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DECARBONISATION THROUGH INNOVATION

EU projects for the process integration of various types of high-temperature heat pumps into existing industrial applications

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Abstract

The electrification of industrial process heat using high-temperature heat pumps (HTHPs) can contribute to the deep decarbonization of the industrial sector. Through its participation in EU projects, the Institute of Low-Carbon Industrial Processes as part of the German Aerospace Center (DLR) is developing, researching and demonstrating the process integration of various types of HTHP into existing industrial applications across different sectors.
This Applied Research Paper shows in the context of the two EU projects SOLINDARITY (www.solindarity.eu) and EEETHOS (www.eeethos-project.eu) an overview and first results of the process integration of HTHPs in the industrial sectors pulp & paper, construction and food industry. This involves supplementing the existing process heat supply by integrating HTHPs in form of reversed Brayton-HTHPs and a Cascade HTHP for steam generation, thereby reducing CO_2 emissions. Various options for providing heat sources are also presented. Exhaust air and solar thermal based waste heat recovery systems in conjunction with heat storage units are used.

Keywords: High temperature heat pumps, reverse Brayton heat pump, Cascade heat pump, applied re-search and demonstration, Waste heat recovery systems

1. Motivation

There is still an increase in greenhouse gas (GHG) emissions in the world. With an increase of approx. 1.9% above the 2022 values, greenhouse gas emissions reached a level of 53.0 gigatons (Gt) CO_2eq. In terms of combustion and processes, the industrial sector alone produces approx. 9.6 Gt CO_2eq [1]. Especially in the temperature range from 100°C to 500°C, HTHPs have a very large potential to reduce GHG [2] [3] [4].

The results of Annex 58 of the IEA TCP are used as an example to illustrate a possible Roadmap for the integration of HTHP in the industry [5]. The department of High-Temperature Heat Pump (HTP) as one of three departments of the Institute of Low-Carbon Industrial Processes and as part of the German Aerospace Center (DLR) is since 2019 actively developing and researching in the field of HTHP. From the very beginning, the focus was not only on theoretical considerations, but also on the development and construction of various types of HTHP prototypes. In Cottbus, a prototype based on the reversed Brayton cycle was built and successfully commissioned using dry air as the refrigerant. Conceptualized somewhat later, a prototype based on the reverse Rankine cycle with water/ steam as the refrigerant is currently in the construction phase in Zittau. These prototypes are supplemented by component test benches, currently primarily for compressor tests. Visual impressions of the two prototypes can be seen in Figure 1.

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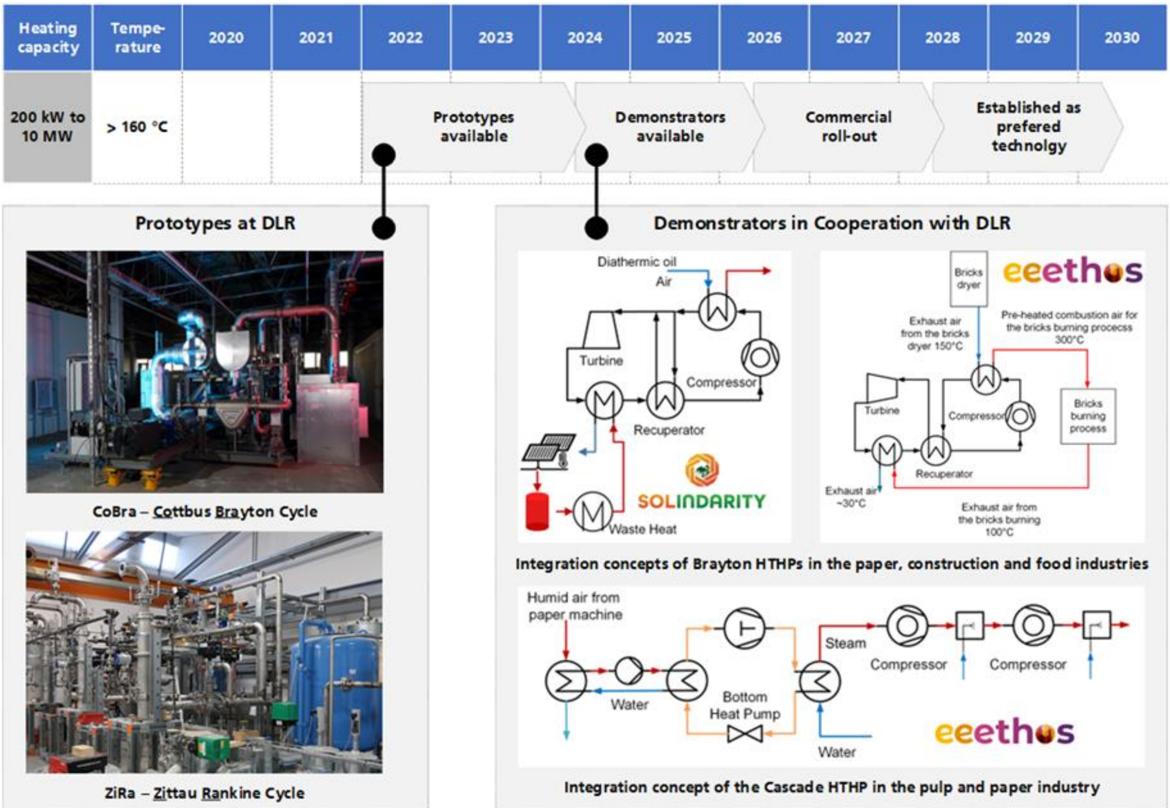

