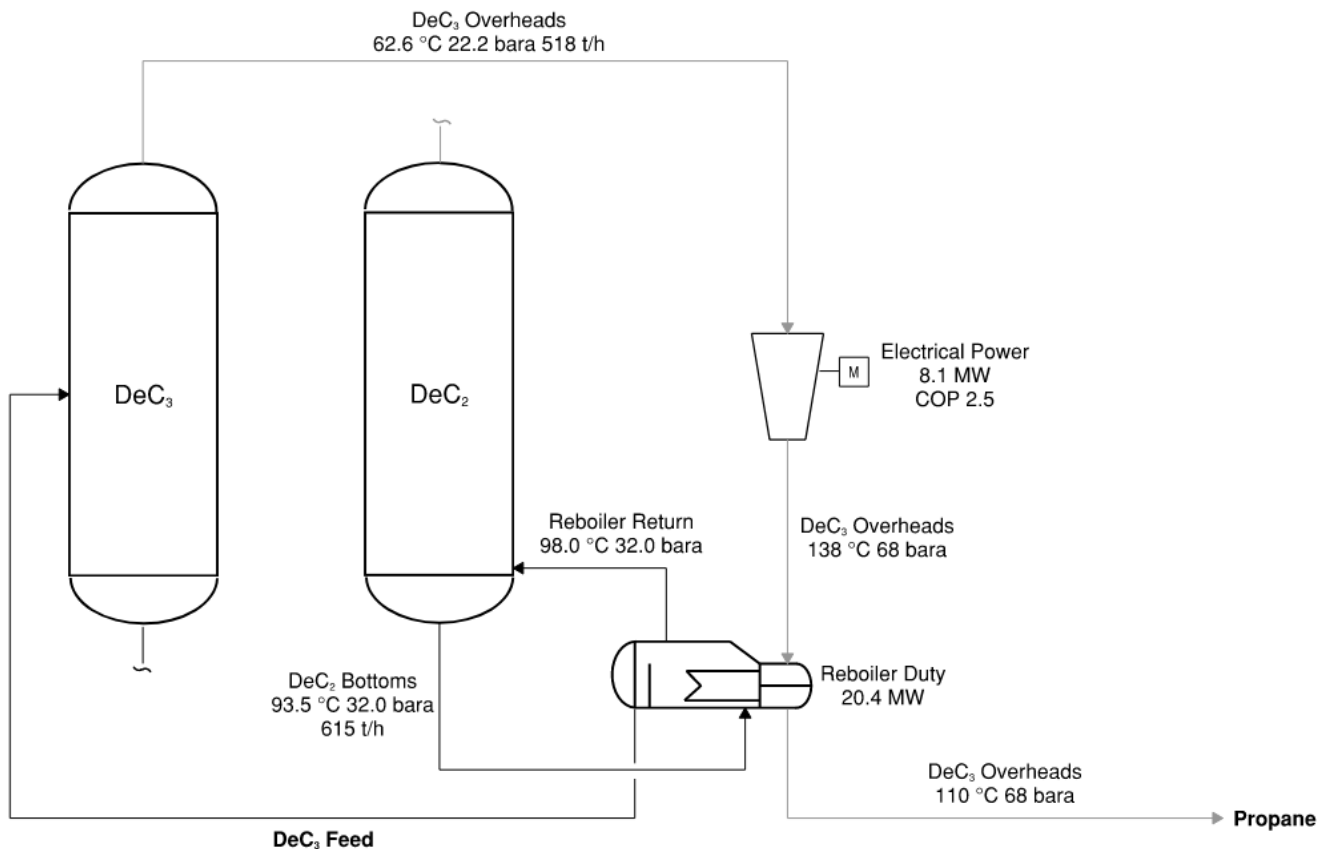


Figure 34 De-Ethaniser Reboiler Open Loop Example Application Schematic



7.5.2 EQUIPMENT AND ELECTRICAL INFRASTRUCTURE

The n-butane heat pump is expected to be supplied as a package by a vendor, with heat transfer fluid loops and replacement reboiler and condenser being supplied by the project separately.

