Technical assessment of Brayton cycle heat pumps for the integration in hybrid PV-CSP power plants

Cite as: AIP Conference Proceedings **2445**, 030014 (2022); https://doi.org/10.1063/5.0086269

Zahra Mahdi, Jürgen Dersch, Pascal Schmitz, et al.

Technical Assessment of Brayton Cycle Heat Pumps for the Integration in Hybrid PV-CSP Power Plants

Zahra Mahdi[1,a)], Jürgen Dersch[2], Pascal Schmitz[1], Simon Dieckmann[2], Ricardo Alexander Chico Caminos[1], Cristiano Teixeira Boura[1], Ulf Herrmann[1], Christian Schwager[1], Mark Schmitz[3], Hans Gielen[3], Yibekal Gedle[3], Rauno Büscher[1]

[1]*Solar-Institut Jülich of the Aachen University of Applied Sciences (SIJ), Heinrich-Mussmann-Str. 5, 52428 Jülich, Germany.*
[2]*DLR Institute of Solar Research, Linder Höhe, 51147 Köln, Germany.*
[3]*TSK Flagsol Engineering GmbH, Anna-Schneider-Steig 10, 50678 Köln, Germany.*

a) Corresponding author: mahdi@sij.fh-aachen.de

Abstract. The hybridization of Concentrated Solar Power (CSP) and Photovoltaics (PV) systems is a promising approach to reduce costs of solar power plants, while increasing dispatchability and flexibility of power generation. High temperature heat pumps (HT HP) can be utilized to boost the salt temperature in the thermal energy storage (TES) of a Parabolic Trough Collector (PTC) system from 385 °C up to 565 °C. A PV field can supply the power for the HT HP, thus effectively storing the PV power as thermal energy. Besides cost-efficiently storing energy from the PV field, the power block efficiency of the overall system is improved due to the higher steam parameters. This paper presents a technical assessment of Brayton cycle heat pumps to be integrated in hybrid PV-CSP power plants. As a first step, a theoretical analysis was carried out to find the most suitable working fluid. The analysis included the fluids Air, Argon (Ar), Nitrogen (N2) and Carbon dioxide (CO2). N2 has been chosen as the optimal working fluid for the system. After the selection of the ideal working medium, different concepts for the arrangement of a HT HP in a PV-CSP hybrid power plant were developed and simulated in EBSILON®Professional. The concepts were evaluated technically by comparing the number of components required, pressure losses and coefficient of performance (COP).

INTRODUCTION

Concentrated Solar Power (CSP) and Photovoltaics (PV) are the two main technologies to convert solar energy into electricity. These can be integrated into a single hybrid system to benefit from the advantages of both technologies. PV electricity is already very affordable today at locations with good solar resources, but large-scale storage technologies are currently not available or relatively expensive. Solar heat from concentrating collector systems, on the other hand, can be easily stored, and the conversion of heat into electricity can take place in line with demand in the conventional steam power block of the CSP system. However, electricity from CSP is currently more expensive than PV electricity, in case there are no additional incentives for storage or dispatchability. By intelligently combining both technologies, the cost effectiveness and flexibility of solar power production can be increased compared to two separately configured systems.

CSP-PV hybrid systems already exist, but so far, hybridization has been limited to a common feed from the separate systems into the power grid. A more effective hybridization could be achieved by coupling the systems by means of a power to heat (P2H) unit (e.g. resistance heater (RH) or high temperature heat pump (HT HP)) and by optimizing the integration of both systems. The investigation of a HT HP together with a molten salt storage system for the integration in PV-CSP hybrid power plants is one of the main aims of the ongoing project SWS, which is carried out in cooperation between SIJ, TSK Flagsol and DLR.

SolarPACES 2020
AIP Conf. Proc. 2445, 030014-1–030014-10; https://doi.org/10.1063/5.0086269
Published by AIP Publishing. 978-0-7354-4195-8/$30.00

APPROACH

Parabolic trough collector (PTC) systems commonly utilize thermal oil as heat transfer fluid (HTF) and operate with a maximum temperature of 393 °C. Solar salt (a mixture of 60 wt.-% $NaNO_3$ and 40 wt.-% KNO_3) allows higher operating temperatures, thus improving power block efficiency and reducing storage costs of the system. HP can be deployed to raise the temperature of the molten salt hot storage to 565 °C in a PTC plant. A PV field can supply the power for the HP, which in turn allows the cost effective thermal storage of electricity from the PV plant in molten salt.

