15TH IEA HEAT PUMP CONFERENCE
MAY 26–29, 2026 | HOFBURG
VIENNA 2026
DECARBONISATION THROUGH INNOVATION

Modularisation and Upscaling of high temperature heat pumps for industrial applications

Varshil Dalal[a,*], Enrico Jende[a]

[a]*Institute for Low-Carbon Industrial Processes, German Aerospace Center (DLR)*
Weinbergstraße 10, 03046 Cottbus, Germany

DLR Institute of Low-Carbon Industrial Processes

Abstract

The decarbonization of industrial heat represents a critical challenge in achieving global climate goals. High temperature heat pumps (HTHPs) offer a promising solution for replacing fossil fuel used for process heat production with renewable electricity, especially in temperature ranges above 100 °C. However, widespread adoption is currently hindered by limitations in capacity, efficiency, and system integration. This paper explores the upscaling and modularization of HTHPs as a strategic approach to overcome these barriers, especially for reverse-Brayton HTHPs with air as the working fluid. Through the activities carried out in the scope of the EU funded project SOLINDARITY (www.solindarity.eu), the scalable architecture and modular design principles that enable flexible deployment across diverse industrial sectors are presented and evaluated. Case studies from food processing, rubber processing, and paper manufacturing plants demonstrate the viability of modular HTHPs in retrofitting existing infrastructure. The findings highlight the importance of standardized components, advanced control systems and integrated thermal storage to enhance performance and adaptability. The paper aims to create a roadmap for industrial-scale implementation, emphasizing the role of innovation and cross-sector collaboration in accelerating the transition to clean industrial heat.

© HPC2026.
Selection and/or peer-review under the responsibility of the organizers of the 15th IEA Heat Pump Conference 2026.

Keywords: Reverse-Brayton heat pump; High temperature heat pump; Modularisation of high temperature heat pump; Upscaling of high temperature heat pump

1. Introduction

The increasing global greenhouse gas (GHG) emissions primarily from fossil fuel combustion in industrial processes represent a critical challenge to achieving climate targets. Industrial heat generation accounts for a significant share of energy use and CO_2 emissions, with many processes requiring high temperatures traditionally met by fossil fuels. High temperature heat pumps (HTHPs) offer a promising electrification pathway to reduce these emissions by efficiently converting electricity, ideally sourced from renewables, into high-grade heat needed for industrial processes. Any coefficient of performance (COP) above 1 enables more heat output per unit of electrical input, reducing overall energy consumption compared to electric boilers and associated emissions compared to fossil fuel-based systems. Emerging HTHP technologies targeting process heat temperatures up to 300°C provide an innovative route for decarbonizing sectors such as food and beverage or paper and pulp, that usually require heat under 300 °C. [1]-[3]

Efforts have been undertaken through initiatives such as the IEA Annex 58 [4] and the Project 68 [5] to compile a comprehensive database of the available heat pump technologies and manufacturers worldwide, with the aim to organize the heat pump market and streamline the heat pump adoption in industries. The adoption of heat pump in the industries has been slow and also encountered many challenges, as most of the market ready heat pumps either cannot completely cover the heat demand or are not economically attractive due to the high engineering costs required for a perfect fit. Padullés et al. [6] has carried out pinch analysis for two different industrial processes and visualized using Grand Composite Curves (GCC) and Lorenz efficiencies, how the division of heat sinks and sources can create opportunities for efficient a heat pump

[*] Corresponding author: varshil.dalal@dlr.de

integration strategy. In addition to the technical challenges, socio-psychological factors also play a role, when it comes to early adoption of a new technology. De Jager et al. [7] carried out a literature review to summarize the learnings based on studies carried out for the household heat pumps.

As a new technology entering the market, heat pumps have to currently be custom designed to fit the requirements of the particular industry or application, even when replacing standardized equipment. The development of a standardized heat pump for green field applications is relatively easy as the heat delivery infrastructure can be designed for the heat pump integration. Whereas for retrofitting in an already operating industry, the heat pump has to match the infrastructure already available. This can be different depending on the standard operating procedures (SOPs) of the considered industrial sector and the geographic location, where the industry is located. This technological barrier has been overcome for household heat pump systems, while substantial advancements have been achieved for large-scale heat pumps for applications in district heating or preheating up to a temperature of 120-130 °C. For temperature beyond that, a heat pump has to be designed and developed individually, making it economically unviable. One possible solution to this problem can be the modularization of the heat pump components for the higher temperature range. Modularization can be defined as the process of breaking down a system or product into separate, independent sections or "modules" that have standardized interfaces. Hence, developing modules that are interchangeable provides a greater chance of covering a larger demand with lower requirement of innovation. [8]

In an attempt to address this topic, three reverse-Brayton HTHPs delivering different thermal power for integration in different industrial sectors, being developed within the EU Project SOLINDARITY are taken as example. The modularization strategy considered for this development and the simulations carried out to support the theory, in order to design and develop the heat pumps without starting from scratch each time, are described and discussed here in this study.