The water-loop compression train is anticipated to be supplied by a single vendor, including motors and variable speed drives. The connecting pipe runs and exchangers are expected to be additional project items to be included in the overall design. Again, for this solution, the first stage compressor suction pipework and rotating equipment sizing are large, hence vendor sizing of the train was received. A suction pipework diameter of 1.5 m could be required using typical velocity criteria.

Direct compression of the de-propaniser overhead vapour would require a custom design with vendors only supplying the individual high-specification multi-stage compressor and reboiler. This process was not able to show a high COP in this instance or achieve complete replacement of the reboiler duty due to the lift required.

Additional electrical infrastructure would be required due to the increase in power required, hence expanded substations and transformers are allowed for.

7.5.3 PROJECT SCHEDULE

The project schedule is expected to be able to proceed alongside operating plant, with major tie ins during planned shutdowns. For all options, the project is anticipated to take ca. 3 years from FEED to Ready-For-Start-Up with sufficient turnaround planning.

7.5.4 PROJECT RISKS AND IMPLEMENTATION DIFFICULTY

Complexity of control is increased for all of the heat pump options and additional training requirements are anticipated. Utilisation of steam as the working fluid for the water-loop enables supplemental or start-up steam from an external supply to be used in the reboiler, whereas the other solutions may need to rely on a backup steam reboiler being in place.

Space requirements are significant for all options, but particularly for the water-loop solution due to the large pipework and individual compressor stages.

7.5.5 PROJECT COSTS AND ECONOMICS

Summary of Project Cost and Economics shows the key project economic drivers and economic results. NPV and IRR are attractive for all options. The open loop COP and reduced duty replacement worsen its overall economics. The relatively high cost of the vendor-supplied n-butane closed loop system also reduces its economics compared with the cheaper compression train employed in the water-based system, which also benefits from the highest COP.

Breakeven emissions pricing required is shown to be relatively low for all options, with the water closed loop indicating no emissions pricing support required.

7.6 D3: FCC Propylene Splitter Reboiler

7.6.1 PROCESS DESCRIPTION

Where downstream operations include separation of polymer-grade propylene from propane, the splitter column requires a very large duty and reflux. This typically uses LP steam as the heat source, alongside various other integrations with hot water or oil circuits.

Overhead and reboiler temperatures are typically much closer than most distillation columns, which incentivises heat pump application due to the low-lift requirement. The representative example requires 66.6 MW of heat, which is matched by the overhead duty of the same column at low temperature difference.

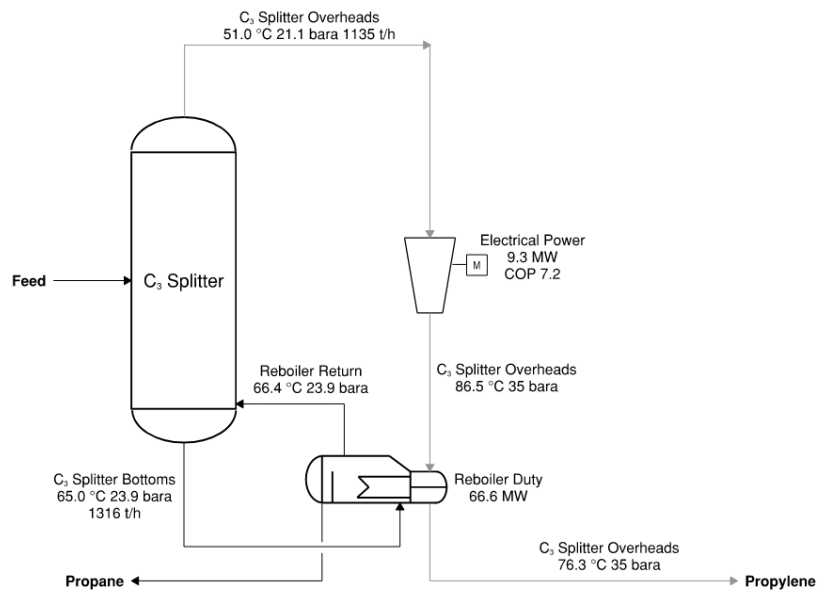
Table 16 Summary of Project Cost and Economics

Parameter	n-Butane Closed Loop	Water Closed Loop	Open Loop
Thermal Output Power (MW)	33.5	33.5	20.4
Electrical Input Power (MW)	10.1	8.2	8.1
COP	3.3	4.1	2.5
CO _{2eq} Emissions Abated (t/h)	9.8	9.9	5.9
Fuel Use Avoided (MW)	41.9	41.9	25.5
Estimated Capital Cost (MMUSD)	49.3	27.2	35.4
NPV (MMUSD)	37.2	64.4	12.0
IRR (%)	16%	27%	13%
Breakeven CO ₂ Price (USD/tCO _{2eq})	29	-21	61

This is a known industrially applied example, though application to these columns remains rare.

