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DECARBONISATION THROUGH INNOVATION

# High temperature heat pumps and steam compressors: a combined pathway to decarbonize chemical industry processes

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**Abstract**

The chemical industry is one of the largest industrial consumers of industrial heat, with a significant share of its energy demand dedicated to steam production for processes such as drying, distillation, evaporation and stripping. Traditionally, this steam is generated by fossil-fuel-fired boilers, representing a major source of $CO_2$ emissions and increasing operating costs. To meet decarbonization targets and improve energy efficiency, the steam electrification through steam generation & high-temperature heat pumps (SGHPs) is emerging as the most promising & economically viable solution.

This paper presents an innovative approach combining a standard range of steam-generating heat pump (SGHP) with steam compressors (SC) to electrify the steam production in chemical plants using low-grade industrial waste heat (30–90 °C) generated by these processes. The system is designed to produce steam up to 230°C, covering a wide range of typical chemical processes.

This work focuses on an application achieving COP of 3 featuring a high-performance centrifugal compressor. It includes an assessment of capital and operational expenditures, payback periods, and sensitivity analyses under varying electricity prices and carbon costs.

The studied SGHP + SC solution shows the potential for over 2,000 $tCO_2$/year avoided per MW. Beyond the environmental benefits, the findings underscore the economic viability of high-efficiency SGHPs in industrial applications, particularly in regions with favorable electricity-to-gas price ratios and strong climate policy incentives, with short payback periods compatible with industrial investment cycles. The paper concludes with recommendations for deployment strategies and policy frameworks to accelerate the adoption of SGHPs in hard-to-abate industrial sectors.

The presented architecture offers a scalable and replicable pathway for the deep decarbonization of process heat in the chemical sector, enabling a shift from fossil-based steam to high-efficiency, electrified systems.

*Keywords: Steam-generating heat pump ; mechanical vapor recompression ; chemical industry ; decarbonization*

## 1. Introduction

Industrial heat represents nearly two-thirds of global industrial energy demand. In EU only, industrial process heat at 100-200 °C, mainly used in the food, paper and chemical industries, accounts for 270 TWh/year and is 77% of it is produced by burning fossil fuels. [1], [2]

Chemical industry is one of the major process heat consumers, estimated to 35 TWh/year in EU-28[3]. It uses mainly steam from 1 to 10 barG (120 to 185 °C saturation temperature) serving as a heating medium for reactors, reboilers, dryers or injected in direct steam stripping processes or cleaning applications [4]. In all these processes, the major part of heat ends up as low-grade waste heat (30 – 90 °C), generally cooled by water loops and dissipated into atmosphere, consuming both electrical power for the pumps and fans, and water in evaporative cooling towers. Instead, they can be efficiently used to generate high-temperature useful heat to feed the same processes.

These processes can operate in continuous, long and short batch mode, with stringent reliability and thermal stability requirements. Despite its desire to decrease the reliance of the sector on fossil sources, steam is still

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predominantly produced by natural gas boilers, making process heat one of the most strategic sectors to decarbonize.

Among the available technologies, Steam Generating Heat Pumps (SGHPs) and Steam Compressors (SC) stand out as the best alternatives to reduce both energy consumption and emissions of greenhouse gases, compared to conventional fossil fuel boilers. SGHP are able to recover and upgrade low-grade waste heat (30 – 90 °C) from condensers, process effluents, or cooling loops into useful heat in form of steam, while SC are widely used in Mechanical Vapor Recompression (MVR) applications to upgrade steam pressure within evaporation or distillation steps.

However, both technologies face inherent operational boundaries that restrict their applicability over the full temperature range of chemical processes. Steam compressors require sufficiently high suction pressure to ensure adequate vapor density and avoid too many compression stages for effective control and cost-efficiency. Below 60 °C, the vapor becomes too dilute for efficient compression, leading to oversized and costly systems. Conversely, SGHPs using high-temperature and non-flammable refrigerants such as R1233zd(E) are limited by the refrigerant's critical and decomposition temperatures. Thermal stability issues around 150 °C prevent operation beyond 140 °C, thereby restricting direct steam generation at the required pressure by chemical processes. In both cases, achieving larger temperature lifts often requires complex multi-stage compression architectures (more than 2 compressors for SGHPs and more than 5 steam compressors), raising system cost and control complexity.