Today only HP systems with maximum outlet temperatures of 165 °C are available on the market. These commercially distributed systems operate according to the Rankine gas compression cycle and are designed for operation with comparatively small temperature differences of less than 100 °C between flow and return, whereby small temperature differences are advantageous as they result in a better coefficient of performance (COP). [1]

HT HP for the temperature range up to 565 °C are not commercially available, although the concept has drawn attention in recent years. [2] The subject of this research is a PV-CSP hybrid plant with a Brayton cycle HP, where the working fluids undergo no phase change in the thermodynamic cycle.

STATE OF THE ART

An advantage of a CSP system is the ability to store energy in its integrated thermal energy storage. According to IRENA, the global weighted average LCOE of concentrating solar power in 2019 was USD 0.182/kWh – 47 % lower than in 2010. However, it is still more expensive than PV electricity. The levelized cost of energy produced by utility-scale solar PV has decreased by 13 % year-on-year in 2019 reaching USD 0.068/kWh. [3] In the case of PV systems, electricity generation is directly dependent on irradiation times, so the prices of PV electricity do not reflect its availability in line with demand. CSP systems with thermal storage can generate solar power largely predictable and according to demand. In addition, the use of thermal storage in CSP plants at suitable locations leads to a reduction in electricity production costs. [4] With PV systems, on the other hand, the electricity generation costs increase considerably, if they are equipped with additional battery storage.

PV-CSP Hybrid Power Plants

Following are some examples of the existing CSP-PV power plant as two independent power generation systems on one site:

- Noor Energy 1 in Dubai: 600 MW from three parabolic trough CSP plants, 100 MW from a solar tower, and 250 MW from photovoltaic panels. [5]
- Ouarzazate Solar Power Station (OSPS) in Morocco: combination of parabolic trough, solar tower and PV with a total power of 580 MW. [6]

The only CSP-PV power plant having a fully integrated individual system concept is the Noor Midelt I project in Morocco, which has been announced last year. The project will have a total installed capacity of 800 MW and upon completion, it will provide dispatchable solar energy during the day and up to five hours after sunset for a record-low tariff at peak hours of USD 7 cents/kWh. The Noor Midelt Phase 1 plant located 20 km north of the town of Midelt in Morocco is now in the planning stage.

In the SWS project, the feasibility of the application of a HT HP instead of electrical heaters to hybridize the CSP and PV systems is investigated.

HT HP Concepts in Research and Development

In the research field of Clausius-Rankine HP there are numerous projects with optimization approaches that aim to increase the achievable process temperatures. In the Rankine cycle process, the working media always experience a change in their phase state, so that the heat quantities transferred are composed of sensitive and latent components. Often, the promised hot side temperatures are limited to values below 200 °C, as technical implementation is difficult beyond this. However, there are also theoretical approaches with working temperatures of up to 400 °C. Some of these currently researched concepts are presented in [7–12].

Object of the research are also HP systems using a Joule cycle, whose working fluids undergo no phase change. In theory, these systems are characterized by very large temperature spreads of more than 600 °C and maximum temperatures above 500 °C. In their terminology, the two types should be separated from each other due to the different thermodynamic conditions. Particularly in the field of thermal intermediate storage of electrical energy on a large scale, research is being conducted with high intensity into solutions for storing and reconnecting electrical energy at low cost and with competitive efficiencies. Some concepts consider the possibility of thermal storage and the subsequent conversion to electricity using suitable HP / heat motors according to the Joule principle. Instead of converting the stored thermal energy back into electricity, it can also be used directly in a heat consumption process. Some of the most important concepts in this field have been presented in [2,13–16].

ANALYSIS

In order to use a HT HP together with a molten salt heat storage tank for the application in PV-CSP hybrid power plants, an evaluation matrix combined with a sensitivity analysis were carried out to find the most suitable working fluid. In a next step, different concepts for the arrangement of a HT HP in a PV-CSP hybrid power plant have been developed, simulated and compared. These two steps will be explained in detail in the next sections.

Selection of the Working Fluid

HPs based on the Clausius-Rankine process are only suitable to a very limited extent for the planned high-temperature application in the SWS project, as the achievable flow temperatures do not reach the desired values. The advantage of these HP is their direct market availability and proven technical feasibility. In comparison, Joule HP allow significantly higher flow temperatures, but generally have poorer COPs and prove to be technically difficult to realize. Typically, larger mass flows of the working medium must be circulated and high thermal loads act on the system components. [17] In most cases, the turbomachinery required for compression and expansion of the working medium is not yet available and extensive development work will be necessary, before it is offered on the market.