Though water-loop heat pumps could theoretically be employed, the very high duty and low required suction pressure is likely to result in technical challenges. COP was shown to be improved by 0.9 from a water closed loop to an open loop where the overhead is compressed before exchanging with the reboiler. An open loop system was therefore selected for analysis as shown in [Figure 35](#).

Figure 35 FCC Propylene Splitter Reboiler Example Application Schematic



7.6.2 EQUIPMENT AND ELECTRICAL INFRASTRUCTURE

This process would require a custom design with vendors only supplying the individual high-specification multi-stage compressor and reboiler. Due to the economics of achieving a close approach temperature in the reboiler, reducing the size and power consumption of the compressor, this is expected to be a focus area of the design with a significant part of the investment applied to the reboiler equipment.

Additional electrical infrastructure would be required due to the increase in power required, hence expanded substations and transformers are allowed for.

7.6.3 PROJECT SCHEDULE

The project schedule is expected to be able to proceed alongside operating plant, with major tie ins during planned shutdowns. The project is anticipated to take ca. 3 years from FEED to Ready-For-Start-Up with sufficient turnaround planning.

7.6.4 PROJECT RISKS AND IMPLEMENTATION DIFFICULTY

Operational difficulty is increased with this technology as the overhead duty is linked with the reboiler. Adjustment of the quantity of overhead vapour routed to the compressor allows further control, but a steam reboiler is likely to be required for trip and startup scenarios.

7.6.5 PROJECT COSTS AND ECONOMICS

Summary of Project Cost and Economics shows the key project economic drivers and economic results. NPV is very high due to the scale of application. IRR is also very favourable over the project duration, accounting for a very high COP and relatively high CAPEX efficiency. Breakeven emissions pricing is negative, indicating that CO₂ reduction benefits are not required to produce positive economics.

Table 17 Summary of Project Cost and Economics

Parameter	Value
Thermal Output Power (MW)	66.6
Electrical Input Power (MW)	9.3
COP	7.2
CO _{2eq} Emissions Abated (t/h)	19.8
Fuel Use Avoided (MW)	83.3
Estimated Capital Cost (MMUSD)	59.0
NPV (MMUSD)	142.9
IRR (%)	28
Breakeven CO ₂ Price (USD/tCO _{2eq})	-33

7.7 D4: SCU De-Octaniser Steam Reboiler

7.7.1 PROCESS DESCRIPTION

The steam cracking unit in olefins production incorporates many distillation operations. The de-octaniser column has been chosen as an example of a very high lift requirement, necessitating a very high lift technology.

The reboiler requires 8 MW of duty in this example, which can be met by the overhead waste heat of the same column. However, the lift requirement is well in excess of 100°C which would require a more novel approach of heat pump technologies.

A Stirling cycle in collaboration with a vendor has been applied to this requirement in this analysis to determine the economic results against other, lower lift applications.

7.7.2 EQUIPMENT AND ELECTRICAL INFRASTRUCTURE

The heat pump system for this technology is deployed in a modular arrangement whereby ca. 0.5 MW thermal output units, each attached to a motor, are duplicated to achieve the required duty. In the example case, the output per unit is between 400–500 kW, requiring ca. 20 units to be installed.

Heat exchangers are also required to allow indirect heat exchange with the process.

Additional electrical infrastructure would be required due to the increase in power required, hence expanded substations and transformers are allowed for.

7.7.3 PROJECT SCHEDULE

Due to the modular nature of the technology, the project duration should be relatively short with RFSU within 3 years from FEED commencement.