This study proposes an innovative hybrid architecture combining a Steam-Generating Heat Pump (SGHP) with Steam Compressors (SC) to overcome these limitations. The combined system allows addressing both the abundant low-grade industrial waste heat (30–90 °C) and industrial steam needs up to 20 barA and 230 °C, while efficiently electrifying and decarbonizing the process heat generation.

## 2. Methods

### *2.1. Description of the SGHP + SC architecture*

The studied SGHP + SC architecture (Fig. 1) features:

- A heat recovery exchanger; recovers heat from the resource by heating water
- A water loop, that transfers the heat from heat source to the SGHP
- SGHP that includes:
    - low GWP and non-flammable HFO refrigerant R1233ZD(E)
    - an evaporator; evaporates low pressure liquid refrigerant by cooling down water loop
    - 2 stages of high efficiency centrifugal compressors
    - a condenser / direct steam generator; condensate high pressure refrigerant while generating low pressure steam
- a train of *n* Steam Compressors (SC) in series; compresses steam to feed steam network adapted to the chemical process (up to 20 barG)

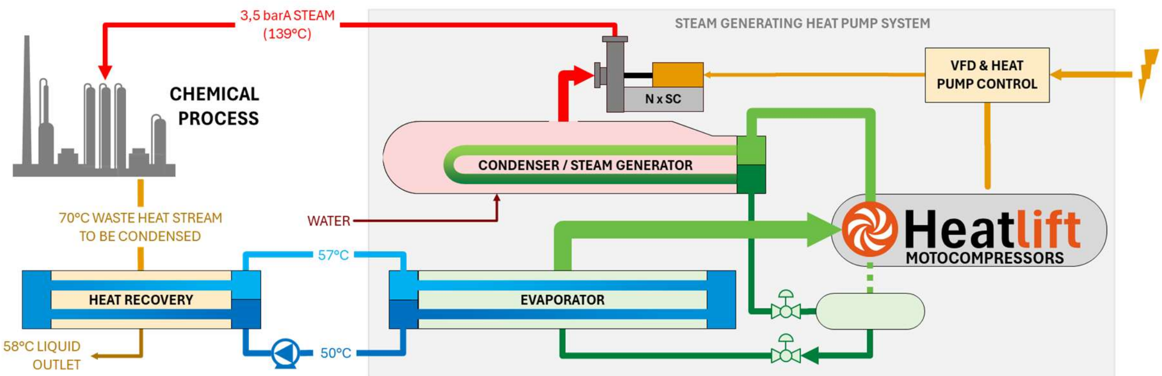



*Figure 1: Diagram of SGHP + SC architecture*

The performances and technical characteristics of this architecture, heat exchangers and centrifugal compressors were evaluated by internal tools developed by Heatlift engineering department.

### *2.2. Case study description*

This work details the performances of the SGHP+SC solution, applied for the replacement of a natural gas boiler used for a stripping process. Table 1 summarizes boundary parameters of the study.

Table 1. Case study boundary parameters

| | | |
|---|---|---|
| Heat source | Hydrocarbon inlet temperature | 70°C |
| | Hydrocarbon outlet temperature | 58°C |
| Heat sink | Water inlet temperature | 20°C |
| | Steam outlet pressure | 3.5 barA |
| | Seam outlet temperature | 160°C |
| | Steam mass flow | 6.17 tph |
| Economic indicators | Natural (fossil) gas cost (excl. $CO_2$) | 50 €/MWh LCV |
| | Electrical power cost | 100 €/MWh |
| | Annual equivalent hours at full load | 8000 h/year |
| | Annual discount rate | 6% |
| Environmental indicators | Natural (fossil) gas CO2 emissions (incl. value chain) | 224 t/GWh |
| | Electricity CO2 emissions (incl. value chain) | 30 t/GWh [5] |
| | $CO_2$ cost | 80 €/t |