In order to choose the best HTF for the present study, primarily, an evaluation matrix has been created for the different HT HP concepts with flow temperatures above 200 °C to ensure the comparability of the systems.

The evaluation is based on a point-based system, where points are awarded for the working media, not for the specific concepts, as the systems for a particular working medium group do not differ greatly from each other. In addition to the points awarded for a criterion of the respective working media, the criteria themselves are weighted. This weighting determines the importance of the criteria among themselves. For example, the property "low corrosion" is less important than the "safety" of the working medium used.

The evaluation criteria were divided into three groups: "fixed requirements", "target requirements" and "optional requirements". The fixed requirements include criteria that must be fulfilled in order for a concept to be included in the evaluation. The target requirements differ from the optional requirements, as they have a stronger influence on the choice of the appropriate concept. This is also reflected in the lower weighting of the listed desired requirements. The HTFs and some of the most important requirements are shown in Fig .1.

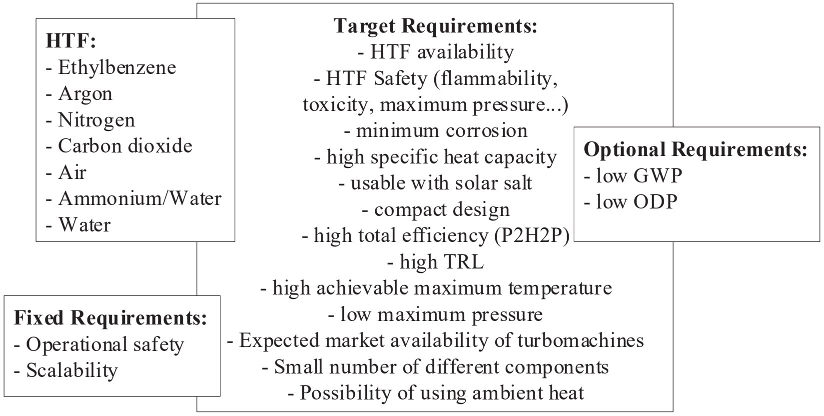

FIGURE 1. Different HTF and some examples of the requirements applied for the evaluation matrix

The definition, weighting and final evaluation of the criteria has been developed based on the literature and the necessities of the project. By directly comparing the selected working media with the respective system concepts as a reference, the system properties could be subjected to a meaningful evaluation. After the evaluation of all individual criteria, a single, integer numerical value is the output for each working medium, which is made up of the product of criterion weighting and evaluation points for the working medium under consideration.

In this evaluation, the concept with air achieved the best overall rating, closely followed by argon (Ar), nitrogen (N2) and carbon dioxide (CO2). These four HTFs have been chosen to be simulated in a next step within the framework of a sensitivity analysis.

Figure 2 shows the system diagram of the basic model used for the analysis. For this configuration, the cold and hot storage temperatures were assumed 290 °C and 560 °C, respectively. The COP and pressure ratio (PR) values as well as the necessary mass flow rates have been compared for different heat source temperature levels and different performance ranges.

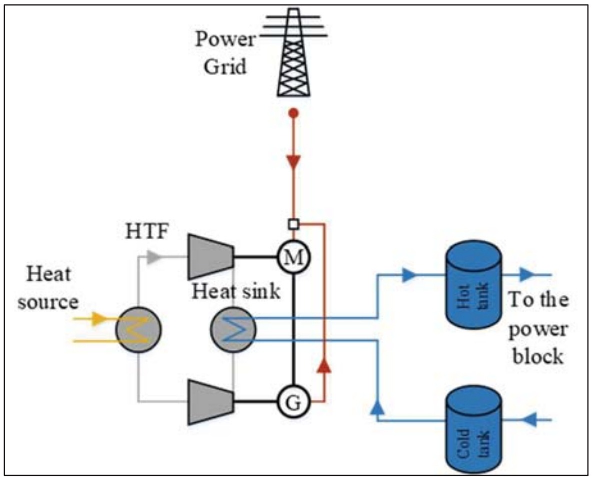

FIGURE 2. Basic model of a HT HP coupled with molten salt storage

With the help of the simulation models created, the system has been adapted for the individual temperature range of the heat source and the resulting thermal power, which can be stored in the hot tank and used later to produce electricity. In addition, different working media in the HP cycle have been applied and compared with each other across individual cases. Based on these results, a suitable HTF for the respective application can be determined.

Case 1: For this case, simulations were carried out for different withdrawal rates on the hot side of the HP. The heat source temperature on the cold side was assumed constant with a value of 400 °C.