7.7.4 PROJECT RISKS AND IMPLEMENTATION DIFFICULTY

The technology is relatively unproven at scale, and installing so many parallel systems may be infeasible or highly complex from a hydraulics and layout perspective. Operation is not expected to be complex, but maintenance is specialised and requires vendor support.

7.7.5 PROJECT COSTS AND ECONOMICS

[Summary of Project Cost and Economics](#) shows the key project economic drivers and economic results. NPV is negative over the project horizon to 2060, with IRR well below the typical threshold of 10%. This is due to a low CAPEX efficiency and very low COP for a heat pump technology. The emissions pricing requirement for breakeven NPV is shown to be very high.

7.8 SI: LP Steam Generation

7.8.1 PROCESS DESCRIPTION

LP steam generation via a heat pump is an attractive option where a site has the ability to consume lower-level steam. The representative High Complexity Refinery has significant LP steam shortage, hence would be a good candidate for on-purpose LP steam production. Where sites currently are LP steam long and utilising backpressure turbines exhausting to the low pressure steam network, there can be a synergy with electrifying these compressor drivers to reduce the quantity of LP steam produced.

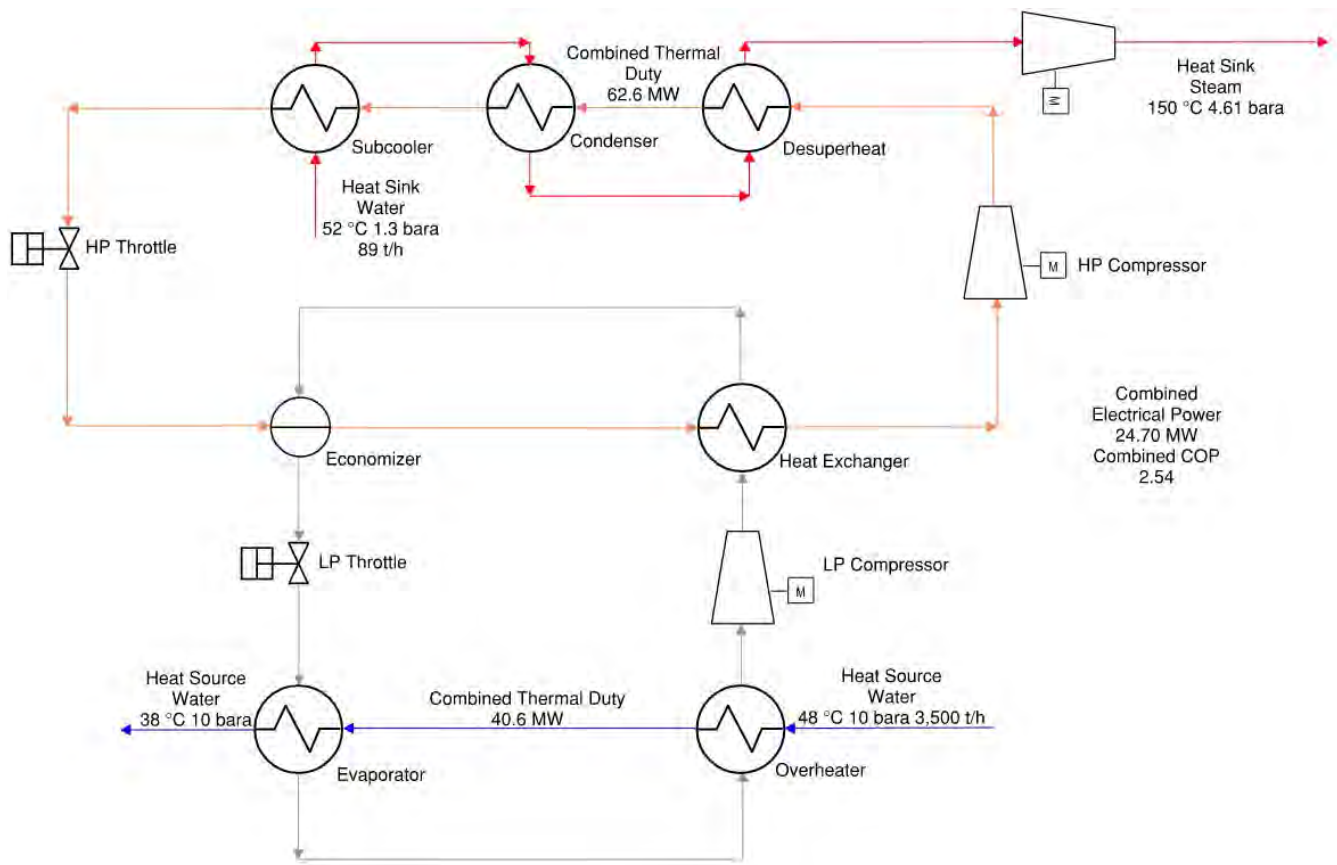
Table 18 Summary of Project Cost and Economics

