

DEVELOPMENT OF HIGH TEMPERATURE HEAT PUMPS IN THE EU-PROJECT SOLINDARITY

E. Jende^{1*}, V. Dalal¹, N. Rogkas², D. Rakopoulos², A. Skembris²

¹ Institute of Low Carbon Industrial Processes

German Aerospace Center (DLR)

² Centre for Research & Technology Hellas (CERTH)/

Chemical Process and Energy Resources Institute (CPERI)

enrico.jende@dlr.de

ABSTRACT

The European Union (EU) funded Project SOLINDARITY (<https://solindarity.eu/>) will develop, demonstrate and validate the feasibility of an integrated Solar Energy-based Heat Upgrade System (SEHUS) comprising solar energy resources (High Vacuum Flat Solar Panels and Photovoltaic), innovative High Temperature Heat Pumps (HTHP), Thermal Energy Storage (TES) and Waste Heat Recovery (WHR) for the deep decarbonization of industrial processes with temperatures up to 280°C. The SEHUS to be developed will demonstrate its effectiveness, robustness, sustainability and cost-efficiency in three industrial sites, belonging to different industrial sectors (Food, Paper, Rubber) and climatic regions (Germany, Greece, Italy).

This study considers first results of the development and integration process of a reversed Brayton HTHP regarding the SEHUS in the case of a thermal oil energy based industrial food production process in Germany. The integration concept and a preliminary dimensioning based on steady-state simulations covering the concept of the HTHP and the starting point for the design phase. First results of the design are also showing. This allow conclusions to be drawn about the process integration of HTHP into thermal oil based industrial processes.

KEYWORDS

High temperature heat pump, Solar Energy-based Heat Upgrade System, industrial demonstration plants

1. INTRODUCTION

Greenhouse gas (GHG) emissions in the world continue to rise. In 2023, the GHG emissions reached the level of 53.0 gigatons (Gt) CO_{2eq}, which is 1.9% higher than the 2022 values. The industrial sector (combustion and processes) alone produces around 9.6 Gt CO_{2eq} [1]. Studies in recent years have shown great potential for the integration of HTHPs in industries, particularly in the temperature range from 100°C to 500°C, in order to reduce the GHG emissions [2–4]. Addressing temperatures up to 280°C and integration of a solar-based energy system within the scope of the EU funded Project SOLINDARITY, three HTHP demonstrators are implemented into operational production facilities of a food company, a rubber flooring production plant and a paper mill. With experience in the conception and design of HTHPs, the German Aerospace Center (DLR) will develop the HTHPs with further German partners for all three demo cases. The largest demo case (approx. 600 kW of thermal power) focuses on a thermal oil energy based industrial food production process in Germany. The first results of the development and integration process of a reversed Brayton HTHP in context of the new SEHUS for this demonstration case are presented in the following study.

* Corresponding author

2. DESCRIPTION OF THE CURRENT PROCESS AND ENERGY SYSTEM

In the case of the thermal oil energy based industrial food production process in Germany, the demo case described below and shown in Figure 1 is a food production plant which produces roasted snacks. The Production facility is divided into a processing and a packaging unit. After heating, the snacks are cooled and temporarily stored before packaging. On the process side, the snacks are fried in sunflower oil at temperatures in the range of 170 °C. Due to the high temperatures, the snacks quickly lose its water content. An extraction system sucks out the resulting exhaust vapor, which are then cooled, oxidized and then cleaned. On the energy system side, the heat required for heating the sunflower oil is delivered in the form of 265 °C hot thermal oil, which is currently provided by a thermal oil heater. This thermal oil heater utilises natural gas as fuel. The frying system consists of two fryers, each with approx. 600 kW of thermal power.

3. INITIAL INTEGRATION CONCEPT

As part of the project SOLINDARITY, the following study takes the industrial food sector as an example application of a "utility replacement" process for an industrial HTHP, respectively in the following described SEHUS. Here, part of the existing energy production, usually thermal oil cycles heated by fossil fuels (e.g. natural gas boiler), is replaced and consequently decarbonized. The heat upgrade system SEHUS aims to generate part of the energy production utilising solar energy. A general concept of the SEHUS Integration strategy is shown in Figure 1 as a block flow diagram. It illustrates the interconnection of the SEHUS systems with the working fluids as well as the arrangements of the energy generation and distribution systems. (Note: The numbers divide the subsystems that are used in the rest of this study).