Figure 1: Excerpt of a possible Roadmap of HTHP integration with DLR activities;
Source: Own illustration based on [5]

In context of these technology paths, the aim is now to utilize the knowledge gained and bring the HTHP technologies to market maturity through transfer projects. This is to take place within the framework of European Union (EU) funded projects SOLINDARITY and EEETHOS. In these, HTHP demonstrators are integrated into the existing process heat supply, exemplary into the pulp & paper, ceramics and food industry sectors. SOLINDARITY was launched at the beginning of 2024 and develops, demonstrates and validates the feasibility of an integrated heat generation system. This system combines HTHP with solar energy, thermal heat storages and heat recovery systems for the decarbonization of industrial processes with temperatures of up to 280 °C. This was followed in November 2024 by EEETHOS, which develops and demonstrates technologies to optimize thermal energy flows in order to increase energy efficiency.
In this EU-Projects, the HTP department is exemplary responsible for taking the development findings of the Brayton and cascade HTHP technology, scaling them up to ~1 MWth as well as integrate and evaluate into different kinds of industrial sectors.

2. Development process of the high-temperature heat pump system

Figure 2 shows an extract of the development processes of the project-related HTHP systems. This is based on the general principles of a development project and categorizes the various phases of HTHP development concept, design, manufacturing and commissioning supplemented by on-site tests of the demonstrators in the factory environments. The planned milestones for both EU projects can also be seen in this Figure 2.

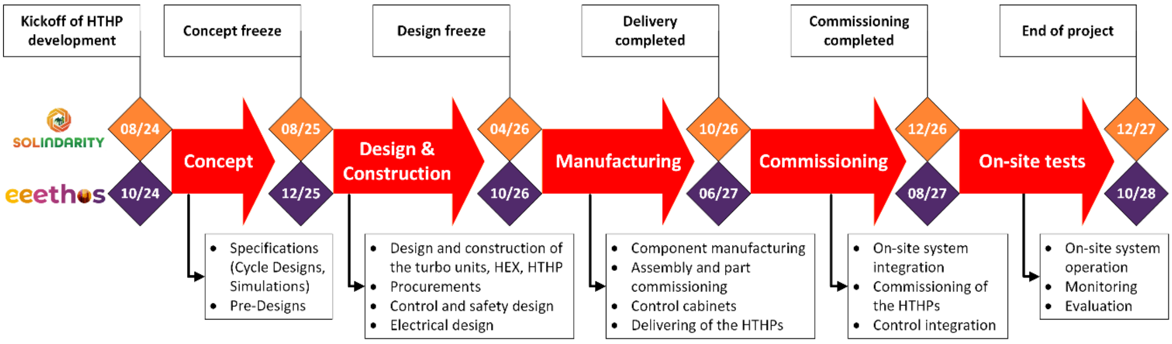

Figure 2: Extract from the development process of the HTHP systems in the both EU-projects; Source: Own illustration