2. Project description

The EU-funded project SOLINDARIY aims to design, develop, and integrate three Solar Energy-Based Heat Upgrade Systems (SEHUS) into operational industrial facilities. Each SEHUS consists mainly of a solar thermal (ST) plant that uses flat-plate vacuum solar collectors to generate heat, together with a Thermal Energy Storage (TES) system that stores the excess heat produced. This generated and stored solar heat serves as the main energy supply for a reverse-Brayton HTHP, which upgrades the heat to the temperature levels required by the on-site heating system.

The three target industries for the SEHUS deployment includes food, paper production, and rubber processing industries. The food and rubber industries currently rely on state of the art diathermic oil-based heating systems, while the paper industry uses steam produced by a biomass boiler as its primary heat source. In addition to the different industrial sectors and the heating systems, the selected industrial facilities are also located in a different European country: the food plant in Germany, the paper mill in Greece, and the rubber processing plant in Italy.

These three countries and demonstration sites were selected to specifically evaluate the performance of SEHUS under different levels of solar irradiation and to assess the reliability of solar-based heat upgrade systems for industrial-scale process heating. The different locations selected here provide a wide spectrum of energy prices and as a result, can be used to extrapolate further for different locations for their expected solar irradiation and the specific cost of energy.

The systems are designed to provide different thermal power at the heat sink: 150 kW_{th} for the Italian site, 385 kW_{th} for the Greek site, and 600 kW_{th} for the German site. This thermal power will be provided to each demonstrator as shown in the Table 1.

Table 1: Heat sink specifications

Demonstrator	Thermal Power [kW_{th}]	Heat sink		
		Medium	Temperature increase	Mass flow Rate [kg/s]
Germany	600	Thermal oil	5	10
Greece	385	Pressurized Water	50	1.812
Italy	150	Thermal Oil	10	20.707

3. HTHP Development Methodology

The methodology used for the development of modularized heat pump components is described in this section. The identification of the heat pump integration point and the consequently carried-out feasibility study are not described here. As a result of the feasibility study, a reverse-Brayton type high temperature heat pump with air as the working fluid was finalized for further investigation. A simplified schematic of a reverse-Brayton HTHP with recuperation can be seen in the Figure 1. As seen in Figure 1, a compressor and a turbine connected using a shaft have been considered with an additional electrical drive systems as per requirement. The thermal energy is transferred to the heat sink from the HTHP and from the heat source to the HTHP via heat exchangers (HEX) HEX-3 and HEX-1 respectively. The HEX-2 is used in the case of recuperation for internal heat exchange between the high- and low-pressure streams of the heat pump.

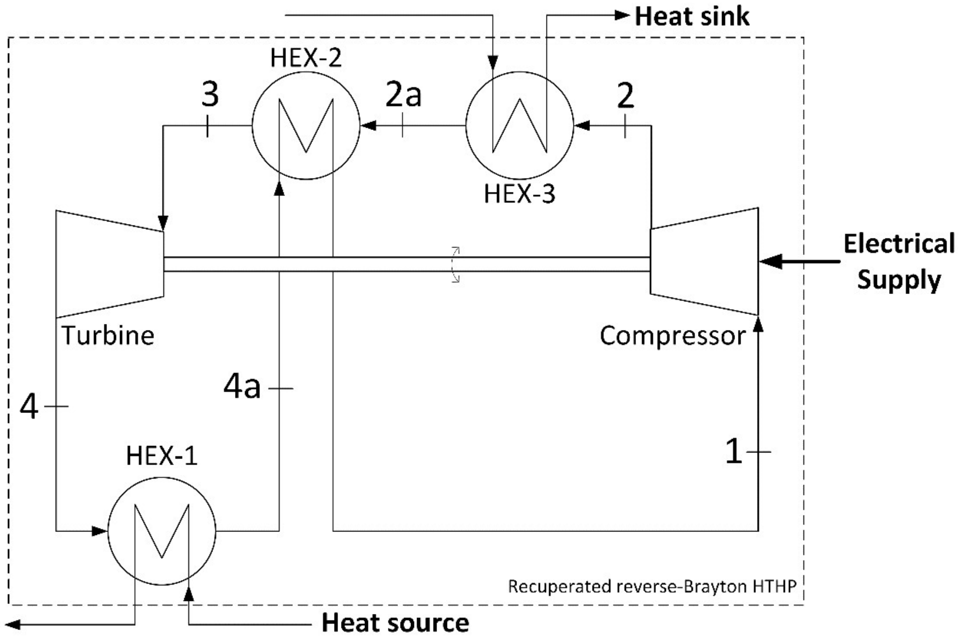

Figure 1: Recuperated reverse-Brayton HTHP

Having fixed the heat pump cycle and the working fluid, the development process begins with fixing the inlet conditions on the heat sink and the heat source, as well as the desired outlet on the heat sink. For the initial feasibility study, the main components of the heat pump, including the compressor, turbine and heat exchangers, are considered to operate at a constant efficiency. If the results from this study are promising, the next step would be the conceptual study. Here, the different heat pump concepts and architectures are modelled and evaluated, in order to optimize the cycle for the maximum achievable Coefficient of Performance (COP). The COP is an evaluating criterion for a heat pump and can be calculated as shown in Eq. 1 by taking the ratio of the thermal power delivered at the heat sink ($\dot{Q}_{HEX-1}$) and the electrical power input (P_{el}) required for it. The results from the concept study and the following basic design study are described and summarized in the following subsections.