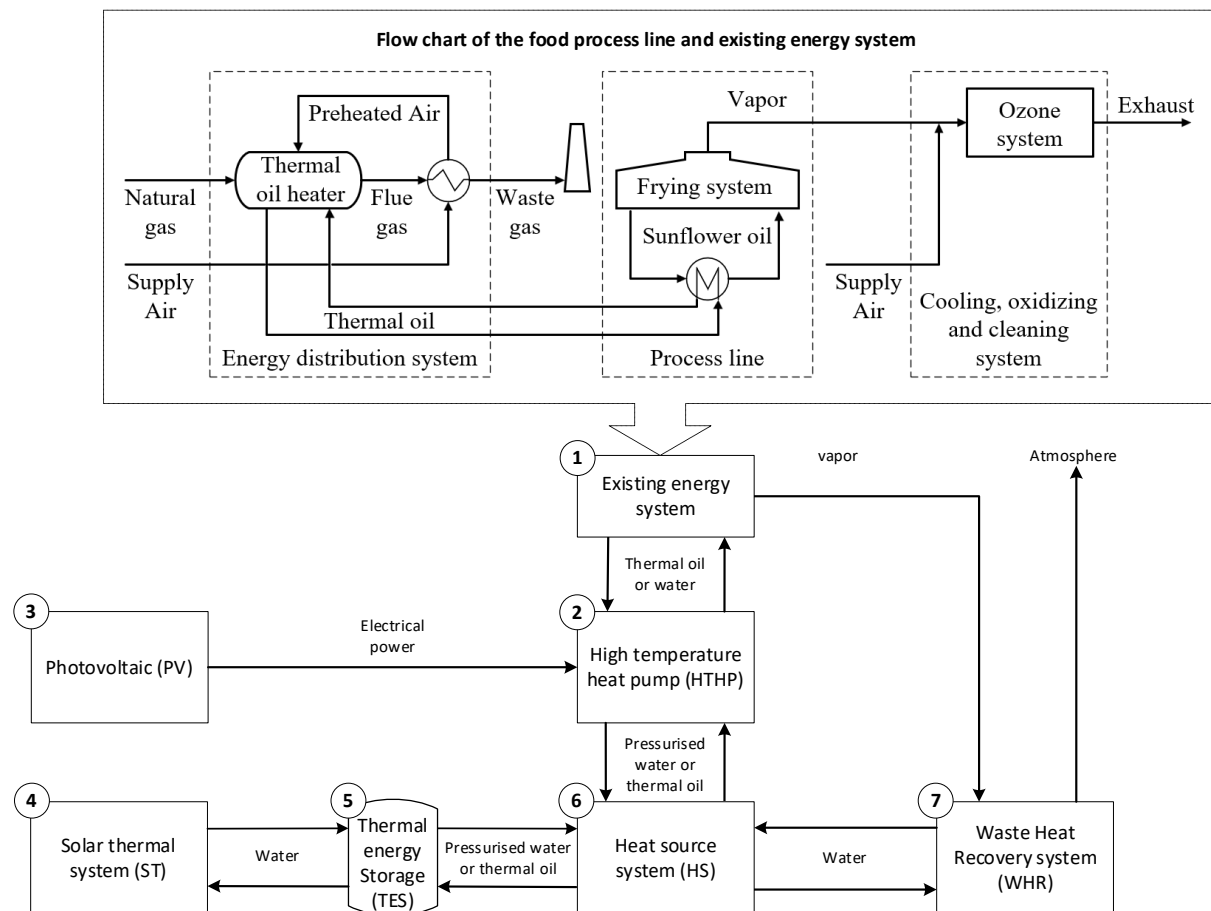


Figure 1: Block diagram of general SEHUS integration concept with existing energy system in detail

The SEHUS starts with the process interface of the existing energy distribution systems at the industrial demonstration cases (1). A High temperature heat pump (HTHP, 2) will perform a heat upgrade. Depending on the demo case, the process integration of the HTHP in the energy distribution system takes place via air/liquid heat exchangers.

Electrical and thermal solar energy plants will be installed as renewable energy sources for the HTHP. As the electrical source, a photovoltaic plant (PV, 3) will provide SEHUS with the electrical power required. This will be distributed to supply the overall system with electricity and to drive the HTHP turbo groups, the biggest electrical power consumers. On the other hand, a solar thermal power plant (ST, 4) will be connected with a thermal energy storage (TES, 5) to serve as the main heat generator of the heat source system (HS, 6) for the HTHP.

In addition, a Waste heat recovery system (WHR, 7) module will recover heat from the existing processes or energy supply system (e.g. flue gas of existing boilers). This energy will be utilized to additionally preheat the working fluid entering the HTHP on the source side or for the provision of thermal energy when the availability of solar thermal energy is not enough.

Shown in Figure 2 the Brayton HTHP is based on a typical reversed and recuperated Brayton cycle. Powered by a direct electrical drive, the compressor (C) raises pressure and temperature of the working fluid, air ($1 \rightarrow 2$). The heat sink heat exchanger (HEX-3) transfers sensible heat to the process and cools down the working fluid ($2 \rightarrow 3'$). Due to the very high inlet temperatures of the thermal oil into the HEX-3, an internal heat exchanger (HEX-2) or Recuperator transfers some of the residual heat from before the turbine to before the compressor, reducing the temperature of the working fluid ($3' \rightarrow 3$) before it expands through a turbine (T). The mechanical output of the turbine, which has the same shaft as the compressor, is used directly to partially drive the compressor. After expansion, the working fluid pressure drops to the initial level ($3 \rightarrow 4$). During this expansion, the working fluid also cools down. Next, the cool working fluid absorbs heat ($4 \rightarrow 1'$) from the heat source through the heat source heat exchanger (HEX-1) and then flows through the internal heat transfer of the HEX-2 to complete the cycle ($1' \rightarrow 1$).