Parameter	Value
Thermal Output Power (MW)	7.6
Electrical Input Power (MW)	5.3
COP	1.4
CO _{2eq} Emissions Abated (t/h)	2.15
Fuel Use Avoided (MW)	9.5
Estimated Capital Cost (MMUSD)	45.0
NPV (MMUSD)	-33.3
IRR (%)	1
Breakeven CO ₂ Price (USD/tCO _{2eq})	379

Vendor feedback was positive on this type of system, which also benefits from the ability to centralise heat pumps outside the process units and use large flows of cooling water return as a heat source, as well as other waste heat if available and convenient.

A 2-stage ammonia cycle with an economiser and post-compression was selected with vendor collaboration to enable the greatest efficiency of COP and CAPEX. Ammonia was preferred from an equipment sizing perspective due to its high-power density and low flow rates.

Figure 36 LP Steam Generation Example Application Schematic



Application to a heat duty of 62.6 MW, raising 150°C LP steam from a heat source of cooling water return is analysed in the following.

7.8.2 EQUIPMENT AND ELECTRICAL INFRASTRUCTURE

No additional exchangers or heat transfer circuits are anticipated as both sides already exchange against water. The vendor-supplied unit incorporates a single multi-stage compressor, hence the overall footprint is relatively small.

Additional electrical infrastructure would be required due to the increase in power required, hence expanded substations and transformers are allowed for.

7.8.3 PROJECT SCHEDULE

Tie ins to the cooling water and steam system likely require a maintenance shutdown, hence site turnaround timing would be a factor in the schedule. Considering the proportion of vendor-package equipment, completion is expected well within 3 years.

7.8.4 PROJECT RISKS AND IMPLEMENTATION DIFFICULTY

An additional benefit to operation with the system is a cooler water return, which could help to debottleneck the site systems in some cases.

Operation and maintenance would require training but is expected to be within the equipment experience of a utilities area.

The heat pump is a package unit supplied by the vendor, though would be custom designed at this scale.

7.8.5 PROJECT COSTS AND ECONOMICS

Table 19 shows the key project economic drivers and economic results for both the heat pump technology described above and for an alternative electrode boiler delivering equal duty.

The heat pump shows strong economics for this application despite a high capital cost and mediocre COP due to the moderate lift required. By comparison, the electrode boiler is much cheaper, but results in a lower NPV and slightly lower IRR over the project due to a much greater power consumption.

Table 19 Summary of Project Cost and Economics

Parameter	Heat Pump (Ammonia, post Compression)	Electrode Boiler
Thermal Output Power (MW)	62.6	62.6
Electrical Input Power (MW)	24.6	62.6
COP	2.5	1.0
CO _{2eq} Emissions Abated (t/h)	18.2	17.3
Fuel Use Avoided (MW)	78.3	78.3
Estimated Capital Cost (MMUSD)	72.8	14.9
NPV (MMUSD)	72.6	27.8
IRR (%)	18	16
Breakeven CO ₂ Price (USD/tCO _{2eq})	25	70

7.9 Summary

The following table summarises the example heat pump applications that were evaluated in this study:

