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DECARBONISATION THROUGH INNOVATION

# Turning industrial waste heat into value – enabling carbon-free steam with steam compressor solutions

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**Abstract**

Industrial decarbonization requires viable solutions for replacing fossil-based process steam while maintaining high reliability and economic performance. A large share of industrial energy demand is released as low- to medium-temperature waste heat, which is still insufficiently utilized. Open-loop industrial heat pump systems based on mechanical vapor recompression (MVR) represent a technically mature option to upgrade such waste heat directly into usable process steam.

This applied research paper investigates the performance and applicability of an open-loop heat pump system using multi-stage radial compressors. After outlining the technical fundamentals and methodological framework, the paper presents a large-scale industrial use case currently under implementation at the BASF site in Ludwigshafen, Germany. The system converts waste heat from a steam cracker into carbon-free process steam with a thermal capacity of up to 50 MWth. Key performance indicators such as achievable temperature levels, coefficient of performance (COP), and scalability are discussed.

The results demonstrate that open-loop, multi-compressor heat pump systems can reliably generate high-temperature process steam (>200 °C) with competitive efficiency and represent a robust pathway for electrifying industrial steam supply.

*Keywords: industrial waste heat; heat pumps; mechanical vapor recompression; open heat pump systems; process steam;*

## 1. Introduction

Process heat accounts for the majority of industrial final energy consumption and is still predominantly generated using fossil fuels. In parallel, large quantities of waste heat are continuously discharged from industrial processes in the form of warm water, exhaust air, or low-pressure steam. From a technical perspective, this waste heat represents a recoverable energy resource that can significantly reduce primary energy demand when efficiently upgraded and reintegrated into production processes.

Industrial heat pumps provide a means to upgrade waste heat to higher temperature levels. While closed-loop systems using refrigerants are well suited for low-temperature applications, their efficiency and feasibility decrease with increasing target temperatures. In contrast, open-loop heat pump systems based on mechanical vapor recompression directly compress water vapor and are particularly suitable for large-scale industrial applications requiring process steam.

This paper focuses on the applied performance of open-loop heat pump systems employing multi-stage radial compressors. The objective is to assess their capability to deliver high-temperature process steam from industrial waste heat under real operating conditions, using a large-scale implementation at BASF Ludwigshafen as a representative use case.

*1.1. Motivation and drivers for decarbonization of industrial process heat*

The majority of industrial final energy consumption is attributed to process heat, which is still predominantly generated using fossil fuels. Therefore, the efficient use and sustainable provision of heat should be at the core of industrial decarbonization strategies. One key tool for this transformation is the utilization of industrial waste heat, which can significantly reduce the need for fossil fuels in the generation of process heat.

Waste heat is produced in nearly all thermal processes: When a paper mill releases steam into the air or a chemical plant discharges heated cooling water, valuable heat is lost that could otherwise be reused. In the EU, an estimated 20–50% of the energy used in industry is lost to the environment each year in the form of waste heat[1]. In addition to the thermal losses, energy is consumed by ventilation systems, cooling equipment, pumps, and other units to remove waste heat from production facilities. This represents a massive waste of valuable energy.

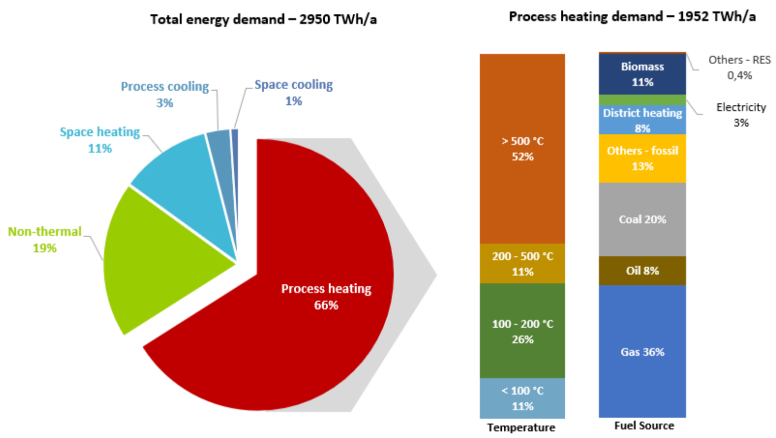


Figure 1 : Breakdown of total energy demand in European industry by general uses (left), process heat demand by temperature level (center) and energy source (right) (re = renewable energy sources). Adapted from [2 3]

*1.2. Potential of economically usable waste heat in Europe*

European industry possesses substantial untapped thermal resources. Recent studies confirm significant waste heat potential, the utilization of which could make an important contribution to the energy transition:

- Across the EU, the technical waste heat potential is estimated at 920 TWh per year, of which approximately 300 TWh are economically usable. This corresponds to 40% of the industrial process heat demand at temperatures below 200°C (see Fig. 2) or 10% of the heating demand of European residential buildings. [4 5]
- In Germany, the potential amounts to approximately 67 TWh per year (15% of industrial heat consumption), while in Austria it makes up around 34 TWh (approximately one third of the national heat demand). [6 7]

Modern heat pump and heat recovery systems now offer thoroughly developed technological solutions to harness these energy potentials in both ecologically and economically meaningful ways.