### *2.3. Main design parameters and techno-economic optima considered*

#### *2.3.1. Heat recovery and water loop*

Heat from hydrocarbons condensation is recovered through an intermediate water loop that transports this heat to the SGHP evaporator. Hot and cold temperatures of this loop are optimized as the best techno-economic compromise between heat recovery heat exchanger, SGHP evaporator, piping design, cost and the overall SGHP project performance.

Overall system performance depends on SGHP evaporation temperature, that is directly related to water loop cold outlet temperature and heat source (hydrocarbon steam) outlet temperature. A higher evaporation temperature increases the performance but increases the size (surface area) and cost of the heat exchangers.

Heat recovery exchangers total cost is generally higher than the SGHP evaporator, generally due to a more resistant metallurgy and a more complex on-site integration. At fixed performance and evaporation temperature, the overall project costs are optimized by increasing the water loop flowrate up to a certain limit related to piping size and costs. Consequently, heat recovery total costs decrease faster than the SGHP evaporator costs increase, leading to an optimized design. For this case study heat source, the optimized hot and cold temperatures for the water loop are given in table 2.

#### *2.3.2. Main process parameters*

The following main process parameters are considered for the study. They correspond to usual values for the studied equipment size and to a technical and economic optimum for heat exchangers.

Table 2. SGHP + SC main design parameters

| | | |
|---|---|---|
| Water loop | Temperature | 57°C / 50°C |
| Evaporator | Approach | 3K |
| Heat Pump Compressors | Stage number | 2 |
| | Isentropic efficiency | > 80% |
| Steam compressor | Isentropic Efficiency | 80% |
| Electrical equipment | Motor efficiency | 96% |
| | Variable Frequency Drive efficiency | 98% |
| Condenser | Approach | 8K |

## 3. Results and discussion

### *3.1. Steam evaporation temperature optimization*

The SGHP steam pressure is a degree of freedom characterizing the interface between the SGHP and the steam compressor. Determination of this temperature is critical to optimize system compactness and CAPEX.

SGHP's lift (difference between outlet steam saturated temperature and water loop outlet temperature), is directly related to the difference between the refrigerant condensing and saturating temperature. This lift is therefore limited by the maximum pressure ratio of the refrigerant compressors. To optimize the CAPEX and footprint of the SGHP, it is necessary to find the best compromise between a large SGHP lift, an efficient compression and a limited number of mechanical and electrical equipment. The refrigerant compression is limited to two stages for simplified mechanical architecture and CAPEX. The pressure ratio of each of the two compression stages is limited to achieve high aerodynamic performances. Based on aerodynamic design criteria from the literature ([6], [7]), the maximum pressure ratio of one single stage of refrigerant compression is 2.9.

After steam is generated at a low pressure, it is compressed by a train of SCs in series, with hot water sprayed at inlet or outlet of each of the SC to control steam superheating while increasing its mass flow. For reference, SC technical characteristics were based on typical steam compressors available on the market which reach a typical pressure ratio of 1.4 per stage in the selected range.

Figure 2 describes the refrigerant pressure ratio, steam pressure ratio, number of centrifugal compressor stages and number of steam compressor as a function of the steam evaporation temperature.