TABLE 1. COP and PR for different HTF independent of various output power

HTF	COP	PR
N2	2.811	2.001
CO2	2.685	3.015
Ar	2.839	1.590
Air	2.809	2.018

The changes in output power have no influence on the COP and PR values and these remain constant over the whole range from 1 to 100 MW. The values are shown in the Tab. 1. The COP for CO2 is 2.685 and approx. 2.8 for the other working fluids. PR for CO2 is above 3, whereas it is almost half for Ar with a value of 1.59. PR in the HP cycle with N2 and air is approx. 2.

The capacity depends directly on the mass flow rate of the working medium in the HP cycle. Figure 3 (a) shows the mass flow rate as a function of the various media and capacities. The course of the mass flow rate of CO2, N2 and air is almost identical at different capacities. For Ar it is almost twice as high, which means a more complex and cost-intensive system from a technical point of view.

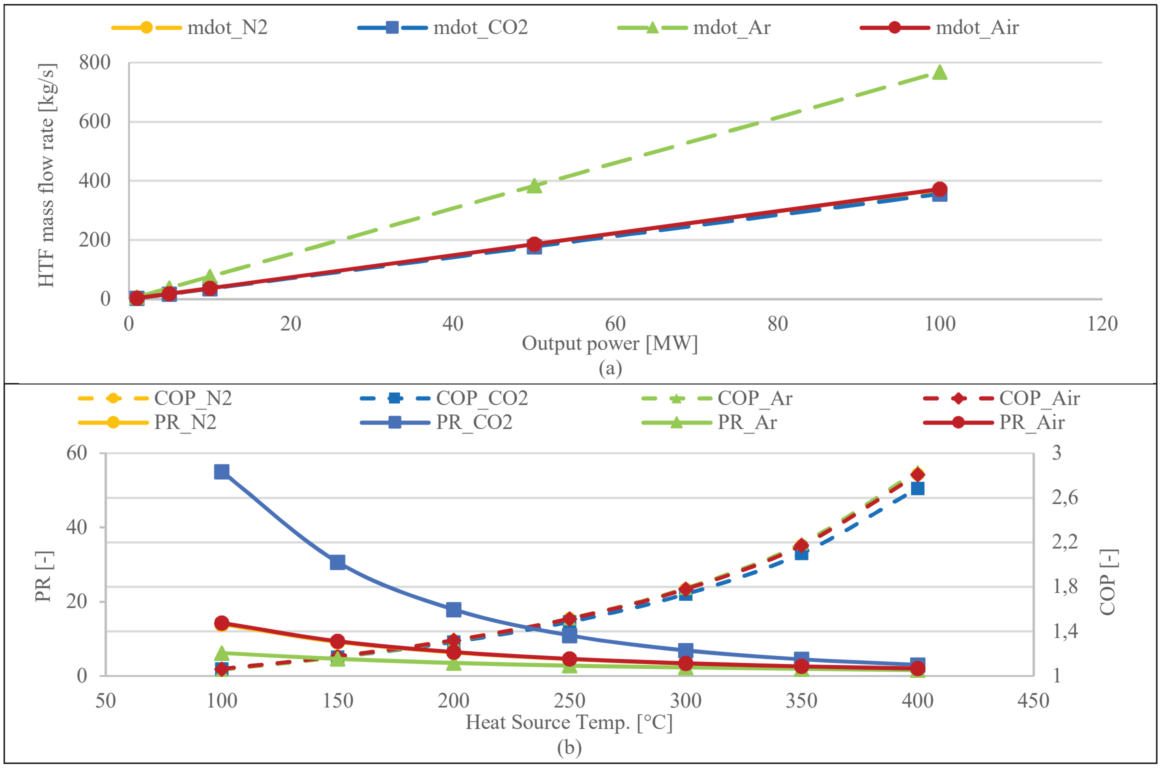

FIGURE 3. (a) HTF mass flow rate vs. output power for different HTFs; (b) COP and PR for different HTFs over various heat source temperatures

Case 2: In this case, simulations were performed for different temperatures of the heat source in a range from 100 °C to 400 °C in 50 °C increments. The heat is fed to the HP on the cold side and heats up the working medium via a heat exchanger. The heat source flow is shown in Fig. 2 with a yellow line. The heat output taken from the warm side of the HP is set at a reference value of 10 MW for all simulations.