Table 20 Summary of Cases

Case	Heat Source and Sink	Heat Pump Technology	Refrigerant	Thermal Duty (MW)	COP	CO ₂ Abated (t/h)	Estimated CAPEX (MMUSD)	CAPEX/ Thermal Duty Efficiency (\$/kW)	CAPEX/CO ₂ Efficiency (MMUSD/tCO ₂)	IRR (%)
U1	Offshore Crude Heating From Seawater	Multi-cycle	R600 (n-Butane)	7.0	3.0	2.0	22.2	3176	10.9	8%
U2	Crude Stabilisation From Compressor Coolers	Steam Compression – Closed Loop	R718 (Water)	8.9	4.2	2.6	14.5	1624	5.5	16%
U4	Hot Water Flood From Air/Other Ambient	Single Stage	R600 (n-Butane)	20.0	3.0	5.8	33.4	1672	5.7	14%
M1	De-Ethaniser Reboiler from	Single Stage	R600 (n-Butane)	33.5	3.3	9.8	49.3	1471	5.0	16%
M1	De-Propaniser Overheads	Single Stage	R718 (Water)	33.5	4.1	9.9	27.2	811	2.8	27%
M1		MVR – Open Loop	-	20.4	2.5	5.9	35.4	1734	6.0	13%
D3	Propylene Splitter	MVR – Open Loop	-	66.6	7.2	19.8	59.0	885	3.0	28%
D4	Deoctaniser	Stirling	R704 (Helium)	7.6	1.4	2.15	45.0	5920	20.9	1%
S1	Steam Generation From Refinery Cooling Water Return	Two-stage with Economiser	R717 (Ammonia)	62.6	2.5	18.2	72.8	1163	4.0	18%

8 Conclusions

A wide variety of heat pump technologies have been reviewed, followed by identification and ranking of promising areas across oil and gas assets. Example project analyses, supplemented by vendor feedback, provided insight into the limitations of some of the applications and technologies.

Very high lift heat pumps beyond 100°C of lift remain relatively small scale and economically unattractive against larger, lower lift applications. The exception to this is steam production whereby post-heat pump compression can be employed relatively cheaply, maintaining a reasonable COP.

Closed-loop heat pumps are well proven to ca. 135°C supply temperature. Bespoke process designs utilizing process industry compressors are specified at duties above ca. 7 MW with much industry experience in similar large compressors. Refrigerant choice is also highly dependent on heat pump outlet temperature, with little vendor experience above 150°C. Sink temperatures of up to ca. 135°C are expected to be achievable from ambient or other low-grade sources, generally requiring a closed loop refrigerant cycle to enable extraction of heat at low temperature.

Applications for up to 230°C outlet temperature can be obtained with an MVR system provided with a heat source of sufficiently high temperature such as column overheads. Stirling cycles, though currently restricted in scale per train, can achieve very high lift to provide outlet temperatures up to 250°C.

Utilisation of water and steam as the working fluid in a closed loop where appropriate was shown to produce an economic advantage via decreased CAPEX due to cheaper compression technology. Open-loop MVR was shown to be competitive in low-lift scenarios, with other closed loop refrigerant packages offering flexibility to low source temperatures.

Economic applications were found across the oil and gas system, with technology types selected based on the process requirements. The top economic performers were large columns that could be integrated with low or low-moderate lifts between overheads and reboilers.

Onshore upstream heating was shown to also have feasible economics and an attractive scale. Importantly, steam production from a centralised, cooling water return source was shown to be attractive and competitive against electrode boilers over the project life despite a much greater capital cost.