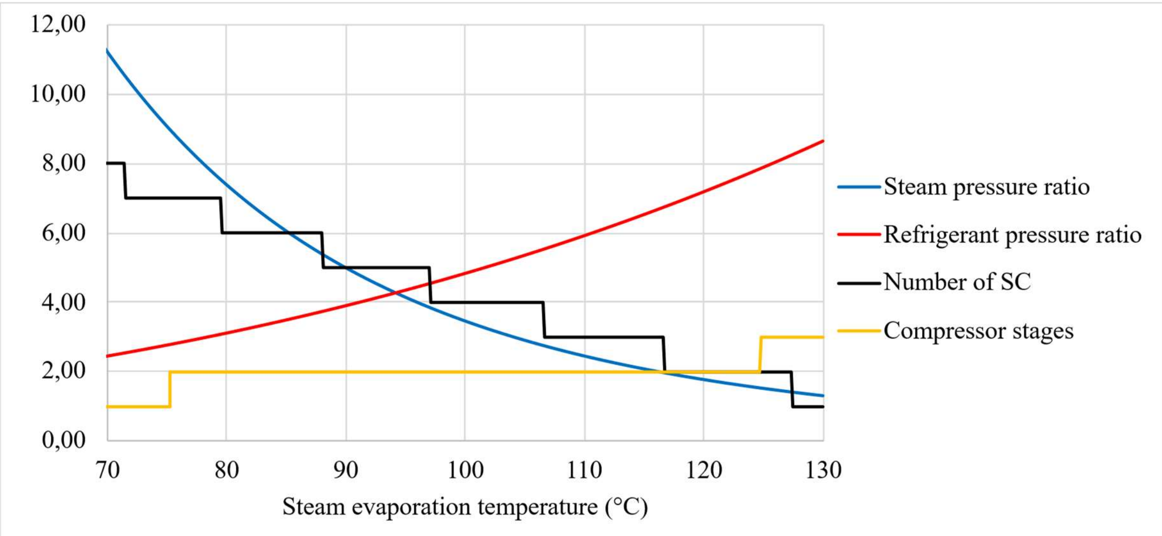



*Figure 2: Number of SGHP compressor stages and steam compressors as a function of steam evaporation temperature*

The SGHP + SC architecture is optimized with a steam evaporation temperature of 120°C, with respectively 2 stages of refrigerant compression and 2 steam compressors. For this temperature, each of the 2 SGHP compressors does a pressure ratio of 2.68, achieving a global pressure ratio of 7.18. Each of the two steam compressors does a temperature lift of 9.5K, raising steam pressure from 2 barA to 3.5 barA.

### *3.2. System performances and dimensions*

Table 3 and Figure 3 summarize the dimensions, performance, technical and economical characteristics of the solution for the case described in the previous section.

Table 3. System design characteristics and performances

| | | |
|---|---|---|
| Water loop | Temperature | 57°C / 50°C |
| Evaporator | Absorbed heat | 2946 kW |
| | Exchange surface | 620 m² |
| | Internal dimensions | 900 x 7500 mm |
| Compressors | Mechanical power | 1178 kW |
| | Electric power | 1277 kW |
| Condenser + preheater | Generated heat | 4124 kW |
| | Steam pressure / temperature | 2 barA / 120°C |
| | Steam mass flow | 6 tph |
| Steam compression | Number of SC *n* | 2 |
| | Temperature rise/stage | 9.5 / 9.4 K |
| | Power consumption /stage | 126 / 129 kW |
| System | Additional heat from mixture subcooling (feedwater preheating) | 265 kW |
| | Total recovered heat | 3 211 kW |
| | Total generated heat | 4 613 kW |
| | Total power consumption | 1542 kW |
| | Coefficient of Performance (COP) | 3.00 |
| Environmental KPI | $CO_2$ savings / year | 8826 t/year |
| Economic KPI | Estimated maintenance OPEx | 50 k€/year |
| | Return on investment | 3.7 years |
| | Internal Rate of Return (IRR) | 21.6 % |
| | Levelized Cost of Heat | 49 €/MWh |