The results of the simulations are shown in the Fig. 3 (b). On the two vertical axes, the pressure ratio (PR) and the coefficient of performance (COP) for different working media and heat source temperatures are displayed. As the heat source temperature increases and the temperature difference between the cold and hot side of the HP decreases, the COP increases and the PR decreases. CO2 has the lowest, while Ar has the highest value of COP for heat source temperatures larger than 200 °C. Compared to Ar, air and N2 the PR for CO2 is higher in each case. A low pressure ratio has a positive effect on reducing the cost and complexity of turbomachinery.

Comparison of Different CSP-PV-HP Configurations

Different arrangement concepts of a HT HP in a PV-CSP hybrid power plant have been developed, simulated in EBSILON®Professional and compared in order to technically evaluate the concepts. Identical parameters have been used for the individual components, which enables an objective comparison of the model results. According to [16] no cold storage was taken into account since this installation would be expensive and the impact is limited in combination with a water/steam cycle for electricity generation. Furthermore, the upper temperature of the HP cycle is limited to about 610 °C since the molten salt considered as storage medium is not heated above 565 °C. Additionally, the thermal load of the compressor can be reduced. The three investigated concepts are:

1. Molten salt is preheated via HTF from the CSP solar field (SF) and heated up with the HP afterwards. Heat from ambient air provides the input for the HP.
2. The molten salt is preheated via HTF from the SF and further heated up with the HP afterwards. Heat from the SF provides the input for the HP. The oil-salt preheater and the heat exchanger at the low temperature side of the HP are connected in parallel.

3. The molten salt is preheated via HTF from the SF and further heated up with the HP afterwards. The oil-salt preheater and the heat exchanger at the low temperature side of the HP are connected in series. The HTF from the SF provides the heat for the HP after preheating the molten salt.

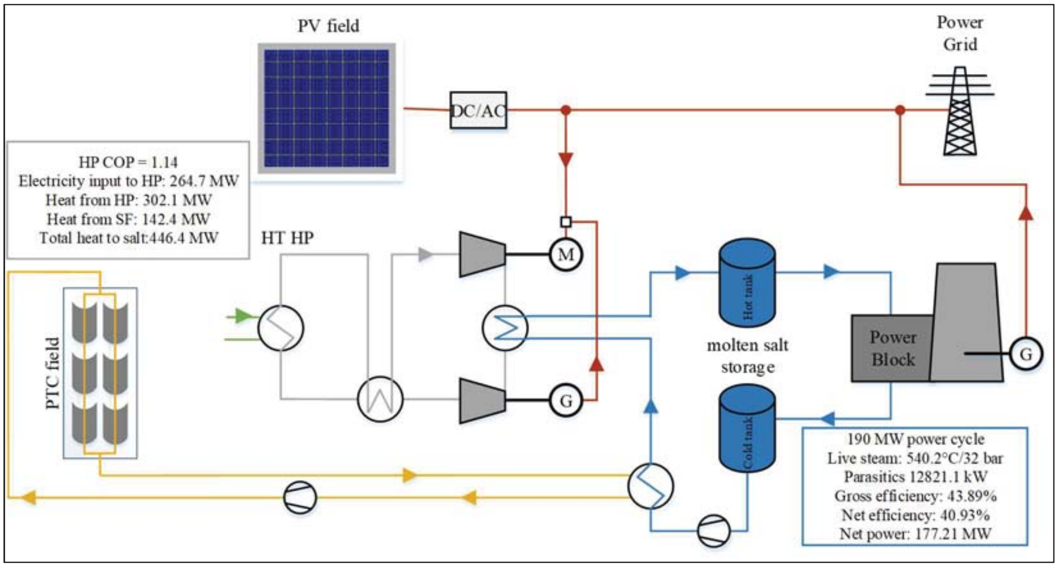

FIGURE 4. Process schematic diagram for the first configuration

Figure 4 shows a schematic diagram of the entire system for the first configuration. The HT HP uses a reverse Joule cycle with N2 as working fluid and is supplied with heat from ambient air. The molten salt from the cold storage (300 °C) is first heated up to 385 °C with heat from the SF and then up to 560 °C with the HP. The model also contains the complete water/steam cycle with steam generator, turbine and generator, which is used for the regeneration of electricity. Although HP and the PB unit are usually not operated simultaneously, this complete model can be used to determine the round-trip efficiency of the process (power to heat to power).

Figure 4 shows that the HP has a relatively low COP of 1.14 when using ambient heat and thus requires a lot of electrical energy. This is primarily due to the large temperature rise that the HP must provide. The heat source has a temperature of 25 °C and the HP must reach over 600 °C to heat the salt to the temperature of the hot storage tank. For reasons of simplification, the figure shows only one compressor and turbine stage each. In the actual design, the plant components may have to be multi-stage.