The development process begins in the concept phase with the definition of the stationary operating points in the design point depending on defined key performance indicators (KPI, e.g. CO_2 reduction, primary energy savings) and boundary conditions of the existing process and energy system. From the HTHP perspective, the specifications at the heat sink and the heat source in particular must be known or assumed for the time being. On this basis, an initial concept or Pre-Design for the HTHP and its cycle design is defined at a low level of detail with the help of suitable simulation environments (e.g. EBSILON® Professional, TesPy). This results in initial estimates of process and component dimensioning parameters. An initial assessment of the economic efficiency is now possible. The typical Coefficient of performance (COP) figure for heat pumps (see Eq. 1) can be used to assess efficiency. The COP as an indicator of efficiency is defined as the ratio between the heat transferred at the heat sink $\dot{Q}_{out}$ to the process as output and the drive power $\dot{W}$ as input of these typical efficiency equation of heat pumps [6].

$$COP = \frac{\dot{Q}_{out}}{\dot{W}} \qquad \text{(Eq. 1)}$$

The design and construction phase are also supported by steady-state and transient simulations to finalise the design of the main components in the form of the compressor, turbines and heat exchangers, as well as the design of the control, safety and electrical systems. If the components are not developed by project partners, procurement have to begin in this phase. The subsequent phases of HTHP development are concerned with component manufacturing and HTHP assembly as well as the delivery to the respective locations as the conclusion of the manufacturing phase. The following commissioning phase covers the hardware-oriented topic of on-site system integration and the step-by-step commissioning of the HTHP, including the integration of the control strategy. The development project concludes with the on-site testing phase. With the focus on on-site system operations, the aim is to monitor and evaluate the KPIs of the demonstrators after implementation, usually for one year.

3. Examples of lessons learned and Innovation in the context of the two EU projects

As can be seen in Figure 2 the development projects of the two EU projects presented are several months apart. While the design and construction phase has already begun in SOLINDARITY, the concepts of the EEETHOS demonstrators are being finalized at the time of writing this applied research paper. In both projects, a tripartite division of the simulation-supported development process can be seen from the beginning of the concept phase to the transition to the design phase:

- Step 1: Feasibility study - Simulation model for process integration
- Step 2: Concept studies - Simulation model for the main component
- Step 3: Preliminary design study - Simulation model for the preliminary design

As mentioned in Chapter 2, the Feasibility study begins with the iteration of the stationary operating points in the design point and boundary conditions of the existing process and energy system. The simulation model used here still has components at a low level of detail. The focus of this Feasibility study is on the component arrangement (e.g. recuperation or non-recuperation, number of heat exchangers (HEX)) and the process and component dimensioning parameters (e.g. cycle mass flow) as a function of a maximum COP. An exemplary result is the initial sizing of the main components: compressors, turbines and heat exchangers (HEX, i.e. HEX surface area, HEX pressure losses, corrected mass flows of turbo machines). As the next step within the concept studies, the level of detail of the simulation environment is increased based on the initial component dimensioning (i.e. maps of the turbo machines, specifications of the HEX). The target variables of these concept studies are the process parameters on a higher detail level and component dimensioning for the design (i.e. Number of Turbo units, HEX heat transfer area) and first off-design simulations. The subsequent preliminary design study, shown as an example in Figure 3, is based on further design parameters and an initial installation concept. The aim of the preliminary design study is to implement the design parameters and the missing components for operating the HTHP (e.g. pipes, valves) in order to finalize the concept and enable transient simulations. The transient model is recommended as it provides support during the design phase when selecting and fixing the other HTHP components, e.g. the pipe sizing and peripherals for operating the HTHP as well as aspects of control, safety and electrical design.

At the time of writing this applied research paper, both EU projects are currently undergoing this simulation-supported development process, whether still in the concept phase or already in the design phase. If the tripartite division of the simulation-based development process described above can be regarded as "lessons learned" for future development and transfer projects, the results of the simulation-based concept phase described and selected in the following section - one from SOLINDARITY and one from EEETHOS - are regarded as innovations in the two EU projects.

Starting with the concept phase of the SOLINDARITY HTHPs, it became apparent that the technology provider could provide a maximum size of turbo unit with a limited portfolio of impellers for the turbomachinery. This and a new development of the turbine side led to further investigations regarding the number of turbo units to provide the required thermal output of the HTHP. The result was a parallel arrangement of the turbo units in order to provide a higher mass flow at the same outlet temperature. Figure 3 shows the result of this study. In conclusion, this approach can be considered as a contribution to modularization when turbo machines with limited capacities are available, but HTHP are to be designed for different and higher process heat requirements.