$$COP = \frac{\dot{Q}_{HEX-1}}{P_{el}} \quad (1)$$

The development methodology applied here has been described in detail by Jende et al. [9] for the German demonstrator. The first two steps of a standard development project, Concept and Design, were illustrated in the above-mentioned literature using the German demonstrator from this project as an example. Similar development procedure was also carried out for the other two demonstrators. In the next subsection, the HTHP concepts based on the respective integration study for the Greek and the Italian demonstrators along with the German demonstrator are shown.

3.1. HTHP Concept

Following the feasibility study, components for three different heat pumps were to be designed and developed. The main aim of this conceptual study was to finalize the specifications of the main components based on the carried-out simulations. At an early stage during the conceptual study, it had become clear to the consortium, that the responsible technology provider could not provide turbomachinery with the specifications resulting from the feasibility study. Hence, the assumptions made during the feasibility study needed to be updated using components that could be manufactured considering the practical and economical limitations.

As illustrated in the Figure 2, Figure 3 and Figure 4, all the three heat pumps have the same available heat source temperature, as solar thermal collectors integrated with thermal energy storage systems are considered as the heat source for all the demonstrators. The thermal power input at required heat source is although different for the different demonstrators. This variation is regulated by changing the mass flow rates of the water for the different demonstrators. This is made possible by sizing the ST field and TES appropriately, by carrying out transient simulations considering the solar irradiation profile of each location. For the sake of comparison, a steady state condition with the maximum possible heat source temperature of 150 °C is simulated and illustrated. On the other hand, parameters such as the heat sink medium, inlet temperature and the delivered thermal power to the heat sink are also different among the different demonstrators. Based on the results of the feasibility study, a recuperated reverse-Brayton cycle has been considered as the starting point for the conceptual study. In order to accommodate the limitations associated with the turbomachinery, it was decided to develop a small turbo-units and then operate more of the same in parallel to deliver the required thermal output and the target temperature. To test this theory, the mass flow of the air within the heat pump loop for the Italian demonstrator was assumed to be 1 kg/s. This assumption was made based on the results of the feasibility study. The mass flow rate of air for the other two demonstrators was consequently derived by scaling the reference value of 1 kg/s to achieve the target thermal power output. Other assumptions adopted for the conceptual study are as listed in Table 2.

The above-mentioned boundary conditions and assumptions as mentioned in Table 2 were used to carry out the simulations in the software EBSILON® Professional (EBSILON). The results of the conceptual study for all three demonstrators for the considered design point are shown in the Figure 2, Figure 3 and Figure 4 using the results from EBSILON. The different fluid streams in the EBSILON simulations are shown using different colors. The yellow lines show air stream, while water is shown using the blue stream. Furthermore, the gray line is used to show the diathermic oil stream and the green line is the shaft connecting the compressor and the turbine.

Table 2: Assumptions adopted for the feasibility study

Component	Parameters	Values	Unit
HEX-3	Lower Terminal Temperature Difference (LTTD)	10.00	K
HEX-1	Heat source temperature difference	20.00	K
	Effectiveness	0.85	-
HEX-2	Effectiveness	0.85	-
Compressor	Isentropic efficiency	0.80	-
	Mechanical efficiency	0.99	-
	Inlet pressure	1.00	bar
Turbine	Isentropic efficiency	0.85	-
	Mechanical efficiency	0.99	-