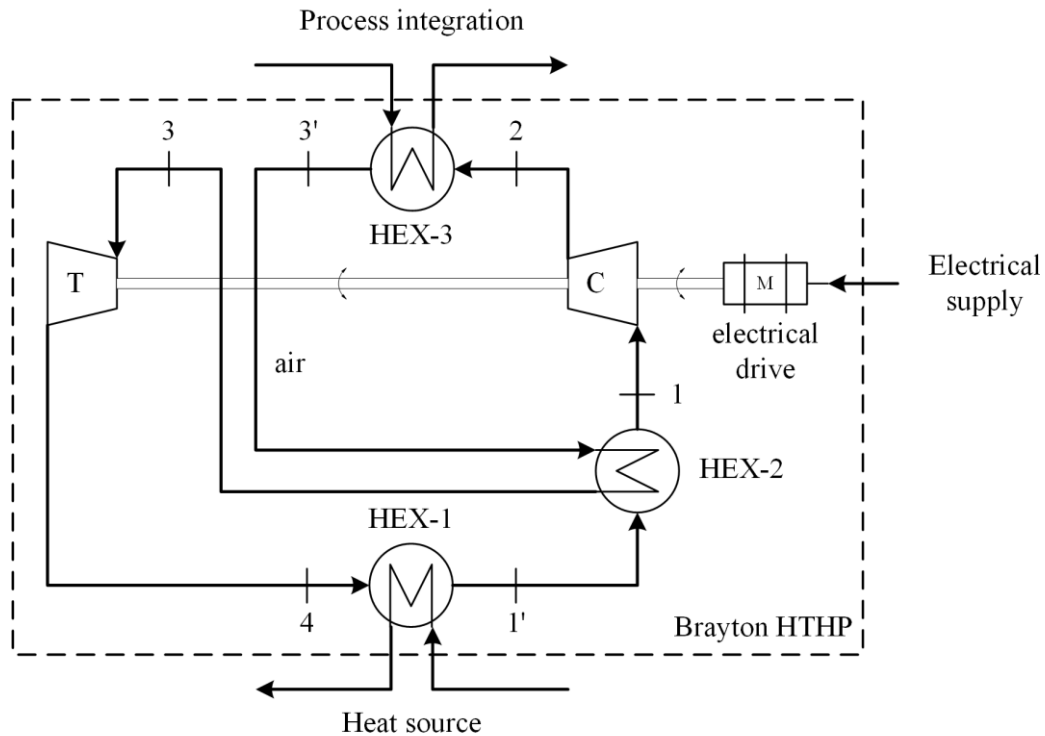


Figure 2: Simplified scheme of reversed recuperated Brayton HTHP

4. DEVELOPMENT PROCESS OF THE HTHP SYSTEM

The HTHP system development process described below is based on the general principles of a development project (Concept, Design, Manufacturing and Commissioning) and categorises the various phases of simulation-based development. The following Figure 3 shows an extract from the simulation-based development process of the HTHP system

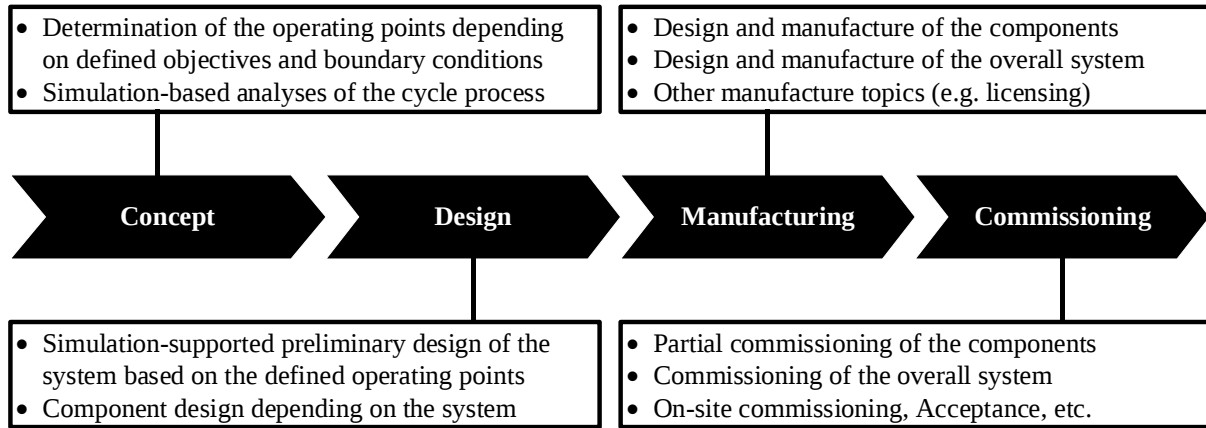


Figure 3: Extract from the simulation-supported development process of the HTHP system

The development process begins with the determination of the operating points depending on defined targets (e.g. CO₂ reduction, primary energy savings) and boundary conditions of the existing process and energy system into which the HTHP is to be integrated. Particularly from the HTHP's point of view, heat sink and heat source parameters must be defined. Based on this, the simulation-based development process begins with the feasibility study as a first step, which defines an initial concept for the HTHP in a low level of detail. Initial estimations of process and component dimensioning parameters as well as component arrangements are outcomes, which among other things are used to assess the economic efficiency. To evaluate the efficiency, the heating power related Coefficient of performance COP (see Eq. 1) is used. The COP 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 [5].