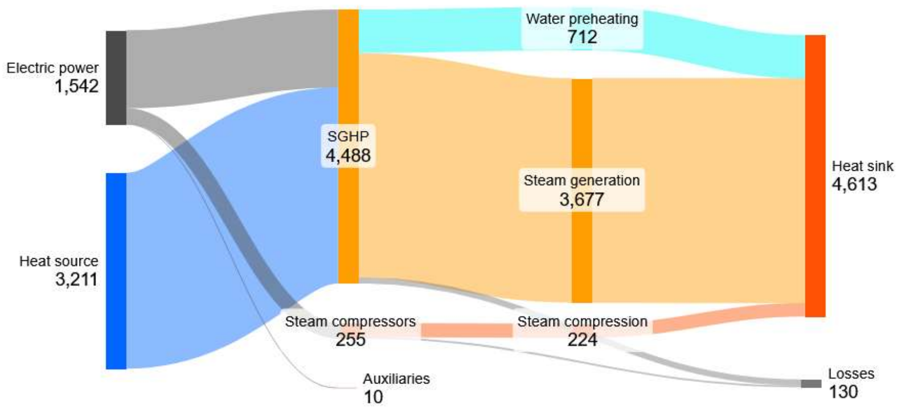



Figure 3: Energy balance of the SGHP + SC studied architecture

To maximize the system performance, it is crucial to preheat fresh water before the evaporator inlet. To this aim, exergy losses at heat exchangers are minimized by preheating water in two steps:

- from 20°C to 57°C directly with the heat source through the intermediate water loop: 265 kW
- from 57°C to its saturating temperature by subcooling the condensed SGHP working fluid: 447 kW

Electric power supplies centrifugal compressors (1277 kW) and steam compressors (255 kW) to generate 6.17 tons per hour of steam at 3.5 barA (4613 kW). Energy losses (130 kW) correspond to electric equipment losses and compressors mechanical losses. Overall system reaches a COP of 3.

### *3.3. Adapted architecture for direct heat generation*

The steam generated by the system is used in a dedicated low-pressure centralized network that distributes the steam to different users and processes. On chemical and petrochemical plants, this steam drives mainly stripping and distillation reboilers, evaporators, reactors and dryers operating.

On large industrial sites, Steam Generating Heat Pumps can be integrated into the process, directly driving the reboilers by generating steam directly in stripping columns and vapours for distillation columns. By generating heat directly at the required temperature, this alternative reduces the overall lift and the CAPEX by avoiding the intermediate steam loop. It increases significantly the overall COP up to 4.0 – 5.0, depending on the temperature difference between source and sink, but requires generally a more complex integration, site installation and operation. When feasible, direct integration should be preferred to maximize the project performance and economic viability.

### *3.4. Economic study and sensitivity analysis*

SGHPs are emerging as a competitive alternative to fossil-fuel boilers for industrial steam production. Natural-gas boilers, which still supply over 75% of Europe's process heat, remain attractive due to low CAPEX, reliability, and high-temperature steam delivery. However, their fossil dependence is increasingly incompatible with EU decarbonization targets, and rising carbon prices under the EU ETS are eroding their cost advantage.

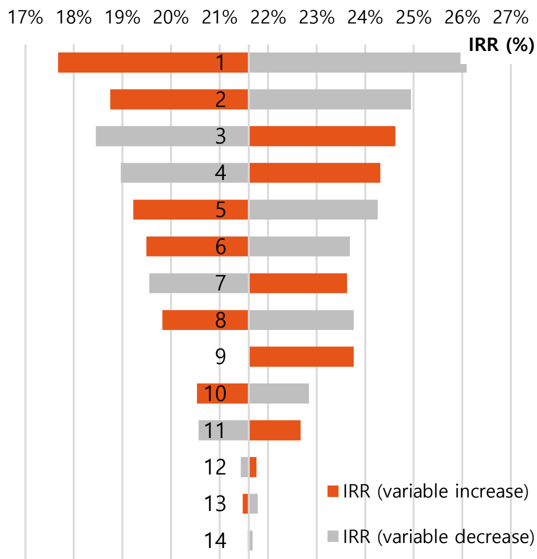
Since 2022, gas price volatility combined with carbon taxation has significantly increased the cost of gas-based heat. SGHPs, despite higher upfront investment, offer stable electricity-linked operating costs and 2–4× higher efficiency by valorising waste heat. When both efficiency and $CO_2$ pricing are included, electrified systems increasingly reach lower total cost of ownership.