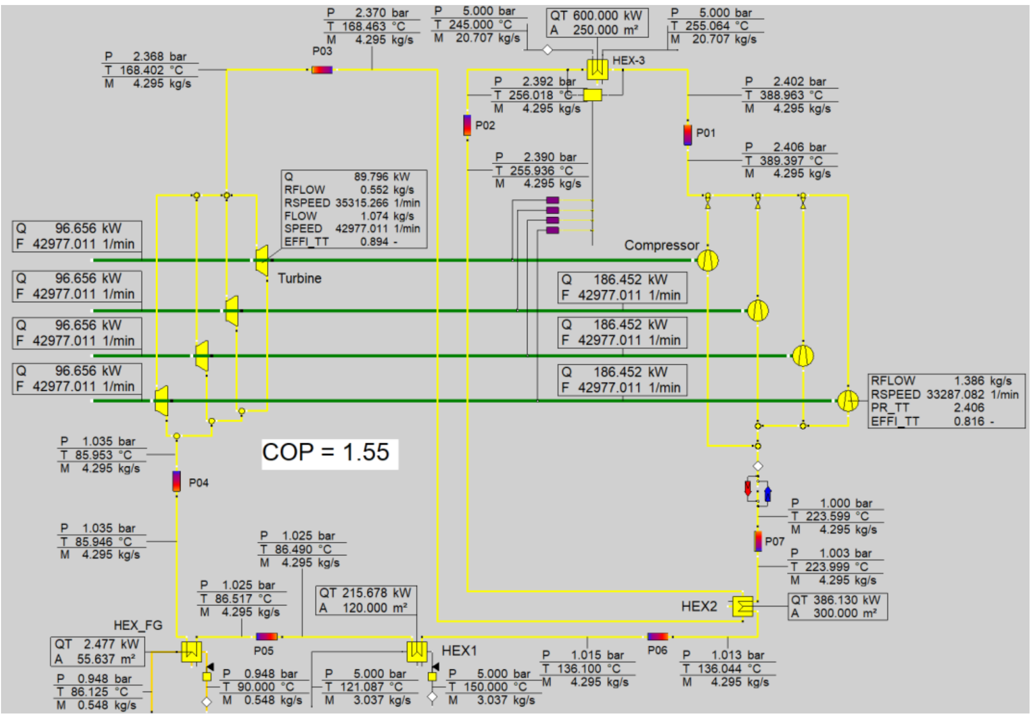

Figure 3: Preliminary design study in EBSILON® as simulation environment; Source: Own illustration

The second innovation was developed in the early stages of the concept phase in EEETHOS and comprises an innovative HTHP design with a new arrangement of components within the HTHP and a new HEX design on the heat sink side. This HTHP design is based on the typical reversed Brayton cycle. At the heat source, the working medium (air) absorbs heat from the heat source using a low temperature HEX (LTHX) and then flows through the Recuperator. The working medium is heated further in the Recuperator to increase the HTHP performance. Compressor 1 (C1), as part of the turbocharger, then increases the pressure and temperature of the air. The hot air then flows through the high temperature HEX (HTHX) for the first time, which helps with both for intercooling between the compressors (C1 and C2) and preheating the process air on the secondary side. Driven by an electric drive (M) with a gearbox, compressor 2 (C2) increases the pressure and temperature of the working medium in order to deliver the required temperature level to the process air. The HTHX is then passed through a second time at the sink and the process air on the secondary side is heated to the target temperature. As the temperature of the working medium after the HTHX is higher than the temperature of the working medium after the LTHX, some of the available heat is transferred to the working medium upstream of the C1 via the Recuperator. One more reasoning for using a recuperator: Transferring heat via HEX is more effective than via a compressor. Better to preheat the working fluid before the compressor than to have higher pressure ratios for both ends of the turbocharger. The working medium then flows to the turbocharger turbine at a reduced temperature. Here it is expanded to the initial pressure level. The resulting mechanical power is used to drive the C1. Finally, the working medium re-enters the LTHX, closing the cycle. A simplified process diagram of the HTWP cycle is shown in the Figure 4.

This innovative HTHP cycle design combines with the new arrangement of the HTHP components a new design of the HTHX in which two HEX are combined with the possibility of using conventional turbochargers and the associated use of largely standard components.