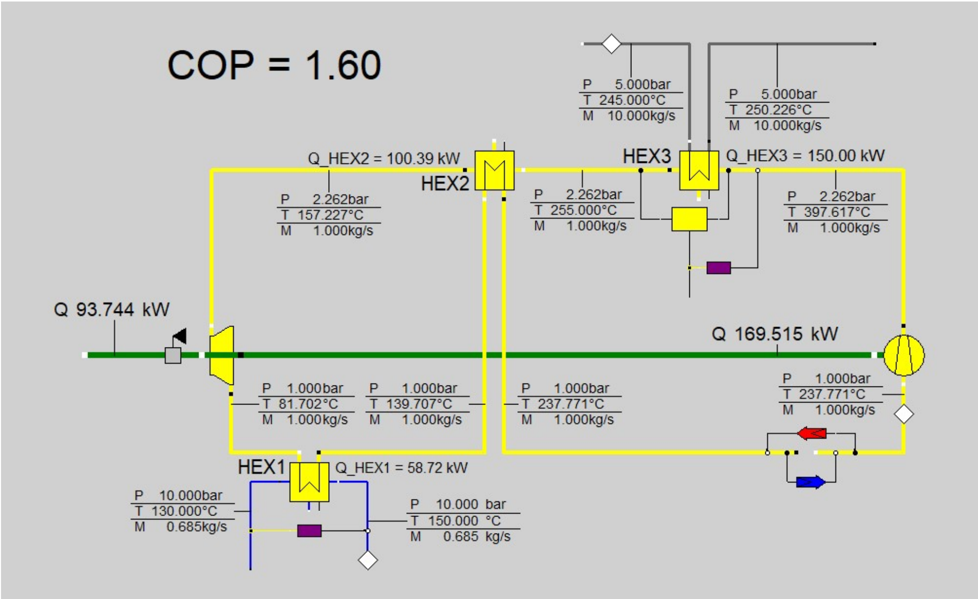

Figure 2: Conceptual study for the Italian demonstrator

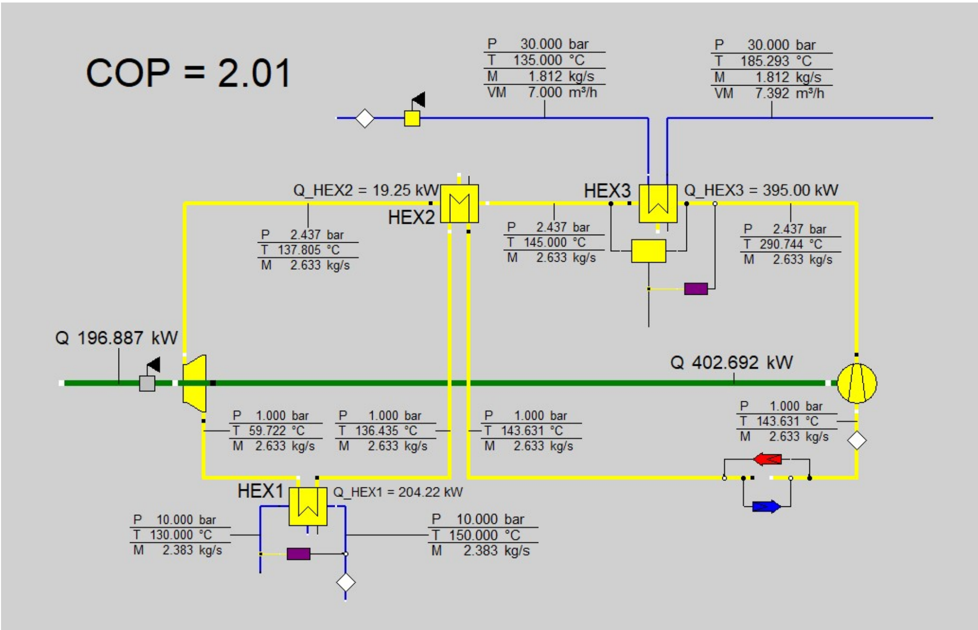

Figure 3: Conceptual study for the Greek demonstrator

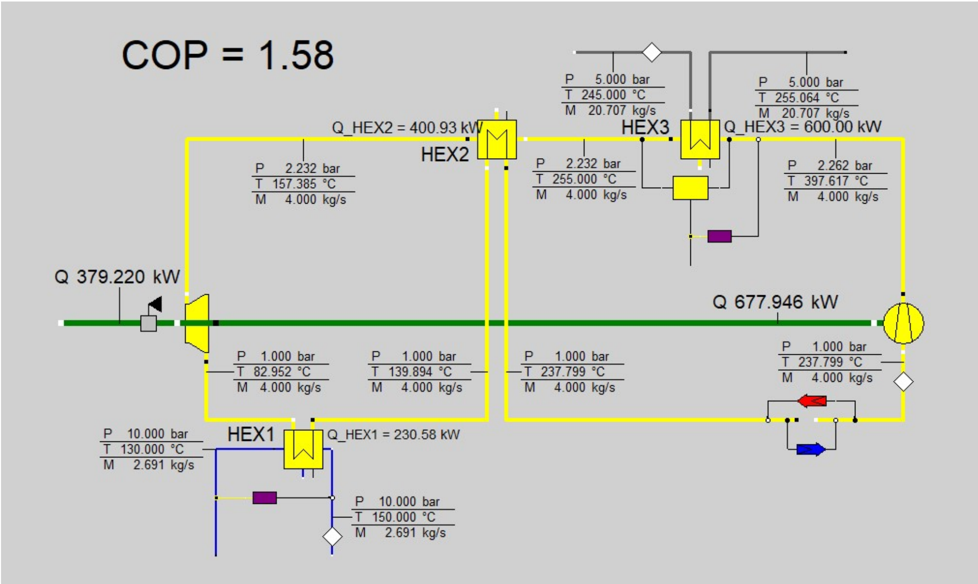

Figure 4: Conceptual study for the German demonstrator

The results shown above indicate that a similar compression pressure ratio is to be delivered by the compressor in all the demonstrators to achieve the required temperature and thermal output on the process side, when considering the same constant isentropic efficiency value. This is mainly due to the similar suction conditions for the compressor and the scaled mass flow rate of air considered in each case. Similarly, the inlet and outlet pressure levels of the turbine are also quite similar for all the demo cases. Even though the temperatures for the Greek demonstrator differs from the other two, it was decided to further investigate the possibility of development using a modular approach in regards to the required turbomachinery.

3.2. Basic design study

Taking insights from the conceptual study, a turbo-unit that could fulfil the requirements of the demonstrator with the smallest thermal output was iterated and developed considering the cycle performance. The developed turbo-unit comprises of a compressor and a turbine mounted on a shaft with a connected direct drive high-speed magnetic motor for the required electrical input. For this development, a compressor impeller already available was identified and a turbine impeller to match the requirements was developed using CFD simulations. In order to validate the approach, the performance maps from both, the compressor and the turbine were integrated into an EBSILON model and compared with the results from the conceptual study. This comparison can be observed in Figure 5.