SGHP economics primarily depend on the difference between COP and the power-to-gas cost ratio, typically 2-3 in markets where gas-fired plants set marginal electricity prices. As renewable penetration expands, electricity becomes cheaper and less volatile, continuously improving heat pump competitiveness. $CO_2$ prices around 100 €/t and extended to all industry increase by ~25€/MWh the gas heat, providing additional advantages to SGHP by significantly reducing the power-to-gas cost ratio.

The economic sensitivity on different parameters is summarized in Table 4 and is made for a comparison with an installed fossil gas boiler. Sensitivity is ordered by decreasing order and is expressed in % Internal Rate of Return for a given variation in hypothesis and a reference scenario. For example, a 10% increase in natural gas cost results in SGHP+SC IRR changing from 21.6% to 24.6%.

Table 4. Sensitivity analysis

| Rank | Inputs | Ref | VAR |
|---|---|---|---|
| 1 | P/G[1] cost ratio incl $CO_2$ | 1,51 | ±10% |
| 2 | P/G cost ratio | 2 | ±10% |
| 3 | Gas price | 50 €/MWh | ±10% |
| 4 | Cold source outlet temp. | 50 °C | ±10 °C |
| 5 | Heat sink temperature | 139 °C | ±10°C |
| 6 | Elec. Price | 100 €/MWh | ±10% |
| 7 | Eq. operation at full load | 8000 h/yr | ±10% |
| 8 | Cost index | 100 % | ±10% |
| 9 | Subsidies | 0 % | +10% |
| 10 | BOP / EXW CAPEX[2] | 70% | ±10% |
| 11 | $CO_2$ price | 80 €/t | ±10% |
| 12 | Lifetime | 20 yr | ±10% |
| 13 | Maintenance OPEX | 50 k€/yr | ±10% |
| 14 | Power $CO_2$ content | 30 kg/MWh | ±10% |




[1] P/G cost ratio : Power to gas cost ratio

[2] BOP : Balance of Plant or integration costs. It includes mechanical erection, electrical connection and all the other equipment, works and services in addition of the Ex-Works (EXW) CAPEX of the system. BOP CAPEX is expressed as % of EXW CAPEX.

### *3.5. Deployment strategy and policy framework*

The previous estimations conclude on the economic viability of Steam Generating Heat Pumps when compared to existing fossil fuel industrial boilers. SGHP offers an efficient electrification pathway to decarbonize Europe's industry, especially in sectors like chemicals but also food and pulp and paper.

Their deployment can be accelerated by supporting access to clean electricity, robust certification systems, and targeted incentives key policy actions that include:

- Extension of emission trading system to all industries impacts the P/G positively for SGHP
- Carbon Border Adjustment mechanism, compelling companies to decarbonize their supply chains and adopt cleaner technologies
- Providing financial and regulatory support for electrified technologies, prioritizing regions with cleaner grids and industries with mature electric alternatives.

With coordinated policies, Europe can lead in clean industrial heating technologies while advancing its climate and competitiveness goals.

## 4. Conclusion

This paper presents an innovative industrial heat pump architecture to decarbonize steam generation for chemical industry processes. By combining a steam-generating heat pump in series with steam compressors, it allows for efficient waste heat recovery below 60°C upcycled to generate useful steam for chemical processes. In the studied scenario, heat is recovered at 58°C and steam is generated at 3.5 barA. The system was found to be optimized in terms of cost, footprint and energy consumption by using two high-efficiency centrifugal compressors for the SGHP, generating steam at 120°C, in series with two steam compressors with a rise of 9.5K each. It includes a preheating of fresh water in two steps that minimize exergy losses to reach a COP of 3. Even in conservative gas-to-electricity price ratio and carbon cost scenarios, the system is found to be a competitive alternative to standard gas boilers.

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