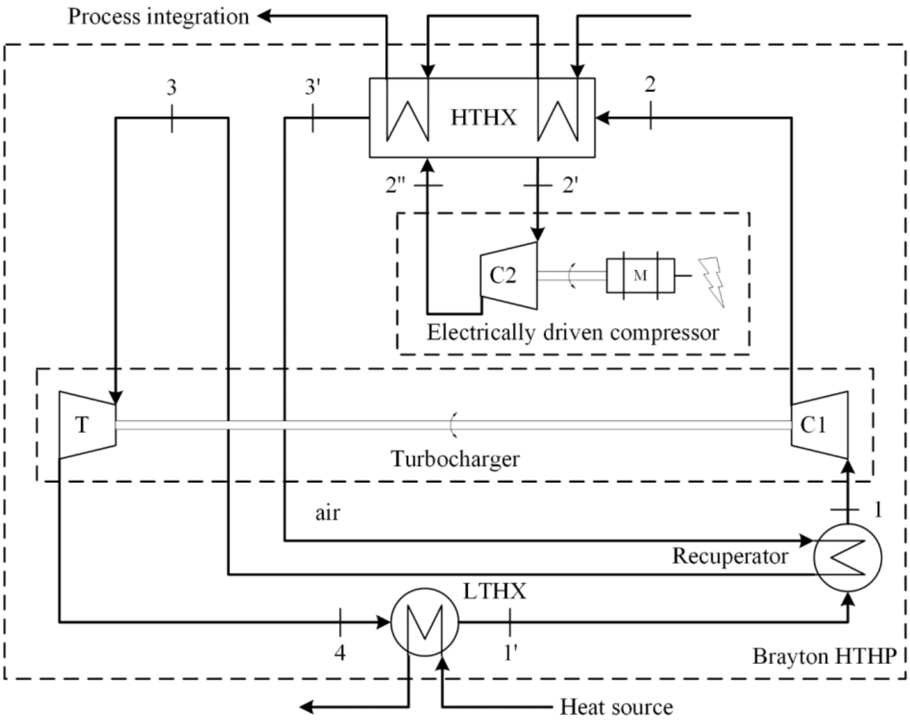

Figure 4: New cycle concept of the reversed Brayton HTHP; Source: Own illustration

4. Conclusion and Outlook

This study began by presenting a possible roadmap for HTHP integration as well as the role and activities of DLR and concrete the HTP department in this roadmap, from HTHP prototypes and demonstrators to commercial roll-out and established preferred technology. The two EU projects SOLINDARITY and EEETHOS were highlighted as transfer projects as the HTP department's contribution to the future market launch of HTHP technology. Based on these two EU projects, a possible development process was explained and the concept and first design results were then presented with a focus on lessons learned and potential innovations. In conclusion, the presented tripartite division of the simulation-based development process can be used as a blueprint for further transfer projects. The second innovation presented in the form of the new cycle concept of the reversed Brayton HTHP will also be evaluated as part of the project and discussed in further publications.

Further development and transfer projects are being worked on in the HTP department at DLR. The direct integration of HTHP into the production machines is a promising new development. The first project of its kind is the E-Fryer, which aims to deeply integrate HTHP into the process. This approach achieves greater efficiency compared to utility solutions and at the same time offers the possibility of modularization and standardization [7].

With this and other projects, the lessons learned, findings and innovations described in this article will be used and further advanced so that HTHP can play an efficient, sustainable and established role in the future energy system.

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Nomenclature			
Abbreviations		*Variables*	
DLR	German Aerospace Center	COP	Coefficient of performance
EU	European Union	$\dot{Q}_{out}$	Thermal power to the process, kW
GHG	greenhouse gas	$\dot{W}$	Mechanical drive power, kW
HTHP	high-temperature heat pump		
HEX	heat exchanger		
KPI	Key performance indicator		
MVR	Mechanical vapor recompression		
EEETHOS	<u>E</u>NERGY <u>E</u>FFICIENCY AND <u>E</u>LECTRIFICATION <u>T</u>ECHNOLOGIES FOR <u>H</u>EAT FLOW <u>O</u>PTIMIZATION IN PROCESS INDUSTRIE<u>S</u>		
SOLINDARITY	<u>SO</u>LAR-DRIVEN <u>IND</u>USTRIAL POWER <u>A</u>ND HEAT UPG<u>R</u>ADED WITH H<u>I</u>GH-TEMPERATURE HEA<u>T</u> PUMPS FOR ENHANCED INTEGRATED PROCESS EFFICIENC<u>Y</u>		

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