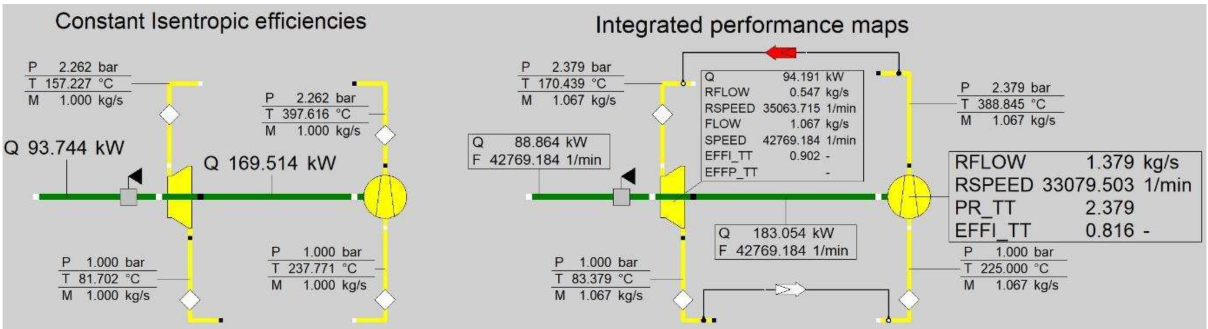

Figure 5: Turbo-unit development

The turbo-unit on the left, shown in the Figure 5, comprises of a compressor and a turbine with efficiencies and boundary conditions as shown in Figure 2. The one on the right shows a turbo-unit with integrated performance maps from the finalized impellers. The compressor impeller is taken from a product already available on the market, hence the performance map is an experimentally measured one. The turbine on the other hand, is a new development within the project as the aerodynamic design was carried out to match the compressor and the process requirements. Hence, the performance map from the turbine is based on simulations. As shown in Figure 5, the turbo-unit performance is close to the desired results. The compressor isentropic efficiency for the design point is a bit lower than the assumed constant value, but the isentropic efficiency for the Turbine is higher. Hence, the overall efficiency and the process parameters are similar to the desired results. Consequently, the performance maps from both these components were integrated into the EBSILON model of the HTHP created for the conceptual design, to test the viability of the modularization strategy using steady-state simulations in the first stage. The results from this investigation can be seen in the Figure 6, Figure 7 and Figure 8.