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

Simulation-based analyses of the cycle process summarise the rest of the process, which is transferred to the design phase of the development process in the form of concept design and preliminary design. The aim of these two further simulation-based steps (concept design and preliminary design study) is to obtain corrected evaluation parameters, a preliminary design, final specifications of the main components and off-design simulations. The following Table 1 summarises the steps of the simulation-based development process and assigns the inputs and the desired outcomes/goals as well as the simulation model detail levels in EBSILON® Professional to the respective steps.

Table 1: Steps of the simulation-based development process

Input	Simulation model detail level	Goals/ Outcome
Step 1: Feasibility study - Simulation model for process integration		
Heat sink and heat source: • Inlet temperatures • Outlet temperature, if possible • Pressure • Working fluids • Mass flow or overall thermal power of energy system	EBSILON® design modelling: • Simple model of turbo machines → const. isentropic efficiencies • Simple model of heat exchanger → const. terminal temperature differences • Optimization to find the Brayton cycle mass flow for best COP • Regulation parameter (i.e. Thermal power, which should be deliver by the HTHP or heat sink outlet temperature)	Process and component dimensioning parameters and component arrangement: • Brayton cycle mass flow • Initial sizing of main components: compressor, turbine & HEX, i.e. HEX surface area, pressure losses, corrected mass flows • Selection of turbo impellers (for maps) • Recuperation or non-recuperation
Step 2: Concept design study - Simulation model for the main component		
First component dimensioning parameter: • Compressor Map • Turbine Map¹⁾ • Terminal temperature differences • First approaches of pressure losses of HEX are sufficient	EBSILON® design modelling: • Map-based compressor • Map-based turbine¹⁾ • Simple model of heat exchanger → const. terminal temperature differences	Corrected process parameters, Component dimensioning and first Off-Design simulations: • Number of Turbo units • Serial, if pressure ratio too high • Parallel, if mass flow too high • HEX heat transfer area
Step 3: Preliminary design study - Simulation model for the preliminary design		
First installation concept: • Turbine Map²⁾ • First model of HEX • Pipes (Length, Number of pipe bends, etc.)	EBSILON® design modelling: • Map-based turbine²⁾ • Dynamic HEX models¹⁾ • Dynamic Pipe models	Corrected process parameters, Preliminary design, final main component specifications and Off-Design simulations

¹⁾ If already available in this step

²⁾ If not already available in the previous step, necessary here

5. FIRST RESULTS OF THE DEVELOPMENT PROCESS

In order to obtain the SEHUS designs and specifications of the main components of the SEHUS HTHP's in the project SOLINDARITY, the three steps of the simulation-based development process described in Chapter 4 were applied. The following sub-chapters provide a brief description, the main input parameters and the final figures of the simulations of the industrial food production demo case of SOLINDARITY. As part of the definition of the boundary conditions, it was determined that two operating points frame the design of the HTHP, which are defined by the minimum and maximum temperatures of the solar thermal energy and thus correspond to the inlet temperatures of the heat source. In conclusion, all simulations are carried out under Max. conditions (inlet temperature of heat source equal to 150 °C) and Min. conditions (inlet temperature of heat source equal to 90 °C).

Step 1: Feasibility study - Simulation model for process integration

After creating the general HTHP model in EBSILON® Professional, the input parameters shown in Table 2 were used for the feasibility study. Due to the very high inlet temperatures at the heat sink and the resulting high outlet temperatures of the HEX-3 in the Brayton cycle, the use of a recuperator was finalized. The internal optimization tool of EBSILON® Professional was used to calculate a mass flow optimized for the maximum COP. With thermal oil as working fluid at the heat source and heat sink, similar material fractions were used in EBSILON® Professional, which are based on the manufacturer's specifications for the actual working fluid in the existing process. Figure 4 and Figure 5 show the final results of the feasibility studies in EBSILON® Professional for max. and min. conditions.

Table 2: Input parameter for the feasibility study

Parameter	Unit	Value
Input parameter of heat source and heat sink		
Inlet temperature heat sink (HEX-3 in Figure 4 & 5)	°C	245
Inlet temperature heat source – Max. conditions	°C	150
Inlet temperature heat source – Min. conditions	°C	90
Pressure heat sink (Estimation)	bar	5
Pressure heat source (Estimation)	bar	5
Working fluid heat sink (HEX-3 in Figure 4 & 5)	-	Diathermic oil
Working fluid heat source (HEX-1 in Figure 4 & 5)	-	Diathermic oil
Volume flow heat sink	m ³ /h	20
Input parameter for EBSILON® design modelling		
Isentropic efficiency of the compressor	%	80
Isentropic efficiency of the turbine	%	85
Lower terminal temperature difference air/ diathermic oil	K	10
Upper terminal temperature difference air/ air	K	30
Regulation parameter 1 – Thermal power of HTHP	kW	600
Regulation parameter 2 – Outlet temperature heat source for mass flow calculation	°C	130
Optimization to find the Brayton cycle mass flow for best COP		