The two other configurations were also modelled using EBSILON. Higher temperatures of the heat source for the HP will lead to higher COP and thus to savings of electrical energy. In a parabolic trough power plant, it is obvious to use the heat of the solar field also for the HP. For this purpose, the solar field must be dimensioned larger compared to the first configuration. The hot HTF mass flow from the SF is partly used to preheat the molten salt and partly to supply the HP (see Fig. 5). The COP of 1.8 is significantly higher than the COP of the plant in Fig. 4. In contrast to the HP in Fig 4, the HP in Fig .5 has no recuperator. It is not needed because the SF can heat the working medium upstream of the compressor to approx. 385 °C, which in turn corresponds to the temperature of the working medium upstream of the turbine. This means that no heat transfer is possible in the recuperator and this component is obsolete.

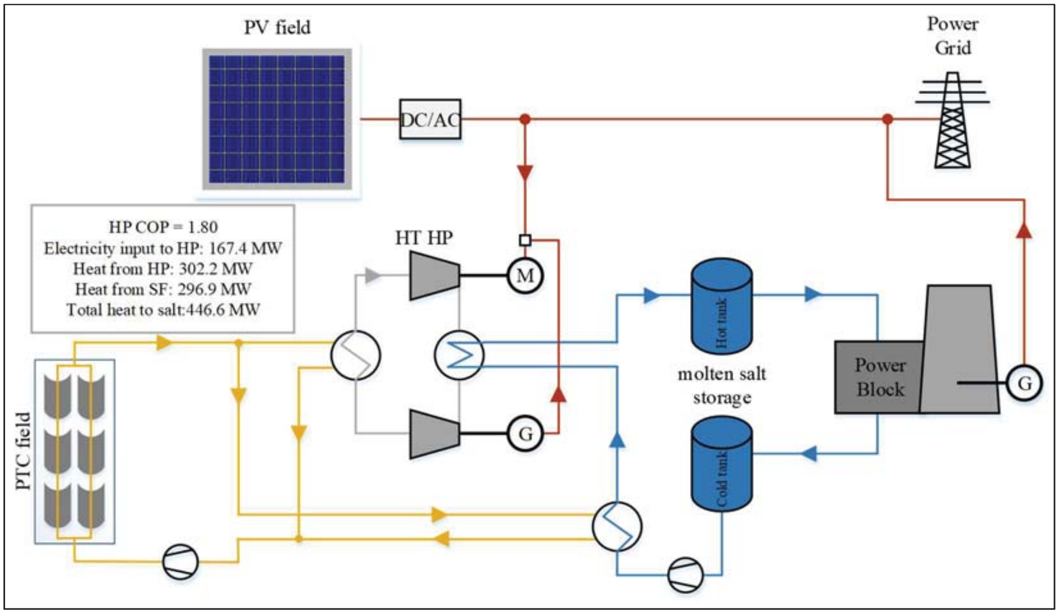

FIGURE 5. Process schematic diagram for the second configuration

In the third configuration, (see Fig. 6**)** the HTF of the SF is used to heat up the cold salt and to supply the HP afterwards. In this case, the heat supplied to the HP is at a lower temperature level, but the average temperature of the HTF in the SF is reduced, which leads to an increase in efficiency in the SF. Therefore, with this configuration, a lower COP of the HP, but a higher SF efficiency can be expected (compared to the configuration in Fig .5). Compared to the configuration with utilization of ambient heat, the COP is higher, but of course, a larger SF is required to supply the HP. The COP is between the COP of the variants in Fig. 4 and Fig .5. Like the configuration in Fig. 5**,** this one is also possible without the need for a recuperator.