## 2. Technical Background and System Concept

Open-loop heat pump systems differ fundamentally from closed-loop systems by using water or steam as the working medium instead of a refrigerant. Waste heat is used to evaporate water under reduced pressure, generating low-pressure steam. This steam is then mechanically compressed to higher pressure and temperature levels and reused as a heat source for industrial processes.

In large industrial applications, multi-stage radial compressors are employed to achieve the required pressure lift with high efficiency. Compression is distributed across several stages, with intermediate cooling to limit steam superheating and reduce compression work. This configuration enables stable operation at high mass flow rates and moderate pressure ratios per stage, which is characteristic of many industrial waste heat sources.

From a thermodynamic perspective, the elimination of an intermediate refrigerant cycle reduces temperature differences during heat transfer and improves overall system efficiency. The achievable performance is primarily governed by the temperature level of the waste heat source, the required steam pressure, and the system scale.

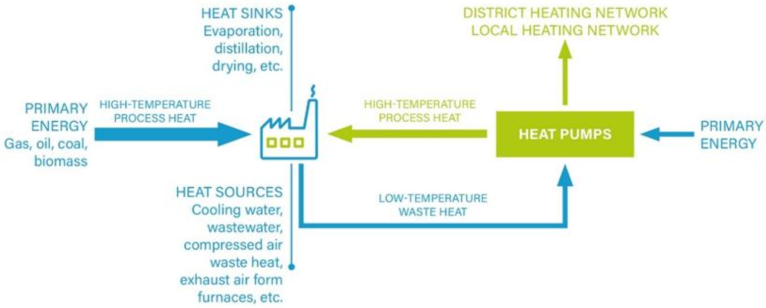


Figure 2: Industrial heat pumps regarding the application in waste heat utilization and waste heat recovery. © GKT

In open-loop heat pump systems, there is no typical refrigerant cycle. Instead, the medium from the waste heat source also serves as the working medium (steam), which is compressed to a higher pressure and temperature level. Alternatively, the energy from the waste heat source is transferred to the working medium (water), causing it to evaporate, after which it is compressed to the target pressure:

Since no refrigerant is used as an intermediate medium, the separate refrigerant cycle is eliminated, and only a single heat exchanger is required.

To efficiently achieve large pressure lifts, open-loop heat pump systems utilize multi-stage compression and intercooling:

- Pressure is increased step by step through a series of subsequent radial compressors.
- After each stage, an intercooling process takes place, to avoid overheating and maintain the saturated state of the steam.

The intercooling process reduces energy demand and is an essential advantage in efficiency compared to the complex and less effective cooling in closed systems.

Due to high performance and scalability, radial compressors are especially well-suited for large-scale industrial processes, in which large amounts of energy are transferred – whether in waste heat utilization, steam generation or providing process heat. Their efficiency and cost-effectiveness enable them to be key technology for sustainable industrial heat supply.

CompriVAP is a brand name of the company GKT and does not represent a conventional machine, rather it is an system that utilizes industrial waste heat sources to generate usable steam. The system operates as an open-loop heat pump.

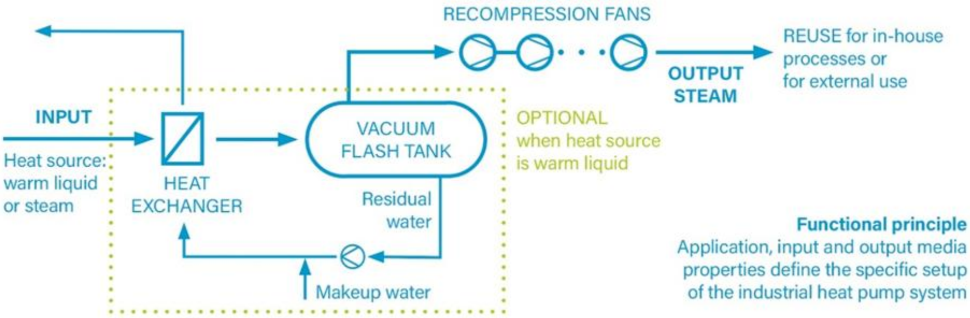


Figure 3: Simplified exemplary PFD of a CompriVAP system with a multi-stage radial compressor system. © GKT