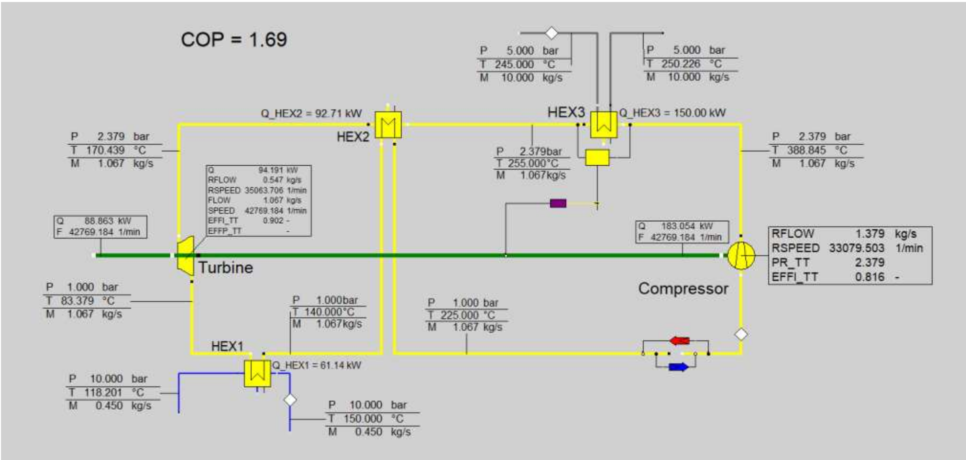

Figure 6: Basic design study for the Italian demonstrator

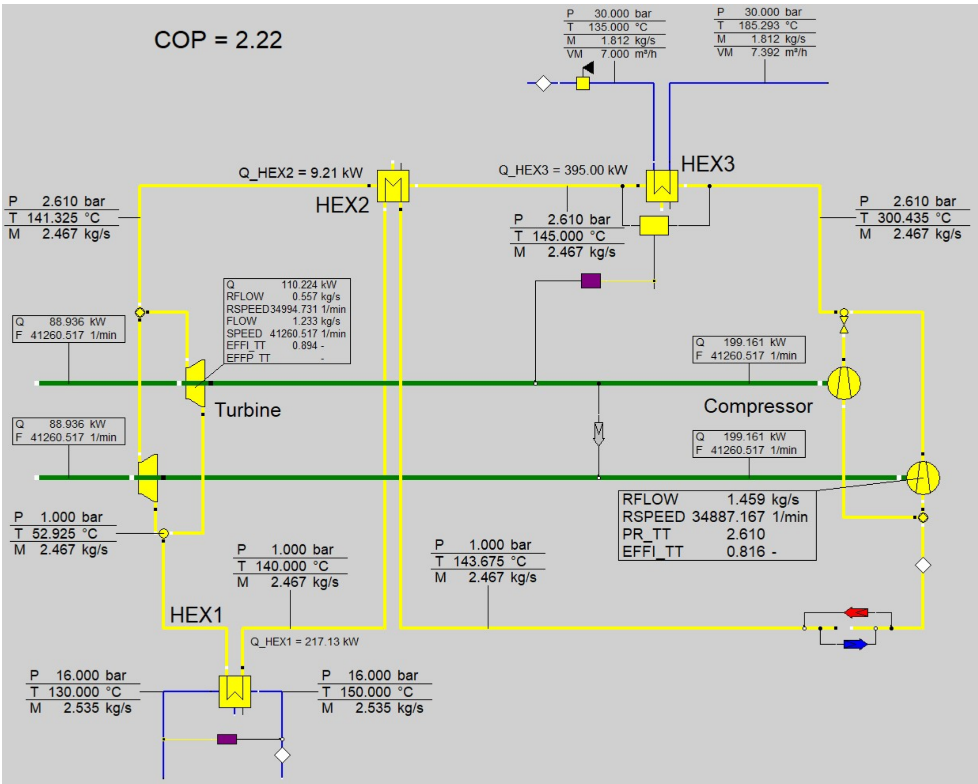

Figure 7: Basic design study for the Greek demonstrator

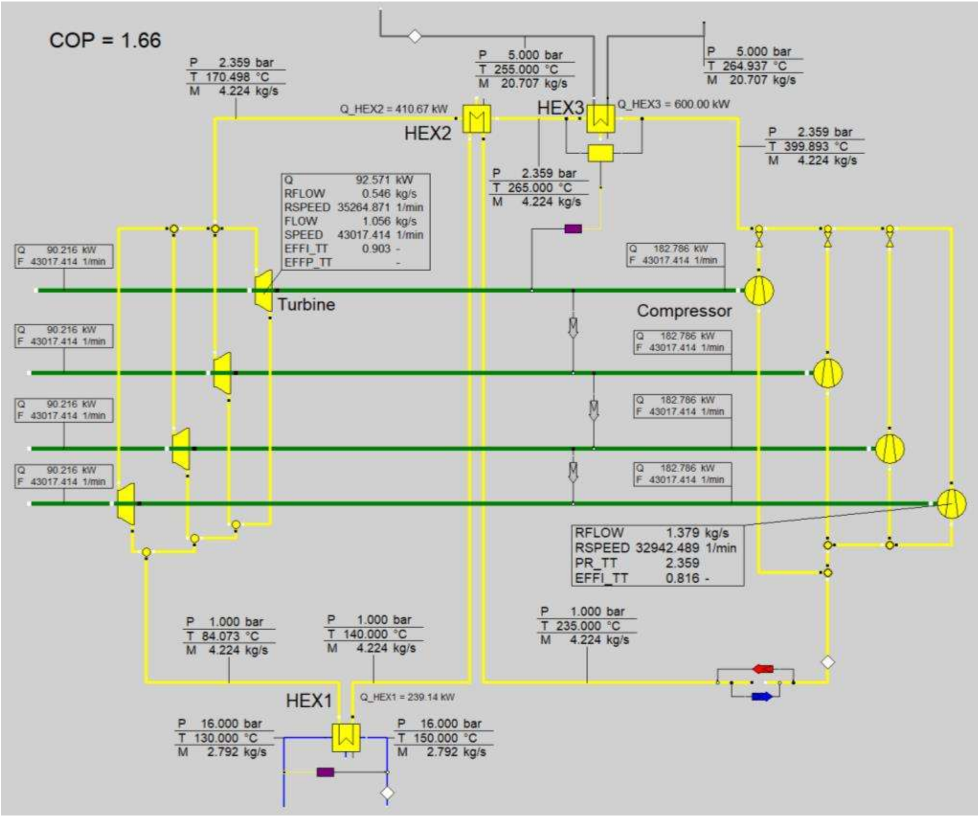

Figure 8: Basic design study for the German demonstrator

The EBSILON simulations for the different demonstrators with the developed turbo-units can be seen in the Figure 6, Figure 7 and Figure 8. As shown in the figures, different numbers of turbo-units are required to deliver the necessary thermal output. For the Greek demonstrator, two turbo-units in parallel are required to provide the required temperature and pressure at the outlet for the given mass flow rate as shown in Figure 7. Similarly, the Figure 8 shows that the German demonstrator would require four turbo-units in parallel to provide the required temperature and pressure for the given mass flow rate.

4. Results and Discussion

The results as shown in Figure 5 and tabularized below in Table 3 show that the simulation results for the developed turbo-unit show similar thermodynamic performance as compared to the assumptions made during the conceptual study. Additionally, the isentropic efficiencies are better than the assumptions for both the compressor and the turbine.

Table 3: Comparison of turbo-unit performance

	Unit	Conceptual study	Basic design study
Mass Flow Rate	kg/s	1	1.067
Pressure Ratio	[-]	2.262	2.379
Compressor Outlet Temperature	°C	397.616	388.845
Isentropic Efficiencies			
Compressor	[-]	0.8	0.816
Turbine	[-]	0.85	0.902

The EBSILON simulations as shown in Chapter 3 indicate that the proposed methodology can be used to effectively deliver different temperatures and thermal powers to the heat sinks by operating multiple identical turbo-units in parallel. This configuration provides flexibility in meeting different thermal demands by adjusting the number of active units, a feature that aligns with the modular concept of the system design. The

COP for all the demonstrators with the developed turbo-units in comparison to the values from the conceptual study can be seen in Table 4. As shown here, the COP for each case increases marginally in response to the higher isentropic efficiencies of the turbo-units.

Table 4: COP for different demonstrators in conceptual and basic design studies

Demonstrator	COP	
	Conceptual study	Basic Design study
Germany	1.6	1.69
Greece	2.01	2.22
Italy	1.58	1.66

The incorporation of a recuperator and a TES on the heat source side plays a crucial role in maintaining a stable compressor inlet temperature. This is particularly important in this case because the input heat source temperature depends on solar irradiation, which is inherently fluctuating and unreliable. By stabilizing the compressor inlet conditions, the recuperator ensures consistent operation and system efficiency even under variable heat source conditions.