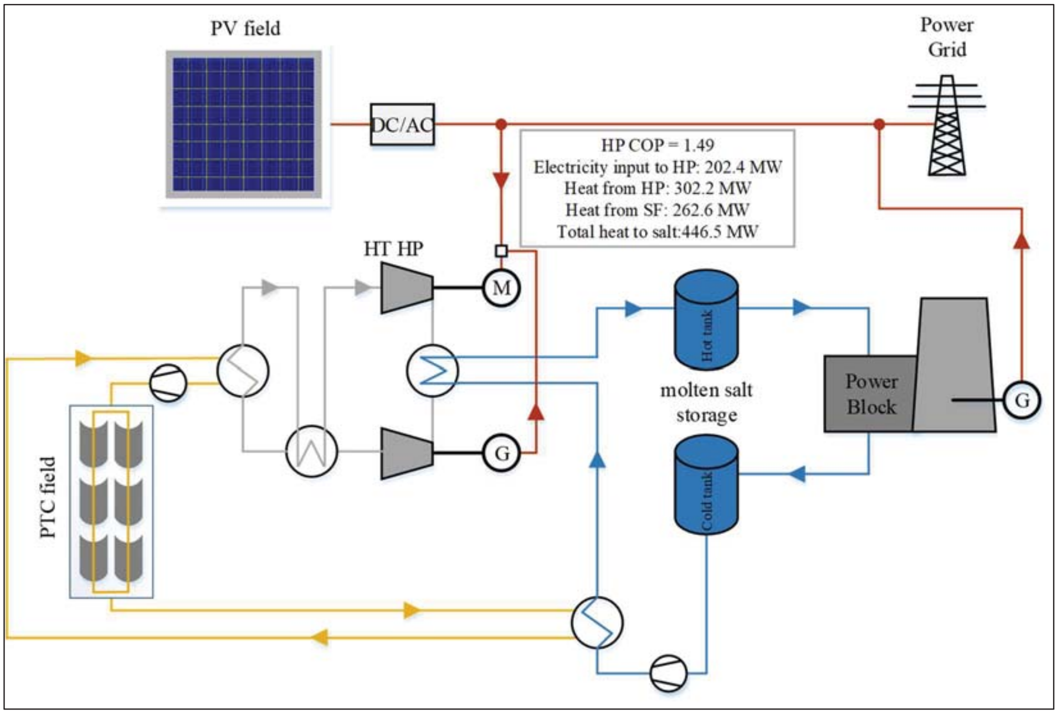

FIGURE 6. Process schematic diagram for the third configuration

Table 2 shows the results of the system designs with EBSILON. It shows that using the cold HTF as a heat source for the HP gives only a very small advantage in SF efficiency over using hot HTF, while the COP is significantly smaller, compared to the parallel configuration.

Using hot HTF as a heat source, on the other hand, promises a high COP and the estimated round-trip-efficiency from electricity to heat to electricity of 70 % also sounds promising.

TABLE 2. System design results with EBSILON

Part	Parameter	Unit	Electrical Heater	HP with Ambient Heat	HP, Heat from SF (series) with Recuperator	HP, Heat from SF (parallel)	HP, Heat from SF (parallel)
Heat Pump	Working Fluid	-	N/A	N2	N2	N2	Ar
	Temperature Heat Source	°C	N/A	25	310	393	393
	Pressure Ratio	-	N/A	2.25	2.3	2.45	1.8
	Heat Input	MW	N/A	56.3	117.9	156.1	153.2
	Electricity Input	MW	305.2	264.7	198.4	167.4	169.4
	Heat Output	MW	302.1	302.1	296.6	302.2	301.5
	COP	-	0.99	1.14	1.49	1.8	1.78
Solar Field	Outlet Temperature	°C	393	393	393	393	393
	Inlet Temperature	°C	310.2	310.2	234.2	301.8	301
	Aperture	m²	246285	246285	450891	482466	508989
	Heat Output	MW	142.4	142.4	257.5	297	294
	Design Efficiency	-	0.6803	0.6803	0.6853	0.6838	0.6797
Storage	Heat Input	MW	446.4	446.4	446.5	446.1	445.7
Overall System	P2H2P efficiency (gross)[1]	%	43.4	50	65.4	79	78.1

Table 3 shows a comparative overview of the required components and their size or rated power for the individual configurations. Compared to the HP solutions without recuperator, the HP solutions with recuperator have the disadvantage that they require this additional heat exchanger, which in the concepts is a high-temperature heat exchanger with gaseous medium on both sides. From these key data, it can be concluded that the recuperator is a large and expensive component with a corresponding cost disadvantage for these configurations.

TABLE 3. Required components and their size or rated power for the individual configurations

Parameter	Unit	Electrical Heater	HP with Ambient Heat	HP, Heat from SF (series) without Recuperator	HP, Heat from SF (series) with Recuperator	HP, Heat from SF (parallel)
Electrical Heater	-	X				
HP: Compressor, Turbine, Piping	-		X	X	X	X
Air / N2 HTEX	-		X			
HTF / N2 HTEX	-			X	X	X
Recuperator	-		X		X	
N2 / Salt HTEX	-		X	X	X	X
Additional CSP Power	MW_{th}			109	120	155
Design PV Power	MW_e	305	265	225	199	167

---

[1] The heat is not included in the value.