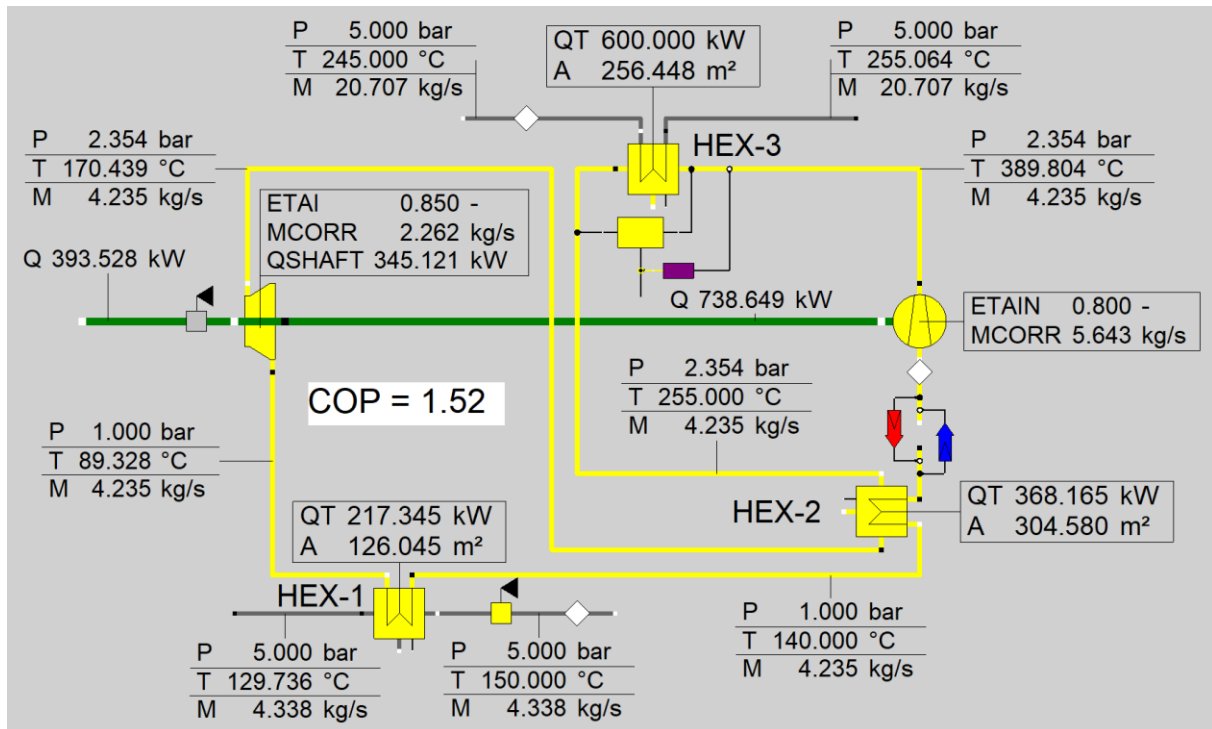


Figure 4: Final Feasibility study EBSILON® design model – Max. conditions

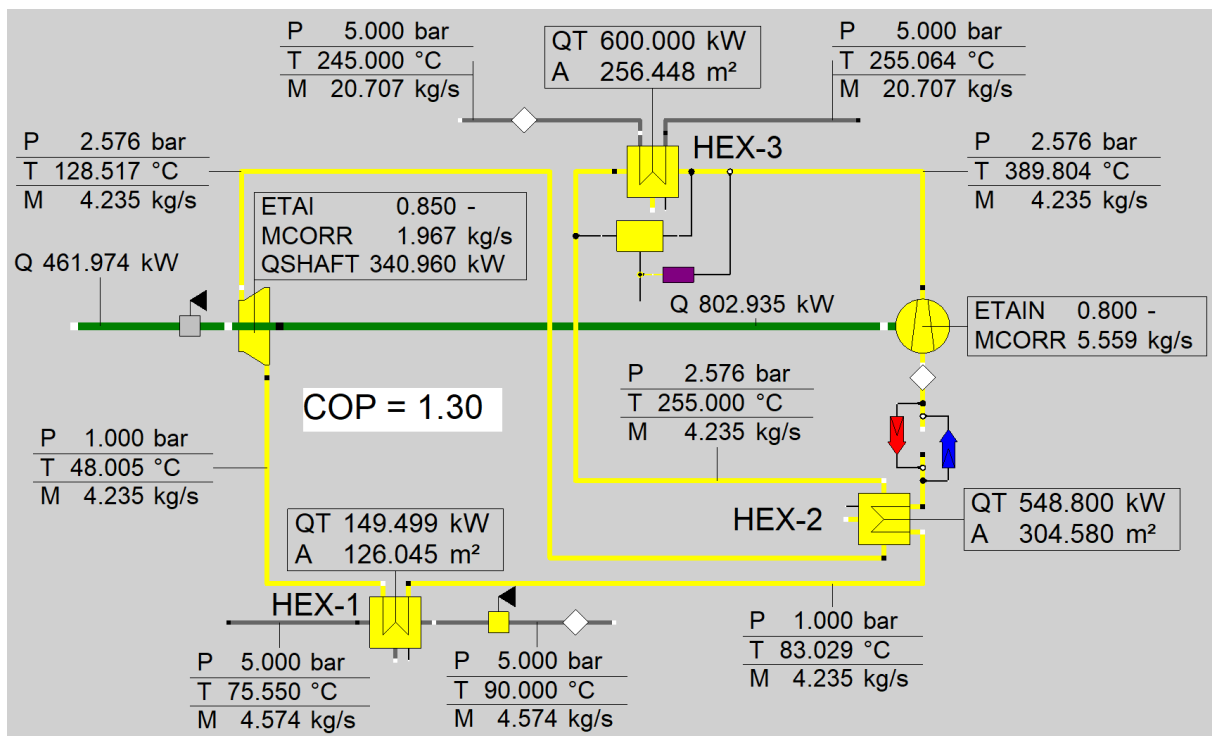


Figure 5: Final Feasibility study EBSILON® design model – Min. conditions

Step 2: Concept studies - Simulation model for the main component

The first draft of the concept study simulation model, representing the second step of the development process, was further developed on the basis of the feasibility studies. This integrates the defined design parameters from the feasibility study in the form of the heat exchanger surface area of the heat exchangers. After initial discussions with manufacturers, the pressure losses can also be assumed, an initial compressor map integrated and specifications made with regard to the turbine characteristics. As no turbine map was yet available, the turbine characteristics can initially be modelled using the corrected mass flow. Table 3 shows the input parameters for the EBSILON® design modelling. As a result of the iterative process of the concept study with component manufacturers, a suitable compressor impeller (and thus a compressor map as input) was identified. A power limitation of the compressor drive system led to the parallel connection of 4 turbomachines in order to generate the required pressure for the available mass flow. Figure 6 and Figure 7 show the final results of the concept studies in EBSILON® Professional for max. and min. conditions.

Table 3: Input parameter for the concept design study

Input parameter for EBSILON® design modelling	Unit	Value
Heat exchanger surface area of HEX-1	m ²	120
Heat exchanger surface area of HEX-2	m ²	300
Heat exchanger surface area of HEX-3	m ²	250
Pressure drop - Brayton cycle side of HEX-1	bar	0.01
Pressure drop - Brayton cycle side of HEX-3	bar	0.01
Pressure drop – High pressure side of HEX-2	bar	0.02
Pressure drop – Low pressure side of HEX-2	bar	0.01
Corrected mass flow of one turbine	Kg/s	0.55