9 Appendix A: List of Heat Pump Applications

Area	Process Unit (Sink)	$T_{in}-T_{out}$ (Sink)°C	Source	$T_{in}-T_{out}$ (Source)°C	Lift°C	Duty (Sink) MW _{th}	COP (Estimated Maximum)
C3/C4 Splitter	Fractionation Column Reboiler	100–100	Condensing Propane	50–40	55	3.4	4.1
Sat Gas Plant / Treater / LPG separation	Fractionation Column Reboiler	70–70	Stripper Overhead Condenser + R/D AC	50–40	26	1.9	8.9
FCC Gasoline HDT	Splitter Reboiler	190–190	Splitter Overhead Condenser + Post- Condenser HX	100–60	106	5.9	1.9
FCC Gasoline HDT	Stabilizer Reboiler	190–190	Stabilizer Overhead Condenser + CW	130–50	102	2.6	2.0
Isom	Regenerant Vapouriser	50–160	-	300–50	0	1.1	10.0
Isom	Stabilizer Reboiler	180–180	Stabilizer Overhead Condenser + CW	90–40	111	9.2	1.8
Isom	Raffinate Column Reboiler	120–130	Column Overhead Condenser + CW	70–50	66	10.2	3.2
Isom	Extract Column Reboiler	130–130	Column Overhead Condenser + CW	70–50	72	4.9	2.9
Alky	Depropaniser Reboiler	110–110	Condensing Propane and Rundown HX	60–50	52	0.3	4.4
Alky	Deisobutaniser Reboiler	110–130	Condensing Butane and Rundown HX	70–40	63	13.9	3.4
Alky	Debutaniser Reboiler	170–190	Condensing Butane and Rundown HX	70–50	120	4.4	1.7
FCC	Stripper Steam Reboiler	90–110	Absorber Overhead Condenser	70–40	47	23.4	5.0
FCC	Debutanizer Reboiler	170–180	Overhead Condenser + CW	60–50	119	81.6	1.7
FCC	C3 Splitter Reboiler	70–70	Condensing Propane	50–50	15	89.2	10.0
Amine (SWS)	ARU Regen Reboiler	130–130	Overhead Condenser + R/D AC	100–60	49	40.9	4.7

Area	Process Unit (Sink)	$T_{in} - T_{out}$ (Sink)°C	Source	$T_{in} - T_{out}$ (Source)°C	Lift°C	Duty (Sink) MW_{th}	COP (Estimated Maximum)
Amine (SWS)	SWS Regen Reboiler	130–130	Overhead Condenser	40–30	96	13.6	2.1
SCU	H2S Stripper Reboiler	140–140	Column Overhead Condenser + CW	110–40	62	4.7	3.5
SCU	Depentaniser Reboiler	130–130	Column Overhead Condenser + CW	70–50	69	8.1	3.0
SCU	Depentanizer Reboiler	150–150	Column Overhead Condenser + CW	110–50	70	4.8	3.0
SCU	Deoctaniser Reboiler	180–180	Column Overhead Condenser + CW	90–40	115	7.6	1.7
SCU	Process Water Stripper Reboiler	120–120	Cooling Water Return	50–40	72	10.2	2.9
SCU	Medium Gasoline Heater	110–130	Cooling Water Return	50–40	80	2.1	2.5
SCU	Cold Flare Methanol Vapouriser	120–120	Cooling Water Return	50–40	74	18.3	2.8
SCU	Amine Stripper Reboiler	130–130	Column Overhead Condenser + CW	110–50	55	61.8	4.1
SCU	HP Depropaniser Reboiler	80–80	Condensing Propane	70–70	11	11.7	10.0
SCU	LP Depropaniser Reboiler	80–80	Condensing Propane	0–20	89	12.1	2.3
SCU	Debutaniser Reboiler	130–130	Condensing Butane + CW	50–50	80	11.9	2.6
LLDPE	Butene Reboiler	40–40	Column Overhead Condenser	40–40	2	0.2	10.0
LLDPE	Hexene Reboiler	100–100	Column Overhead Condenser	100–100	2	0.4	10.0
LLDPE	Nitrogen Pre-heater	30–100	Cooling Water Return	50–40	22	0.4	10.1
LLDPE	ICA Reboiler	60–60	Column Overhead Condenser	60–60	2	0.1	10.0
PP	Gas Polymerisation Heater	40–90	Cooling Water Return	50–40	22	0.5	10.1
PP	After Treatment Jacket Heater	Ambient–90	Cooling Water Return	50–40	15	0.1	10.0
Aromatics	Reformate Splitter Reboiler	190–190	Column Overhead Condenser	120–90	89	7.0	2.3
Aromatics	ED Column Reboiler	160–170	Column Overhead Condenser	100–80	74	5.6	2.8