The open-loop heat pump system is based on the well-established Mechanical Vapor Recompression (MVR) technology:

- Functional principle: Steam is mechanically compressed to a higher energy level using electrically driven compressors and can then be reused as a high-grade heat source.
- Water as the “refrigerant”: Water is used as the working medium, though ideally the waste heat source itself is directly utilized.
- Process stages: Depending on the heat source, heat exchangers and flash tanks as preceding process stages can be necessary in order to independently operate heat source and process steam.
- Reliability: All core machines and components are well-established systems, which have been field-proven and reliably deployed over decades.

## 3. Methodology

The applied research methodology used in this study is based on a system-level performance evaluation of an open-loop industrial heat pump under defined boundary conditions. The assessment includes:

- Definition of heat source characteristics (temperature level, thermal capacity, continuity)
- Description of the open-loop heat pump configuration, including evaporation, compression stages, and steam delivery
- Evaluation of key performance indicators, particularly thermal output, pressure and temperature levels, and coefficient of performance (COP)

The system concept allows for different configurations depending on heat source quality. When waste heat cannot be used directly, heat exchangers and flash tanks are applied to decouple the heat source from the steam cycle. The analysis focuses on steady-state full-load operation, which is representative for base-load industrial processes.

## 4. Results: Example of a real open-loop waste heat recovery system application at BASF

### *4.1. Use Case: BASF Ludwigshafen – carbon-free steam from industrial waste heat utilization*

A representative industrial application of this technology is the planned industrial heat pump system at BASF’s location in Ludwigshafen. BASF SE has decided to install an open-loop heat pump system. The project will become one of the world’s most powerful industrial heat pump installations of its kind. The plant will recover waste heat in the form of warm water from a steam cracker and convert it into carbon-free process steam using MVR based technology. Powered by renewable electricity, the system will deliver thermal capacity of up to 50 MWth and is expected to save up to 100,000 metric tons of $CO_2$ emissions annually. Start-up is scheduled for early 2027.

### *4.2. General requirements, performance and system sizes*

Open-loop heat pump systems offer flexible integration into existing industrial processes but require specific technical conditions to be met. To ensure efficient and reliable operation, several key parameters of the heat source must be considered:

- Suitable heat sources: Compatible heat sources include liquid waste streams, such as wastewater or process condensate, as well as gaseous streams, including waste steam, and exhaust air from drying processes or process gases. In the reference project it is process water from the steam cracker process with 1700 t/h at 72°C.
- Energy content: The thermal power of the heat source in the project is around 35 megawatts.
- Given the parameters of the requirements, the system was simulated, resulting in a configuration with 11 compressor stages.
- The system has a turn-down ration of 50% according to the specific requirement of the customer

### 4.2.1. Performance ranges

Open-loop heat pump systems feature a modular design and are available in a range of capacities, making them highly adaptable to different process requirements. In the concrete application following parameters apply:

- Thermal power on the exit side (enthalpy upgrade): approx.46 MW
- Steam production rate: up to 60 metric tons per hour
- Steam pressure: 6 bar(a)
- COP up to 3.3


Figure 4: Visualization of the large-scale MVR based open-loop heat pump system for the BASF location in Ludwigshafen. @ GKT

The BASF use case demonstrates that open-loop, multi-compressor heat pump systems can operate at a scale relevant for primary industrial steam supply. This system will provide approximately 7% of the steam consumption of the factory.

Compared to closed-loop heat pumps, the open-loop configuration enables higher temperature levels and avoids the complexity and safety considerations associated with large refrigerant inventories.

The achieved COP values indicate that significant reductions in primary energy consumption and $CO_2$ emissions are possible, particularly when renewable electricity is used. The main limiting factors for broader deployment are the availability of sufficiently warm and continuous waste heat sources and the required minimum system scale.

## 5. Conclusions

This applied research study confirms the technical feasibility and industrial relevance of open-loop heat pump systems based on multi-stage radial compressors for high-temperature process steam generation. The BASF Ludwigshafen project illustrates that waste heat can be upgraded to carbon-free steam at capacities of tens of megawatts with competitive efficiency.

Open-loop heat pumps represent a robust solution for electrifying industrial steam supply where suitable waste heat is available. Their deployment can substantially reduce fossil fuel consumption and support the decarbonization of energy-intensive industries.

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