These findings highlight the potential for a modular and scalable system architecture. The concept was validated through steady state simulations and will be further assessed through experimental demonstration with physical prototypes. Modularization not only simplifies system adaptation for different operating conditions but also enhances reliability and maintainability. Having multiple similar turbo-units operating in parallel also helps add a level of redundancy, that is required for any stable and reliable industrial operation.

The selection of the turbo-unit as the core component to be modularized is justified by both technical and economic considerations. Developing compressors and turbine is usually a resource-intensive process. Large-scale production can although significantly reduce per-unit manufacturing costs, making it feasible for widespread deployment once the design with standardized interfaces for modular integration in HTHPs is finalized. This phenomenon has already been demonstrated in the automobile industry using the example of turbochargers. Initially developed for high-performance racing cars, turbochargers became economically viable for use in standard passenger vehicles as a result of modular design and large-scale production processes. Furthermore, the modularization approach extends naturally to the heat exchangers. Depending on the type of heat exchanger used, adjusting the number or size of pipes, baffles or plates allows the fine-tuning of heat transfer capabilities to meet the specific thermal requirements. This adaptability contributes to the overall modular nature of the proposed system, enabling flexible and cost-effective solutions for various applications.

5. Conclusion and Outlook

The modularization of HTHP components as illustrated here presents a promising pathway to improve the economic viability of HTHPs and accelerate industrial deployment. By enabling cost reductions through standardized mass manufacturing, modular HTHP units can significantly reduce capital expenditures and simplify system integration. The development of dedicated turbo-unit configurations designed for power ratings relevant to industrial-scale applications further supports the realization of efficient and reliable heat pump systems. Such standardized turbo-components would allow for streamlined system design, facilitate replication, and enhance operational performance across a range of use cases.