CONCLUSION AND OUTLOOK

Different HTF for the HT HP have been simulated and compared. The simulations with Ar have shown the best results for the COP and PR values, nevertheless the necessary system components are in this case more complex and cost-intensive regarding the higher mass flow rates. Therefore, N2 has been chosen as the optimal HTF for the system.

In a second step, different configurations of PV-CSP-HP systems have been developed, simulated in EBSILON®Professional and compared in order to evaluate the concepts from a technical point of view. Identical parameters have been used for the individual components, which enables an objective comparison of the model results.

The simulations have shown that the second concept in which the oil-salt preheater and the heat exchanger at the low temperature side of the HP are connected in parallel has shown the most promising results.

In a next step, a techno-economic analysis for the different concepts will be carried out to evaluate the commercial potential of them and detailed dynamic simulations of the whole systems will be performed, as the next milestone of the SWS project.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the financial support from the LeitmarktAgentur.NRW and the state government of North Rhine Westphalia.

REFERENCES

1. C. Arpagaus, Hochtemperatur Wärmepumpen, Literaturstudie zum Stand der Technik, der Forschung, des Anwendungspotenzials und der Kältemittel. NTB Interstaatliche Hochschule für Technik Buchs; Institut für Energiesysteme (IES) (2017).
2. R. B. Laughlin, Pumped thermal grid storage with heat exchange. Journal of Renewable and Sustainable Energy 4 (2017).
3. IRENA, *Renewable power generation costs in 2019*, <https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Jun/IRENA_Costs_2019_EN.pdf?la=en&hash=BFAAB4DD2A14EDA7329946F9C3BDA9CD806C1A8A>.
4. U. Herrmann, B. Kelly, and H. Price, Two-tank molten salt storage for parabolic trough solar power plants. Elsevier Ltd. 5-6 (2004).
5. HELIOCSP, *Dubai 950 MW Concentrated Solar Power +PV Noor Energy 1 breaks 8 world records*, <http://helioscsp.com/dubai-950-mw-concentrated-solar-power-pv-noor-energy-1-breaks-8-world-records/>.
6. KfW, *Solar Complex Ouarzazate - Morocco*. *Project information*, <https://www.kfw-entwicklungsbank.de/PDF/Entwicklungsfinanzierung/Themen-NEU/Projekt-Marokko-Solar-2016-EN.pdf>.
7. M. Olafsen, Optimization and Process Improvements of a High Temperature Heat Pump using Butane as Working Fluid. Norwegian University of Science and Technology; Department of Energy and Process Engineering (2018).
8. J. Lange, Thermodynamic Design of a Pumped Thermal Energy Storage, Master Thesis. DLR (2018).
9. W.D. Steinmann, The CHEST (Compressed Heat Energy STorage) concept for facility scale thermo mechanical energy storage (2014).
10. M. Morandin, F. Marechal, M. Mercangöz, and F. Buchter, Conceptual design of a thermo-electrical energy storage system based on heat integration of thermodynamic cycles e Part A: Methodology and base case. Elsevier Ltd. (2012).
11. Y.-M. Kim, D.-G. Shin, S.-Y. Lee, and D. Favrat, Isothermal transcritical CO2 cycles with TES (thermal energy storage) for electricity storage. Korea Institute of Machinery and Materials; Swiss Federal Institute of Technology Lausanne (2012).
12. Viking Heat Engines, *HeatBooster HBS4*. *Industrial heat pump for sustainable heat production up to 160 °C*.
13. Energy Storage Technology Descriptions, *Pumped Heat Electrical Storage*, <https://ease-storage.eu/wp-content/uploads/2016/07/EASE_TD_Mechanical_PHES.pdf>.
14. Vipluv Aga et al., *Supercritical CO2-Based Heat Pump Cycle for Electrical Energy Storage for Utility Scale Dispatchable Renewable Energy Power Plants*, <http://sco2symposium.com/papers2016/Thermal/094paper.pdf>.

15. P. Vinnemeier, M. Wirsum, D. Malpiece, and R. Bove, Integration of heat pumps into thermal plants for creation of large-scale electricity storage capacities. Elsevier Ltd. (2016).
16. P. Vinnemeier, M. Wirsum, D. Malpiece, and R. Bove, Integration of Pumped-Heat-Electricity-Storage into Water / Steam Cycles of Thermal Power Plants, 5th International Symposium - Supercritical CO2 Power Cycles. Institute for Power Plant Technology RWTH Aachen; GE Power Baden (2016).
17. A. Dietrich, *Assessment of Pumped Heat Electricity Storage Systems through Exergoeconomic Analyses*, Technische Universität Darmstadt, 2017.