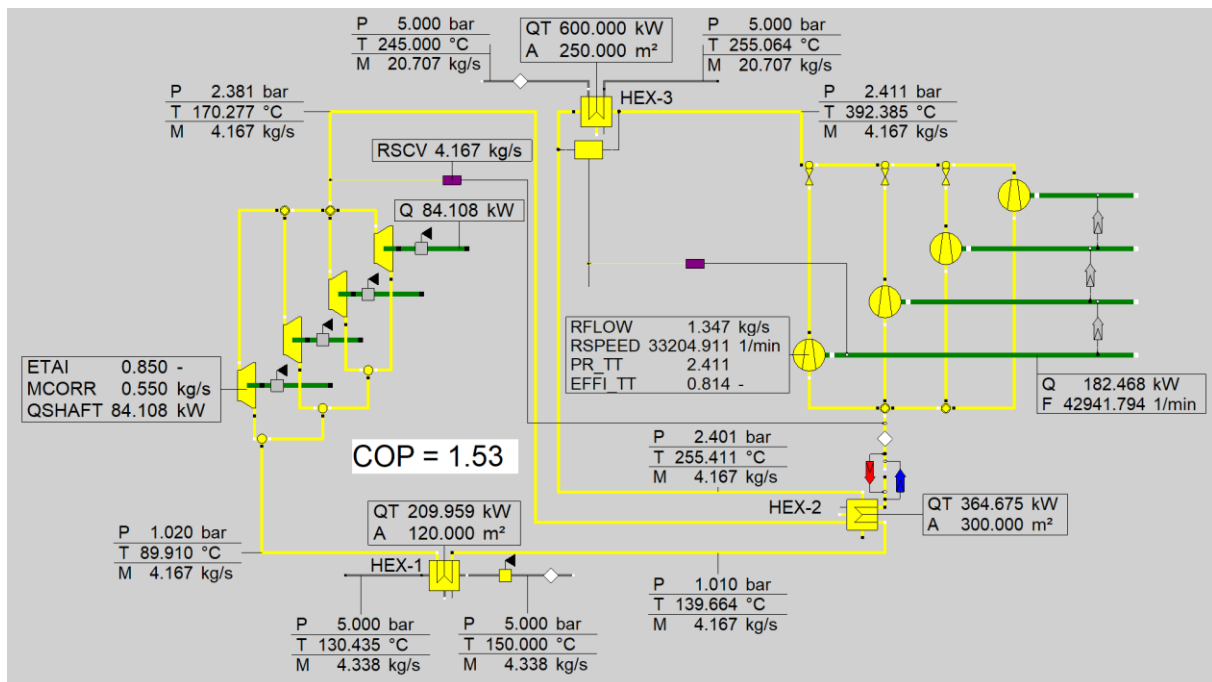


Figure 6: Final Concept study EBSILON® design model – Max. conditions

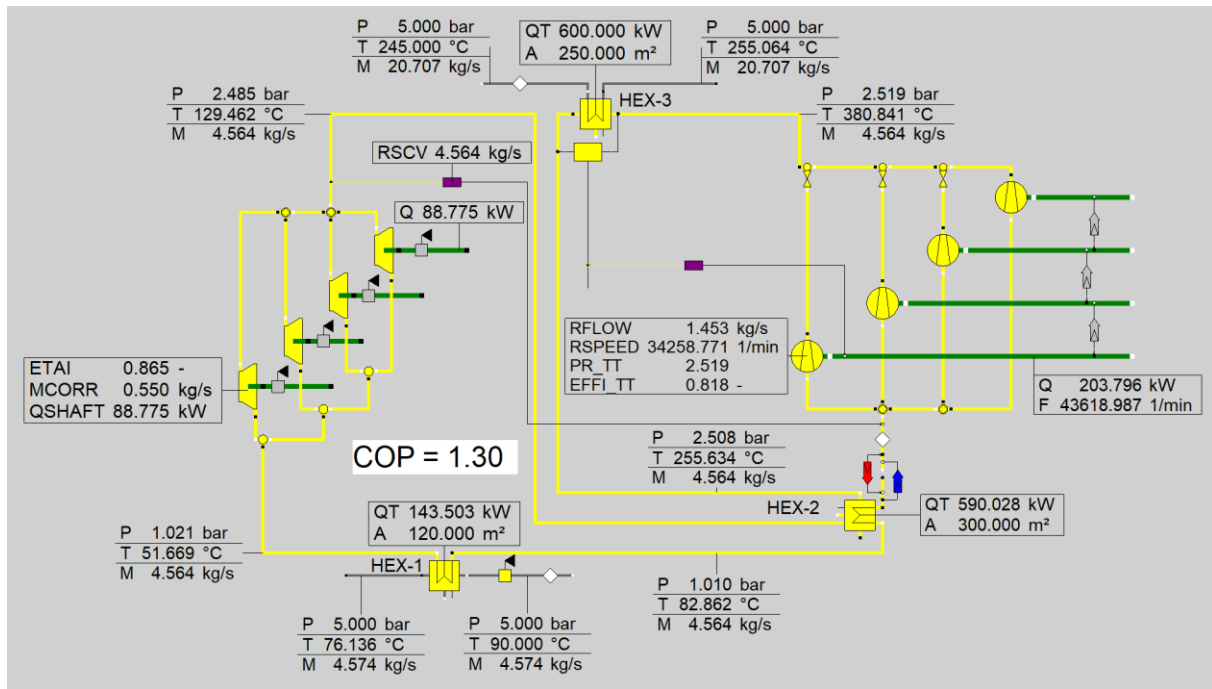


Figure 7: Final Concept study EBSILON® design model – Min. conditions

Step 3: Preliminary design study - Simulation model for the preliminary design

In an atypical occurrence, the configuration of the Brayton cycle process underwent modification during this phase. This alteration transpired as a consequence of deliberations pertaining to the incorporation of the WHR. To increase the efficiency of the heat input of the WHR, the heat exchanger for the flue gas (HEX_FG) was placed between the turbine and HEX-1. This in turn led to a further operating point to be considered, as the HTHP can also be operated exclusively with the WHR as the heat source. This ultimately leads to the consideration of the three operating points for all following simulations “Max. conditions” (WHR and operation of the heat source with an inlet temperature of 150 °C), “Min. conditions with Solar thermal” (WHR and operation of the heat source with an inlet temperature of 90 °C) and “Min. conditions without Solar thermal” (WHR and no operation of the heat source).

An iterative process with the manufactures of the turbo machines and heat exchanger with the concept design model resulted in the input parameter and maps for the preliminary design. In addition, the constructor drew up an initial installation concept, as a result of which initial estimates of the pipe lengths and number of pipe bends could be made. As a result, the pressure losses of the pipework could be calculated. However, this is still based on a number of assumptions (thickness of the insulation, pipe diameter, material, etc.) and can be deepened as often as required in further iteration steps, thus increasing the level of detail of the simulations. Figure 8 Figure 6up to Figure 10Figure 7 show the first iteration of the preliminary design study in EBSILON® Professional for the three operation points. These results represent the conclusion of the results presented here, as this was the most up-to-date status at the time this study was prepared.