A comprehensive market analysis remains essential to identify the most promising capacity ranges for development and commercialization. The analysis should consider industrial heat demand profiles, sectoral temperature requirements, and typical plant size distributions. Preliminary assessments suggest that modular HTHPs rated at 1, 2, 5 and 10 MW_{el} could effectively serve installations requiring total thermal outputs between approximately 1 and 50 MW_{th}, allowing systems to be scaled in standard increments according to process demand. This approach would allow manufacturers to optimize production efficiency and ensure adaptability across various industrial sectors.

While parallel operation of components can potentially enhance system functionality and flexibility, they also significantly increase the complexity, particularly regarding control and safety aspects. The extent of this complexity cannot yet be fully determined, as the required control and safety strategies are currently under development. Furthermore, pressure losses from splitting and merging of different streams and the temperature losses from the additional piping also cannot be fully estimated at this time. These parameters, along with the control and safety evaluations will be comprehensively assessed once the physical demonstrators are commissioned and operational.

The presented methodology focusses on modularization of individual components equipped with standardized interfaces. However, an alternative approach to the modularization of heat pumps could involve developing a modularized heat pump. In this case, the heat pump would be a complete system capable of delivering a set thermal output for the given source and sink conditions. Multiple such systems could be connected in parallel to deliver the desired output. An advantage of this configuration can be the utilization of different heat sources or the possibility to serve different heat sinks without requiring an extensive heat delivery network. A disadvantage for such a complete system can be the fixation of the heat exchanger parameters, which might lead to mismatch with the available source or the desired sink.

In summary, the combination of modular design, standardized component development, and market-driven capacity selection can create a scalable and economically sustainable framework for the widespread application of HTHPs in industrial thermal energy systems. These strategies provide a foundation for transitioning to low-emission heat supply while maintaining flexibility and cost efficiency in system integration.

Acknowledgements

The research for this work and the project received funding from the European Union's Horizon Europe Framework Programme under grand agreement No 101136148 (SOLINDARITY). The authors thank all involved project partners and all involved members of the department of high-temperature heat pumps for their support. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them.

Nomenclature

Abbreviations		*Variables*	
COP	Coefficient of Performance	$\dot{Q}_{HEX-1}$	Thermal power to the process, kW
DLR	German Aerospace Center	P_{el}	Electrical power, kW
EU	European Union		
GCC	Grand Composite Curve		
GHG	Greenhouse Gas		
HTHP	High-Temperature Heat Pump		
HEX	Heat Exchanger		
LTTD	Lower Terminal Temperature Difference		
SEHUS	Solar-Energy based Heat Upgrade System		
SOP	Standard Operating Procedure		
ST	Solar-Thermal		
TES	Thermal Energy Storage		
SOLINDARITY	SOLAR-DRIVEN INDUSTRIAL POWER AND HEAT UPGRADED WITH HIGH-TEMPERATURE HEAT PUMPS FOR ENHANCED INTEGRATED PROCESS EFFICIENCY		

References

[1] Fraunhofer ISI (2024): Direct electrification of industrial process heat. An assessment of technologies, potentials and future prospects for the EU. Study on behalf of Agora Industry.
[2] DLR (German Aerospace Center). "High Temperature Heat Pumps - Technology Status and Perspectives." DLR Report, 2023.
[3] Abu Khass O. and Wittstadt U. (2023) RD&D Activities in High-Temperature Heat Pumps in Germany. IEA HPT Annex 58, 14th Status Meeting, 2023-04-25, Aarhus, Denmark.
[4] Zühlsdorf. (2024). Annex 58 High-Temperature Heat Pumps Final Report. In Technology Collaboration Programme on Heat Pumping Technologies. https://doi.org/10.23697/2qxe-av87
[5] Heat Pumping Technologies. (2025, September 29). Task 1 - Project 68. Project 68. https://heatpumpingtechnologies.org/project68/task1/
[6] Padullés, R., Walmsley, T. G., Lincoln, B. J., Andersen, M. P., Jensen, J. K., & Elmegaard, B. (2024). Process integration and electrification through multiple heat pumps using a Lorenz efficiency approach. Energy, 311, 133348. https://doi.org/10.1016/j.energy.2024.133348

[7] Lynn A. de Jager, Liesbeth Claassen, Geeske Scholz, Emile J.L. Chappin & Anne van Bruggen (2025) Household heat pump adoption and user behaviours: a systematic review of drivers and barriers, International Journal of Sustainable Energy, 44:1, 2488174, https://doi.org/10.1080/14786451.2025.2488174

[8] Martin, T. (n.d.). All you need to know about modularization. https://www.modularmanagement.com/blog/all-you-need-to-know-about-modularization

[9] Jende E., Dalal V., Rogkas N., Rakopoulos D. and Skembris A. (2025) *DEVELOPMENT OF HIGH TEMPERATURE HEAT PUMPS IN THE EU-PROJECT SOLINDARITY.* SDEWES2025, 2025-10-05 - 2025-10-10, Dubrovnik.