Area	Process Unit (Sink)	$T_{in} - T_{out}$ (Sink)°C	Source	$T_{in} - T_{out}$ (Source)°C	Lift°C	Duty (Sink) MW_{th}	COP (Estimated Maximum)
Aromatics	Stripper Column Reboiler	180–190	Column Overhead Condenser	70–60	124	3.4	1.6
Upstream	Offshore Oil Heating	50–70	Environmental (Seawater)	20–0	50	7.0	4.6
Upstream	GOSP Crude Stabiliser Reboiler	70–80	Compression Coolers	130–50	10	8.0	10.0
Upstream	Remote Unconventional Field	75	Environmental (Water)	25	63	20.0	3.4
Upstream	Heavy Oil Hot Water Flood	75	Environmental (Water)	25	63	20.0	3.4
Midstream	DeC2 Steam Reboiler	90–100	DeC3 Overhead Condenser	60–60	35	34.0	7.0
Midstream	DeC3 Steam Reboiler	140–150	Column Overhead Condenser	60–60	79	55.0	2.6
Midstream	DeC4 Steam Reboiler	130–140	Column Overhead Condenser	70–60	67	26.0	3.2
Midstream	Amine Regenerator	130–130	Column Overhead Condenser + R/D HX	100–60	49	100.0	4.7

10 Appendix B: Pricesets Used

	"High" Scenario Power Cost (\$/MWh)	"High" Scenario Natural Gas Cost (\$/MWh)	"Medium" Scenario CO ₂ Cost (\$/t)
2024	69.6	32.2	44.0
2025	65.0	30.5	50.0
2026	62.0	28.6	53.0
2027	59.6	28.0	56.0
2028	57.6	27.5	59.0
2029	55.1	27.5	62.0
2030	53.4	27.3	65.0
2031	51.8	27.6	69.0
2032	50.1	27.3	72.0
2033	48.6	27.3	74.0
2034	47.2	27.4	77.0
2035	46.2	27.0	80.0
2036	45.7	24.7	84.0
2037	45.0	24.6	88.0
2038	44.2	24.5	92.0
2039	43.3	24.3	96.0
2040	42.8	24.1	100.0
2041	42.3	24.1	106.0
2042	41.8	24.0	112.0
2043	41.4	23.9	120.0
2044	40.9	23.9	130.0
2045	40.6	23.9	140.0
2046	40.1	23.8	150.0
2047	39.8	23.8	162.0
2048	39.3	23.7	174.0
2049	39.1	23.7	187.0
2050	38.8	23.7	200.0
2051	38.8	23.5	212.0
2052	38.8	23.4	224.7
2053	38.8	23.3	238.2
2054	38.8	23.3	252.5
2055	38.8	23.2	267.6
2056	38.8	23.1	283.6
2057	38.8	23.1	300.7
2058	38.8	23.0	318.7
2059	38.8	22.9	337.8
2060	38.8	22.8	358.1

Original sources for price progressions:

Power	BloombergNEF, "LCOE Prices, Tariffs & Auctions 2023," BloombergNEF, 2023. [Online]. Available: https://about.bnef.com/ .
Natural Gas	BloombergNEF, "Natural Gas Prices 2023," BloombergNEF, 2023. [Online]. Available: https://about.bnef.com/ .
Emissions	O. Richters, "NGFS Climate Scenarios Data Set," Zenodo, November 2023. [Online]. Available: doi: 10.5281/zenodo.10079020.

Description of selection and processing is provided in OGI report: "Refining Industry Electrification Economics".



ogci.com | partner website if applies

Copyright © 2025 The Oil and Gas Climate Initiative

The Oil and Gas Climate Initiative has tried to make the information in this publication as accurate as possible. However, it does not guarantee that the information in this publication is totally reliable, accurate or complete. Therefore, the information in this publication should not be relied upon when making an investment or commercial decisions, it is intended to provide general guidance only.

All figures included in this publication are stated on an estimated basis unless referenced. This publication is not designed to provide legal or other advice, nor should it be relied upon as a substitute for appropriate technical expertise or professional advice. The responsibility for the interpretation and use of this publication lies with the user and in no event will OGCI or any of its members past, present or future, regardless of their negligence, assume liability for any foreseeable or unforeseeable use made thereof, which liability is hereby excluded. Consequently, such use is at the recipient's own risk on the basis that any use by the recipient constitutes agreement to the terms of this disclaimer. This disclaimer should be construed in accordance with English law.

All discussions and work within OGCI are conducted in accordance with anti-trust competition law principles. OGCI has implemented measures to ensure that all activities are compliant with competition laws, and all involved are trained and vigilant at all times to ensure such compliance.