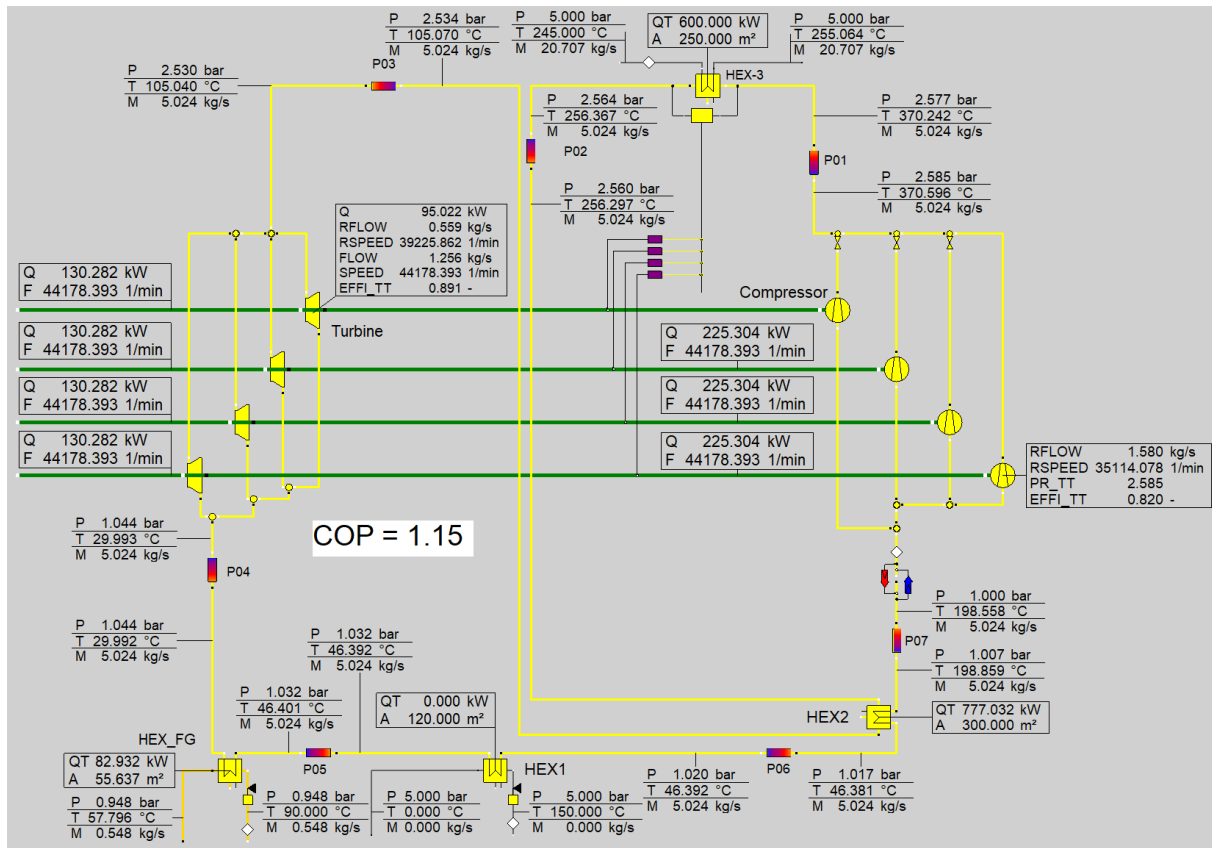


Figure 10: Preliminary design study EBSILON® design model – Min. conditions without Solar thermal system

6. CONCLUSIONS AND OUTLOOK

This study presents first results of the development process of a reversed Brayton HTHP regarding the heating generation system SEHUS in the case of a thermal oil energy based industrial food production process in Germany. With the description of the current process and energy as well as the initial integration concept of the SEHUS and the Brayton HTHP, the starting point of the development process is shown in the first two chapters. Thereupon, the methodology of the development process is described and subsequently carried out using the example of the Brayton HTHP in the demo case of the food production process in Germany. The results of the design steps are also shown. The integration concept and preliminary dimensioning, which are based on steady-state simulations, provide a starting point for the design phase, as they encompass the concept of the HTHP. The investigations in the design phase are the next step and should be compared with the results of the concept phase. Changes are to be expected, for example in the COP, as pressure and heat losses become clearer (these were not yet available at the time of writing this paper).

This is the most up-to-date status at the time of writing of this study and will be extended to the other two demo cases as the project progresses. Furthermore, at the start of the design phase, a dynamic volume model of the SEHUS based on this steady-state simulation will be created, which will help with the detailing of operation points and the detailed engineering of the of SEHUS system.

Once the SEHUS have been commissioned to the respective demo cases, the models can be verified and conclusions can consequently be drawn about the quality of the model as part of development process. At this stage, following discussions with the planners, it can be said that this simulation-based concept phase procedure has proven to be essential, particularly due to the holistic investigations of the thermodynamic cycles.

7. ACKNOWLEDGMENT

The research for this work and the project received funding from the European Union’s Horizon Europe Framework Programme under grant agreement No 101136148. The authors thank all involved project partners. 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.

8. NOMENCLATURE

Abbreviations	
C	Compressor
COP	Coefficient of performance
DLR	German Aerospace Center
EU	European Union
GHG	Greenhouse gas
Gt	Gigatons
HEX	Heat exchanger
HEX-1	Heat source heat exchanger
HEX-2	Internal heat exchanger/ Recuperator
HEX-3	Heat sink heat exchanger
HS	Heat source system
HTHP	High Temperature Heat Pumps
PV	Photovoltaic
SEHUS	Solar Energy-based Heat Upgrade System
SOLINDARITY	Project Name, https://solindarity.eu/
T	Turbine
TES	Thermal Energy Storage
WHR	Waste Heat Recovery
Variables	
$\dot{Q}_{out}$	Heat flow of the heat sink [W]
$\dot{W}$	Drive power [W]

REFERENCES

- [1] European Commission, IEA, GHG emissions of all world countries, Publications Office, Luxembourg, 2024.
- [2] M. Rehfeldt, T. Fleiter, F. Toro, A bottom-up estimation of the heating and cooling demand in European industry, *Energy Efficiency* 11 (2018) 1057–1082.
- [3] T. Naegler, S. Simon, M. Klein, H.C. Gils, Quantification of the European industrial heat demand by branch and temperature level, *Int. J. Energy Res.* 39 (2015) 2019–2030.
- [4] G. Kosmadakis, Estimating the potential of industrial (high-temperature) heat pumps for exploiting waste heat in EU industries, *Applied Thermal Engineering* 156 (2019) 287–298.
- [5] C. Arpagaus, *Hochtemperatur-Wärmepumpen: Marktübersicht, Stand der Technik und Anwendungspotenziale*, VDE Verlag GmbH, Berlin, Offenbach, 2019.